Australian Society of Exploration Geophysicists

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FRONT COVER

Thomas Ostersen in the field. Tom recently completed his PhD at the University of Tasmania on the "Geo-electric structure of the Tasmanian lithosphere from multi-scale magnetotelluric data". See *Education matters* in this issue for more information.

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https://www.tandfonline.com/toc/texp20/current

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Editor's desk

This Christmas issue of *Preview* is not only a bumper issue but comes with bells and whistles. There should be something in these pages for even the most jaded reader!

Don Emerson delivers with a special on "Garnet: The colourful silicate, a speciality mineral" - a gem for the season if there ever was one! We also feature our annual summary of student theses completed in 2021. Twenty seven students contributed to this summary making it clear that specialised training in geophysics is thriving in Australia. Graduates in geophysics should also have their pick of jobs in coming years, as it is pretty clear that we are on the cusp of a boom time in mineral exploration in Australia and around the world. This boom is being driven by the demand for "critical" minerals, or "new economy" minerals in the parlance of the Queensland Government. These "minerals" include some of our old favourites, such as nickel – without which electrification of our economies will not be happening!

In addition to these features we have two technical notes, one on "Metadata standards for magnetotelluric time-series data" and one on "The Australian national differential RTP grid" – meaty stuff!

And, of course, our regular commentators continue to surprise and delight. David Denham (*Canberra observed*) reviews the outcome of COP26. Marina Pervukhina (*Education matters*) interviews Ishtar Barranco from Chevron about what new graduates can expect in her industry. Mike Hatch (*Environmental geophysics*) encourages Dave Allen to describe the development of the AgTEM – a story that is very entertaining! Terry Harvey (*Mineral geophysics*) considers evolution in the application of geophysical techniques. Mick Micenko (*Seismic window*) reviews wavelets, spectra and transforms. Tim Keeping (*Data trends*) investigates domaining, and Ian James (*Webwaves*) marks up and down.

As another COVID year bites the dust, I'd like to thank all *Preview*'s regular contributors - especially our Associate Editors – for their contributions. *Preview* would be nothing without you!!

And, on behalf of the *Preview* team, a very happy festive season and a happy New Year to you all!!

Lisa Worrall
Preview Editor
previeweditor@aseg.org.au

The Editor researching locations for AEM 2023 – any excuse!

Letter to the Editor

Dear Editor

In Roger Henderson's interesting article on "The first measurements of gravity in Australia", which was published on-line last April, he mentions the visit of the Malaspina expedition to Sydney in 1793 and noted that "It is presumed that Malaspina had swung a pendulum there".

There is actually no need for any presumption, because Malspina himself noted in Volume III of his diary (translated into English by John Dunmore and published by the Hakluyt Society in 2004) that "by the 25th … the most detailed experiments had been carried out with the pendulum (p.73)". The site was also specified. It was not at the observatory that had been established by William Dawes, the colony's astronomer, where he had measured gravity in 1788 but, for security reasons "on a point one and a half cables to the east of the corvette". In a footnote Dunmore noted that this placed Malaspina's observatory at the site of today's Sydney Opera House.

Roger also posed the question "What happened to these results? And did they include determinations of gravity?", and once again the question is easily answered. The gravity results were set out and discussed in Appendix III of Josef Espinosa y Tello's "*Memorias sobre las Obervaciones Astronomicas, hechas por los Navegantes Españoles en Distintos Lugares del Globo*". Unfortunately, the descriptions reveal that the accuracy was very low indeed, because the measurements were made by counting the number of full oscillations of the pendulum in one hour. Since this pendulum made 3609 oscillations in one hour at the equator and there is no suggestion of fractional swings being recorded, a one-oscillation error would produce an error of several hundred mGal. The results were barely usable for Malaspina's global reconnaissance (he went to the equator, and as far from it as Alaska), and no use at all for anything else.

The same objection almost certainly would have applied to the results obtained on the *La Pérouse* expedition, but those, again almost certainly, the first gravity measurements to be made in Australia, were lost when the ships of the expedition were wrecked on Vanikoro. There were no survivors. The measurements made by Dawes not only preceded those by Malaspina but were much more accurate, because Dawes measured the timing error of a pendulum clock, which could be observed for days on end.

Regards

John Milsom
gladassoc@btinternet.com

AEGC 2023

The Australian Exploration Geoscience Conference will be returning to Brisbane Convention and Exhibition Centre.

Date
13 - 18 March 2023

Venue
Brisbane Convention and Exhibition Centre

Co-Chairs
- Megan Nightingale
- Bill Reid

S3, The Precinct 12 Browning Street
West End, QLD 4101, Australia

aegc@arinex.com.au
2023.aegc.com.au

AEGC
Australasian Exploration Geoscience Conference

President's piece

Kate Robertson

The ASEG Federal Executive developed a three-year strategic action plan during 2021. This plan was launched during the ASEG Federal Executive's annual Strategy Day (which, due to COVID, was not actually a day but a series of Strategy zoom sessions). Some objectives of the plan are to improve geophysics education, streamline ASEG processes, reward and acknowledge the commitment and service of ASEG volunteers and Members, increase professional development opportunities for Members, position the ASEG during the upcoming energy transition, financially diversify the Society, improve Member value and reverse the decline in membership numbers. We are excited about seeing some changes and progress from these actions over the coming years!

In October, amongst the strategy sessions, I was also happy to chair the virtual ASEG Council meeting. ASEG Secretary Leslie Atkinson describes this meeting in her *Executive Brief*, which also appears in this issue of *Preview*.

In other news, I am sure you're all very aware that the UN Climate Change Conference UK (COP26) was held in Glasgow from 31 October and to 12 November. Research by the Climate Action Tracker found current plans presented by countries in Glasgow would lead to at least 2.4°C of global heating. Whilst the COP27 was supposed to be held in 2026, it will now be held in Egypt in November 2022, giving all parties about a year to revisit and strengthen their 2030 targets to reflect the goals of the Paris Agreement signed in 2015; to hold global temperature rises below 2°C, and strive toward 1.5°C

During the COP26 you may have found yourself defending your profession to friends and family, or perhaps you found yourself in agreement with the media that Australia could have signed up to do more. In it's plan the Australian Government relies heavily on driving down costs of technological advancements to reach Net Zero targets in 2050. Indeed, investing in greener operating methods and emissions reduction technologies to meet emissions targets and decarbonise, such as electrification and use of hydrogen-powered technologies, will be of utmost importance in this quest.

Regardless of the measures put in place by the government, companies are already making changes and taking steps toward a Net Zero future. The International Council on Mining and Metals (ICMM) commits to a goal of Net Zero Scope 1 and 2 Greenhouse Gas (GHG) emissions by 2050 or sooner in line with the ambitions of the Paris Agreement. The ICMM represents companies that make up one-third of the global mining and metals industry, and includes companies such as Anglo American, BHP, Newmont, Newcrest and Vale - just to name a few. Beach Energy and Santos are just two Australian petroleum companies that have Net Zero emissions targets for their own operations by 2050 or earlier. In addition, many companies have released sustainability plans and much greater importance is being placed by investors and customers on companies meeting Environmental, Social and Governance (ESG) criteria.

The implementation of these goals, and the changes that are likely to result, has led to the prediction that the demand for geophysicists will increase. Even with the gradual move away from fossil fuels, near surface characterisation will be hugely important for carbon capture and storage, hydrogen exploration, and the discovery of minerals needed to build renewable technologies.

Attracting students into our profession is critical, and the above-mentioned steps and the announcement of targets by mining and energy companies may help to attract new students who want to ensure that they are making an environmentally conscious career choice.

On 23 November we conducted an ASEG Zoom panel session on the "Challenges and opportunities for geophysics". The discussion focused on the role of geophysics in the move towards a Net Zero future and the associated energy transition. This is a conversation we would love to continue next year, when we are planning to host a one – two day workshop on the topic.

This month we farewell David Annetts from the Federal Executive. David has made a very significant contribution to the leadership of the ASEG over the past seven years, first as webmaster for four years, followed by President Elect, President in our 50th year, and as Immediate Past President. I am especially grateful for David's incredibly valuable mentorship and coaching as I stepped into the President Elect role and then President's role. On behalf of the Federal Executive I would like to extend a huge thank you to David for all of his efforts, and his dedication and commitment to our Society.

I hope all our Members have a very happy and safe Christmas and are able to spend it with their loved ones. I am looking forward to taking several weeks off in January - for a honeymoon after getting married in a hybrid wedding (imagine knowing what that was, back in 2019?!) in early December.

Kate Robertson
ASEG President
president@aseg.org.au

Executive brief

The Federal Executive of the ASEG is the governing body of the ASEG. It meets once a month via teleconference, to deal with the administration of the Society. This brief reports on the monthly meetings that were held in October and November 2021. If there is anything you wish to know more about, please contact Leslie at fedsec@aseg.org.au.

Finances

The Society's financial position at the end of October 2021 was:

Year to date income - $203 705

Year to date expenditure - $269 370

Net assets - $1 175 179

Membership

As of 1 November 2021, the Society had 844 financial Members, compared to 880 at this time in 2020. The ASEG currently has eight Corporate Members, including three Corporate Plus Members. Our state branches also have local sponsors. These sponsors are acknowledged at all branch meetings and at the beginning of all webinars.

A reminder to renew your membership, as your current membership will expire at the end of December. Five-year membership options are available to Active/Associate and Retired members. Early and mid-career members are also encouraged to join the ASEG Young Professionals Network at www.aseg.or.au/about-aseg/aseg-youngprofessionals.

Call for nominations:

The next ASEG AGM will be held on Thursday 7 April 2022, and we are putting a call out for nominations for all those interested in joining the Federal Executive. We have a number of long-standing members who will be stepping down in 2022, so we are on the lookout for new faces. If you have any suggestions or would like to nominate for any position on the FedEx, please contact Leslie at fedsec@aseg.org.au or send your nomination to secretary@aseg.org.au. Please see the nomination form for more details.

The FedEx also has some vacancies on our standing committees and is looking for volunteers to fill these roles.

At the AGM there will be some Constitutional changes that will need to be voted on by the membership. These will be detailed in the February 2022 edition of *Preview*.

Strategy days

The newly elected FedEx committee normally meets for a strategic planning day immediately after the AGM. Due to the on-going restrictions surrounding COVID-19, the usual strategy day was, once again, unable to be held as a face-to-face meeting in 2021. The FedEx committee, instead, held three online meetings to discuss the important issues currently facing the Society. The discussion centered on membership, financials and education, with the focus being on innovative ways to attract and retain Members and students. This year the use of the Miro interactive software made for some entertaining and valuable discussion around these important areas of our Society's future in an increasingly uncertain climate.

Council meeting

The ASEG held a Council Meeting on Tuesday 12 October via Zoom. The President, Kate Robertson, updated attendees on the progress the Society has made over the past 18 months, including the signing of a new contract with our secretariat, the development of a Code of Conduct policy and the formation of a Diversity Committee. Kate also spoke of her initiative in sending care packages to Members heavily impacted by the COVID lockdowns (these were greatly appreciated), and our commitment to keep the Society active during these difficult times.

The AEGC 2021 conference was a great success, despite the need to move it to a fully virtual event. Due to its success, the AEGC 2023 conference committee will investigate hybrid opportunities for the upcoming conference, to be held in Brisbane in March 2023. The recipients of the ASEG Honours and Awards, as well as the winner of the ASEG Research Foundation's Richard Lane Scholarship, announced at the conference were also introduced at the Council meeting.

Finally, a summary of the activities of the various committees was given, along with ideas about how we can make the ASEG voice stronger going forward, and promote the science of geophysics.

Leslie Atkinson
ASEG Secretary
fedsec@aseg.org.au

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
Joseph	Behan	Rio Tinto Iron Ore	WA	Australia	Associate
Conor	Byrne	Byrne Geophysique	WA	Australia	Active
Lauren	Found	Discover Geoscience	WA	Australia	Associate
Timothy	Leonard	Intrepid Geophysics	VIC	Australia	Associate
Benjamin	McCarthy	Qeye	WA	Australia	Active
Lucy	Soares dos Santos	Curtin University	WA	Australia	Student

Invitation for candidates for the Federal Executive

In accordance with Article 8.2 of the ASEG Constitution, "the elected members of the Federal Executive are designated as Directors of the Society for the purposes of the Act". These are the President, President-Elect, Secretary and Treasurer. They shall be elected annually by the Members of the Society at the Annual General Meeting. These office bearers shall succeed the previous ones upon the conclusion of the Annual General Meeting. At the end of their term each officer will retire, but may nominate and be eligible for re-election.

The Federal Executive shall comprise up to 12 members, and shall at least include the four elected members:-

(i) a President
(ii) a President-Elect
(iii) a Secretary
(iv) a Treasurer

These officers will be elected by a ballot of Members.

In addition, the following offices are recognised:

- Vice President
- the Immediate Past President (unless otherwise a member of the Federal Executive)
- the Chairperson of the Publications Committee
- the Chairperson of the Membership Committee
- the Chairperson of the State Branch Committees (unless otherwise a member of the Federal Executive)
- the Chairperson of the Communications Committee
- the Chairperson of the Education committee
- the Chairperson of the Diversity Committee
- Up to three others to be determined by the Federal Executive.

These officers will be appointed by the Federal Executive Committee but nominations will be welcome.

Please forward the name of the nominated candidate and the position for which they are being nominated, together with the names of the nominators, who must be two Members eligible to vote, to the Secretary:

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c/- ASEG Secretariat
PO Box 576, Crows Nest NSW 1585
Tel: +61 2 9431 8622
Fax: +61 2 9431 8677
Email: **secretary@aseg.org.au**

Nominations should be received via post, fax, or email **no later than COB Monday 7 March 2022**. Positions for which there are multiple nominations will then be determined by an online ballot of Members, and results declared at the Annual General Meeting.

ASEG Annual General Meeting

The 2022 Annual General Meeting of the Australian Society of Exploration Geophysicists will take place at:

5:30 pm AEST, on Thursday, 7 April 2022, via Zoom and face-to-face at a venue to be advised.

Be there to make a difference!

For more information, contact ASEG Secretariat at secretary@aseg.org.au, or by telephone on +61 2 9431 8622

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

ASEG Technical Standards Committee: JORC update

Kim Frankcombe and David Pratt have submitted a proposal to Fedex from the Technical Standards Committee regarding the current JORC review. This proposal is summarised below.

The Australasian Code for Reporting of Exploration Results by the Joint Ore Reserve Committee (JORC) has shortcomings with the definition of a Competent Person. Those currently signing off on a stock market or public release documents are required to be either a Member of the AIG or the AusIMM and self-assess that they are suitably qualified and experienced in the subject matter. There is a move by the Australian Stock Exchange (ASX) to have the competency of a Competent Person assessed and confirmed. The suggested way to achieve this has been to require the Competent Person to be an AusIMM, Chartered Professional in the Discipline of Geology (CPGeo) or AIG, Registered Professional Geoscientist (RPGeo). These categories are quite broad and what constitutes sufficient experience in specialised areas is being discussed. The benefit to the public would be that the information provided was accurate and not misleading or false. The benefit to the ASEG would be that geologists learn more about geophysics and that geophysicists are more highly valued by contributing to specialist sections of ASX reports. It would work against the steady decline in the numbers of geophysicists and their relative status within organisations. Having geologists with a better understanding of geophysics may lead them to use geophysical data more often, or at least feel more comfortable with it.

In other news more test ranges for airborne surveying have been a recent topic of discussion and similar ranges for electrical techniques are also on the table. Rio Tinto's query to the committee was thrown to Kim Frankcombe who laments a lack of reproducible IP sites with defined geology. If you share this interest, please inform the committee so that we can begin sharing ideas and drive interest for future research.

Tim Keeping
ASEG Technical Standards Committee Chair
technical-standards@aseg.org.au

ASEG Young Professionals Network: Queensland joint society/student/industry networking bingo night

After a rollercoaster year of increasing and decreasing restrictions, PESA Queensland Division was happy to co-host our first student-industry mixer event for 2021 in October. This event was also our first industry wide event, which was jointly hosted and sponsored by the Queensland Divisions of the AIG, PESA, GSA, IAH and ASEG.

We had fantastic engagement, with 80 people in attendance and a relatively even mix between students and early career and advanced industry professionals. The joint event was a great opportunity for students to network amongst a diverse spread of disciplines: from exploration, petroleum and mineral geologists and geophysicists, to hydrogeologists, academics, and a few engineers for good measure.

The crowd at the mixer event (photo taken by Nick Josephs).

Following a nice priming round of drinks on the bar tab, we opened the evening with a game of networking bingo. This was a 5 x 5 card full of "find and meet someone who…", with options such as; "has worked on a drill rig", "dropped something down a well or sump", "lost something in the field", "worked in another career". We had some beautiful rock samples as prizes for either "single line" winners, or the super awesome meteorite prize for a decidedly harder multi-line combination. It was great to see everyone get involved; the rock prizes seemed to be a good motivator (as they should) with all of them snapped up within about 30-40 minutes. The night continued with nibbles and more drinks, officially wrapping up around 9 pm.

The prizes at the mixer event (photo taken by Nick Josephs).

With such a successful evening under our belts we look forward to running a similar joint society mixer next year.

Kat Gioseffi
PESA Qld Committee Member

ASEG branch news

Australian Capital Territory

The ASEG-ACT chapter have been winding down after furious activity leading up to AEGC 2021, where chapter members from GA, **Neil Symington**, **Anandaroop Ray**, **Yusen Ley-Cooper**, **Richard Taylor** and **Ross C. Brodie** won the best near surface geophysics paper award for probabilistic integration of AEM data and sonic bore salinity measurements in the Kimberley.

The ASEG-ACT Committee organised a Christmas lunch on 27 November – which was a welcome opportunity to catch up with colleagues - and are in the process of scheduling technical talks for next year.

Anandaroop Ray
actpresident@aseg.org.au

New South Wales

With summer around the corner, NSW is gradually opening up again, so cheers to field work in regional NSW, going back to the office, and beers at the pub! After a tough year, we're all looking forward to finally kicking off summer with the NSW Branch Annual Dinner at the Australian Heritage Hotel on 1 December.

While we were still in lockdown in October, ASEG NSW hosted a Zoom event, **Dr Sam Matthews** (GSNSW) and **Astrid Carlton** (GSNSW) presented a "GSNSW Geophysical Update". Sam explained how starting with the QA/QC of metadata harvest of legacy geophysics data, an algorithm was applied to quantitatively aid survey selection for merging the high-resolution company data. He also included a small workshop to demonstrate to attendees how to access this data through the GSNSW online portal; MinView. Astrid discussed the many and varied surveys currently occurring in NSW from 2021 and into the future, including Cobar AEM and AMR surveys and the Mundi AEEM survey. Watch this space!

An invitation to attend NSW Branch meetings is extended to interstate and international visitors who happen to be in town at the time. Most talks are livestreamed on Zoom and uploaded to ASEG's YouTube page later, so you also have the option to join us online. Meetings are generally held on the third Wednesday of each month from 5:30 pm at Club York. News, meetings notices, addresses and relevant contact details can be found at the NSW Branch website. All are welcome.

Stephanie Kovach and Jim Austin
nswsecretary@aseg.org.au
nswpresident@aseg.org.au

Queensland

In October the Qld Branch welcomed **Randall Taylor** of Taylor Exploration Consulting who presented a talk on "The OZ Min Explorer Challenge 2019: When petroleum explorers go searching for minerals". Randall presented a comprehensive overview of his team's contribution to the OZ Min challenge, giving us all food for thought on different methods of collating, reviewing and summarising large datasets. For minerals geophysicists it was great to see how seismic data could be expertly integrated with more traditional mineral exploration methodologies.

Following on from the virtual ASEG Award Ceremony at the AEGC, the Queensland Branch was proud to host a joint in-person awards night with our annual Trivia Night hosted jointly with PESA. Thanks to the Awards Committee for sending through the awards. We were able to present **Mal Cattach** with his ASEG Gold Medal, **Henk Van Paridon** with his Honorary Membership and **Fiona Duncan** with her ASEG Service Certificate. The Trivia, as always, was expertly hosted by Henk and nearly 40 attendees fought it out in a tight contest which included a biscuit identification round and some rockin' tunes.

*Mal Cattach receiving his ASEG Gold Medal from James Alderman and **Jim Wordsworth** (GAP GM).*

Our last planned hybrid online and in-person technical talk of the year was on 16 November, when **Peter Fullagar** presented the second part of his talk from earlier in the year titled "Beyond plates – fast TEM inversion using conductive ellipsoids".

We look forward to our joint end of year Christmas Party with PESA, FESQ, QUPEX and SPE on 25 November.

Finally we would like to thank all our members for their contributions during another tough year for many in the industry, and we look forward to more engaging events in 2022.

James Alderman
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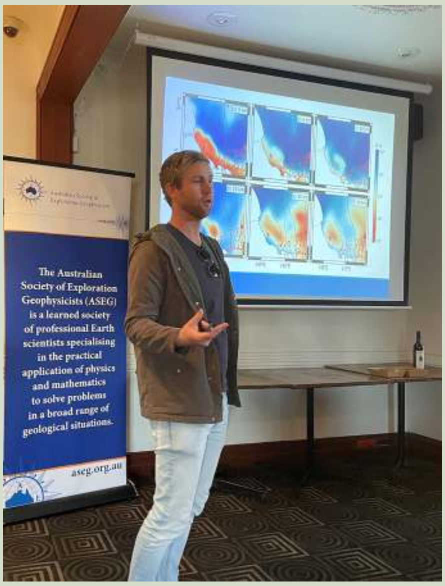
South Australia & Northern Territory

On 5 October we had **Sam Jennings** from the University of Adelaide present at the Coopers Alehouse where members were given new insight into the origins of the Newer Volcanic Province. Sam's talk entitled "Crustal resistivity of the Mt Gambier sub province: origins of the Newer Volcanic Province and implications for exploration in the Western Otway" was well received. He discussed the origins of the NVP, the role of complex basement structures in providing fluid pathways and the implications of a distal melt source for exploration in the Western Otway Basin.



Sam Jennings from the University of Adelaide presenting his talk entitled "Crustal resistivity of the Mt Gambier sub province: origins of the Newer Volcanic Province and implications for exploration in the Western Otway".

We had our Spring Fling networking event at the Havelock Hotel on Thursday 21 October. This event is jointly run by the ASEG, SPE, YPP and PESA. It was great to have the event outside with the weather warming up and is always great to catch with new and old friends.

Attendees at the annual Spring Fling networking night at the Havelock Hotel.

ASEG SA/NT Branch Melbourne Cup lunch attendees cheering on the race.

The SA/NT Branch had our annual Melbourne Cup luncheon with 58 Members and guests at the Premiership Suite at the Adelaide Oval. It was great to have **Neil Gibbins** from Vintage Energy back as our MC on the day and a big thank you to Sam Jennings and **Josh Sage** for organising the event and ensuring the day ran smoothly. The food was fantastic and it was great to see everyone getting into the Calcutta sweep again this year.

*ASEG Federal President **Kate Robertson** presenting long standing Member **Danny Burns** with the ASEG Service Medal at the Melbourne Cup lunch*

We had our annual Student Honours Presentation night on Thursday 11 November and were excited to hear talks on their Honours projects by **Emily Lewis** "Bottom-Up Exploration: Imaging Resistivity of a Mineral System from Source to Sink", **Yi He** "Curnamona Cube: 3D Lithospheric Architecture of a Proterozoic Province", and **Alex Hill** "Hunting Palaeorivers in the Gippsland Basin using 3D Seismic Datasets: Drainage Landscapes of the Southeastern Australian Continental Shelf".

On Friday 3 December we'll be ending the year with a bang with our Annual Industry and Christmas night. This is always a great way to hear what our sponsors have been up to while getting into the Christmas spirit for a fun night at the Coopers Alehouse.

As usual, we couldn't host any of our fantastic events without the valued support of our sponsors and we look forward to seeing as many of you as possible at the upcoming events. The SA/NT Branch is sponsored by **Beach Energy**, **Borehole Wireline**, **Oz Minerals**, **Vintage Energy**, **Minotaur Exploration**, the **SA Department for Energy and Mining**, **Zonge**, **Santos** and **Heathgate**.

Ben Kay
sa-ntpresident@aseg.org.au

Tasmania

Tasmanian student **Zak Weidinger** is the winner of the inaugural ASEG RF Richard Lane Scholarship. Zak, who is in the process of completing an honours degree in geophysics at the University of Tasmania, wins $5000. Zak's supervisors are **Matt Cracknell, Clare Miller** and **Mike Roach**.

Matt Cracknell, the Tasmanian Branch Secretary presenting a $5000 cheque to Zak Weidinger.

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 keep an eye on the seminar/webinar 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
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ASEG news

Victoria

There are 30 cows in a field and 28 chickens. How many didn't?

If you answered 10, congratulations – you are quite the thinker. Raise your hand if you are still wondering how the sentence even makes any sense. Yup, this one stumped me, too. My eight year old daughter came home from school the other day and lobbed this pre-teen vernacular at me. I had to write it down on paper. I read it, re-read it then saw red. How could this be possible? Pow! It hit me like a wrecking ball (solution below). For all my education, social interaction and life experiences, I was thoroughly bamboozled.

In any case, this confusing riddle inexplicably led me to contemplate a little more about the AI (Artificial Intelligence) revolution that is upon us, the so-called Fourth Industrial Revolution. Could AI have helped solved this riddle? Could it have predicted a reasonable outcome? Maybe. Maybe not. Maybe if the right (correct?) question was asked to begin with. Maybe if an eight year old was allowed to train the AI with enough riddles - or maybe, in that case, it would just answer with another riddle…

So, this is happening, and it is happening fast. AI, ML (Machine Learning), DL (Deep Learning), IoT (Internet of Things) and other technologies are impacting every facet of almost every industry today. You name it - from healthcare to education, banking and financial services, to retail and e-commerce, gaming and entertainment, the automotive industry and of course, the geosciences – the list goes on. The resources industry has a terribly effective habit of acquiring all manners of data it can think of, and at breakneck speed. If we're not collecting data, we're reprocessing it, re-imaging it, re-creating it, re-shaping it or simply reducing it fit for purpose. Then there's data that has been acquired some time ago, perhaps even decades ago - historical data. Data that was previously recorded, that became awkward, too difficult or simply dismissed and not followed up due to a plunging gold price. While this data isn't necessarily lost (or is it?), it has certainly been overlooked, neglected, perhaps even forgotten. Big data is exploding, and historic big data is problematic such that it's been quietly swept under the rug. I notice there has been a reasonably slow up-take for AI services in our industry, probably because of the low number of specialist vendors out there, but it will only be a matter of time until these opportunities accelerate through rapid adoption. Our conventional wisdoms in assessing, appraising and interpreting most of this data simply doesn't cut the mustard. It's ok to ask for help. Whether we like it or not, there is a data-supernova coming, assuming isn't already here!

The Victoria Branch miraculously organised one final technical meeting night for 2021 on November 25, and it was an in-person meeting! **Ian Nielson,** chief geologist of First AU, tried to convince us that there might be another Fosterville lurking in Eastern Victoria with his talk titled "The Land that Time Forgot: The Victorian Eastern Goldfields". Any bookies on here willing to give me 10:1 odds against? And finally, the Victoria Branch would like to announce one final event for the calendar year. ASEG Victoria, together with PESA and SPE societies, have agreed to host a joint Christmas luncheon in mid-December. A final date, venue and guest speaker will be announced in due course, but it should be a cracker! Please keep an eye out for notifications (I have one last rabbit to pull out of the hat regarding this luncheon) 👈

Before the year is out, the Victoria Branch committee would like to say thank you to all members for their support, patronage, and observance after enduring another wretched COVID plagued year. I wish you all a superb Christmas and a wonderful New Year. Don't forget to renew your membership for 2022. Onwards and upwards!

Solution: *'28' chickens could be read as twenty 'ate' chickens. Think you're smarter than an 8 year old now?*

Thong Huynh
vicpresident@aseg.org.au

Western Australia

Hi fellow geos, once again from Perth. WA ASEG has been pretty active and will continue to be active right through the rest of the year. Our October Tech night was well-attended - at the Shoe Bar in Yagan Square in the Perth CBD. **Barry Bourne**, Principal Consultant and Founder of Terra Resources presented an interesting talk on the "Petrophysics of the Paterson Orogen and implications for exploration" in that very prolific (and Nifty) area. Barry received a well-deserved bottle of wine from ASEG for his efforts. Just before the talk it was my honour to present **Katherine McKenna** with the ASEG 50th Anniversary Special Award for her many contributions and career achievements. Thanks, Kath!

The October Tech Night was the last Tech Night of the year. On 24 November, the WA ASEG hosted an all-day face-to-face minerals case-study symposium ("MAG21") in Kings Park (Perth, of course). A tonne of work was required to organise this, so kudos to our MAG21 team.

Barry Bourne presenting to the WA Branch.

Kath McKenna receiving her ASEG 50th Anniversary Special Award from Todd Mojesky.

WA also sponsored another symposium, a student earth science symposium ("GESSW-WA"), which was held at Curtin on 25 November. We have been busy…

And lastly, we will be holding our AGM and Christmas Party at the Stables Bar in Perth CBD on the evening of 16 December. At that time I'll be announcing to the general public that I'll be abdicating my presidency, and that our local secretary will also be leaving. Bittersweet, but there you go.

Stay happy and healthy, people, and keep strong that healthy interest in the doings of the Earth.

Todd Mojesky
wapresident@aseg.org.au

ASEG national calendar

Date	Branch	Event	Presenter	Time	Venue
ASEG Branch face-to-face meetings have been disrupted in many states due to COVID outbreaks. Some branches are hosting webinars. Registration is open to Members and non-members alike, and corporate partners and sponsors of state branches are acknowledged before each session. Recorded webinars are uploaded to the ASEG's website (https://www.aseg.org.au/aseg-videos), as well as to the ASEG's YouTube channel (https://bit.ly/2ZNglaZ). Please monitor the Events page on the ASEG website for the latest information about upcoming webinars and other on-line events					
25 Nov	QLD	Christmas party	Various	16:00	Jade Buddha 14/1 Eagle St, Brisbane City
1 Dec	NSW	Annual dinner	Various	1800	Australian Heritage Hotel, Sydney
3 Dec	SA/NT	Annual Industry and Christmas night	Various	TBA	Coopers Alehouse, 316 Pulteney St, Adelaide
15 Dec	Vic	ASEG-PESA-SPE Lunch	Michael Asten	12:00	The Kelvin Club, Melbourne
16 Dec	WA	AGM and Christmas Party	Various	17:00	The Stables, Perth

The ASEG in social media

Have you liked/followed/subscribed to our social media channels? We regularly share relevant geoscience articles, events, opportunities and lots more. Subscribe to our Youtube channel for recorded webinars and other content.

Email our Communications Chair Millicent Crowe at Communications@aseg.org.au for suggestions for our social media channels.

Facebook: https://www.facebook.com/AustralianSocietyOfExplorationGeophysicists

LinkedIn company page: https://www.linkedin.com/company/australian-society-of-exploration-geophysicists/

Twitter: https://twitter.com/ASEG_news

YouTube: https://www.youtube.com/channel/UCNvsVEu1pVw_BdYOyi2avLg

Instagram: https://www.instagram.com/aseg_news/

Geoscience Australia: News

Geoscience Australia, in collaboration with its state and territory partners, finished the year with another solid programme of strategic geophysical surveying around the continent. The Geological Survey of Queensland's Canobie airborne gravity programme, the Northern Territory Geological Survey ground gravity programme over the eastern Tanami, and the extension of AusArray through southern Northern Territory - all managed in conjunction with Geoscience Australia - will also see regional geophysical surveying continue well into the ides of December.

With this *Preview* edition, we are also pleased to announce the completion of the Western Australia regional airborne EM programme across southern Western Australia (AusAEM20). The final release of data is expected in January following a release of the south-western blocks last month (documented below). Figure 1 and the tables following this section show GA-managed survey status as of November 2021.

AusAEM coverage through Western Australia

Geoscience Australia and Western Australia (Department of Mines, Industry Regulation and Safety) commissioned the 'AusAEM-20' survey as part of the national airborne electromagnetic acquisition programme, to complete 20 km line separation AEM coverage over Western Australia. The 60 000-line km programme was jointly acquired by geophysical contractors Xcalibur (fixed-wing Tempest) and SkyTEM (rotary wing) throughout 2021. Acquisition was completed in November 2021.

All fixed-wing data (covering the central to eastern portions) were released earlier in the year, with the first phase of the rotary component (covering the south coast, blocks A -D), released during this quarter. Table 1 details survey specifications, with flight lines shown in Figure 2.

Figure 3 shows an example of the quality of the data, including stacked profiles and GA inversion results on line 100901, just to the south of Peel Inlet and the township of Pinjarra. Saltwater incursion into Tertiary gravels and sands of the Perth Basin limit EM penetration until east of the inlet, where a number of conductors within the Jurassic give some idea to the variation in depth to sub-basin depo-centres. Further along, the rise into the Darling Ranges is clearly identified by a steeply dipping conductive sheared gneiss of the Darling Scarp contact, with more resistive granitic terrain continuing to the east. While somewhat noisier, this resistive terrain has a depth of investigation well

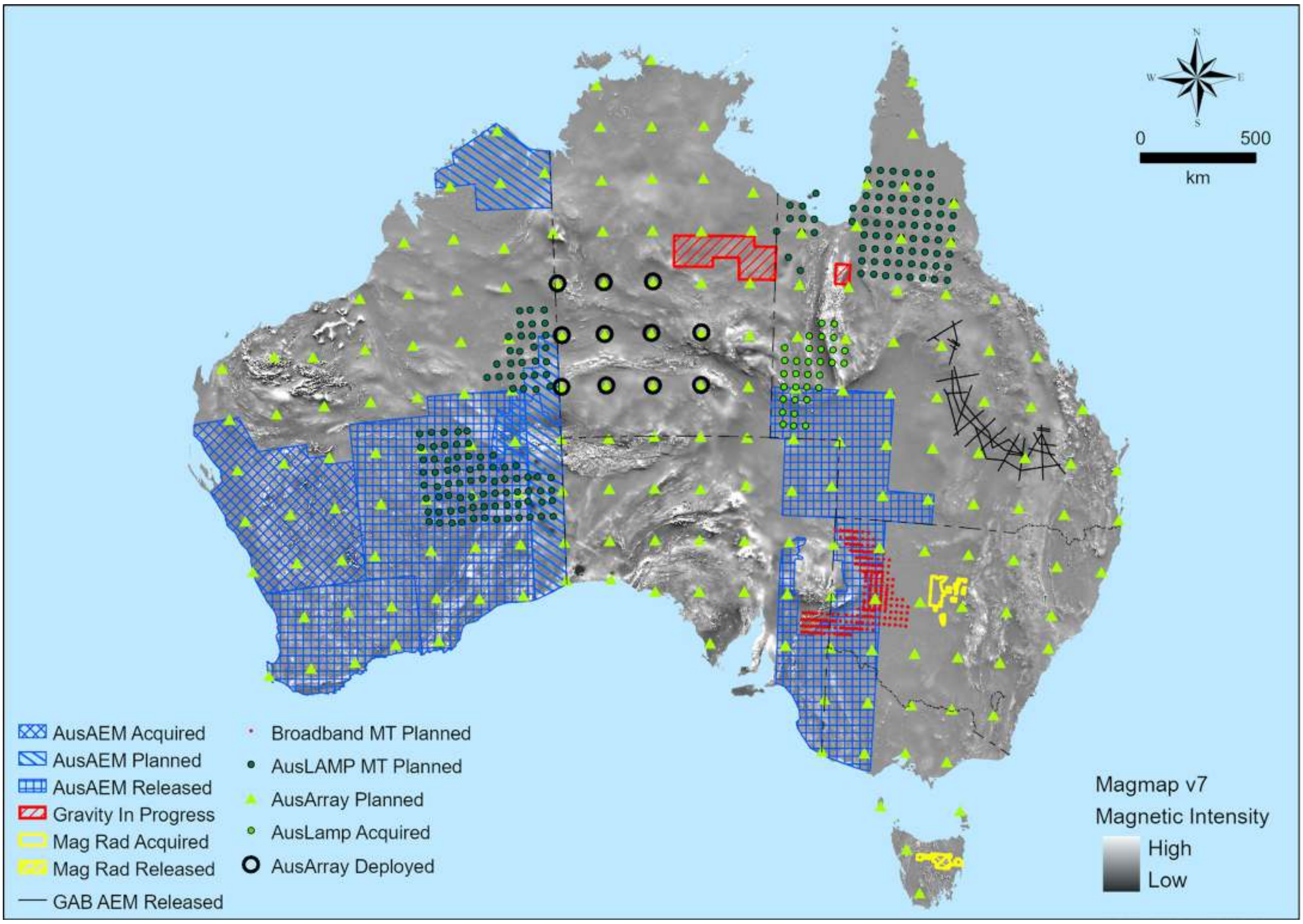

Figure 1. *2020 -2021 geophysical surveys – in progress, planned or still for release by Geoscience Australia in collaboration with State and Territory agencies. Background image of national TMI compilation, Geoscience Australia, 2019.*

Table 2. Survey specifications for Southwest-Albany Airborne Electromagnetic survey blocks as part of AusAEM20 (WA) programme.

Survey name	SkyTEM AusAEM-WA, Southwest-Albany Airborne Electromagnetic survey
State	Western Australia
Custodian	Geoscience Australia
Contractor	SkyTEM Australia Pty Ltd
Aircraft	Company United Aero Helicopter Type AS350 B3
AEM system	SkyTEM312 FAST (Interleaved Low Moment and High Moment)
Line spacing	20 km
Line direction	E-W and N-S variable line direction
Total survey line kilometres	12 500 km
Nominal terrain clearance	45 – 60 m (nominal) above ground level
Survey start date	October 2020
Survey end date	April 2021

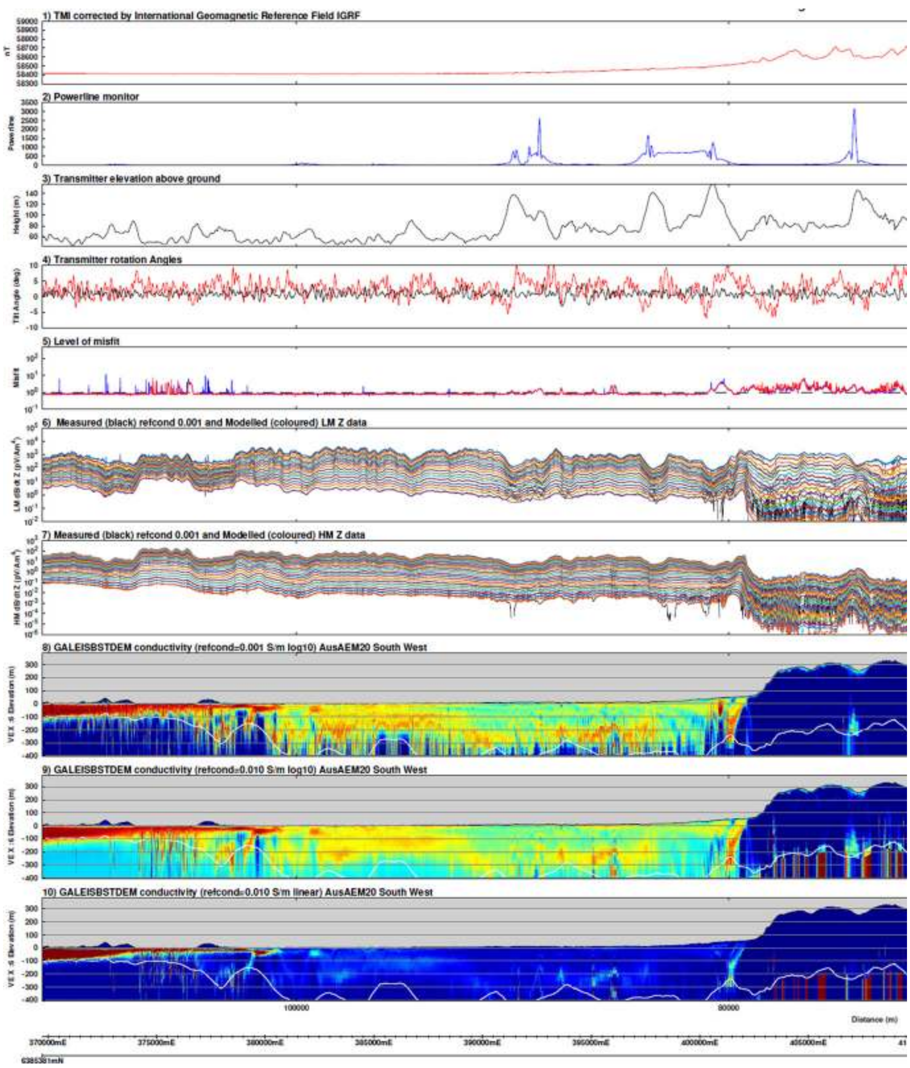

Figure 3. *Multi-plot presentation of the western end of Line 100901, AusAEM20 (WA). Line segment location is approximately half way up the green section of Figure 2. Stacked profiles presented with GA's own GALEIBSTDEM inversion results, with reference models of 0.001 and 0.01 S/m.*

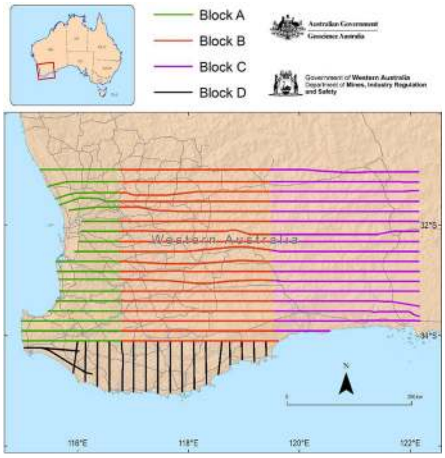

Figure 2. *Locality map of the AusAEM-WA, Southwest-Albany Airborne Electromagnetic survey showing the regional (20 km line spacing) flight lines. Flight lines have been deliberately deviated to intersect geological points of interest, including outcrops, boreholes, locations with mineral occurrences and over areas with known kimberlite and meteorite impacts.*

into the hundreds of meters, allowing the identification of even subtle conductive features at depth.

The data, inversions and survey details can be downloaded through Geoscience Australia's catalogue at: https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search#/metadata/146042 or via the Geological Survey of Western Australia's portal at: https://magix.dmirs.wa.gov.au/surveys/view-survey/3098 (survey notes) and https://geodownloads.dmp.wa.gov.au/downloads/geophysics/71588/ (data).

Many thanks to the geophysical team at the Geological Survey of Western Australia for designing, planning and facilitating AusAEM20, along with their ongoing assistance with project management and stakeholder engagement. We are also truly appreciative of the dedication of the two contracting teams: Xcalibur and SkyTEM, for delivering such high quality data and for showing consideration to all stakeholders and executing the programme with zero safety incidents.

Mike Barlow
Geoscience Australia
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 November 2021).

Further information about these surveys is available from Mike Barlow Mike.Barlow@ga.gov.au (02) 6249 9275 or Ron Hackney Ron.Hackney@ga.gov.au (02) 6249 5861).

Table 1. Airborne magnetic and radiometric surveys

Survey name	Client	Project management	Contractor	Start flying	Line km	Line spacing Terrain clearance Line direction	Area (km^2)	End flying	Final data to GA	Locality diagram (*Preview*)	GADDS release
Tasmanian Tiers	MRT	GA	MAGSPEC	Mar 2021	Up to an estimated 25 000	200 m 60 m N–S or E–W	4300	Apr 2021	May 2021	See Figure 1 in previous section (GA News)	https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search#/metadata/145547
Cobar	GSNSW	GA	GPX	Jun 2021	53 000	200 m	11 600	Aug 2021	Sep 2021	See Figure 1 in previous section (GA News)	Nov 2021

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 (km^2)	End survey	Final data to GA	Locality diagram (*Preview*)	GADDS release
Canobie	GSQ	GA	Xcalibur	Nov 2021	~5000	1–2 km	5300	Dec 2021	Jan 2021	See Figure 1 in previous section (GA news)	TBA
Brunette Downs Ground Gravity	NTGS	GA	Atlas Geophysics	Oct 2021	~ 12 000	2 x 2 km grid	55 000	TBA	TBA	TBA	TBA
Melbourne, Eastern Victoria, South Australia	AusScope GSV DEL WP	GA	Sander Geophysics	TBA	137 000	0.5–5 km	146 000	TBA	TBA	See Figure 1 in previous section (GA news)	TBA
Kidson Sub-basin	GSWA	GA	Xcalibur Multiphysics	14 Jul 2017	72 933	2500 m	155 000	3 May 2018	15 Oct 2018	See Figure 1 in previous section (GA news)	Set for release Feb 2022
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	Set for release Feb 2022
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	Set for release Feb 2022
Warburton-Great Victoria Desert	GSWA	GA	Sander Geophysics	Warb: 14 Jul 2018 GVD: 22 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	Set for release Feb 2022
Pilbara	GSWA	GA	Sander Geophysics	23 Apr 2019	69 019	2500 m	170 041	18 Jun 2019	Final data received Aug 2019	See Figure 1 in previous section (GA News)	Set for release Feb 2022
SE Lachlan	GSNSW/ GSV	GA	Atlas Geophysics	May 2019	303.5 km with 762 stations	3 regional traverses	Traverses	Jun 2019	Jul 2019		Set for incorporation into the national database in 2021

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
Eastern Resources Corridor	GA	GA	Xcalibur Multiphysics	Apr 2021	32 000	20 km	640 000	Jul 2021	Oct 2021	See Figure 1 in previous section	Oct 2021 http://pid.geoscience.gov.au/dataset/ga/145744
Mundi	GSNSW	GA	NRG	Mar 2021	1900	2.5	~ 5000	Apr 2021	Dec 2021	See Figure 1 in previous section (GA News)	Oct 2021
AusAEM20	GSWA	GA	Xcalibur Multiphysics & SkyTEM	Aug 2020	62 000	20 km	1 240 000	Nov 21	Dec 2021	See Figure 1 in previous section (GA News)	TBA. Survey in production

TBA, to be advised

Table 4. Magnetotelluric (MT) surveys

Location	Client	State	Survey name	Total number of MT stations deployed	Spacing	Technique	Comments
Northern Australia	GA	QLD/NT	Exploring for the Future – AusLAMP	366 stations deployed in 2016–19 32 stations deployed in 2021	50 km	Long period MT	The survey covers areas of NT and Qld. Data package: http://pid.geoscience.gov.au/dataset/ga/134997 Model: http://pid.geoscience.gov.au/dataset/ga/145233 News article: http://www.ga.gov.au/news-events/news/latest-news/exploring-for-the-future-takes-a-deeper-look-at-northern-australia Acquisition of 32 new sites in SW Qld completed mid-2021, data to be released late 2022 together with additional data planned to be acquired under Exploring for the Future during 2022.
AusLAMP NSW	GSNSW/GA	NSW	AusLAMP NSW	~300 stations deployed 2016-21	50 km	Long period MT	Covering the state of NSW. Acquisition is essentially complete with fewer than 10 sites remaining to be acquired or reacquired. Phase 1 data release: http://pid.geoscience.gov.au/dataset/ga/132148.
Southeast Lachlan	GSV/GSNSW/GA	VIC/NSW	SE Lachlan	Deployment planned to commence early/mid-2021	~4 km	AMT and BBMT	~160 stations in the Southeast Lachlan. Acquisition delayed due to COVID-19 travel restrictions.
Spencer Gulf	GA/GSSA/UofA/AuScope	SA	Offshore marine MT	12 stations completed	10 km	BBMT	This is a pilot project for marine MT acquisition. https://www.auscope.org.au/news-features/auslamp-marine-01 Preliminary results were presented at the Australasian Exploration Geoscience Conference in Sep 2021.

TBA, to be advised

Table 5. Seismic reflection surveys

Location	Client	State	Survey name	Line km	Geophone interval	VP/SP interval	Record length	Technique	Comments
Central Darling Basin	CINSW	NSW	Central Darling seismic survey	~208	10 m	10 m	6-16 sec	2D high resolution and deep crustal seismic	GA and CINSW signed MoU to acquire and process 2D high resolution and deep crustal seismic data in Central Darling Basin. New seismic data will be acquired, processed and interpreted to assist in proving up a geological resource in NSW for the safe and permanent storage of CO_2 emissions. The additional seismic data obtained will provide greater certainty in the future drilling exploration programme. The data acquisition was completed in May 2021. CINSW contracted Velseis to process the data and the GA seismic team is QCing the processing of this dataset. Processing of these data started in Jul 2021 and is due for completion by the end of 2021.

(*Continued*)

Table 5. Seismic reflection surveys (*Continued*)

Location	Client	State	Survey name	Line km	Geophone interval	VP/SP interval	Record length	Technique	Comments
Officer Basin	GA	SA	Shallow legacy data	~2000	Varies	Varies	3-6 sec	2D shallow legacy data, explosive, vibroseis	GA commissioned reprocessing of selected legacy 2D seismic data in the Officer Basin, South Australia, as part of the Exploring for the Future programme. The objective is to produce a modern, industry-standard 2D land seismic reflection dataset to assist industry to better target areas likely to contain the next major oil, gas and mineral deposits. Reprocessing by Velseis is complete and data have been QC'ed. Release of the Velseis direct processed data package is planned for Nov 2021. A Velseis direct processed data package is available on request to clientservices@ga.gov.au.
Officer Basin	GA	SA	L137 Officer Basin	550	40 m	240 m	20 sec	2D deep crustal seismic explosive reflection seismic	GA commissioned reprocessing of 2D legacy deep crustal seismic data in the Officer Basin, South Australia, as part of the Exploring for the Future programme. The objective is to produce a modern, industry-standard 2D land seismic reflection dataset to assist industry to better target areas likely to contain the next major oil, gas and mineral deposits. Reprocessing by Velseis is complete and data have been QCed. A GA website data package (images, segy and metadata) is available from http://pid.geoscience.gov.au/dataset/ga/74944 A Velseis direct processed data package is available on request to clientservices@ga.gov.au
Pedirka Basin	GA	SA	Shallow legacy data	~2000	Varies	Varies	3-6 sec	2D shallow legacy data, explosive, vibroseis	GA commissioned reprocessing of selected legacy 2D seismic data in the Pedirka Basin, South Australia, as part of the Exploring for the Future programme. The objective is to produce a modern industry standard 2D land seismic reflection dataset to assist industry to better target areas likely to contain the next major oil, gas and mineral deposits. Reprocessing of these data by Geofizika started in May 2021 and is planned to be complete by the end of Nov 2021
Eastern Goldfields	GSWA	WA	L132 1991 Eastern Goldfields Seismic	260	40 m	160 m	20 s	2D deep crustal seismic explosive reflection seismic	Project completed. GSWA/GA MoU covered reprocessing of legacy explosive data acquired by GA's predecessor agency, the Bureau of Mineral Resources in 1991. GSWA contracted Velseis Processing Pty Ltd. to reprocess these data set using modern processing techniques, which were unavailable at the time of the original data acquisition and initial processing. GA provided QC and monitoring of the reprocessing. The improved seismic data complements other geoscience datasets in GSWA's Eastern Goldfields Reinterpretation Project, and GSWA's Accelerated Geoscience Program. The work was funded by the WA Government's Exploration Incentive Scheme. Data release on GA website: http://pid.geoscience.gov.au/dataset/ga/74951
Central Darling Basin	Coal Innovation NSW (CINSW)	NSW	Central Darling seismic survey	~208	10 m	10 m	6-16 sec	2D high resolution and deep crustal seismic	GA and CINSW signed an MoU to acquire and process 2D high resolution and deep crustal seismic data in the Central Darling Basin. New seismic data will be acquired, processed and interpreted to assist in proving up a geological resource in NSW for the safe and permanent storage of CO2. The new seismic data obtained will provide greater certainty in planning for future drilling. Data acquisition was completed in May 2021. CINSW contracted Velseis to process the data and the GA seismic team is QCing the processing of this dataset. Processing of these data started in Jul 2021 and is due for completion by the end of 2021.

(*Continued*)

Table 5. Seismic reflection surveys (*Continued*)

Location	Client	State	Survey name	Line km	Geophone interval	VP/SP interval	Record length	Technique	Comments
2019 Camooweal 2D Seismic Survey Archiving Project	GSQ	Qld	Camooweal seismic survey	~300	30 m	10 m	20 s	2D deep crustal seismic	Under a MOU with GSQ, GA is preparing a Data Processing Package for the 300 line km 2019 Camooweal 2D Seismic Survey. This data package will support an interpretation project being undertaken by GSQ to produce new precompetitive geoscience information to assist industry in better targeting areas likely to contain significant gas and sedimentary-hosted mineral deposits.

Table 6. Passive seismic surveys

Location	Client	State	Survey name	Total number of stations deployed	Spacing	Technique	Comments
Australia	GA	Various	AusArray	About 180 temporal seismic stations	~200 km spacing	Broad-band ~18 months of observations	The survey will cover all of Australia to establish continental-scale model of lithospheric structure and serve as a background framework for more dense (~50 km) movable seismic arrays. Deployment of this national array commenced with an initial 11 seismic stations deployed in the NT and will progress to other States and Territories depending on the pace of land clearance process and the status of COVID-19 travel restrictions.
Northern Australia	GA	QLD/NT	AusArray	About 265 broad-band seismic stations	50 km	Broad-band 1 year observations	The survey covers the area between Tanami, Tennant Creek, Uluru and the Western Australia border. The first public data release of the transportable array was in 2020, with further data and model releases expected by Dec 2022. See: http://www.ga.gov.au/eftf/minerals/nawa/ausarray Various applications of AusArray data are described in the following Exploring for the Future extended abstracts: · AusArray overview: http://pid.geoscience.gov.au/dataset/ga/135284 · Body wave tomography: http://pid.geoscience.gov.au/dataset/ga/134501 · Ambient noise tomography (including an updated, higher resolution model for the Tennant Creek to Mount Isa region): http://pid.geoscience.gov.au/dataset/ga/135130 Northern Australia Moho: http://pid.geoscience.gov.au/dataset/ga/135179
Australia	GA	Various	AusArray, semi-permanent	12 high-sensitivity broad-band seismic stations	~1000 km	Broad-band 4 years observations	Semi-permanent seismic stations provide a back-bone for movable deployments and complement the Australian National Seismological Network (ANSN) operated by GA, ensuring continuity of seismic data for lithospheric imaging and quality control. Associated data can be accessed through http://www.iris.edu

Mineral Resources Tasmania: New state wide data stitches

Mineral Resources Tasmania has produced new state wide stitches of magnetic and radiometric data, incorporating the Tiers survey flown in February-March 2021 in collaboration with Geoscience Australia (Figure 1). As with previous versions, the merged data set includes offshore surveys acquired by Geoscience Australia. Despite the new addition, the state wide compilation still contains data from surveys as far back as 1966.

Images and grids of the revised data merge and derivatives including first vertical, tilt and analytic signal are being rolled out through MRT's usual channels, including the website (https://www.mrt.tas.gov.au/home), online map viewer and web mapping services (for dynamic online viewing in your GIS), as well as new versions of the 1:500 000 scale state wide maps made available in PDF, ECW and JPG formats.

The new data merges are being introduced to the local geoscience community at the Tasmanian Geoscience Forum. The 2021 edition of this now-traditional event, at which several other aspects of MRT's recent work will also be presented, is being held at the Tullah Lakeside Lodge in western Tasmania on 2 December 2021.

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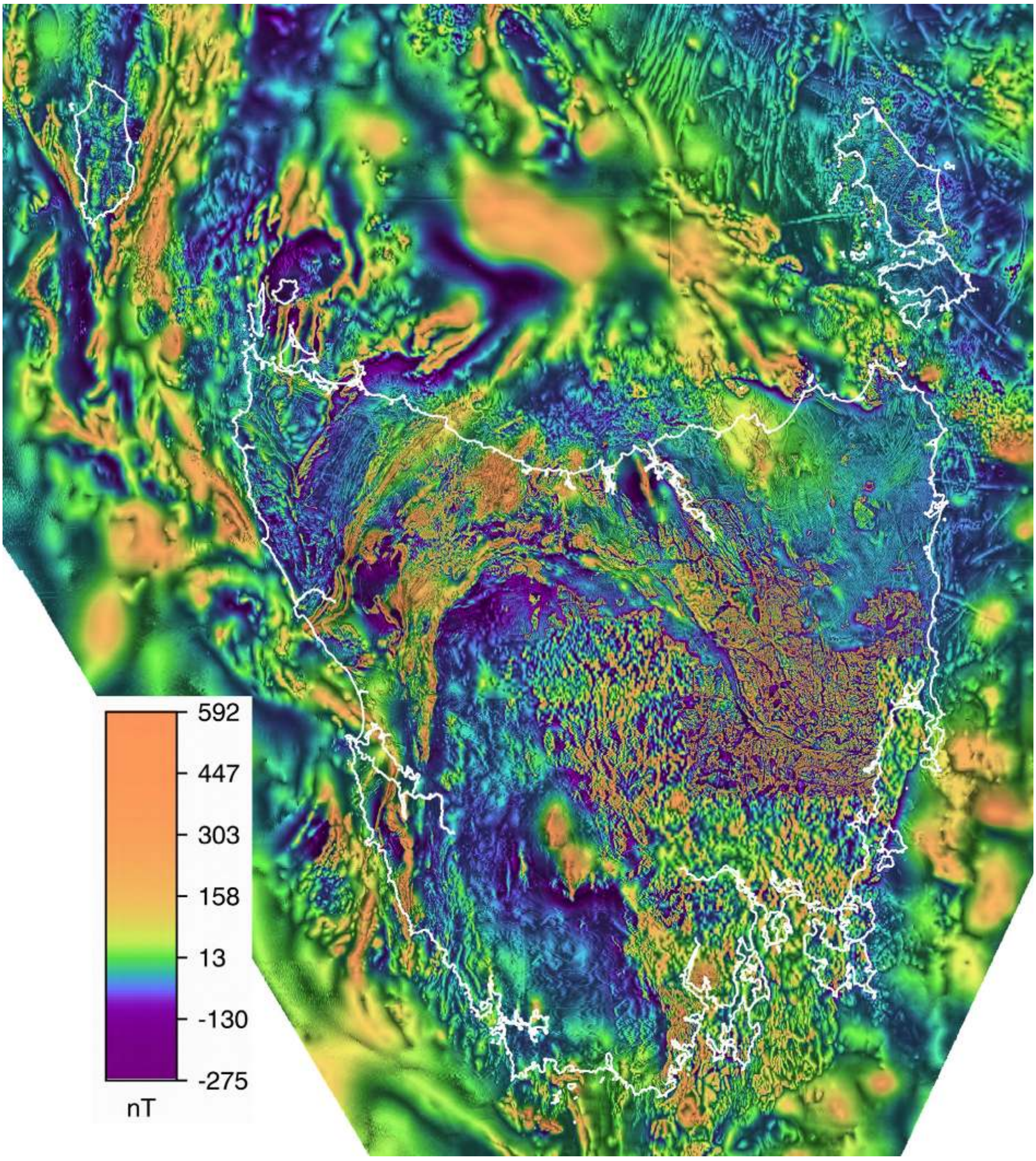

Figure 1. *New total magnetic intensity compilation for Tasmania and surrounds, output histogram equalised after clipping to 99.5% (the full non-anthropogenic IGRF-removed data range is from -1600 to well over 20000 nT), intensity shaded by tilt angle (Miller and Singh 1994).*

Geological Survey of New South Wales: Update

The Mining, Exploration and Geoscience (MEG) group in the Department of Regional New South Wales (DRNSW) aims to make NSW the number one mining investment destination in Australia. NSW is experiencing a mineral exploration boom as companies search for high-technology metals. There are many reasons that make NSW an attractive location for exploration. These include NSW's relatively under-explored terrains, excellent infrastructure that supports regional development, our cooperative drilling programmes, a strong mining regulatory framework with workable legislation to support environment and community obligations, and our world class pre-competitive data.

Titles Management System

DRNSW's new Titles Management System (TMS) is an online application that gives industry end-to-end management of exploration and mining titles with increased transparency and accountability.

TMS has a user dashboard that displays real-time multi-stage status tracking of lodged applications. Users can also pay application and pre-grant fees via a secure payment portal, attach documents post lodgement, view correspondence, and receive system notifications.

TMS is also used for annual reporting and allows the user to upload geophysical surveys acquired over/on their tenement. Data must be submitted in standard formats to ensure usability and interoperability. These data can be made open-file after five-years. Open-file geophysical surveys are made publicly available through MinView. Large, high-quality airborne magnetic and radiometric surveys are incorporated into our state-wide merges, which can also be found on MinView.

MinEx Collaborative Research Centre (CRC)

MinEx CRC is the world's largest mineral exploration collaboration, bringing together industry, government, research organisations and universities. The project will further our understanding of geology, minerals and groundwater in areas that are under cover. GSNSW is a major participant in the MinEx CRC project and has committed $16M to the programme over ten years. Work commenced in 2018 and GSNSW is focused on five areas in NSW that are known extensions of mineralised terrain under cover in regional NSW.

Geophysical surveys are an integral component of this project; with details of surveys completed and proposed provided in the 2021 August edition of *Preview*. These surveys support geological interpretation to target areas for stratigraphic drilling using the Deeper Exploration Technologies CRC coiled-tubing drill rig.

MinView

MinView is GSNSW's online application that makes it easy to view and access open-file and pre-competitive data. Geophysical survey data, images and grids can be downloaded and viewed in various ways through MinView. For instructions on how to download state wide geophysical imagery or grids, and survey data watch this instructional video:

https://www.youtube.com/watch?v=dwEQkiYeWXc&t=1386s

MinEx CRC Cobar Airborne Magnetic and Radiometric (AMR) survey

DRNSW's Geological Survey, with Geoscience Australia, coordinated an AMR survey over the greater Cobar and Nyngan region (Figures 1 and 2). The survey was undertaken as part of GSNSW's commitment to MinEx CRC.

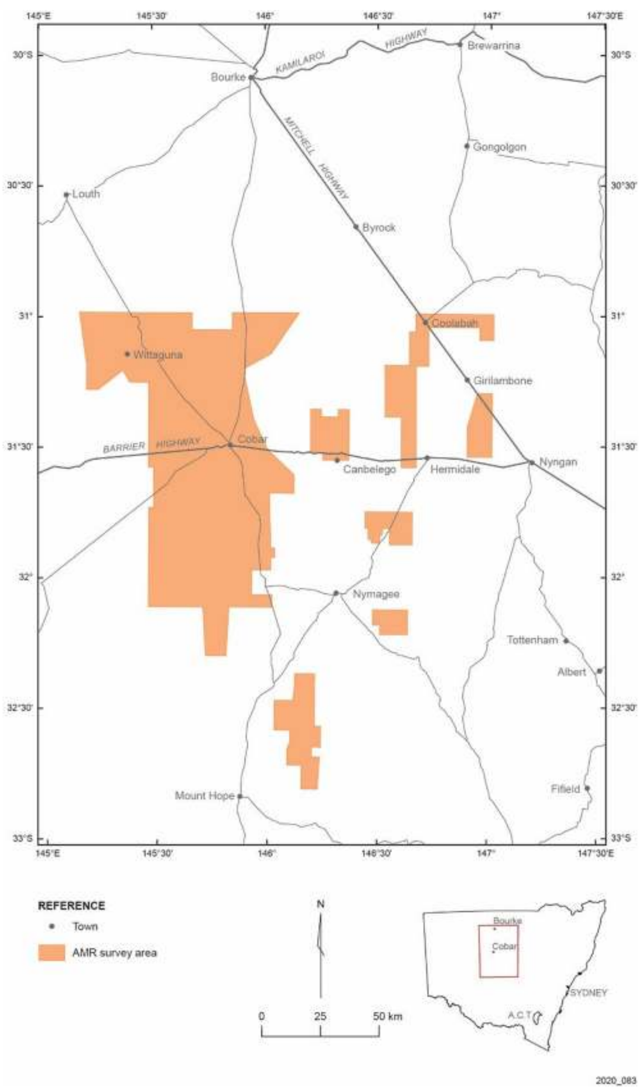

Figure 1. *Map showing MinEx CRC Cobar AMR survey area.*

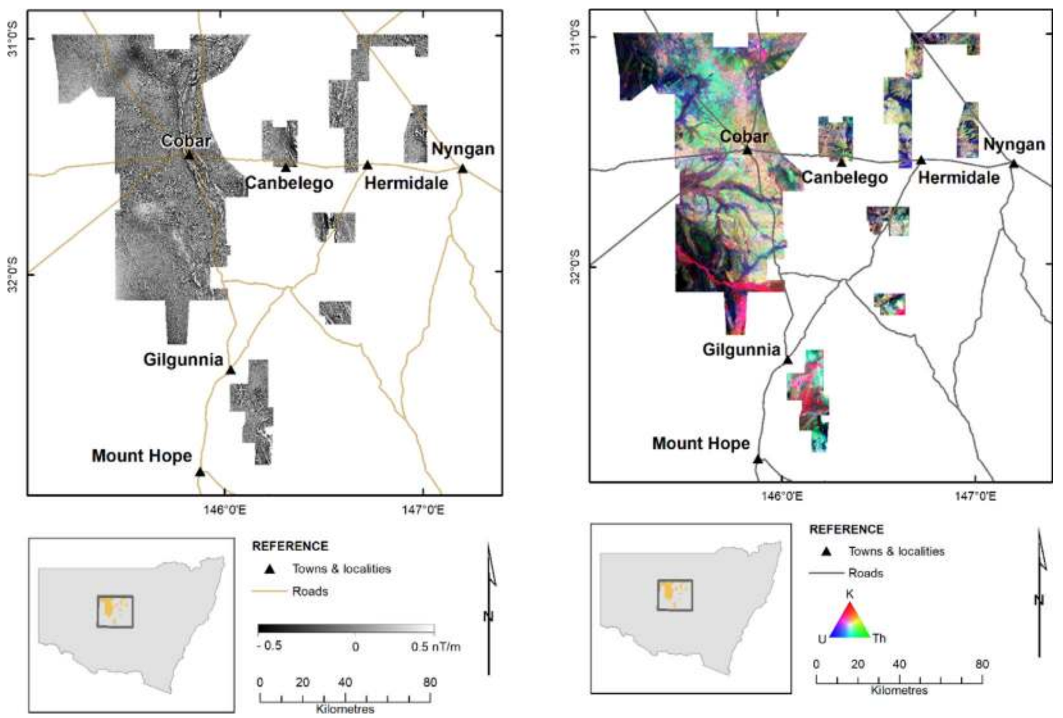

Figure 2. *Maps showing first vertical derivative of the total magnetic intensity (left) and ternary radiometric (Right) images from MinEx CRC Cobar AMR survey.*

GPX Surveys was contracted to undertake the survey. 53 513 line km were acquired 60 m above the ground along lines spaced 200 m apart. Some areas were flown with a closer line spacing as part of industry-funded infill. Government-funded data acquired is available for download through our on-line application MinView, with one industry infill area already released and available for download. The remaining infill areas will be available publicly in December 2022 through MinView.

The survey has filled gaps in our existing coverage and improves the resolution where existing surveys have a wider line spacing. The Cobar region has a long exploration history and there are many geophysical surveys covering the area, some Government funded, others by exploration companies. Open-file company surveys have been used in our state wide merge, with government surveys planned around existing open-file surveys. Some of the company surveys used were acquired in the 1970s, which modern survey standards now supersede.

The shape of the Cobar AMR survey is irregular for a government survey as it has been designed to:

- Replace company data that no longer meets modern standards
- Avoid areas where higher-resolution company data exists (that will be open-file soon)

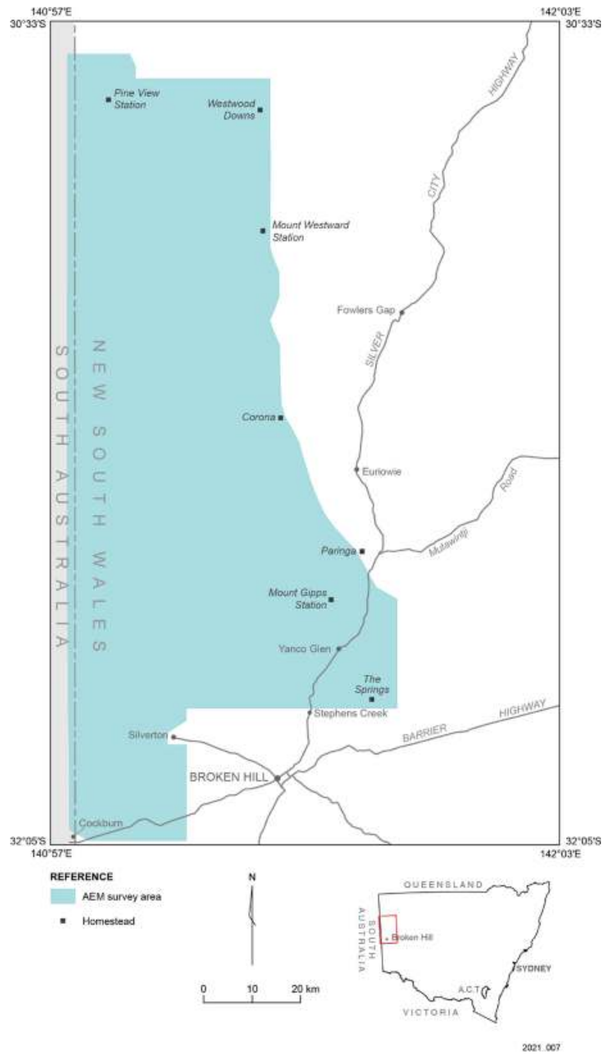

Figure 3. *Map of showing MinEx CRC Mundi AEM survey area.*

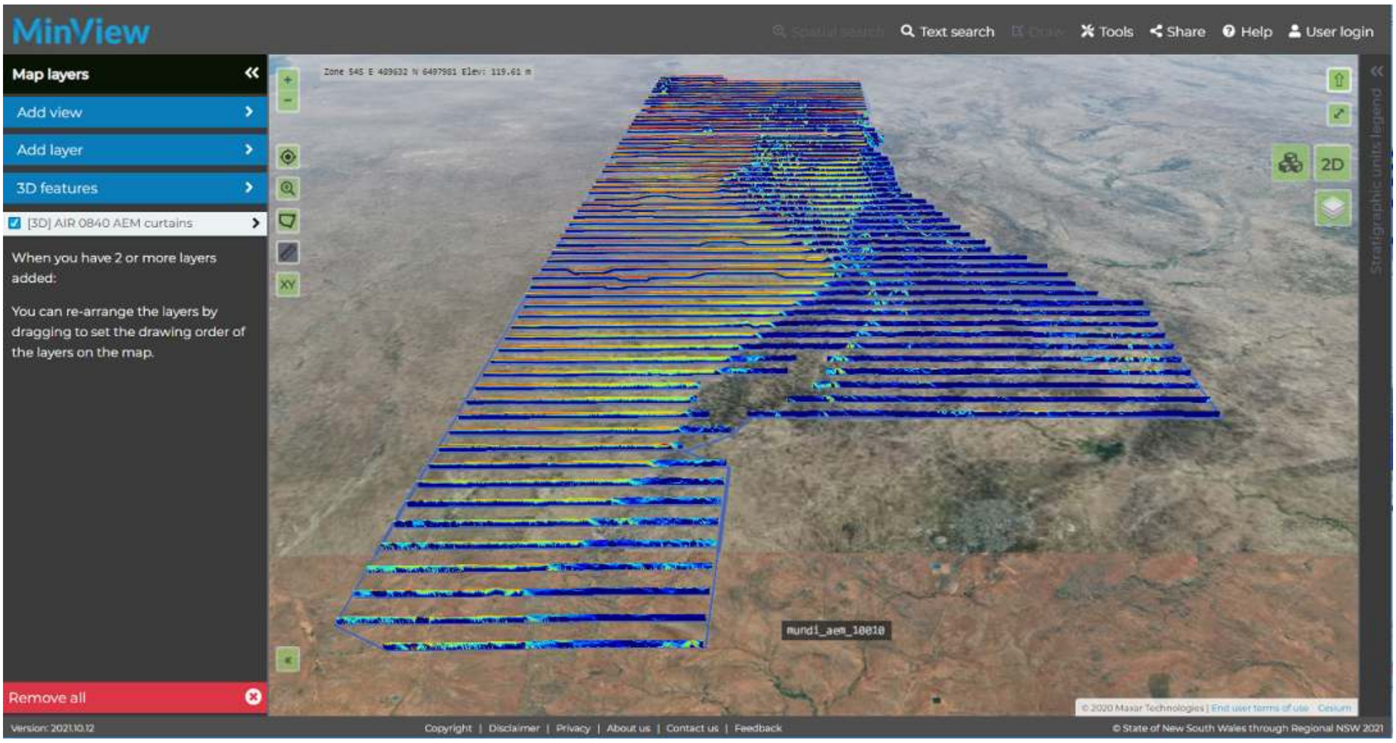

Figure 4. *Screen capture showing MinEx CRC Mundi AEM sections in MinView in 3D.*

- Fill gaps in our radiometric data, as old company surveys were often flown without a spectrometer.

MinEx CRC Mundi Airborne Electromagnetic (AEM) survey

In April 2021, The Geological Survey and Geoscience Australia's Exploring for the Future programme coordinated an AEM survey over the Mundi Mundi Plains, north west of Broken Hill (Figure 3).

New Resolution Geophysics (NRG™) carried out the survey using their Xcite™ system. A total of 2940 line km were acquired with the sensor at a height of 30 m above the ground, along 66 east–west lines. Lines were typically around 40 km long and spaced up to 5 km apart. Lines deviated from east–west to fly over drill holes and waterbores.

The data acquired is available for download or viewing on MinView (Figure 4). To view the data in 3D click on the '2D' button on the right-hand side, then zoom to you area of interest. To tilt the view press 'Ctrl', left click and drag the cursor.

The programmes and surveys above would not have been possible without the technical, project-management and in-kind support of our collaborative partners, including Geoscience Australia and MinEx CRC. We would also like to thank the various geophysical contractors for their commitment to data quality, safe operations and maintaining good relations with our community stakeholders.

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The ASEG in social media

Have you liked/followed/subscribed to our social media channels? We regularly share relevant geoscience articles, events, opportunities and lots more. Subscribe to our Youtube channel for recorded webinars and other content.

Email our Communications Chair Millicent Crowe at Communications@aseg.org.au for suggestions for our social media channels.

Facebook: https://www.facebook.com/AustralianSocietyOfExplorationGeophysicists

LinkedIn company page: https://www.linkedin.com/company/australian-society-of-exploration-geophysicists/

Twitter: https://twitter.com/ASEG_news

YouTube: https://www.youtube.com/channel/UCNvsVEu1pVw_BdYOyi2avLg

Instagram: https://www.instagram.com/aseg_news/

Geological Survey of South Australia: New state wide magnetic imagery and an update on the AusArray SA and Lake Eyre Basin passive seismic arrays

New state wide magnetic imagery

The geophysicists at the Geological Survey of South Australia have created new state wide magnetic imagery, incorporating the new Gawler Craton Airborne Survey (GCAS) data and other newly released public-domain survey data. This suite of images (Figure 1) represents the 2021 update to previous South Australian magnetic datasets and derivatives.

Total Magnetic Intensity (TMI) is the magnitude of all magnetic influences measured at a point. The SA_TMI grid was produced by merging company and government survey grids within South Australia using Intrepid Software by Intrepid Geophysics. A series of geophysical products used in geological interpretation have been derived from SA_TMI also using Intrepid (see individual descriptions below).

Data is provided in the ERMapper Raster (ERS) and georeferenced TIFF (GeoTIFF) image formats. ERS files are set in the SA Lambert projection with technical details in the accompanying ERS text file. Each grid has been gridded to a cell size of 80 m.

The suite of grids include:

- SA_TMI, a total magnetic intensity grid of South Australia.
- SA_TMI_VRTP, a variable reduction to pole (RTP) grid of SA_TMI.
- SA_TMI_VRTP_1VD, the 1st Vertical Derivative of SA_TMI_VRTP.
- SA_TMI_VRTP_TILT, the TILT angle of the SA_TMI_VRTP.
- SA_TMI_VRTP_AS, the analytic signal of the SA_TMI_VRTP.
- SA_TMI_VRTP_AGC, the automatic gain control filter of the SA_TMI_VRTP.
- SA_TMI_VRTP_Tz, the vertical component of the SA_TMI_VRTP.
- SA_TMI_VRTP_Tzz, the vertical gradient of the SA_TMI_VRTP.
- SA_TMI_VRTP_Cauchy_3rd, a 3rd order derivative of the SA_TMI_VRTP.
- SA_TMI_VRTP_PseudoGravity, the pseudo gravity of the SA_TMI_VRTP.
- SA_TMI_VRTP_BigT, the amplitude of the total vector of the SA_TMI_VRTP.
- SA_TMI_VRTP_BigE, a gradient of the magnetic strength in the SA_TMI_VRTP.

Some comments on individual components are included below.

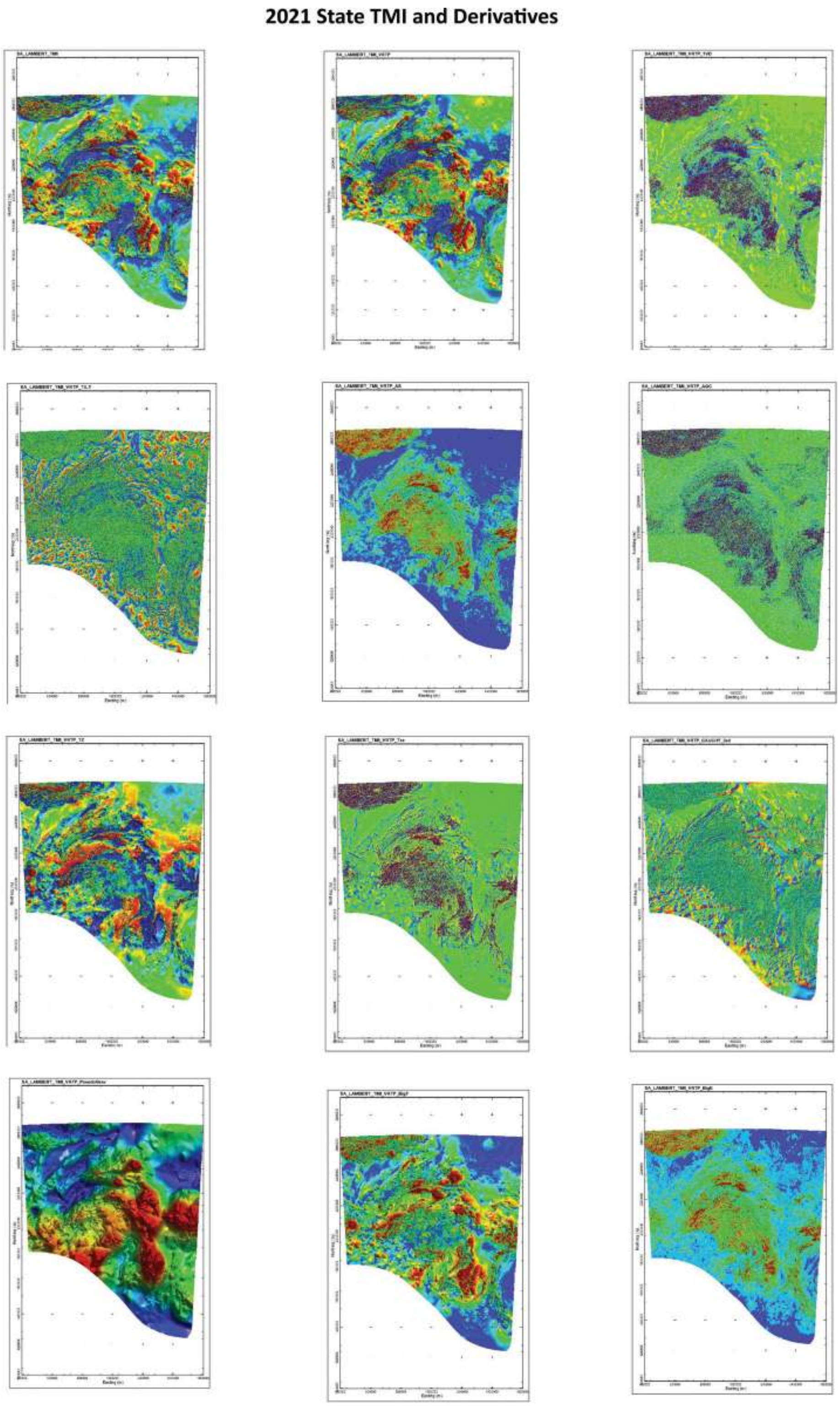

Figure 1. *2021 State TMI and derivatives.*

TMI_AS: AS = (dt / dx ^ 2 + dt / dy ^ 2 + dt / dz ^ 2)

Where t = the magnetic anomaly.

All bodies with the same geometry will have the same analytic signal (AS). The peaks of the analytic signal functions are symmetrical and occur directly over the edges of wide bodies. Over narrow bodies, the peaks occur over the centres, therefore, the AS in principal provides indications of the magnetic source geometry.

TMI_BigT: BigT = sqrt(Tx* Tx + Ty* Ty + Tz* Tz)"

In case of induced magnetisation only, the curvature of RTP and BigT should be in sync, if not there is the likelihood of remanence. So if the RTP tilt (curvature) is negative and the BigT tilt is positive there is remanence. This works quite well on sharp (near surface) anomalies but fails in basin areas.

TMI_BigE: BigE = sqrt(((Txx+ Txy+ Txz)* (Txx+ Txy+ Txz) + (Txy+ Tyy+ Tyz)*(Txy+ Tyy+ Tyz) + (Txz+ Tyz+ Txz)*(Tzz+ Txy+ Txz))/2)"

TMI_TZ: TZ is the vertical component of the total magnetic field (TMI) derived by a phase transform.

TMI_Tzz: Combination of Txx and Tyy provide a measurement in the downward component (Tzz - vertical gradient).

TMI_VRTP: The RTP "Reduction to the pole" filter attempts to transform the input field data by converting the frequency components to that which would be observed at the Earth's pole. Anomalies at low magnetic latitudes which are generally asymmetric in appearance will be converted to symmetric anomalies directly over the source body. The VRTP filter consists of the standard RTP filter, where the dataset is divided into a number of tiles. The origin longitude and latitude vary for the centre of each tile. This process endeavours to increase the RTP result over large areas.

TMI_VRTP_AGC: The Automatic Gain control filter (AGC) converts magnetic waveforms of variable amplitude into waveforms of close to constant amplitude. This removes amplitude characteristics from the grid file and results in a grid that equalises the high and low amplitudes.

TMI_VRTP_TILT: The tilt filter calculates the arctan of the angle between the vertical gradient and the horizontal gradient of the magnetic field (VRTP).

TILT = arctan(dM/dz / sqrt(dM/dx ^2 + dM/dy ^2))

Where M = the magnetic anomaly.

All images are available for free download via SARIG (https://map.sarig.sa.gov.au/). For assistance with downloads please contact Customer Services (dem.customerservices@sa.gov.au).

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Update on the AusArray SA and Lake Eyre Basin passive seismic arrays

Over the course of several trips from mid-August to mid-October, the GSSA carried out the second service run of the AusArray SA broadband passive seismic array. With our ANU collaborators unable to enter South Australia due to COVID restrictions, the GSSA also took on the mantle of servicing the Lake Eyre Basin seismic array (Figures 1 and 2). Having racked up a cumulative 14 500 km in our trusty LandCruiser, we are pleased to have another tranche of seismic data to analyse and fresh batteries and memory cards in the seismic stations to see them through the coming summer.

The composite AusArray SA and Lake Eyre Basin array will shed light on the 3D seismic structure of the eastern Gawler Craton and its margins. Data from the permanent stations of the Australian National Seismic Network and Australian Seismometers in Schools program, and from preceding temporary arrays, will also be leveraged (Figure 1).

A range of passive seismic modelling techniques will be applied to map the structure of the eastern Gawler Craton from the upper crust to the lithosphere-asthenosphere boundary (e.g., body and surface wave

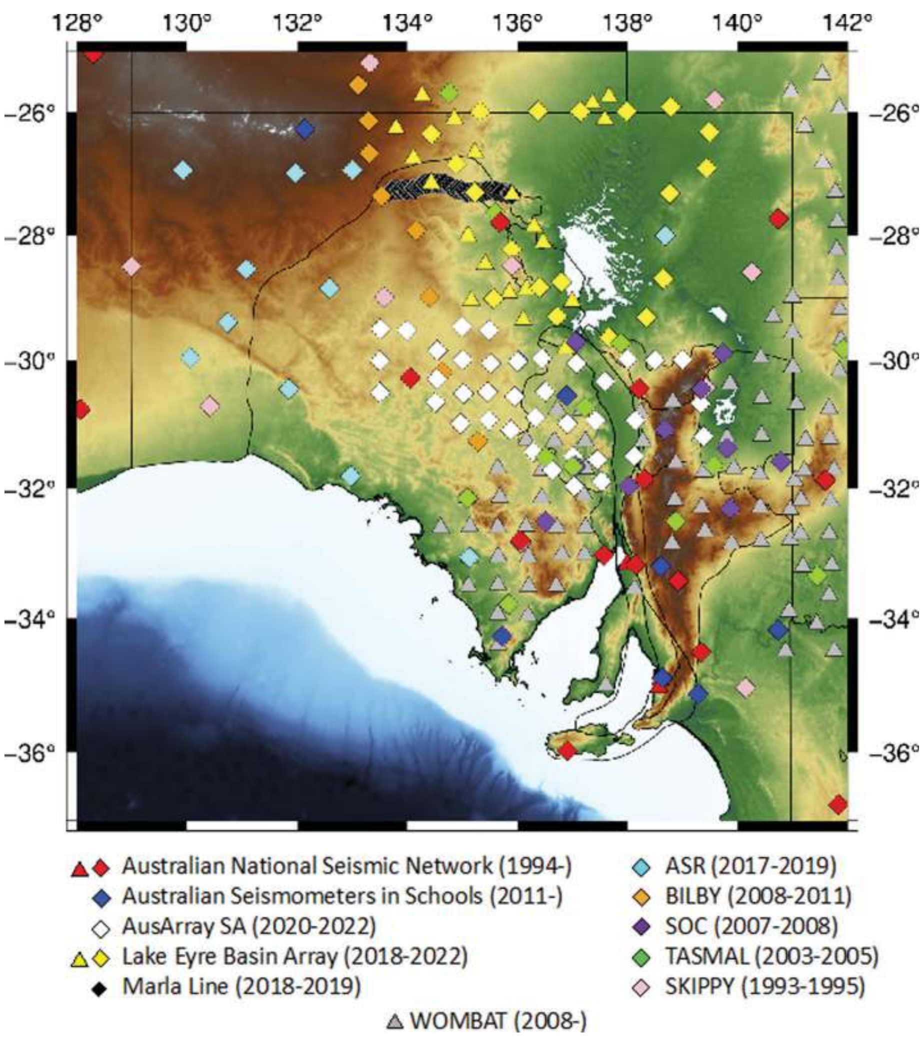

Figure 1. *Passive seismic stations in South Australia, past and present.*

Figure 2. *Auscope's Goran Boren servicing an AusArray SA broadband seismic station close to Lake Finniss in August 2021. The digitiser, logger, battery and solar panel are protected from animal interference by the metal mesh enclosure. The exposed seismometer can be seen in the hole at bottom right.*

tomography, variably using teleseismic earthquakes, local earthquakes and the ambient noise field for illumination; receiver functions; noise autocorrelation; shear wave splitting; Love-to-Rayleigh scattering; seismicity mapping). Furthermore, the contrasting sensitivities of seismic and magnetotelluric data to factors including temperature, composition, fluids and melt will facilitate a more robust identification of primary indicators of mineral prospectivity such as metasomatism and fluid pathways.

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Geological Survey of Western Australia: Forging a pathway for geoscience – a review of GSWA Open Day 2021

The Geological Survey of Western Australia (GSWA) held its annual Open Day on Friday 12 November 2021 at the Hyatt Regency Hotel in Perth, WA. Just like the GSWA itself, the Open Days have a proud history. In previous years, they have been held in February and in Fremantle. We would fill half the room with information displays and give presentations on our research in the other half. We have also hosted separate minerals and petroleum days. Significant time was taken to reflect on what we had done in the past – what worked and what didn't – and to move forward with a common purpose and drive.

Steve Mudge (Vector Geoscience) at the registration desk

The Hon. Bill Johnston MLA, WA Minister for Mines and Petroleum giving the welcoming address

Moving forward, we focused on three core themes: forging a pathway for geoscience, inspiring young professionals, and engaging successfully with industry. With these themes in mind, we moved the date to November, the location to central Perth, and dropped our ticketing fee from $130 to $50. We modernised our branding and the way we display information, planned an intentional and purposeful marketing campaign, arranged the schedule to engage and stimulate, and used our creativity to design some surprises on the day.

Thanks to these many diverse changes, we were pleased to see our online ticketing reach its highest numbers ever. Many GSWA staff were inundated with requests for tickets in the days leading up to Open Day. While we did offer very limited door sales to accommodate, this feature will likely be phased out. Attendees represented over fifty different organisations across geoscience research, mining and metals, oil and gas, universities, emerging energy, and data/information services. Hopefully in 2022, we will once again be able to welcome guests from interstate.

Many attendees were familiar with our Open Days and found some elements the same, but many that were adapted or entirely new. Relevance and accessibility have been core values of our stakeholders, and we kept that in mind. The Open Day commenced at 09:00 with welcoming addresses from our Executive Director, Jeffrey Haworth, and The Hon. Bill Johnston MLA, Minister for Mines and Petroleum. Session One focused on the strategic outlook for the GSWA – who we are, what we do, and where we are going, featuring presentations by Director of Regional Geoscience Simon Johnson and MinEx CRC CEO Andrew Bailey. Michele Spencer, Director of Mineral and Energy Resources, also introduced a film screening of 'This is GSWA', marking the short film's first broadcast to a live audience.

During the day, we hosted an online event space on the Slido application. All questions were submitted through the app, and we hosted some engaging live polls too. Attendees had opportunities to liaise with online systems professionals and managers of our renowned WAMEX, WAPIMS, and MINEDEX databases. There was also a stunning display of our breakthroughs in photogrammetry, 3D geology, and drone technology. Some of our more creative staff hosted a puzzle competition that was hotly contested!

Session Two provided the latest research outputs from the Accelerated Geoscience

Attendees reviewing the AGP Critical Minerals information display

Program (AGP) from each theme leader – State GIS, Critical Minerals, South West Yilgarn, Far East Yilgarn, and New Energy Systems. Session Three consisted of a series of shorter talks that concentrated on significant ongoing research projects. All of our presenters are experts in their fields and have the kind of knowledge that can only be finely-tuned at an institution like the GSWA. Before and after each presentation, our staff had the invaluable opportunity to network with attendees and make important connections. These sessions captured the collaborative and pertinent nature of our research, ranging from projects that are finalised to those that are just getting off the ground.

We ended our Open Day with an industry-wide panel discussion that conversed on the direction of geoscience over the next ten years. This incredible group of geoscience experts and industry representatives brought a wealth of professional and personal perspectives that combined into a truly rare experience. We capped the day off with a well-deserved sundowner to celebrate a successful event.

The GSWA Open Day 2021 was an open day like no other! Progressive, relevant, expertly organised, and inclusive. Like any live event, some things worked very well and some things will be fined tuned for the future. All in all, we can't wait to do it all again in 2022 and bring you along with us.

Keep an eye on our LinkedIn and Facebook pages for any announcements regarding this event and all our others. If you'd like to receive GSWA news directly to your inbox, please subscribe here - http://eepurl.com/haAERH. You can also use this link to update your details if you have new contact information.

Sabrina Bednarski
Stakeholder Engagement Coordinator
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Our panellists (L-R) – Katy Evans, Klaus Gessner, David Giles, Cam McCuaig, Simon Johnson, Jayne Baird, Sandra Occhipinti, Steffan Hagemann, and Geoffrey Batt.

CSIRO: New mobile petrophysical laboratory

CSIRO, together with AuScope, the National Collaborative Research Infrastructure Strategy (NCRIS) and The University of Melbourne, have containerised a petrophysical logging system – the Geotek Multi-Sensor Core Logger (MSCL) – for use across Australia by government, researchers, and industry. The system provides a stable and reliable platform for measuring co-located petrophysical properties on core through a suite of passive and active geophysical and geochemical sensors.

The Mobile Petrophysical Laboratory (MPL) will facilitate the collection of petrophysical data on a national scale, building a continental petrophysical database that is standardised and nationally comparable. These collated data will provide constraints to geophysical modelling and improve the current understanding of rock properties across the continent at regional, exploration project and ore body scales.

These data will also augment existing mineralogical and geological datasets, resulting in a more complete dataset for input into more complex and machine-based algorithms that will improve the use of multi-disciplinary approaches to modelling. This will provide a step-change in our interpretation and assessment of geological features and properties at both regional and local scales, ultimately providing crucial information for the identification of mineral footprints through cover.

The end goal of this project is to improve models developed from geophysics, by increasing the acquisition of petrophysical data within mineral exploration programmes and to develop research that informs how these data can be used to complement existing data and interpretation to assist with bridging the gap between geophysics and geology.

For more information or to request use of the laboratory please contact Shane Mulè. (MPL Project Lead) or visit https://research.csiro.au/mpl/.

Shane Mulè
Mineral Resources, CSIRO
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The new Mobile Petrophysical Laboratory (MPL)

The interior of the MPL featuring the Geotek Multi-Sensor Core Logger (MSCL-S).

Canberra observed

David Denham AM
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COP 26 in Glasgow reveals the Leaders and the Laggards

The 2021 United Nations Climate Change Conference, more commonly referred to as COP26, had some bad press, but it did force the Australian Government (albeit kicking and screaming) to develop a "Long Term Emissions Reduction Plan" to achieve net zero emissions by 2050.

The global challenge is immense

With the rebound of global emissions from pre-COVID-19 levels to record levels in 2021, the challenge to control the Earth's climate just gets harder. Figure 1 shows that COVID had little or no effect on the addition rate of CO_2 to the atmosphere.

In fact, the jump of 2.6 ppm over 2019 levels was the fifth-highest annual increase in NOAA's 63-year record. Since 2000, the global atmospheric carbon dioxide amount has grown by 43.5 ppm, an increase of 12%

(see https://www.iea.org/reports/global-energy-review-2021).

And this is without any mention of methane from the cattle herds and the melting of perma-frost.

The projected numbers for fossil fuel contributions in 2021 are; coal 14.7 Gt of CO_2, oil 11.5, gas, 7.7 and cement 1.7. The oil contribution fell slightly because of the reduction in air-travel, but coal demand, mainly from China, and the demand for gas continues to increase.

Australia could and should do better

Australia's contribution to keeping the global temperature increase to

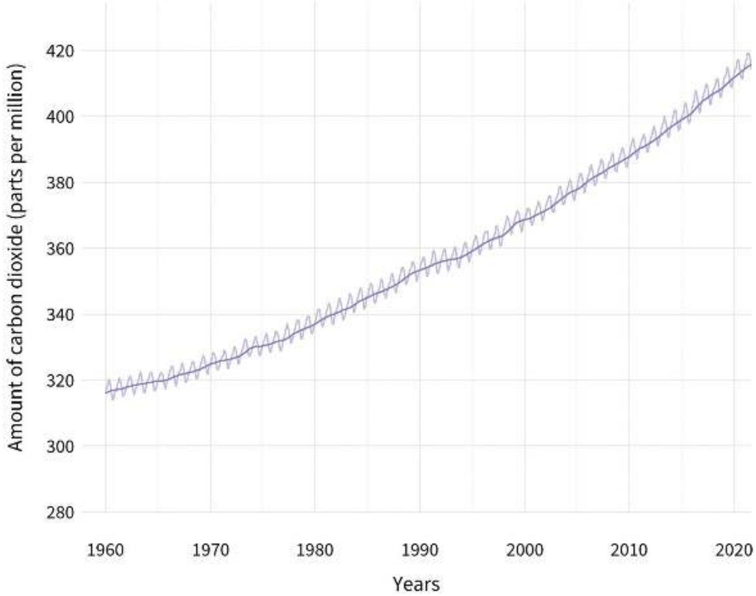

Figure 1. *Atmospheric carbon dioxide levels from 1960-2021 (https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide).*

the 1.5°C has so far been woeful. A consortium of German research institutions (*https://ccpi.org/wp-content/uploads/CCPI-2022-Results_2021-11-07_A4-1.pdf*) produced a Climate Change Performance Index 2022 – Rating Table, especially for COP26. These tables have been published annually since 2005.

The Climate Change Performance Index is an independent monitoring tool for tracking the climate protection performance of 60 countries and the EU. This group of countries represents 92% of global emissions. There are four categories estimated, and an overall assessment. These reveal the Leaders and the Laggards, as shown in Table 1, along with Australia's position.

I am not surprised we came last on Climate Policy. The document tabled at COP26 is vague and states that the:

"Long-Term Emissions Reduction Plan is to achieve net zero emissions by 2050 in a practical, responsible way that will take advantage of new economic opportunities while continuing to serve our traditional markets.

The Plan focuses on the technology road map, which is the cornerstone of the plan, and prioritises technologies that will help Australia cut emissions while creating jobs and growing our economy.

The Plan outlines how we will:

- *drive down the cost of low emissions technologies*
- *deploy these technologies at scale*
- *help our regional industries and communities seize economic opportunities in new and traditional markets*
- *work with other countries on the technologies needed to decarbonise the world's economy."*

Table 1. Leaders and Laggards in the Climate Change Performance Index 2022. Source: https://ccpi.org/wp-content/uploads/CCPI-2022-Results_2021-11-07_A4-1.pdf

Category	Leaders	Laggards	Australia
GHG* Emissions	UK	Iran	56th out of 64
Renewable energy	Norway	Iran	52nd out of 63
Energy use	Ukraine	Canada	54th out of 64
Climate policy	Luxembourg	Australia	64th out of 64
Overall Assessment	Denmark	Kazakhstan	58th out of 64

** Green House Gas*

There is nothing about reducing emissions from fossil fuels, providing incentives for people to change to electric or hydrogen driven cars, or a road map to get to zero emissions by 2050. In fact, the last 15% reduction needed to achieve the net zero goal depends on new technologies not yet known. It is a bit like the old Papua New Guinea cargo cult.

At least the Minister Angus Taylor was honest when he said, "As long as there are buyers for our coal, we will keep selling it."

Moomba is a bright spot

Santos and its project partner Beach Energy have been awarded a A$15M grant from the Australian Government's Carbon Capture Use and Storage Development Fund towards the development of the ~A$210M Moomba Carbon Capture and Storage (CCS) project. The plan is to permanently store 1.7 Mt of carbon dioxide (CO_2) per year with capacity for up to 20 Mt annually across the Cooper Basin. Santos Chief Executive Officer and Managing Director Kevin Gallagher said the project will also be one of the lowest-cost CCS projects in the world at A$25-30 per tonne.

If CCS is going to work successfully, Moomba is as good a site as it gets. The geology is well known. The area is crossed by hundreds of kilometres of seismic lines and the Cooper Basin is still producing gas. Let us hope it will be more successful than Chevron's Gorgon CCS project on Barrow Island in Western Australia.

In many ways the two projects are similar. Both structures were found quite early in the search for oil in Australia and both look very suitable for sequestering CO_2. Chevron announced earlier this year that it had it had finally succeeded in sequestering 5 Mt of carbon dioxide at its CCS facility on Barrow Island. Although this as a significant milestone, it falls short of what was promised to regulators when the massive A$70B LNG project was first announced in 2009. The project is supposed to be capable of storing at least 80% of the carbon dioxide produced by the Gorgon LNG facility, or around 4 Mt a year, and CCS was one of the key conditions for state government approval to develop the gas fields.

Chevron conceded that it had missed its targets and was now in discussions with the WA Government about how it could make good its failure to deliver on the expected storage of CO_2. Apparently, sand clogging parts of the storage system was one of the main causes for not meeting the storage targets (*https://reneweconomy.com.au/chevron-concedes-ccs-failures-at-gorgon-seeks-deal-with-wa-regulators/*).

Carbon Capture and Storage has, so far, not been as successful as expected. A lot depends on the Gorgon and Moomba projects, because these locations should be very good for sequestering CO_2. If it does not work at these sites, the strategy of using this technique to reduce greenhouse gases may not progress.

We wish Chevron, Santos and Beach well – we need CCS to work.

Education matters

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Understanding the whole value chain

In this issue, we are continuing a series of interviews with industry leaders in order to understand what they expect from tertiary education in the field of earth sciences. I am honoured to introduce our second guest, Ishtar Barranco, Earth Science Digital Advisor with Chevron.

Ishtar Barranco

MP: Thank you very much again for being here today for this interview. Can you tell the readers a little bit about yourself and your current position in Chevron?

IB: I was born in Mexico. When I was 19 years old, I got a scholarship to study in France. I did an engineering degree in environmental and earth science at the University of Toulouse and a master's degree in petroleum geoscience at the French Petroleum Institute. I graduated in 2000 and I got a job with Schlumberger in Indonesia. I worked as field wireline engineer in the Duri steam flood field in Sumatra. That's where I met my husband. He was an Indonesian petroleum engineer working for Chevron.

When I got pregnant, we decided to move back to Mexico. My husband couldn't find a job in Mexico, but he got a job offer with Weatherford in France and then Aberdeen. I put my career on hold for two years to follow him and look after my son.

MP: My story is very similar. When we moved to Japan, my kids were four and two years old, and I stopped working for two years. I was taking care of kids, learning Japanese, and screening job advertisements in Japanese newspapers.

With the energy transition and CCS, we're moving to more integrated projects and we need people that are able to understand the whole value chain.

IB: When I remember back to that time, I was feeling that my career was over because I had to stop for two years.

In 2003 my husband got a fly in fly out position in Nigeria. I decided to go back to Mexico because I wanted to go back. I was lucky that the industry was booming, so after a couple of months I got a job with Schlumberger as geo-modeller in Ciudad del Carmen, an island in the Gulf of Mexico. It was a great experience. I was in charge of building the geological model of the Cantarell field, which was the largest producing oil field in Mexico. This was the first model I ever built. I was very fortunate to work with an experienced reservoir engineer from Venezuela. She was a great mentor for me. My son was two years old, and my husband was still working FIFO in Nigeria. She was divorced with two kids, so she understood very well the challenge of being a working mum. We helped each other a lot with the kids whenever one of us had to work late. We became friends for life, and we also managed to build the first fully history-matched model of the Cantarell field. It was a quite challenging but exciting time.

In 2005 I got pregnant with my second child and I moved to Mexico City, where I oversaw the relationship between Schlumberger and the two main universities in Mexico. I loved that job, working with students and mentoring them in their bachelor and master's thesis projects. I also worked with the Mexican Petroleum Institute, building models and training researchers on geological modelling in Petrel. I also provided training to the reserves department of PEMEX, introducing the concept of probabilistic modelling. At that time most of the reserves were calculated using deterministic methods mainly based in well data and 2D maps.

In 2006 I got transferred to Adelaide to do geo-modelling consulting, support, business development and training for east Australia and New Zealand. I got to work and travel a lot to Melbourne, Sydney, Brisbane, Cairns and Wellington. It was an exciting but also challenging time because my kids were four and one years old when we moved to Australia, my husband was working FIFO in Angola, and we didn't have any family in Australia. We liked Australia so much that we decided to settle down here.

In 2008 I joined Chevron as geologist for the Gorgon Carbon Capture and Storage (CCS) project and I worked on this project until 2018. After that I worked across Chevron Australia's operated and non-operated projects, including Jansz-Io Compression (JIC), North West Shelf, and WA Oil. Over the past two years my role has been CCS and Earth Science Digital Advisor working to identify and prioritise digital solutions based on business value. This has included: leading agile teams to design, develop and deploy digital tools; owning the product vision and roadmap from ideation to deployment; and leading change management, adoption, and digital fluency among practitioners.

Working in the Gorgon CCS project has been the one of the most exciting parts of my career. It's one of the most interesting and challenging projects in the world, not only because of the technical, legal and operational complexity, but also because it's the biggest system of it's kind.

The project is operated on Barrow Island, a Class A nature reserve subject to some of the most stringent quarantine regulations in the world. It's not easy to operate in a place with so many environmental restrictions. It's amazing to see all the effort that the operations and health, safety and environment teams of Chevron do to protect the unique flora and fauna in Barrow Island.

In the Gorgon CCS system, Chevron is demonstrating carbon capture technology at a scale not seen before.

The Intergovernmental Panel on Climate Change (IPCC) and International Energy Agency (IEA) have both noted CCS will need to be deployed around the world on a big scale to meet global emissions reduction goals – we're sharing the lessons we're learning at Gorgon to support this.

Since the early days of the project, we have been working with universities, consortia, and research centres in Australia and around the world to develop CCS technologies. We have more than 15 years of collaboration with Curtin, CSIRO and the CO2CRC in this area.

Since we started injection in August 2019, more than 5.5 million tonnes of greenhouse gas emissions have been injected at Gorgon. However, CCS is not an "easy technology" – we must handle multiple subsurface, facilities and project uncertainties. We have to be prepared for many different outcomes. This is something that we're used to doing in the oil and gas industry: uncertainty and risk assessment and mitigation plans. We have the knowledge, the experience, and the *savoir-faire* in our industry.

MP: In this complex world and rapidly changing energy landscape, what does industry expect from tertiary education? What would you recommend to students and young graduates?

IB: I've been working with vacation students and my eldest son is in uni now. I tell my kids and mentees that they need to have a growth mindset, be willing to think outside the box and learn beyond their speciality. There will still always be room for specialists, but in uncertain environments you must be very adaptable and resilient to thrive. The energy transition space, it's very exciting, but we need to be very flexible because we don't know how the energy market with evolve. There are so many economic, political and technical elements that can have a big impact on the energy landscape. It's hard to predict what will happen 40, 50 years from now. We need people in the industry that are flexible, and that can adapt to constant changes. This is not new. The O&G industry has always had ups and downs. If you look at my career, I went from running wireline tools in the rigs, to building geological models, then CCS and now digital technologies. The current energy transition is one of the biggest structural changes that we have seen not only in industry but in society, in many decades. People in our industry will need to learn to adapt at a much faster pace.

With the energy transition and CCS, we're moving to more integrated projects and we need people that are able to understand the whole value chain. Scientists and engineers sometimes want to solve all the uncertainties, but we also need to understand the value chain to ensure that project is viable. We can't afford to have people working in silos, we need people that can work in collaboration and understand the whole picture, technical, economic, political, etc. to make optimum decisions.

MP: This integrated economics plus business plus technical skills approach looks very interesting. The recruits you are hiring now, are they trained in this way? Do they already have these qualities? How difficult is it to find such specialists?

Diversity and inclusion are becoming more and more important in our society, so it's important to identify people that can work well with people from different backgrounds.

IB: I'm very, very pleased with the trainees and graduates that we have had in Chevron. They are very technically savvy; they have a growth mindset, and they are very proactive, and they have good emotional intelligence and communication skills.

They come with a more open mind than we used to have in the past. They are not expecting that their career will be linear. They are willing to learn and to try different things. I don't know if they are learning this at university or somewhere else. Nowadays you don't need to learn everything at university. You can learn so many things online.

MP: Thank you, it is what I also emphasised in my *Education matters* piece in *Preview* 210. It is good to know that the new generation coming will be better than we were. It brings us to the next question. How has the recruitment process itself changed? How do you choose the best people from those applying for a position?

IB: In my current role I'm not directly involved in the recruitment process in Chevron, but I mentor university graduates and new migrants looking for jobs. I can see that a lot of the recruitment is done through internship and via networking. Having a good CV is essential, but that will only open you some doors. You need to get good interpersonal skills to get the job. It's hard to assess those skill in just a couple of interviews. When I worked with Schlumberger I was involved in the recruitment process, and we used to have full day workshops to assess candidates for their team working and collaboration skills. The other way we used to recruit people was by offering mentoring, internships, and training in the universities. It's much easier to assess interpersonal skills when you work closely with a candidate. It's important to evaluate the whole person rather than just their achievement and grades. It also allows you to assess their ability to innovate. Diversity and inclusion are becoming more and more important in our society, so it's important to identify people that can work well with people from different backgrounds.

MP: Indeed, our industry is very diverse. You have worked in many countries and speak several languages.

IB: Yes, Spanish is my native language, I learned French for my studies and then English for work. It's kind of normal in the international community. Most of my friends speak two or three languages. It's the beauty of working with people from different parts of the world. Cultural diversity is very enriching and something very close to my heart since I have a multicultural family: Australia, Mexico, Indonesia and Canada. I'm very passionate about diversity and inclusion not only in terms of gender but also cultural diversity. I try to raise awareness of the challenges that the migrants face in Australia, and the value that they bring to the community. I'm currently the Chair of the Inclusion Council and the Lead of the Latin American employee network in Chevron Australia. I'm also a mentor in the kaleidoscope mentoring programme for migrants. This programme helps people migrating to Western Australia to find job in their areas of expertise.

MP: From your point of view, should we expect evolution or revolution, and what is the role of tertiary education in assuring a smooth transition to clean energy?

IB: We're already experiencing the evolution. I think it's going to be a smooth transition to clean energy, however we can't just replace fossil fuels overnight. The global energy demand keeps growing and the alternative energies can only cover a fraction of the current demand. We will continue needing oil and gas for several years, but we need to produce them in way that minimises our environmental impact. This is where CCS plays an important role. CCS is not the goal. It's a transitional technology while other clean energies continue to develop. In terms of tertiary education, most of the skills that we teach petroleum engineers and earth scientists will be relevant to the energy transition. Most of these skills are transferrable to CCS and the hydrogen industry. We may enrich a little bit with more emphasis on the digital technologies, modelling and the integration across geology, petrophysics, geomechanics, geophysics and engineering and the new technologies for CCS monitoring.

There are also the alternative energies, like solar, geothermal, wind and hydrogen that will require earth scientists and engineers.

We will also need to continue increasing the collaboration between industry, research and academia to accelerate technology deployment at the pace and scale required to meet the global emissions reduction goals.

MP: You have already started answering my next question on the role of digitalisation in the clean energy transition. What kind of education is required to guarantee efficient digitalisation of the sector?

In terms of tertiary education, most of the skills that we teach petroleum engineers and earth scientists will be relevant to the energy transition. Most of those skills are transferrable to CCS and the hydrogen industry.

IB: Digital technologies have a very important role to play in the energy transition. We're dealing with a more integrated system with a huge amount of monitoring data. It has to work all the way from the CO_2 capture or separation to transportation to the storage site. You need to make sure that everything is CO_2-resistant, because of the corrosive properties of CO_2. You also need to ensure that you will have good injectivity for the duration of the project, and that the CO_2 will remain permanently underground. With hydrogen, we are adding another level of complexity on that element, because it is a different fluid with different properties.

For example, in modelling we're used to flow simulate reservoir modelling. In CCS, we can't assess fields just based on the geological perspective or the volume of hydrocarbons in place. We have to think all the way from the integrity of the existing field, the geomechanical parameters, the geochemical reaction of the CO_2 with the reservoir fluids and rocks, and the integration of the data (4D seismic, satellite data, passive seismic monitoring, saturation logging, surface monitoring, pressure monitoring, etc). The integration of all these data sets requires leveraging digital technologies to help us with the forecasting and real-time monitoring of the field to make decisions on the optimum operational parameters.

In terms of the kind of people we need to work on the digital projects, we need people that understand the business project, we need experts in the area (geophysicists, geologists, etc.), and we also need software engineers, data scientists and data architects. The data scientists can be earth scientists or engineers that have learnt data science. In general it's easier to train a geophysicist, geologist or a petroleum engineer in data science than for a data scientist to become a domain expert. One of the foci in the digital transformation roadmap is to train our people in digital technologies.

We also need people with experience in design thinking and agile project management to help us design, execute and deploy the solutions.

MP: Thank you. My last question is what kind of specialists are required to pursue the clean energy economy in Australia?

In general, it's easier to train a geophysicist, geologist or a petroleum engineer in data science than for a data scientist to become a domain expert. One of the foci in the digital transformation roadmap is to train our people in digital technologies.

IB: If we are talking about CCS and blue hydrogen, we will need the similar kind of specialists that we need in oil and gas projects. We will need drillers, geologists, geophysicists, petrophysicists, geomechanics, petroleum engineers, HSE engineers, facilities engineers, production engineers, chemical engineers, electrical engineers, mechanical engineers, project managers, decision analysts, etc.

It is the same specialists, they will just need to develop additional skills. They will also need to develop a different mindset, to assess and integrate across the whole value chain. They will need to work in more collaborative way.

I think a lot will change in the way we do exploration because we are not going to be exploring for existing hydrocarbon accumulations. With CCS what happens is you find the optimum reservoir close enough to your carbon emissions. You can find a great reservoir for CO_2 storage but if it's too far away from your source of emissions then the project may not be economical. In CCS we have to assess injectivity, containment and capacity. In CCS the containment (seal) and the injectivity (permeability and pressure) are in many cases more important than the pore volume of the reservoir. You also need to assess the subsurface integrity of the field and the well integrity of existing wells if you're injecting CO_2 in depleted oil and gas fields. You need to bring that integration from the screening phase to assess the viability and cost of the project.

For hydrogen and a wind and solar and the new energies there will be other kind of specialists that will be needed: lots of engineers, chemical, electrical, and mechanical engineers.

MP: Thank you so much.

Theses in geophysics completed in 2021

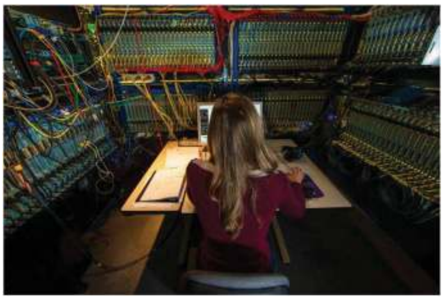
PhD theses

Zhengguang Zhao, The University of Queensland: *Automated microseismic event detection with machine learning.*

Automatic microseismic event detection involves algorithms and/or workflows to discriminate genuine microseismic events from noise. Limitations in traditional physics-based methods are that user-defined thresholds impose too much impact on the detection accuracy, and inappropriate pre-set thresholds are prone to bring about low detection accuracy.

In this thesis, we proposed a "Classification Is Detection" strategy that cast microseismic detection as a supervised classification problem. The well trained support vector machine classifier was used as a microseismic event detector for distinguishing microseismic events from noise and proved to be able to achieve comparable, if not better, event detection accuracy than traditional methods.

Joanne Stephenson, Australian National University: *Cylindrical anisotropy of Earth's inner core re-examined through robust parameter search.*



The Earth's inner core (IC) remains one of the most enigmatic parts of our planet. The structure and dynamics of the IC have been at the forefront of deep Earth research ever since the discovery of Earth's innermost shell in 1936 by Inge Lehmann. However, the formation, internal structure and dynamics of the IC still remain a fundamental puzzle for researchers. The core of the Earth is responsible for the geodynamo, generating Earth's magnetic field and protecting life on Earth from solar radiation.

Global seismology is an excellent tool to provide insights into the IC. Seismic waves travel at different velocities through media of varying densities and reflect off sharp discontinuities. This allows us to infer structure below the surface of the Earth. In particular, the seismic phase "PKIKP" traverses the IC and is the primary data used throughout this thesis. As the number of data increases and computational techniques improve, the variability and complexity of IC models have increased dramatically. Each model is unique, and interpretation is often dependent on data choice, processing and methodology employed. In particular, this thesis explores the hypothesis of IC cylindrical anisotropy - the idea that seismic rays traveling through the IC parallel to the Earth's rotation axis travel faster than those parallel to the equator.

This thesis investigates the anomalously fast South Sandwich Islands (SSI) to Alaska seismic paths. On these paths, PKIKP differential travel times show a consistent deviation of 2-4 seconds from predicted travel times in the outer region of the IC - an observation arguably responsible for the proposal of IC anisotropy in the upper part of the IC. However, the origin of the anomaly is poorly understood. Research in this thesis focuses on a detailed analysis of the waveforms from SSI earthquakes. Novel methods are employed to pick a comprehensive new data set of differential travel times from 36 events. Results show that the significant travel time anomaly present in the data is unlikely to be a result of systematic error in picking of the core phases. Instead, analysis shows that the anomaly is likely a result of strong heterogenous structure elsewhere within the deep Earth. In addition to the new SSI dataset, this thesis contributes further data to the global PKP differential travel time dataset, focusing primarily on polar antipodes.

Most significantly, this thesis investigates the radial dependence of cylindrical anisotropy in the Earth's IC. Varying models have been created for an innermost IC (IMIC), with radius anywhere between 300 and 800 km. To investigate the existence of the IMIC, the direction of fast/slow axes and its radial extent, global absolute PKIKP data from the International Seismological Centre (ISC) is used in conjunction with the parameter search method the "Neighbourhood Algorithm" (NA). The merit of the ISC catalogue is in the numerous available PKIKP travel times collected over many decades, along with improved location algorithms. The NA provides a robust means of testing this hypothesis where it produces ensembles of all models that satisfactorily fit the data. This method can be employed without regularisation or needing to employ any subjective choices such as binning of phase data. In addition to the NA, a complementary likelihood ratio approach is used to further constrain uncertainty on anisotropy parameters. This investigation suggests that spatial averaging methods are unnecessary to observe the IMIC and may be partially responsible for disagreements between models of IC anisotropy. Results further show that the IMIC is not defined by a change in strength of anisotropy, but by a significant deviation in the slow direction of propagation at 650 km. Such a result could be interpreted as a phase change in iron or mineralogical impurities at depth within the IC.

Tobias Stål, University of Tasmania: *The Antarctic lithosphere revealed by multivariate analysis.*

The Antarctic continent, at 14 million km^2, is larger than Australia; yet, due to the ice cover and inaccessibility, its geology and lithospheric structure are to a large extent unknown. During recent decades, particularly since the International Polar Year of 2007-08, a growing number of studies have provided new and improved datasets of the continent's surface, cryosphere, crust and upper mantle. The new data enable new or refined questions to be addressed in the Antarctic Earth sciences. For instance, how does large-scale geophysics correlate with sparse geological observations and interpretations? What are the extents of tectonic domains and affiliations with former neighbours in Gondwana? What is the spatial distribution of geothermal heat flow in the deep interior?

Advancing our understanding of the Antarctic continent addresses fundamental knowledge gaps in plate tectonics, the dynamic foundation for our planet. Understanding the Antarctic lithosphere is also of urgent relevance due to ongoing anthropogenic climate change and the consequent need to better constrain interactions between the solid Earth and the cryosphere. Challenges to build on existing research include the lack of agreement between different studies, and uncertainties that are difficult to constrain. Methodologies previously employed are generally univariate, modelling the solid Earth structure or character from only one observable. However, the growing number of datasets affords an opportunity to combine constraints from multiple observables, embrace the uncertainties, and draw new, considered interpretations. In this thesis, studies that employ multivariate syntheses of recently compiled data are presented, with a focus on combining geophysics and geology.

In particular, a new 3D model and software framework for spatial multivariate and multidimensional computation is presented. This is enabled by a newly developed software package, agrid, which contains methods for data import, visualisation, and export of results in compatible formats. Using this toolbox, a grid model of continental Antarctica is created from geophysics and geology combined. A range of illustrative maps of lithospheric properties are generated to exemplify the functionality of the framework. This includes a new isostatic model from seismic tomography data and a new approach to calculate geothermal heat flow from energy balance based on geophysics and geology. The dynamic and flexible 3D model of the lithosphere is designed with research addressing solid Earth and cryosphere interaction and feedbacks in mind.

Multivariate methodology is used to investigate the presence of deep-seated lithospheric boundaries in East Antarctica. Three independent datasets are utilised: seismic shear wave speed at 150 km depth, free air gravity anomaly, and surface elevation. From each dataset, boundaries that indicate transitions in value, gradient, frequency, or pattern are suggested, with rated uncertainty and resolution. A range of likelihood maps is generated; the most conservative maps show regions where we are confident that an upper mantle boundary exists, whereas the least conservative maps contain a greater number of less confidently suggested boundaries. When boundary likelihood is compared with observed crustal geology, we find a good match. The East Antarctic lithosphere is revealed to comprise multiple domains, and internal geological complexity. Domains in the subglacial interior, with no geological outcrop, are very likely.

The computational framework, agrid, is used to generate a geothermal heat flow map using over 15 datasets as input observables. A multivariate similarity method is applied, carefully modified for application to the datasets available for Antarctica. The new map, Aq1, is of higher resolution than previous heat flow maps of the continent, and robustly constrained with quantified uncertainty. The map confirms higher heat flow in West Antarctica, and lower heat flow in East Antarctica. The highest values are computed for the Thwaites Glacier region and the Siple Coast, locally over 150 mWm^2. High heat flow, over 80 mWm^2, is also likely in parts of Marie Byrd Land and Palmer Land, and elevated values, above 70 mWm^2, occur for Queen Mary Land. Parts of the interior of Wilkes Land, Wilkes Sub-glacial Basin, and Coats Land, show very low values, under 40 mWm^2.

The thesis concludes with a synthesis of common themes running through the core research chapters, including a discussion of the value of probabilistic geological mapping. Spatial uncertainty metrics are outlined in terms of the added insights they provide in the appraisal of newly generated models. In summary, multivariate maps and models of the 3D continent including a wide variety of data from geophysics and geology are produced using newly written computational tools. Our understanding of the Antarctic lithosphere is thus advanced in a quantitative and repeatable way, and the new solid Earth geoscience results may be readily accessed for ongoing cryosphere and other interdisciplinary research.

Yao Qian, Australian National University: *Environmental magnetism of eastern Mediterranean sediments and aeolian dust flux changes over orbital timescales.*

Magnetic techniques have been used widely in environmental studies for the past few decades. Environmental magnetism typically involves conventional room temperature measurements of bulk magnetic parameters and more advanced component-specific magnetic approaches. Conventional bulk parameters can provide continuous records of magnetic mineral concentration and/or particle size variations in sediments, respectively. However, such parameters are not necessarily well suited to identifying magnetic components within individual magnetic mineral assemblages. More advanced techniques, such as first-order reversal curve (FORC) diagrams and low-temperature (LT) magnetic measurements, can enable detailed discrimination of magnetic mineral assemblages. However, these measurements are time-consuming, so they cannot be used to develop high-resolution records. Furthermore, although these techniques have been used more frequently in recent years, much work remains to be done to unlock their full diagnostic power in environmental magnetism.

In this thesis, I use marine sediments from the eastern Mediterranean Sea to assess bulk magnetic measurements, FORC diagrams, LT measurements, X-ray fluorescence core-scan elemental data, and transmission electron microscope

(TEM) observations to investigate the benefits and limitations of conventional and advanced environmental magnetic techniques for sediments deposited under variable redox conditions, and to explore the use of LT magnetic properties for detecting different magnetic particle types in marine sediments. Eastern Mediterranean sediments were selected because they contain complexly varying mixtures of detrital, biogenic, and diagenetically altered magnetic mineral assemblages that were deposited under varying oxic (organic-poor marls) to anoxic (organic-rich sapropels) conditions.

I demonstrate in this work that conventional bulk magnetic parameters can be used to provide high-resolution records of environmental magnetic variations, while advanced measurements provide direct ground-truthing of mineral magnetic assemblages that enables calculation of magnetization contributions of different end members. Thus, a combination of conventional bulk parameters and advanced magnetic techniques can provide detailed records from which the meaning of environmental magnetic signals can be unlocked. In this work, I also demonstrate that LT studies enable clear identification of the extent of the presence of biogenic magnetite, superparamagnetic particles, and surficial maghemitisation of magnetite particles. Furthermore, new high-resolution magnetic and planktic foraminiferal stable oxygen isotope (d18O) proxy records are presented together with published geochemical data from eastern Mediterranean sediments to discuss the causes of increased dust inputs from the Sahara Desert across the mid-Pleistocene Transition (MPT). After assessing hypotheses for increased Saharan dust inputs across the MPT, including increasing source-area aridity due to reduced precipitation, expanding dust source areas, and atmospheric CO2 reduction that led to decreased vegetation and soil cohesion, I find that increasing climate extremes boosted wind-blown dust production and emissions. This is important because the resultant aeolian aerosols play a major role in both the radiative balance of climate and biogeochemical cycles in areas where the dust settles. This work provides valuable insights into the application of conventional bulk and more advanced component-specific methods in identifying mineral magnetic assemblages in palaeoceanographic and palaeoenvironmental reconstructions, and in explaining increased Saharan dustiness across the MPT.

Thomas Ostersen, University of Tasmania: *Geo-electric structure of the Tasmanian lithosphere from multi-scale magnetotelluric data.*

This project encompassed the Tasmanian leg of the Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP) and investigated the geo-electric structure of the Tasmanian lithosphere at different scales driven by three separate newly collected or newly compiled MT data sets. Long period MT data were collected over the course of a major field campaign across Tasmania and Flinders Island in Bass Strait, yielding a regionally spaced data set with periods ranging 5s to 16000s. Induction arrow patterns in these AusLAMP data agree with earlier MT studies in highlighting a region of low resistivity coincident with, and extending southward from the Tamar River in northern Tasmania. Three-dimensional inverse modelling of the AusLAMP data set illuminated the geo-electric structure of the entire island spanning the upper-crust through to lithospheric mantle depth range (~1 0km to ~100 km), revealing anomalously low electrical resistivities along major terrain boundaries in the mid- to upper-crust likely resulting from conductive mineral phases and pore fluids in shear zones. At deeper levels in the model, in the mid- to lower-crust, clear differences in the electrical character between geologically distinct Eastern and Western Tasmanian terrains emerge, with the Eastern terrain returning consistently higher resistivities likely reflecting the depletion of conductive mineral phases following voluminous melt extraction in the Devonian. Electrical heterogeneity in the Western terrain includes regions of anomalously low resistivities that continue from the lower-crust to the lithospheric mantle and are interpreted as being due to subduction-related mantle metasomatism potentially associated with the intrusion of ubiquitous Jurassic dolerites.

In addition to the long period MT surveys, two broadband MT traverses were acquired for shallower investigations of the lithosphere beneath western and north western Tasmania. These surveys transected major crustal boundaries between Precambrian Tyennan basement and the highly metalliferous Cambrian to Devonian Dundas-Fossey Trough. Two-dimensional inverse modelling of the traverses broadly agree with regional 3D modelling derived from AusLAMP MT data, and bring the geo-electric structure of the upper crust in these regions into sharper focus. In the west transect, upper crustal rocks within the Precambrian basement are considerably less resistive than younger Dundas-Fossey rocks and preserve internal heterogeneity potentially imaging relict metamorphic fluid pathways. The highly resistive Dundas-Fossey Trough also contains small-scale low resistivity structures coincident with crustal-scale faults observed at surface.

Six of the AusLAMP long period MT sites were deployed in central eastern Tasmania surrounding the Lemont geothermal prospect, a region of anomalously high surface heat flow that was the subject of exploration for geothermal energy by KUTh Energy Ltd between 2007 and 2011. A 255-site broadband MT data set was acquired by KUTh Energy Ltd at Lemont between 2008 and 2010 which culminated in the inversion of a 3D resistivity model of the area. The newly acquired long period MT data, together with the existing broadband data, presented an opportunity to re-model the Lemont MT data set. This modelling exercise improved on the previous 3D resistivity model by increasing the horizontal resolution of the model space, and incorporating the AusLAMP 3D model as a priori model structure. Together with different inversion approaches to static shift effects in the data, these improvements yielded significant differences in subsurface resistivity structure relative to the previous model, with the updated model containing more detail. The distribution of low resistivity zones in the updated model agrees with inferred subsurface fault structures thought to represent porous conduits for fluids radiogenically heated by underlying Devonian granitoids.

Cyrille Njiteu, University of Douala**,** Cameroon**:** *Mechanical behaviour of the lithosphere in the North-Central African Region (Cameroon, Central African Republic, Chad) and modelling the sources of the Bangui Magnetic Anomaly.*

The Central African sub-region in Cameroon and Central African Republic is marked in its intra-continental part by two particular mega-structures: the Congo Craton and the Central African Orogenic Belt (CAOB). All of them are intersected by a gigantic anomaly whose sources are still unknown: the Bangui Magnetic Anomaly (BMA). Different approaches to spectral analysis, applied to ground gravity and satellite magnetic data, allowing determination of the Moho and Curie depths were applied. Similarly, a regularised non-linear inversion method based on satellite-only gravity data, as well as the analysis of the coherence function between the topography and the Complete Bouguer anomaly, allowed analysis of the mechanical behaviour of the lithosphere, thus highlighting (1) the deepest location of the sources associated to the BMA; (2) the link between the BMA and the long wavelength positive gravity anomaly at the northern edge of the Congo Craton in Cameroon; (3) the geological origin of the BMA.

Thus, it has been shown that the sources related with the BMA are a set of relatively dense and magnetic structures. Interactions with regional shear zones have also been demonstrated, showing the imprint of thermal, tectonic and seismic events on the setting of the magnetic sources. The crustal architecture was validated by the seismic results of 32 stations from the Cameroon Broadband Seismic Experiment (CBSE), those available from previous gravity studies and by comparison with some global MOHO models: CRUST1.0 and GEMMA. Direct modelling 2.3/4 D shows an increase of the magnetisation from Cameroon to Central African Republic. In some local areas, the crust beneath the BMA is magnetic. The BMA can be associated with (4) a magnetic crust and an intrusion of deep and dense materials such as mafic granulites and Banded Iron Formations.

Christopher Mathews, Australian National University: *Methods for tracking material properties within an unstructured, adaptive mesh computational modelling framework, with application to simulating the development of seismic anisotrophy at spreading centres and transform faults.*

The ability to accurately and efficiently track material properties in a Lagrangian sense during geodynamical flows, as well as evaluate how they evolve through both space and time, is of vital importance to our understanding of the structure, dynamics and evolution of Earth's mantle and lithosphere. An approach for achieving this, widely advocated by the geodynamics community, is the so-called particle-in cell technique. With this scheme, material properties are tracked by a large number of particles that are advected with the flow field. These properties can represent a wide range of parameters (e.g. material composition or strain) and the information they carry can be accessed during a simulation to feed back into the flow equations (e.g. composition controlling material density), as well as generate diagnostic fields for analysis (e.g. the generation of lattice-preferred orientation).

In Chapter 2, we develop a particle-in-cell scheme within an adaptive, unstructured, anisotropic mesh computational modelling framework called Fluidity. Regions of geodynamic interest often vary throughout a simulation, and the combination of the particle-in-cell scheme with a state-of-the-art adaptive mesh algorithm enables both the mesh resolution and particle density to capture areas of interest with high resolution (or density), while reducing resolution (or density) in areas of little geodynamic interest. This ensures that a high level of accuracy is maintained throughout the computational domain, while also greatly improving numerical efficiency. The implementation of this scheme saw several inherent challenges which had to be overcome, including the treatment of particles during mesh adaptivity, the transfer of particle between processors, and the interpolation of values between particles and nodes of the mesh.

In Chapter 3, validation of the implemented particle-in-cell scheme is undertaken for a series of well-known thermo-chemical convection benchmark tests. For each benchmark, particles track material composition as they are advected throughout the computational domain, with material composition feeding back onto the density field and influencing the buoyancy of materials. Results from the particle scheme are compared with results from a field-based control volume, flux-limited conservative difference scheme known as HyperC. Both schemes perform favourably across the series of benchmark tests, with HyperC displaying superior mass conservation and the particle scheme exhibiting superior shape preservation, resulting in a smoother material interface and the visualization of finer scale features. The particle-in-cell scheme is favoured, as it is more flexible in its application to tracking generalized material properties, enabling it to be applied to a wide range of geodynamical problems, such as the tracking of material texture.

In Chapter 4, we develop the software package PyDRex, which is capable of converting tracked deformation parameters into predictions of material lattice-preferred orientation and seismic anisotropy. The generation of lattice-preferred orientation and subsequent observations of seismic anisotropy within Earth's mantle yields some of the most direct constrains available on both past and present-day deformation. By simulating these processes with geodynamics models, it is possible to generate synthetic seismic anisotropy predictions, which can be compared with observations in an attempt to constrain the prevalent flow regime in the upper mantle.
In Chapter 5, we utilize the PyDRex software package with Fluidity and develop three sets of oceanic plate boundary models, being 2D and 3D mid-ocean ridge models, and 3D mid-ocean ridge models with a transform fault offset. We compare anisotropy predictions from these models with seismic observations of anisotropy, allowing inferences to be made on the prevalent flow regime and distribution of material anisotropy surrounding oceanic plate boundaries.

Luke Mahoney, The University of Melbourne: The structure and evolution of the northern Australian margin: Insights from the Papuan Fold and Thrust Belt, Papua New Guinea.

The Papuan Fold and Thrust Belt (PFTB) in Papua New Guinea (PNG), located on the leading edge of the northern Australian continental margin, has been subject to complex tectonism as a result of its location throughout much of the Cenozoic between the obliquely converging Australian and Pacific plates. The remoteness and inhospitable terrain characterising the PFTB make it one of the least well-known fold and thrust belts on Earth.

The architecture of the northern Australian continental margin has been affected by both extensional and compressional tectonic forces, which first formed, and subsequently deformed, the Papuan Basin in the period from the early Mesozoic through to the present-day. Defining the geology, structure and evolution of the PFTB and Papuan Basin is central to our understanding of the geological and tectonic evolution of the northern Australian margin. In this thesis, a multidisciplinary approach is used to investigate the evolution of the PFTB, Papuan Basin and northern Australian continental margin.

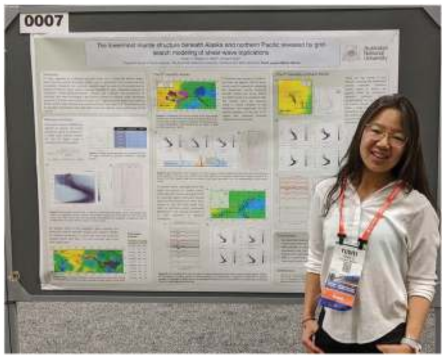
Field mapping and structural analysis within the remote Western Fold and Thrust Belt (WFTB) provide significantly improved constraints on the geology, structure and evolution of the fold belt. New geological constraints acquired over > 100 km of traverses suggest that the exposed Cenozoic Darai Limestone has very low shortening between ~ 12-22% yet structures in the Muller Range are elevated up to 7 km above regional. Structural work utilising regional-scale geological observations suggest that the inversion of pre-existing rift architecture on the northern Australian continental margin is the primary influence on the evolution of the area. The huge structural relief is produced by both tectonic inversion on deep-rooted normal faults and their linkage to the surface via triangle zones that form within the incompetent Mesozoic passive margin sedimentary sequence. Local- and regional-scale heterogeneities within the northern Australian continental margin, such as accommodation-zones and transfer structures are now expressed in the fold belt structure as discontinuities and cross-cutting structural features that are recognised throughout the PFTB.

The 2018 Mw 7.5 PNG Highlands earthquake and aftershock sequence has provided an unprecedented opportunity to observe and analyse the crustal processes that have ultimately controlled the evolution of the PFTB. Seismological, GPS and remote sensing data offer constraint on the complex nature and spatiotemporal distribution of crustal deformation during the event, revealing that the PFTB experienced up to 1.2 m of uplift and ground deformation over 7500 km^2. Remarkable spatial and morphological similarities exist between the distribution of co-seismic ground deformation associated with the event, and the less-inverted and un-inverted extensional architecture that is well-constrained in the foreland across the Stable Platform. This suggests that the 2018 Highlands earthquake sequence was related to tectonic inversion along a previously unidentified extensional fault system beneath the PFTB, indicating the northern Australian passive margin has had a primary control on the evolution of structural styles observed throughout the PFTB.

New low-temperature thermochronology data from extensive field surveys in the Muller Range were combined with legacy data in modern thermal history modelling tools to investigate the thermotectonic evolution of the WFTB and Papuan Basin. In particular, the Late Cretaceous to Oligocene history of the region is largely unknown due to the absence of a continuous stratigraphic record. Thermal history models based on these data suggest two major Cenozoic cooling episodes. The youngest, and best constrained, is clearly recorded in the stratigraphic record and relates to Neogene collision at the northern margin of the Australian continent. An older episode of comparable or greater magnitude occurred in the Eocene to Oligocene and may relate to the removal of 1500 - 3000 m of Late Cretaceous to Eocene stratigraphic section across the Muller Range prior to the widespread deposition of the shelfal Darai Limestone. It is suggested that extension along major faults beneath the Muller Range accommodated sedimentation from the Late Cretaceous to the Eocene, consistent with long-lived extensional structures observed in the foreland across the Stable Platform. The selective removal of this sequence across the Muller Range suggests it was uplifted in the Eocene to Oligocene, possibly in part facilitated by the inversion of extensional faults in the Muller Range area. This inversion is interpreted to have resulted from the Eocene to Oligocene collision of the expansive Sepik Terrane to the northwest of the PNG margin, an interpretation that has significant implications for the tectonic evolution of PNG and Southeast Asia.

The studies presented in this thesis provide several key insights that significant advance our understanding of the geological, structural and tectonic evolution of the PFTB, Papuan Basin and northern Australian margin. An ongoing theme relates to the complex interplay between spatial variations in the architecture of the margin and spatial and temporal variations in the compressional stress field associated with an evolving tectonic setting between the Australian and Pacific plates.

Yuwei Li, Australian National University: *Imaging the D" structure using waveform modelling.*



The D" region of the Earth, the lowermost few hundred kilometres of the lower mantle, is designated as a thermal boundary layer and chemically distinct layer above the core-mantle boundary (CMB). It plays an important role in mantle convection, core convection and the resulting geodynamics. Characterising the structure of this region is crucial to a better understanding of the mantle's thermo-chemical evolution and the nature of core-mantle interactions.

The top of D″ region characterises a velocity discontinuity - the D″ discontinuity, which likely originates from the phase transition from bridgmanite (Bm) to post-perovskite (pPv) at the pressure-temperature conditions of the lowermost mantle. This discontinuity has been widely observed in a few regions, while much of the Earth is still unmapped. This poses a challenge in deciphering the origin of the D″ discontinuity and resolving the debate whether it is a global feature.

This thesis presents a compilation of published, accepted and submitted work. The main objective is to provide new insights on the origin of the D″ region and its relationship with mantle dynamics. There are three chapters of the thesis. Chapter I contributes to probing the global existence of the D″ discontinuity by adding new observations in unexplored areas on the Earth. Chapter II focuses on the development of a new method to fill in the gaps of the existing methods. Chapter III is dedicated to investigating the potential origin of the D″ region by applying this new method to the D″ region beneath Alaska, Northern Pacific and Central America.

To explore the distribution of the D″ discontinuity in the globe, we first add a new observation of D″ discontinuity beneath the Central Atlantic with new data that greatly improved prior poor data coverage. Through forward waveform modelling, we observe a D″ discontinuity with varying depth and sharpness along a high velocity corridor from north to south beneath the Central Atlantic. Our results also provide evidence on the potential origin of the D″ discontinuity, which is attributed to a Bm-pPv phase transition within both pyrolitic mantle and slab debris beneath Central Atlantic.

To address some of limitations of the current methods on imaging the detailed seismic structures in the D″ region, we develop a grid-search scheme to constrain the detailed 1-D shear-wave velocity structure in the D″ region with quantitative assessment of the uncertainty of 1D models. This new method addresses problems of non-uniqueness and subjectivity in the conventional trial-and-error waveform modelling method which evaluates the fit between data and synthetics qualitatively. A good recovery of the input model with a vertical resolution of 10 km from synthetic experiment demonstrate the feasibility and effectivity of applying grid search method to investigate the 1-D shear wave velocity structure in the D″ region.

In order to probe the global existence and origin of the D″ discontinuity, we apply the grid search method to the lowermost mantle beneath Alaska, northern Pacific and Central America. Our detailed seismic imaging studies allow for speculation that D″ layer is caused by both thermal and chemical effects. Beneath Central America, the D″ layer is dominantly caused by thermal effects associated with Farallon slab remnant, but also affected by varying chemical compositions in the lowermost mantle. By contrast, in regions such as northern Pacific and eastern Alaska, subduction-related chemical heterogeneities are likely to play a dominant role to explain the sharp velocity change in adjacent areas. This difference in the D″ origin could be tightly linked to the slab history in different regions. This thesis shed a light on a better understanding of the D″ origin and its associated mantle dynamics.

Steve Kuhn, University of Tasmania: *Machine learning for mineral exploration: Prediction and quantified uncertainty at multiple exploration stages*.

Machine learning describes an array of computational and nested statistical methods whereby a computer can 'learn' and subsequently make predictions or identify patterns in data. With the increasing volume and variety of numerical data in the geosciences, and widespread availability of the needed computing power, machine learning techniques are a logical addition to the numerous possible approaches that can be applied to the search for ore deposits.

The three core research chapters in this thesis develop the application of machine learning in the context of mineral exploration. Emphasis is placed on the Random Forests algorithm for mapping lithology in a range of settings and at a variety of stages in the exploration process. Information entropy is used to assist both in assessing and communicating any complex combinations, and potential inaccuracy, of classification results. Through the thesis, methods are employed with future practical usage in mind, such that machine learning may be used by the geologist (as domain expert) in an objective manner.

The first of these core studies uses the Random Forests algorithm to re-classify the solid geology lithology map of the Heron South project, located in the Eastern Goldfields of Western Australia. This study uses geophysical and remote sensing data, in the absence of geochemical samples and geological ground truthing with most of the project under transported cover. This is characteristic of an early stage, reconnaissance exploration project. A sparse training sample of 1.6 percent of the total area, is taken as training data, allowing much of the areas geology the freedom to be reclassified. This study demonstrates that Random Forests, with proper consideration given to sampling and training data selection, can be used effectively to produce or improve geological mapping in little explored areas. Information entropy is shown to be valuable in predicting where classification was likely to be inaccurate or a region highly complex.

The second core study uses Random Forests to produce a solid geology map of the Kliyul porphyry prospect of British Columbia, Canada, using a fusion of available geophysical and geochemical data, typical of a greenfields stage exploration project. Soil and rock chip sample sites were taken as training data, used to classify the remainder of the project area. Assessment of the probability distributions produced using the Random Forests algorithm enabled regions with an elevated probability of intrusions (a key indicator lithology) to be mapped, even where not observed in training data. The results of this study highlight the value of a soft, ensemble classifier such as Random Forests, and the value to be gained from an assessment of the spatial distribution of class probabilities as opposed to viewing a final map as a solution in isolation.

In the third and final core study, a range of training data sampling paradigms are tested in a data rich area located in the Domes region of the Central African Copper belt hosting the Sentinel (Ni) and Enterprise (Cu) deposits. This study simulates early and advanced stage exploration project maturity in incorporating a priori geological Information. It culminates in the use of Random Forests to undertake an objective audit of the present company geological map. Further to this, unsupervised clustering is used in the production of a geological map in the absence of training or constraint through identifying the natural grouping of data. The results of these studies highlight the importance of proper sample balancing and explore the repercussions of limited and/or non-representative training data. The use of the information entropy proxy is developed to identify where a classification may depart from the domain represented by training data. The ranking of input data that is performed in association with the Random Forests classification can be used to improve clustering results through optimising dataset selection.

Through the three core research chapters, a set of practical considerations and recommendations for explorers are provided. It is demonstrated that Random Forests can provide an objective audit and subsequent refinement of a pre-existing geological map. The expression of uncertainty using information entropy, and the assessment of class probabilities, can be used to appraise the results from the machine learning analyses. This includes validation in the case of complex outcome combinations, and generation of new insights. Ranking of input datasets via Random Forests can enhance understanding of data and improve both Random Forests classification results and improve clustering. With the proper selection of appropriate datasets, clustering (for example immobile trace elements) and scaling can indeed produce results that correspond well with lithology. Studies presented in this thesis use data from current/active exploration projects and methods are distilled to streamlined workflows using industry standard software and data formats. In summary, these methods, previously the domain of computer and data scientists, are now developed to be more widely accessible to mineral explorers.

Marcus Haynes, Australian National University: *A Bayesian reappraisal of Australian crustal heat flow and temperature.*

Geothermal data offers a unique perspective from which to image the Earth. However, geothermal data is difficult to collect and this has necessitated a reliance on industrial data collection during the exploration for mineral and petroleum resources. Resulting data quality issues have limited previous studies in their ability map the information contained in the data into robust model inferences. In this thesis I employ a Bayesian statistical framework to address these issues, predominantly through the Bayesian re-appraisal of Australian crustal heat flow and temperature data. This has been achieved by defining sensitivity kernels for surface heat flow determinations, examining the sources and magnitudes of noise in primary geothermal data sets, and developing methods to assign petrophysical rock property a priori distributions with spatial variability scaled appropriate to the length-scales of modelling. I combine these factors and use them to infer the surface heat flow field across Australia. This demonstrates the existence of a relationship between surface heat flow determinations and lithospheric thickness. Remote sensing and Argo sea float data have been used to derive a national land-surface temperature coverage, providing the basis for detailed crustal temperature modelling. This is supported by a new framework for assessing the uncertainties inherent in bottom-hole temperature measurements, enabling us to leverage vast industrial data sets to model crustal thermal fields. The significance of these outcomes is that they advances us on the pathway towards genuine joint-inversion involving geothermal data. The quantification of uncertainty distributions on geothermal data sets provides the means to calculate the degree with which a given earth model is consistent with available geothermal data. In doing so, this thesis establishes the basis for future data integration projects to build detailed models of Australian crustal structure and composition, and through doing so, to better constrain the Australian lithospheric heat budget.

Congcong Gai, Australian National University: *Palaeomagnetic and rock magnetic study of North Pacific and South China Sea sediments.*

Magnetism plays an important role in marine science. On the one hand, palaeomagnetism helps us to understand ancient geomagnetic field behaviour that can also facilitate geochronological studies. On the other hand, rock magnetism can provide valuable information concerning palaeoenvironmental and paleoclimatic processes. However, magnetic particles in marine sediments are influenced by multiple geological and environmental processes, and commonly occur in mixed magnetic mineral assemblages, which complicates magnetic parameter interpretation. Therefore, to apply environmental magnetism in marine science, it is crucial to be able to discriminate magnetic signals in marine sediments and to relate these signals to relevant processes.

In this study, detailed palaeomagnetic and rock magnetic studies have been performed on sediments from the North Pacific Ocean (NPO) and the South China Sea (SCS). The main conclusions of this work are as follows. Magnetite is the dominant magnetic mineral throughout SCS Hole U1431D, and its remanence is used to reconstruct a magnetostratigraphic time framework for the past ~6.5 Ma. A single authigenic greigite-bearing interval is identified at 130.5-132.0 mbsf, whose age is estimated at ~2.53-2.55 Ma is associated with oceanographic changes that coincided with intensification of northern hemisphere glaciation. Sedimentary magnetic parameters are affected mainly by the East Asian monsoon and are used to indicate monsoon evolution over the past 6.5 Ma. The summer and winter monsoon were stable before 5 Ma. The summer monsoon intensified from 5 Ma to 3.8 Ma, when it started to weaken. The winter monsoon weakened at 5 Ma, and then intensified after 3.8 Ma, finally stabilizing at 0.6 Ma. Spectral analyses indicate that there was a direct response of the summer monsoon to low-latitude insolation between 6.5 and 3.2 Ma. Since 3.2 Ma, both low-latitude insolation and high-latitude global ice volume have influenced summer monsoon evolution. In NPO core NP02, three visible tephra layers are identified, and can be correlated to the To-Of, Spfa-1, and Kt-3 tephra layers. Together with a radiocarbon date, an initial age model was reconstructed over the ~22-57 ka interval for core NP02. Magnetic analyses suggest that the remanence is carried by detrital vortex state and biogenic single domain magnetite. These two components record similar relative palaeo-intensity (RPI) patterns, and the fidelity of the core NP02 RPI record is further verified by comparison with other RPI stacks and records. Therefore, the RPI-assisted chronology is used to date the studied NPO sediments by tuning the initial core NP02 age model using RPI variations. Hard isothermal remanent magnetization (HIRM) is dominated by the hematite concentration and is used as a proxy for Asian-sourced dust content. Low dust contents are identified at ~25, 39, 48, and 55 ka, which can be linked to Heinrich events 2, 4, 5, and 5a, and are likely caused by southward shifts of the westerlies associated with Atlantic meridional overturning circulation (AMOC) slowdowns. AMOC slowdowns increase the meridional temperature gradient and, therefore, lead to intensified and southward-shifted westerlies. In this situation, the main westerly axis shifts away from the NP02 core site and, therefore, low dust contents are recorded at this site.

Qassim M. F. Al-Aesawi, University of Wollongong/University of Basrah, Basrah, Iraq: *Oceanographic characteristics of alluvial estuaries, North-West Arabian/ Persian Gulf.*

A morpho-sedimentological and morphodynamic assessment of recent changes in the dominant physical processes in Shatt Al-Arab estuary in Iraq and their dynamic effects is an utmost necessity. Shatt Al-Arab is the main freshwater resource into the Arabian/ Persian Gulf, and to southern Iraq and the surrounding agricultural areas. It also has a significant position in the economy for international ship transport, and in its geopolitical setting as it forms the border with Iran for 110 km. Contemporary human advancements have influenced the physical processes by increasing global warming and anthropogenic changes in the feeder catchment, the mouth of the river and the active/ discharge channel. Previous studies have shown that the study area is flagged as one of many catchment areas controlled from upstream by hydraulic construction of dams and levees that leads to alteration in the characteristics of the channel and its mouth. In this study, a hydrodynamic strategy is developed to observe and assess the main forces that control the hydrodynamics in Shatt Al-Arab channel and its offshore area including its geomorphology, sediment transport, and seawater intrusion into the fluvial channel of Shatt Al-Arab. This study provides a new strategy using a numerical model to determine how much upstream freshwater discharge is required to manage the saltwater intrusion from downstream.

To understand the transport of suspended load and its accumulation as modern sediment along Shatt Al-Arab channel and estuary, and to determine which parameters control the interaction with the sea, this study employed field data collection and measurements, such as discharge flow measurements, and sediment and water samples, along the lower 110 km of the channel. Five stations along the channel were employed to collect data as test points for correlation with the numerical model to investigate where and when the discharge impacts on the tidal force.

A mapping study was conducted with new data obtained from the bathymetric survey for use in the digital shoreline analysis system (DSAS method in GIS applications), and in the hydrodynamic system in the MIKE21 numerical model. The data used in the study include suspended sediment concentrations (SSC), tides and bathymetry. A sediment transport model (MIKE21 Mud Transport (MT) for combined currents) and SSC was used to quantify and determine the movement of fine sediments along Shatt Al-Arab estuary and its channel. The hydrodynamic module HD simulated water level variations and discharge flow in response to a variety of forcing functions in the study area. Several modelling scenarios were employed to evaluate the impact of different discharge values on the salt intrusion in Shatt Al-Arab dynamics. Suspended sediment transport was simulated utilising the SSC data derived from the different scenarios of upstream discharge into the estuary. The simulated SSC transport and dispersion patterns were compared to field measurements and showed a consistent direction and magnitude along the channel.

The primary results present significant changes in the location of erosion and deposition, and in the rates of change. It was observed that tides, winds and currents are essential physical factors that control the dispersal patterns. Mapping the shoreline dynamics revealed significant shoreline movement and differences in the rates of change between the left (Iranian) and right (Iraqi) banks. Analysing changes between 1971 and 2016, it was found that on the Iranian shoreline the area of the estuary mouth inside Shatt Al-Arab channel has increased by 2967.98 m^2 while on the Iraqi side, the area along the shoreline has reduced by 1050.04 m^2. In the model, different scenarios simulated Shatt Al-Arab channel conditions when different discharge values are supplied from upstream. These findings could potentially change the classification of the river mouth from a delta to an estuary, and, subsequently, affect the delineation of the border between Iraq and Iran. Also, the freshwater discharge from upstream influences suspended load transport and controls the pattern of erosion and deposition in the mouth of Shatt Al-Arab. The results confirmed a significant relationship connecting the freshwater discharge and seawater intrusion that can provide a useful understanding of seawater distribution over the estuarine channel. This enhances MIKE21 as a useful tool to investigate water resources in tidal zones.

It is hoped that the findings of this study will be helpful to understand the overall hydrodynamic and geomorphological changes of the river and suggest possible future research to be implemented on this river. The study recommends that water management and decision-makers plan how to prevent the destruction of freshwater resources in this area. They need to consider the oceanographic influences and develop a plan for a long-term project to monitor and find a solution for the erosion of the channel margins and shallowing of the navigation channel that needs constant dredging under the current situation.

It is also recommended that initiatives, such as installing additional environmental stations to record important characteristics along the channel, are implemented and supported by the Iraqi government and decision makers in the Basra governance in order to reduce and improve the negative environment/human interventions impacting the whole environment setup along the channel and threatening the economy and freshwater supply to Basra city and surrounding agricultural areas.

MSc/MPhil theses

Xiaoran Wang, Australian National University: *Mass balance change in West Antarctica, focusing on the accuracy of techniques and consequences of different estimated spatial patterns.*

In this thesis, I discuss the spatial patterns of mass balance change in the West Antarctic Ice Sheet (WAIS) estimated by satellite laser-altimetry mission and three different published GRACE (the Gravity Recovery and Climate Experiment) mass concentration (mascon) solutions. In addition to the various native spatial resolutions, mass balance estimates generated by Goddard Space Flight Center (GSFC) displays an obvious different "smooth" spatial pattern both in the monthly mass anomalies and the long-term mass balance trend. The main aim of this project is to identify whether the cause of different spatial patterns is the construction of the regularization matrix (the key component in GRACE mascon solutions). Experiments in the static state normal equations from the ANU GRACE mascon solutions identify that the "smooth" property is derived from the nonzero covariance between the mascon blocks and the diagonal constraints only calculated by the mascons' distance-related value in WAIS. The different correlation distance also has an influence. Besides, prior constraint correlations generated by the geographical models could lose the regional signal in other areas where GRACE mascon solutions are popularly applied to research. Considering all the effects, a modified regularization matrix is generated; this modified approach reduces the workload and is more suitable for the different spatial-resolution ANU mascons. The estimated mass balance based on this regularization matrix doesn't display "smooth" characteristics in spatial patterns and agrees with the previously published results. This project enhances the understanding of GRACE mascon solutions and is helpful to obtain high-accuracy mass change balance estimates in WAIS.

Andriana Stoddart, Australian National University: C*haracterising the magnetic mineralogy of Australian dust source areas.*

The Australian dust cycle has an extensive influence on the environment, extending from iron cycling in oceanic ecosystems to the transportation of dusts to major cities. Investigations into mechanisms governing the Australian dust cycle predominantly involve a dust "sink" analysis, focusing on the magnetic mineralogy of marine sediments without consideration of the magnetic mineralogy of dust sources. Such analysis limits efforts to understand the Australian dust cycle, therefore this investigation involved exploring the magnetic mineralogy of dust sources, namely Australian desert regions. Using samples collected from major dune fields across Australia, commonly employed environmental parameters were used to test if magnetic mineral properties have the potential to determine the provenance of aeolian dust preserved in marine sediments. By observing the range of environmental magnetic parameters obtained for distinct bioregions, based on the Interim Biogeographic Regionalisation for Australia, it was established that Australian deserts display a complex and variable array of magnetic properties that cannot be readily differentiated. Additionally, by sieving samples to obtain fractions representative of aeolian dust, the magnetic mineralogy of deflatable Australian dust was found to consist of a large low coercivity component alongside a highly variable high coercivity component. Such results challenge the commonly held assumption that the magnetic mineral assemblage of dusts is dominated by high coercivity material. Furthermore, commonly employed parameters designed to identify relative and absolute abundances of high and low coercivity magnetic minerals were found to be inaccurate. This was established to be the result of typical laboratory fields being incapable of magnetically saturating samples, as well as the use of conventional methods that neglect the overlap of behaviours when separating magnetic mineral components based on coercivity. Such limitations result in abundances of high coercivity material being underestimated, which could impact the interpretation of parameters and inferences concerning dust quantification and characterisation. While investigations into Australian dust sources may potentially be able to provide a means for identifying dust provenance, doing so accurately requires an understanding of the limitations involved with using such environmental parameters. It is recommended that future analysis of the full coercivity distribution of deflatable dusts is employed for accurately characterising the magnetic mineral properties of dusts in regions. Additionally, while alternative methods for dust provenance may provide sufficient detail to delineate dust sources, it is also recommended that future investigations supplement the sample set used in this study to enable a more comprehensive data set for analysis.

Julian Diaz Rodriguez, University of Sydney: *Predicting the emplacement of Cordilleran porphyry copper systems using a spatio-temporal machine learning model.*

Porphyry copper systems occur along magmatic belts derived in subduction zones. Current understanding of their formation is restricted to overriding plate observations, resulting in a knowledge gap with processes occurring in the convergence zones through time. An association between key tectonic processes and the timing and location of these systems requires linking geological observations to plate tectonic subduction models. This thesis is connecting the evolution of subduction zones and down-going slab properties with the history of porphyry ore deposition across the Americas by using spatio-temporal data mining. These spatio-temporal properties are used to apply a wide range of machine learning methods and show the results in terms of accuracy of predictions on the test dataset. It is provided spatial visualisations in deep-time showing highly prospective areas for porphyry Cu mineralisation along areas not related with known mineral occurrences in North and South America. Results show that the orthogonal plate convergence speed is the most important feature related to the formation of porphyry Cu systems. This parameter is linked with the thickening of continental arcs which has been proved to enhance Cu transport within plutons. It also controls the volume of plate material subducted into the upper mantle, including carbonate phases in the upper volcanic portion of the ocean crust and water-rich pelagic deep sea sediments, which have been demonstrated to enhance sulphur and metal transport, respectively, boosting metasomatic enrichment of the mantle wedge in volatiles, sulphur, and fluid-mobile large ion lithophile elements, promoting the formation of porphyry Cu systems. By using plate tectonic reconstruction models and machine learning applications in the generation of copper mineralisation prediction maps, it is demonstrated the potential of spatio-temporal data mining applications in global mineral exploration related with subduction-related systems.

Oliver Hatswell, Flinders University: *What can geophysical geoarchaeology reveal about the archaeology and depositional history of the site of Klein Hoek 1, South Africa?*

The primary goal of this research project was to utilise geophysical techniques to further understand the stratigraphy and archaeology of Klein Hoek 1, an open-air site located immediately adjacent to the Doring River in southern Africa. This survey utilized three geophysical methods; electrical resistivity tomography, magnetometry, and magnetic susceptibility. The results of the electrical resistivity tomography survey showed that the stratigraphic unit where an important cluster of bifacial points is located extends throughout the subsurface of the rest of the site and is at least 8 m thick. The magnetometry survey revealed evidence of hearth anomalies within the subsurface, which are interpreted as areas of archaeological potential due to a correlation between the bifacial cluster and prehistoric burning. Finally, the magnetic susceptibility test displayed evidence of a palaeosol in the subsurface on the eastern side of the site.

Southern Africa is one of the most significant archaeological regions in the world due to it being one of the earliest locations of behaviourally modern humans. The bifacial cluster located on the surface of Klein Hoek 1 is one of the most important collections of bifacial points in southern Africa, due to it being one of the only stratified, *in-situ* open-air collections of such artefacts in the region. Southern African archaeology has a long history of focusing research on rock shelter sites at the expense of open-air sites. This is due to the lower informative return of time and costs open-air sites have due to their complicated stratigraphy and potential loss of integrity. However, rock shelters only represent limited points in the landscape and history, and thus this focus has created a perspective of southern African prehistory that does not include all the available information making it limited and biased.

The results of this geophysical survey will primarily assist in future study and excavation of Klein Hoek 1. The ERT survey will provide a greater understanding of the stratigraphy of the site, while the magnetic susceptibility survey will locate any palaeosols within the stratigraphy. Meanwhile, the magnetometry survey will identify any hearths within the subsurface and locate the areas of archaeological potential for future excavations. The success of this survey also demonstrates that geophysical methods are effective in a southern African open-air context. The further utilisation of geophysics in southern African archaeology could be invaluable in identifying the high archaeologically potential points of open-air sites making the study of these sites more time and cost-effective.

Shan Cao, Australian National University: *Estimation of crustal discontinuities using active and passive seismic data.*

The evolution of the Australian continent can be traced back to the migration of more than 3000 km since the Eocene. Undergoing a complex set of interactions with its neighbours, the lithosphere of Australia experiences intensive alteration. In past decades, Earth scientists have adopted various geophysical and geochemical techniques to study the lithospheric structure of Australia and rich information has been accumulated. Based on the analysis of these information, various tectonic and velocity models have been proposed to explain the complicated lithospheric structure. However, detailed information is essential to understand the continental structure and tectonic evolution of Australia.

In this thesis, we adopt a seismic technique, auto-correlation, to extract reflected seismic wave signals from the transmitted waves. We firstly carry out testing on the tuning parameters for auto-correlation to verify the proper values for various signal processing techniques. Their effects on the estimated reflected signals from discontinuities are illustrated from autocorrelograms of two permanent stations, which are respectively located above a sharp Moho region and an ice bedrock region. The whitening window of 0.5 Hz is required for stations above shallow ice bedrocks, while the stations on the sharp Moho need values lower than 0.5 Hz, preferring the value of 0.1 Hz. These values are applied to two arrays, Bilby array and MINQ array, trending North - South and East - West directions in central Australia. The data from these profiles show some indication of Moho reflection in the classic receiver function analysis, yet the auto-correlation technique profiles do not show a clear and consistent Moho signal, instead they show a consistent shallow reflection which might be interpreted as sedimentary covers in the regions. These results suggest that auto-correlation technique could be used to estimate some stratification within the shallow layers of crust, where classic methods like receiver functions usually fail.

BSc (Honours) theses

Zak Weidinger, University of Tasmania: *Time-lapse geophysical investigation of the Royal George tailings repository, Northeast Tasmania*

The legacy Royal George mine is a historical greisen tin mine located in northeast Tasmania that was mined between 1911 and 1922. Closure of the Royal George mine was not executed in accordance with current mine closure standards leaving a 270 m long by 35 m deep, steep-sided open cut, and a tailings repository retained in six rudimentary dams in an adjacent valley. Tailings sediments have elevated concentrations of copper, zinc, lead, cadmium and chromium. Acid and metalliferous drainage (AMD) flows from the tailings repository into St. Pauls River, which was formerly the primary source of water for the town of Royal George. The low pH of water from the tailings together with elevated concentrations of copper, zinc, cadmium and aluminium exceed ANZECC guidelines and currently requires provision of potable water for the township via a communal water tank.

Remediation efforts carried out between 2008 and 2019 have been generally successful in revegetating and stabilising the tailings, however AMD remains an issue in some areas on site and for waters leaving the tailings repository. AMD production and mobilisation is likely due to the continued influx of overland and groundwater flow into the tailings repository from the catchment to the south and east. Prior to this study, the hydrology and hydrogeology of the tailings repository and surrounding catchment was poorly understood.

This study employed a range of complementary geophysical techniques and time-lapse hydro-geophysical methods to image and detect change in internal waterflow pathways and assess the thickness and structure of tailings in the Royal George tailings repository. Gamma ray spectroscopy was effective for mapping the extent of the tailings material which have elevated U concentrations relative to the original granite regolith. A normalised difference vegetation index (NDVI) map created from multispectral drone imagery clearly delineated of the extent of AMD impacted vegetation and thus provided a measure of revegetation success. Electrical methods such as electrical resistivity imaging (ERI) and frequency domain electromagnetics (FEM) were effective for imaging spatial and temporal water table variations, including a seep from one of the tailings dams (Dam 3). Ground penetrating radar (GPR) effectively imaged the interface between tailings and the underlying original soils and found an average tailings thickness of ~1.5 m and a maximum tailings thickness of 3.7 m. Seismic refraction tomography effectively imaged the top of the relatively impermeable weathered granitic basement but could not be used to discriminate tailings from underlying granitic regolith.

From the interpreted thickness of tailings, depth to basement and prior test pit data, it is predicted that during periods of reduced rainfall, such as the summer months, the water table is beneath the tailing material but during wet periods significant proportions of the tailings are fully saturated. This hydrological variation has important implications for seasonal variation in AMD production, leaching and contaminant flow into the St Pauls River. Time lapse geophysical imaging and surface observations also suggest that there is a time lag between rainfall and pooling within the tailings of up to two weeks.

Amy Soper, University of Wollongong: *The characterisation of fracture and fluid flow properties of the Hawkesbury Formation in the Tahmoor region, NSW.*

Fractures and associated networks can significantly affect subsurface fluid flow. Subsurface fluid flow is of greatest significance in rocks with favourable aquifer characteristics. In this study, the Hawkesbury Formation, a natural groundwater reservoir is analysed to characterise fracture networks. Longwall mining under the Hawkesbury Formation is common in the Southern Sydney Coalfields region, NSW. Therefore, the Hawkesbury Formation is subject to altered fracture networks due to the increased stress and brittle nature of the Formation.

Previous literature focuses heavily on the primary porosity and permeability of the Hawkesbury Formation with little regard for the influence fracture and associated fracture parameters have on subsurface fluid flow. This is because characterising groundwater flow in fractured rock aquifers is difficult. However, this study highlights the need to better understand how flow yields are likely to change with changes to fracture networks.

Through the analysis of mechanical stratigraphy including bed thickness, parameters of fracture spacing and fracture aperture this study focuses on the calculation of fracture parameters to model and characterise reservoir flow properties. This was achieved through both observational and geophysical analysis of sedimentary core holes within a 30km radius around the Tahmoor South mine. Examining the observational fracture spacing and bed thickness of the Hawkesbury Formation was subsequently compared to the inferred bed thickness from geophysical gamma logs.

The results found that both the fracture parameters and fluid flow results align with previous literature. The predicted mean fracture porosity value of 0.012% is considered insignificant, with fluid flow being predominantly matrix facilitated. The predicted average hydraulic conductivity of 0.055m/d are in close relation to the hydraulic conductivity of 0.041m/d from Tahmoor South. However, further investigation is required as the relationship between bed thickness and fracture spacing did not correlate to the hydraulic conductivity values. With refinement, this model can be used in future studies to predict reservoir flow properties and how they are likely to change if stress from longwall mining occurs.

Jared Carl Magyar, Australian National University: *Geophysical inversion with optimal transport.*

Our state of knowledge of Earth can only be informed by what we can observe at the present, and from the surface. However, the properties and events of greatest interest generally cannot be measured directly with these fundamental restrictions, whether this be due to them being buried at great depths beneath the surface, or far in the past. By searching for the parameters that most adequately explain accessible observations, a window into the hidden processes can be revealed. This process of taking observable data and inferring the underlying mechanisms is formally known as solving the inverse problem, and this reverse way of thinking is foundational for much of our understanding of the internal structure and dynamics of the planet.

Whilst processes that behave in a linear fashion can generally be well understood within an inversion framework, more complex non-linear problems are not so straightforward. Developing new techniques to address the issues arising from non-linear processes is therefore a topic of considerable interest with far-reaching consequences across seismology, geodynamics, geodesy, geomagnetism, and many more. Recent attention has developed around the use of optimal transport (OT) in solving such inverse problems (Engquist and Froese, 2014) (El Moselhy and Marzouk, 2012). OT gives a new perspective on both optimisation-based and probabilistic inversion techniques.

In this study, we first consider the OT-derived Wasserstein distance as a measure of misfit, seeking to avoid the suboptimal convergence that is frequently encountered in non-linear inversion. The procedure is derived in a general setting, feasibly allowing a variety of inverse problems to be considered. We reframe the minimisation of the Wasserstein distance as a least-squares problem and solve it using the Gauss-Newton optimisation method. To the best of our knowledge, this is the first time the problem has been cast in this manner and may allow numerous other techniques from classical least-squares to be applied. An application of fitting Raman spectra for volcanic glasses with mixture models is considered as a test case. This simple example provides a vital building block for more complex mixture modelling tasks in the future. A more intricate waveform fitting task is then explored. Two key innovations are made here: a new method for converting arbitrary signals into a form compatible with OT is developed, and the sliced Wasserstein distance introduced as a misfit measure for inversion, seemingly for the first time. We see that these two concepts can work in tandem to avoid cycle-skipping when considering simple waveform functions.

We then consider the alternative Bayesian approach for non-linear inversion. A transport-based sampling method to compete with Markov chain Monte Carlo is proposed. Based upon the work of El Moselhy and Marzouk (2012), solving the Bayesian inference problem can be expressed as finding a map that transports the prior distribution to the posterior. While this concept is not new, a novel implementation is developed. The mapping methodology is then found to be well suited for prior sampling tasks, where a full understanding of the inverse problem is developed before observations are made. A simple test problem is explored, and promising initial results found.

Through the various concepts discussed here, and in the wider literature, OT is found to have a multitude of uses for solving non-linear inverse problems, many of which are yet to be explored deeply in a geophysical context.

Sinan Özaydın, Affiliation: Macquarie University: *Three-dimensional magnetotelluric constraints on compositional variations of the Southern African mantle.*

In the absence of significant thermal anomalies, the electrical conductivity distribution in the cratonic mantle is still highly variable, which indicates the highly differing chemical and physical properties of the mantle. It is not well understood which forms and styles of chemical differences (metasomatism) are related to observed electrical conductivity distributions in magnetotelluric models. The primary aim of this thesis is to unravel such relationships between electrical conductivity distribution and mantle composition in Southern Africa, which is chosen as the study field because not only it has excellent magnetotelluric data, but also it is rich in kimberlite-hosted xenoliths and xenocrysts.

Emily Lewis, University of Adelaide. *Bottom-up exploration: Imaging resistivity of a mineral system from source to sink.*

Ore deposits are broadly defined as geochemical anomalies that have been concentrated from significantly larger volume sources at depth. This requires a mineral system process through which elements in the lower crust or mantle are entrained and moved to the surface. In various locations around the world, the source region of a mineral system has been shown to have a distinct electrical resistivity signature as a result of past magmatic fluid processes which have left a geochemical overprint. This project focuses on the Curnamona Province, a Paleo-Mesoproterozoic craton which extends across South Australia and New South Wales with approximate dimensions of 300 km east-west and 300 km north-south. A previous broadband magnetotelluric (MT) (102 to 0.01 Hz) traverse of 60 stations spaced 2 km across the Curnamona Province identified a 2D geophysical signature with a footprint similar to that below the IOCG Olympic Dam deposit in the Gawler Craton. In this project, broadband MT measurements (104 to 0.01 Hz) were collected along four parallel lines of 1 km spaced sites, and with line separation of 5 km to develop the 3D context. We image a discrete low-resistivity zone on three of the lines, which extends from the surface down to 20 km depth, where it is linked to a conductor of 1Ωm. It appears to be bound between two resistive blocks and is not laterally continuous. The outcomes of this model are comparable to pathways across the Gawler Craton. We show a very strong relationship between deep crustal conductors and narrow pathways, inferring a signature which is responding to past magmatic events.

Fletcher Howell, Australian National University: *Constraining the nature of dynamic topography to guide inverse geodynamical models.*

Oceanic lithosphere is formed at a mid-ocean ridge and subsides as it spreads away from the ridge axis. This subsidence, measured as the evolution of bathymetry, provides a unique constraint on the dynamics and evolution of the mantle's upper thermal boundary layer. The variation in depth with age of oceanic lithosphere is controlled by heat transfer and can be described by a 'cooling model'. Despite developments in cooling models since the 1970s, some observations of the seafloor remain enigmatic and are not explained by these models.

To enable exploration of prevalent, regionally-variable influences on oceanic lithosphere, we have designed a robust set of flowlines — time series of oceanic lithosphere created at the same location on a mid-ocean ridge. Analysis of cooling models at the regional-scale, using these flowlines, reveals the global ubiquity of the effect of hydrothermal circulation in stalling conductive cooling at young ages (0-5 Ma), and the regional-variability in the extent of deviations from linear cooling behaviour at old ages (> 70 Ma). It has been proposed that such regional variability could be a consequence of dynamic topography, the response of Earth's surface to underlying mantle flow. This study provides the first quantitative, regional-scale analysis of oceanic lithosphere cooling using bathymetry corrected for predicted dynamic topography.

Analysis at this scale provides novel insight into the influence of dynamic topography on the spatio-temporal evolution of oceanic lithosphere. A synthetic dynamic topography prediction is used to correct bathymetry, showing an improvement in the quality and consistency of fit to both global and regional-scale amalgamations. This correction allows us to better highlight oceanic lithosphere cooling trends in isolation, revealing significant regional variability in the presence, onset, and expression of deviations from a half-space cooling regime beyond 70 Ma. Dynamic topography appears to account for a portion of 'flattening' behaviour seen in global amalgamations, but it does not completely account for deviations in cooling behaviour at old ages.

Our study has implications for the understanding of the physical basis for the behaviour of oceanic lithosphere in the context of cooling trends. While the plate model provides an acceptable empirical fit to the variation of bathymetry with age in the majority of regions, there is no necessity for the plate thickness parameter to be underlain by a single, globally ubiquitous physical mechanism.

Yi He, University of Adelaide: *Curnamona Cube: 3D lithospheric architecture of a Proterozoic province.*

The Curnamona Cube project was developed to define the properties of the Province over a scale of 400 km by 400 km, and from the surface to 400 km depth, defining a cube of geophysical information. In this first part of the project, broadband MT data were collected and over 200 sites with site spacing of 25 km or less, to observe the entire Curnamona Province at higher resolution at crustal depths. In this paper, new Curnamona Cube MT data are combined with legacy broadband and long-period MT data from the last decades to provide further constraints on the morphology. The primary outputs are a new 3D resistivity model that maps out the lithosphere with long-period MT responses, and more detailed crustal images from new broadband MT. The 3D models indicate significant low-resistivity structures (< 1 Ohm.m) that extend from depths of 5 km to 30 km depth, dipping from the eastern margin of the Province towards the centre. Such models show correlations of low-resistivity lower-crust with known copper occurrences and resources, and diamond-bearing kimberlites with the thickened lithosphere to the west of the Province.

Annalise Cucchiaro, University of Wollongong: *An investigation into the behaviour of the magnetic field from 1 Ga to present day.*

The magnetic field of Earth and its behaviour over time is linked to its origin within Earth's liquid outer core. Complex internal processes that operate within the outer core are not only responsible for the creation of the geomagnetic field, but also the magnetic field's strength, stability, and position on Earth. The magnetic field acts as a critical barrier of protection, shielding Earth from harmful solar radiation from the sun and confining Earth's atmosphere beneath the exosphere. As Earth's core evolves and cools over time, it releases heat at the core-mantle boundary (CMB), the magnetic field reflects this evolution by weakening, strengthening, and reversing in polarity over time. It is important to study and form a better understanding of the behaviour of the magnetic field and its intensity over time, as its ability to weaken may give rise to biological and technological damage to Earth and its inhabitants.

Variation in magnetic field behaviour over time is preserved in the geologic record, but data is scarce and poorly constrained, thus, numerical modelling solutions remain an essential aspect of paleo-geomagnetic field analysis. In this study, we analyse model-predicted core-mantle boundary heat flux as a proxy indicator of the dynamic evolution of the magnetic field, from 1 Ga to present for four model cases. We do this in aim of including periods known to exhibit the weakening of the magnetic field (superchrons, hyperactive periods and periods of biological extinction), and also investigate the spherical harmonics and Pearson correlation between these data and the current paleo-geomagnetic reversal rate data of two previous studies (Hounslow *et al.* 2018, Olson *et al.* 2013). Results conclude that CMB heat flux correlates weakly with the geomagnetic reversal rates, with equatorial CMB heat flux variability (q* equatorial) correlating the greatest of all quantities investigated. Spherical harmonics analysis reveals a 200 Myr cycle in magnetic field intensity that may correlate with Earth's 200 Myr deep mantle convection cycle.

Dina Chu, University of Tasmania: *Geophysical Characterisation of the Pine Creek Gold Deposit.*

The Pine Creek area, Northern Territory contains structurally controlled orogenic gold mineralisation within quartz-sulphide veins that are typically concentrated in hinges of antiforms. Limited geophysical prospecting has been undertaken in this environment and the potential effectiveness of geophysical methods for discrimination of gold mineralisation, rock types and stratigraphy has not previously been tested.

Petrophysical measurements conducted on drill core from the Gandys and International prospects characterise the properties of mineralisation and host stratigraphy, and can be used to assess the likely efficacy of large-scale geophysical survey methods. Quantitative and qualitative interpretation of regional aeromagnetic data here provide a basis for interpretation of the structural framework in the Pine Creek area.

Drill core petrophysical measurements cannot be used to reliably discriminate local lithological and stratigraphic variations at Pine Creek or to identify mineralised rocks. Rock physical properties have been homogenised primarily by the effects of thermal metamorphism and alteration. Northwest-trending regional magnetic anomalies are interpreted, on the basis of modelling, to be concordant to bedding and likely delineate stratigraphically controlled zones of disseminated pyrrhotite formed by thermal metamorphism of original pyritic beds. The regional magnetic anomaly pattern provides a basis for detailed structural interpretation.

Petrophysical measurements indicate that geophysical methods are likely to be ineffective for mapping local lithological or stratigraphic variations at Pine Creek or for direct delineation of mineralisation. However, downhole wireline logging suggests that some mineralised intervals may be associated with elevated electrical conductivity and chargeability and this possibility should be further evaluated. Structural interpretation of the regional aeromagnetic data has highlighted antiformal regions under shallow cover that may be prospective for Pine Creek style mineralisation.

Rebecca Chapple, University of Wollongong: *3D geological mapping of fracture networks in the Hawkesbury Sandstone and their implications to groundwater flow.*

Throughout history, there has been extensive research performed on the Hawkesbury Sandstone, however, little has been done within academic literature on the fracture networks throughout it, specifically on their influence on groundwater flow and storage. The regional deformation is also believed to be due to basement control, with little research performed on alternate theories of deformation. This study aims to develop a better understanding of the fracture networks in the Hawkesbury Sandstone and how fractures may contribute to the flow pathways between underground and groundwater systems. It also aims to determine the possibility of an alternate theory for regional deformation, in the form of detachment folding.

This study was conducted on the Southern Highlands of New South Wales, with a key focus on three rock outcrops at Yanderra. Photogrammetry models were developed which were then uploaded to a 3D geological software program (IPM-MOVE™) for geological interpretation. The established mesh surfaces were interpreted to develop cross-sections and quantitative results, with a particular focus on fracture length and spacing at each outcrop. The acquired fracture measurements, along with three test apertures were used to develop a conceptual model of the porosity and hydraulic conductivity of fracture networks within each outcrop.

The calculated porosity of the fractures in the Hawkesbury Sandstone, based on observed fracture length, ranged from 0.001-0.011% with three different apertures, while the conceptual model based on fracture spacing ranged from 0.001-0.022%. The expected hydraulic conductivity of fractures ranged from 0.040 m/day to 15.64 m/day. The depth to detachment was calculated to be approximately 325 m, which indicates a detachment layer is possibly within the Illawarra Coal Measures.

Fractures are a clear host to fluid movement through rock outcrops. Longwall mining can cause movement on existing fractures due to subsidence, and thus, have implications for the movement of groundwater throughout them. This could have the potential to affect recharge within aquifers throughout the Sydney Basin and should be considered in future fracture studies and mining operations.

Environmental geophysics

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Figure 1. *AgTEM cart side view.*

Figure 2. *AgTEM front loop (Slingram) may be added as an option to create a second independent dataset.*

Welcome readers to this issue's column on geophysics applied to the environment. Recently I was contacted by one of my previous contributors, who had a column idea that I thought was worth sharing. In this column I am happy to reintroduce Dave Allen, founder and main thinker behind Groundwater Imaging, who is spruiking developments to his towed TEM system that he calls AgTEM. Here is what Dave has to say:

AgTEM – a development story

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AgTEM (Figures 1 and 2) is a towed transient electromagnetic (TEM) system initially designed to survey cleared, levelled agricultural land – mostly to map salinity and help site bores. Over time it has been recognised as being useful for mining and geotechnical applications as well. AgTEM processing provides maps and vertical sections of bulk earth resistivity from just a few metres below the surface to tens of metres depth (Figure 3 shows an example data set). It is well suited to image conductive features up to 100 m deep below otherwise resistive strata. The system is normally towed behind a 4WD ute (Figure 2) but can also be towed by quadbikes, ATVs and even floated behind a boat. There is a new lightweight version that can be hand-carried in difficult terrain.

How did we get here? Well, back in the 1990s I was doing 100 m x 100 m loop TEM surveys working for one of the old contracting companies (Geoterrex) near Cloncurry in NW Queensland and was frustrated with the slow progress laying loops. I put together my first towed system, looping a whole lot of wire around a wooden structure and then towing it behind a ute. Being naïve about the limited capacity of transmitters to turn off current rapidly I hooked up 20 turns to a Geonics EM37 transmitter and surveyed away. Unfortunately, the results were disappointing due to the long turnoff time and induction into the metal towing vehicle. In the end it was an expensive experiment: the transmitter lasted that survey but shortly after some

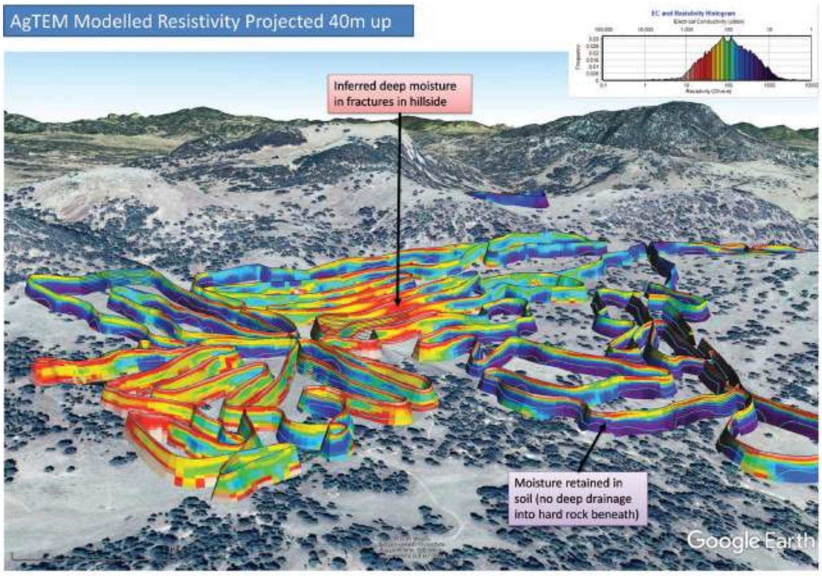

Figure 3. *A sample of AgTEM data collected in one day revealing potential groundwater sources in deep rock fractures. Data are projected along survey lines, to depth of 40 m.*

components failed due to the damage done by the high inductive load.

Back in the early 2000s I got involved with some work that Zonge Australia was doing with a University of Adelaide MSc student (Brian Barrett – with one of his supervisors, Mike Hatch), they were towing a Zonge NanoTEM equipped wooden frame behind a boat, collecting TEM data, while I was working on towing a resistivity streamer, as part of my PhD research. We were looking for salt water intrusion into the river bed and both techniques were successful. Inspired by the success on the Murray River with Zonge, I tried the same on land using a crazy, low-cost 6 m x 6 m loop of PVC pipe and electrical cable reels. Again, I used the Zonge NanoTEM equipment and single turn transmitter and receiver loops. It was good, but I thought that I could do better.

About this time I got the chance to visit the Hydrogeophysics Group (HGG) at Aarhus University in Denmark where the PATEM towed system (a transmitter sled with a receiver towed behind) was being developed; this system was towed by a tracked walk-beside vehicle. This project went by the wayside months later as HGG focused on developing the SkyTEM airborne TEM system, which has been a huge success for that group. Seeing the potential in the PATEM system, I was inspired to continue to develop a "niche" towed TEM system.

I got my next transmitter/receiver system from Monex Geoscope (a spinoff of some research work that Professor Jim Cull and Duncan Massie were doing). Using the terraTEM solved my instrumentation problems. After that, most of my problems were practical, structural problems – how do you tow a sufficiently large loop to get signal into the ground, without any structural metal, in field conditions that are often rough enough to damage a 4WD?

I got to test some interesting towing ideas by bootstrapping funding I got to run some TEM trials on a platinum exploration programme. I tested and ran towed TEM surveys as an adjunct to a standard 100 m x 100 m moving-loop TEM survey. For this work I towed the transmitter and receiver loops on a sheet of plastic (super tough irrigation channel liner) behind a quadbike. The 2 mm thick sheet only wore out after surveying several hundred kilometres, but it was very difficult to get the 7 m x 7 m sheet through the many farm gates in the field area. But the data sets were awesome, providing the client with high quality subcrop mapping; the subcrop complexity was surprising given the lack of evidence on the ground surface.

I conducted similar towed TEM surveys using plastic sheets at Menindee Lakes the following year; again the results were impressive revealing a number of locations that were potentially suitable for managed aquifer recharge. It was on this survey that a road train passed us at 100 km/hr as we surveyed the road verge and my 200 kg plastic sheet was lifted into the air, demolishing the transmitter. This led to the decision to avoid any further use of large, dragged plastic sheets.

The next stage in the development of the AgTEM system consisted of designing and building a large wooden platform for the transmitter loop. This proved to be too costly to maintain due to wood rot and was cumbersome to run. A receiver dragged on a separate mat far behind the wooden cart made the whole system challenging to drive, especially through farm gates and in traffic. Many designs followed with narrow towed mats and towed carts made from PVC pipe. The receiver antennae mounted on plastic mats never lasted long enough in the field, which led to their abandonment yet again, but those early plastic pipe carts showed considerable promise.

As plastic pipes are not designed for structural flexure, I started working on an extruded fibreglass cart, but that was ultimately too costly to duplicate (and operate). With a total weight of about 700 kg its non-metallic wheels and axles failed too quickly. I ran a number of surveys using that system, including one in the Burdekin Delta, where the system mapped aquifers and saline intrusion to as deep as 90 m.

I went back to the PVC pipe construction, this time simplifying the physical design by eliminating the need for a troublesome rear towed mat receiver. It took some effort and thought but I ended up using a 4 m^2 receiver loop that overlapped the transmitter loop in such a way that the system minimized the mutual induction between the receiver and transmitter loops. Once this was stabilised I found that the data were just as good as those collected using the towed mat receiver loop (and the system was far more compact and useable). The receiver and transmitter loops were mounted on boom arms that were held in place with elastic straps and could therefore fold up during the survey and pass through most farm gates and gaps between trees. I patented the structural concept and set to develop it commercially. The original "null mutual induction cart" was rather large, so I also started working on making smaller carts. With the help of an industrial engineer we also developed a lighter-weight, thinner fibreglass pipe structure.

At about this time drought started to grip eastern Australia, and demand for surveys took away all of our time and resources for development, as we sited bore after bore for farmers and local councils. When the rains started again in early 2020 the work dried up and there was again time to work on commercialising the AgTEM cart. “Interestingly” (frustratingly?), the process of moving from invention and product development to commercial manufacture is proving to be both expensive and more difficult than the development steps. Part of the commercialisation process was to design a cost-effective freight solution for the system. Once this was completed we airfreighted a system to the USA - unfortunately right in the midst of the COVID freight crisis. The system is there, finally, and is undergoing field trials at the moment.

And development continues: I have added a version of the Slingram receiving antenna that is now mounted in front of the vehicle (Figure 2). Instead of towing a receiver by cable behind the cart, which makes the towed cart array very long, with the towed receiver catching on fence posts and gates and wearing out due to ground abrasion on gravel roads, the second Slingram receiver is now mounted ahead of the towing vehicle. With the loop about 3 m off the ground it is relatively easy to manoeuvre through gates and trees on narrow tracks while towing the transmitter loop system.

Development of the AgTEM system has been a long and arduous process, but the final versions are truly tried and tested, just waiting to be used in new environments, agricultural, geotechnical and mining.

Minerals geophysics

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Evolution

Geophysical techniques evolve over time and their mode of usage can change. The evolution of magnetotellurics (MT) as a geophysical method for mineral exploration here in NW Queensland is a good illustration.

MT was traditionally viewed as the electromagnetic method for deep investigation on a regional scale. Some trial MT surveys were done over known ore deposits with a view to evaluating their regional setting, but MT wasn't really seen as a method suited to detailed systematic surveys.

The development of MIMDAS (MIM distributed acquisition system) in the late 1990s drove a resurgence in our use of IP-resistivity in NW Queensland, in part due to the relative cheapness and simplicity of the sensors (stainless steel plates) compared with those needed for electromagnetics (receiver coils). The string of collinear receiver dipoles required for the MIMDAS dipole-pole pole-dipole IP-resistivity array meant that, with the added input from a set of magnetometer coils, a simplified EMAP style of MT could also be surveyed.

Initial in-house processing of the MT data employed OCCAM 1D inversion. As with any 1D inversion routine used to generate 2D sections, the resulting resistivity sections included artefacts relating to 2D (and 3D) geometry of the environment (see Figure 1). Sections constructed from 1D inversions represented an advance on those constructed from apparent resistivities, but difficulties were created when these 1D inversion sections were interpreted too literally, leading to mismatches with the geology and disappointing drill-test results. The potential depth of investigation of MT might not have been oversold, but the validity of the finer detail in the resistivity sections certainly was. MT lost credibility with our geologists.

Ten years later, mineral exploration in NW Queensland had expanded away from the areas of outcrop and shallow (<75 m) transported cover. We were now tasked with exploring for bulk tonnage targets beneath 200 m or more of transported cover. Magnetics and gravity were the obvious choices, and while they did provide detectable anomalies, distinguishing these from the plethora of other similar features was proving difficult. We needed another petrophysical property contrast and resistivity/conductivity offered that possibility. The difficulty was that the cover was not only very thick, but also very conductive (maxima over 1 mho/m). High power TEM with Squid sensors had had some success in this environment, but only for highly conductive targets. Our targets, while substantial in size, were expected to be much less conductive, and might only exhibit relatively subtle contrasts with the geo-electrical environment.

We reasoned that MT had potential, trading off its deep penetration capability against the debilitating effects of the conductive cover; we also felt there may be some inherent capacity for discrimination of relatively subtle resistivity variations within the 'basement'. The spatial resolution of the technique was a concern, but 2D MT inversion routines were now well established and therefore artefacts from 2D effects should be less of a problem. We were also proposing full five component MT (three magnetic plus two electrical) rather than the abbreviated version used in the past. Given our previous unfortunate history with the method, some selling of this proposal was required!

Initial trials showed that the 'new' MT method was apparently capable of mapping quite subtle variations in basement electrical properties beneath substantial conductive cover. A station spacing of 250 m produced sufficient detail for our purposes; spatial discrimination at this scale seemed valid (see Figure 2).

Overall, results were encouraging enough for MT to become an accepted technique in the exploration for bulk tonnage targets in this challenging environment. Past experience, a change in attitude, and need, drove the evolution of MT as a tool in our geophysical arsenal, facilitated by improvements in instrumentation and advances in data processing and presentation.

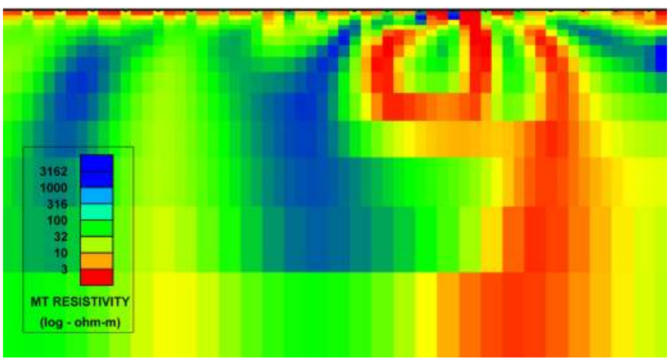

Figure 1. *A 2000 MT OCCAM 1D inversion section – section extent 2 km x 1.1 km*

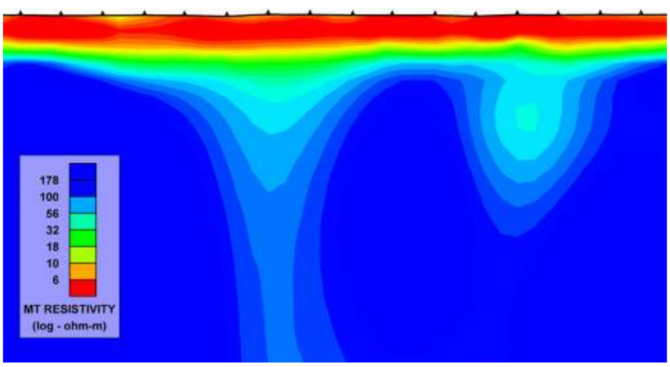

Figure 2. *A 2012 MT 2D inversion section – section extent 4 km x 2.1 km*

Seismic window

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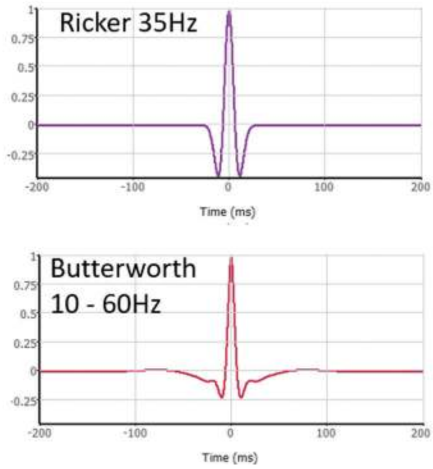

Figure 1. *Selected assortment of wavelets showing the differences are essentially in the side-lobe amplitude and extent*

Wavelets, spectra and transforms

I know I've done this before (*Preview* December 2017) but posts on various user's groups suggest there is still some misunderstanding of the application of spectral decomposition. Spectral decomposition is the process of breaking down seismic data into discrete frequency components and its main use by interpreters is to aid stratigraphic interpretation. The method relies on tuning curve properties to isolate thin beds and estimate their thickness. Here are some common user questions and answers with illustrations based on simple models.

What wavelet should I use in modelling?

I prefer one that matches the seismic data but extracted wavelets are difficult to describe so a mathematical wavelet is more useful. There are many theoretical wavelets that could be used and quite often a Ricker wavelet is chosen but in practice there is little difference between wavelets once the frequency range is known. Figure 1 has some example wavelets. The Ricker wavelet is the neatest with only a single but higher amplitude side-lobe while the Ormsby and Butterworth wavelets have broader side-lobes with more reverberation. Something to remember is that all seismic sources are impulsive and start at time zero and it is only in processing that symmetric wavelets are created.

How can bed thickness be determined? What are these plots?

Spectral Decomposition relies on the tuning effect where for thin beds constructive interference between reflections from the top and base of a bed result in a high amplitude anomaly when the bed thickness is a quarter of a wavelength (the primary top reflection and side-lobe peaks from the base reflection are a half cycle apart in TWT and align). Obviously the wavelength depends on frequency so different wavelengths give information on different bed thicknesses. Figure 2 is a handy table that shows the tuning thickness for some given frequency and velocity.

Frequency Hz	Estimated tuning thickness				
	Velocity m/s				
	2000	2500	3000	3500	4000
10	50	63	75	88	100
15	33	42	50	58	67
20	25	31	38	44	50
30	17	21	25	29	33
40	13	16	19	22	25
50	10	13	15	18	20
60	8	10	13	15	17

Figure 2. *Table of tuning thicknesses associated with various frequency and velocities. A table like this is handy to have on your desk.*

One way to analyse the seismic data and determine bed thickness is to use a Frequency vs TWT plot at a specific place such as a proposed well location (Figure 3). The colour depicts the amplitude of each frequency. On this type of display a single bed will appear as an anomalously high amplitude (caused by tuning) at the tuning frequency and TWT of the bed. Figure 3 shows the spectral decomposition results for a 10 m thick bed. The 45H z peak frequency estimates the bed to be 10.1 m.

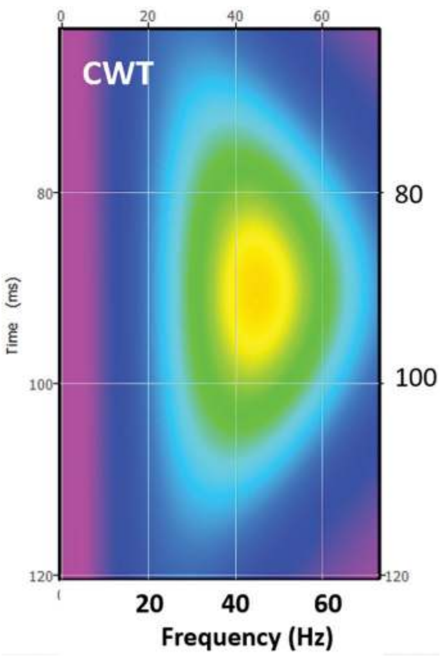

Figure 3. *Continuous wavelet transform of a single bed 10 m thick at 90 ms. The CWT predicts the correct thickness and location of the bed. (Velocity used is 2000 m/s).*

What is the wavelet effect and how can it be removed?

Failing to take account of the wavelet spectrum is a pitfall for the unwary. The wavelet spectrum can often affect the thickness calculation because it is embedded in the data and is commonly the dominant part of the spectrum. One way to remove this overprint or reduce the wavelet effect is to normalise each frequency. This will flatten the spectrum and reduce the wavelet effect. Figure 4 shows the wavelet effect on a single interface model. Because there is no tuning only the wavelet frequency information is present. In this case the wavelet spectrum is output – and it is similar to the output of the 10 m bed model (Figure 3).

What is better, FFT or CWT?

This is not a simple question to answer because the method used needs to match the geology, but my first choice would be the Continuous Wavelet transform (CWT). The CWT gives good vertical positioning as well as more accurate bed thickness prediction. There are other transforms described by various experts but I do not have the software to test them. Using the single 10 m thick bed model (Figure 5) three versions of a spectral decomposition were calculated and displayed - a Fast Fourier transform (FFT) with a 48 ms window, a short window (28 ms) FFT and a CWT. The CWT correctly displays a tuning peak at 45 Hz (10.1 m) slightly shallow vertical location and is the preferred transform because it has better vertical accuracy. Similar results are obtained using a model with a single 20 m thick bed except the tuning frequency is now 25 Hz (Figure 6).

However it's not that simple and things get interesting when there is more than one bed. Figures 7 and 8 have the same net bed thickness of 20 m but it is distributed as two and four beds respectively.

The two bed case of Figure 7 produces results similar to the single bed case and the tuning peak (F) is obvious but there is another local peak frequency (E) at 15-20 Hz which is the thickness of the gross package. The next case (Figure 8) also has 20 m net that is distributed in four 5 m beds separated by 5 m. Once again multiple anomalies account for the different bed combinations possible from 5 m thick (100 Hz) to 35 m gross thickness (15 Hz).

One intriguing aspect of the multi-bed cases is the similarity between the CWT and the long windowed FFT. Why? I believe it is because the multilayer models appear more like a continuous function within the calculation window. On the other hand the CWT uses a varying length wavelet to match the data and because of the reverberations there are several possible matches spread across a large time interval.

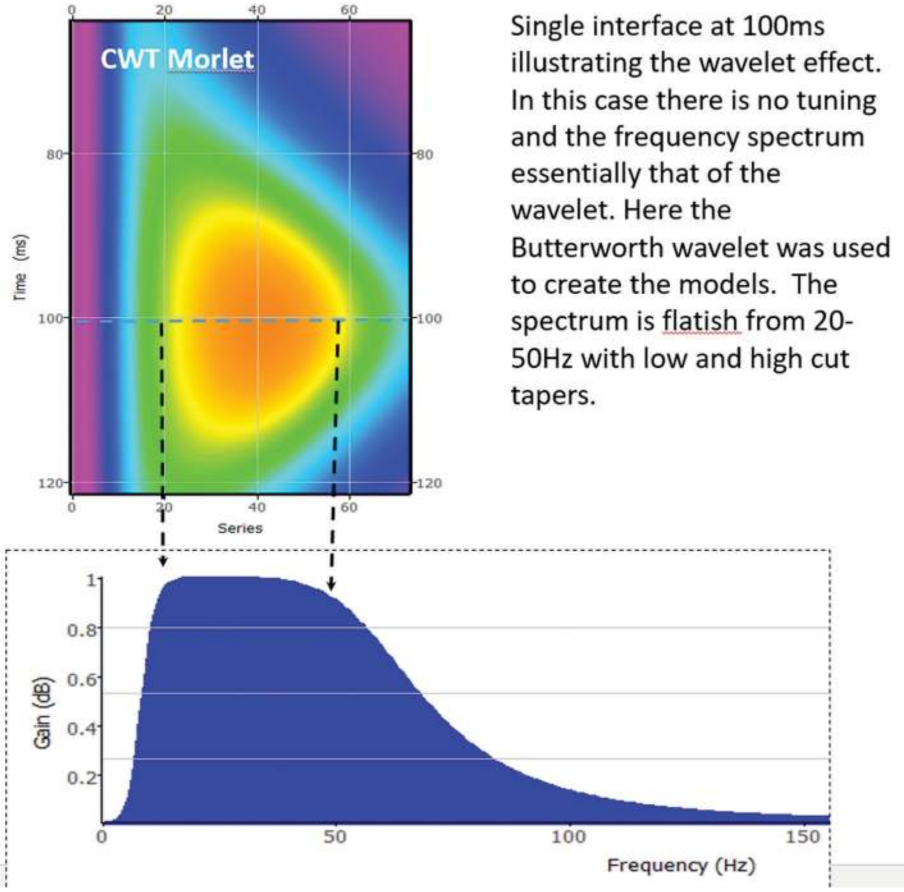

Figure 4. *Time vs frequency plot of a single interface model (top) showing the amplitude spectrum of the wavelet compared with the more familiar way to display the frequency spectrum of a wavelet (bottom).*

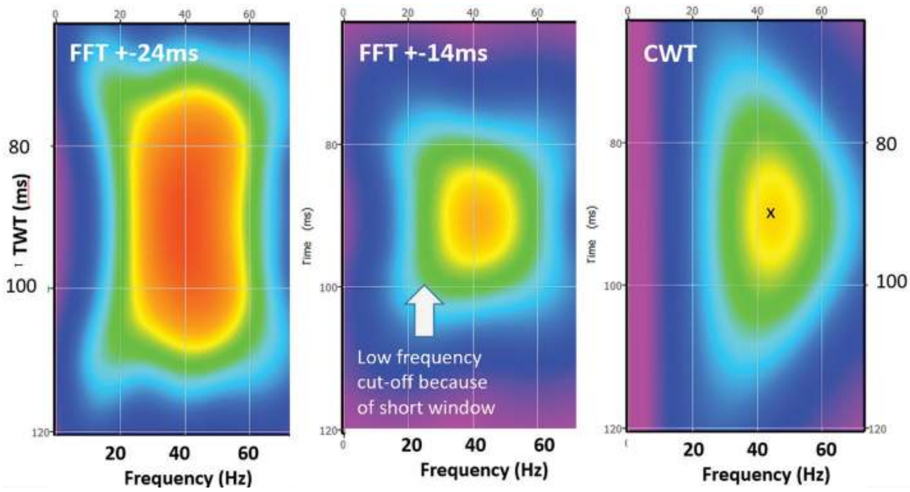

Figure 5. *A comparison of FFT and CWT using the modelled 10 m thick bed as input. Here the CWT (right) gives a good anomaly at the tuning frequency. The short window FFT (centre) also gives a good result while the longer window FFT (left) cannot give an unambiguous vertical positioning. The short window (28 ms) FFT has a low frequency limit of ~20 Hz because the window is not large enough for long period wavelets (CWT continuous wavelet transform, FFT Fast Fourier Transform).*

Time or depth data?

Theoretically spectral decomposition should use time data as input because the frequency spectrum is relatively stationary. Depth domain data may have wavelet shape changes as velocity changes but in practice this is not really observed. Most software companies have implemented the ability to use a depth domain input with no problems and the results are the same – it's just a little trickier to describe what's going on.

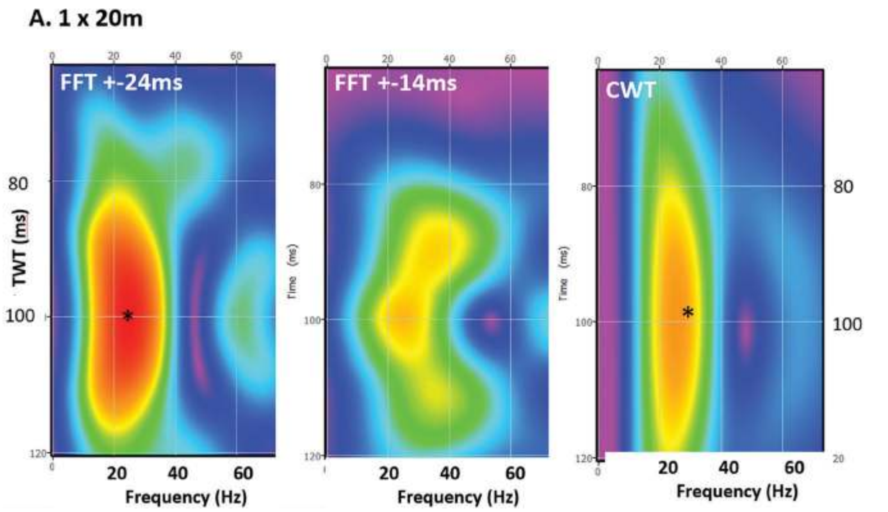

Figure 6. *Spectral Decomposition of a single 20 m thick bed. The peak amplitude at 25 Hz (*) successfully predicts the bed thickness. The short window FFT +-14 ms also has a peak amplitude at 25 Hz however frequencies below 20 Hz are attenuated and poorly estimated because the window length of the FFT is too short.*

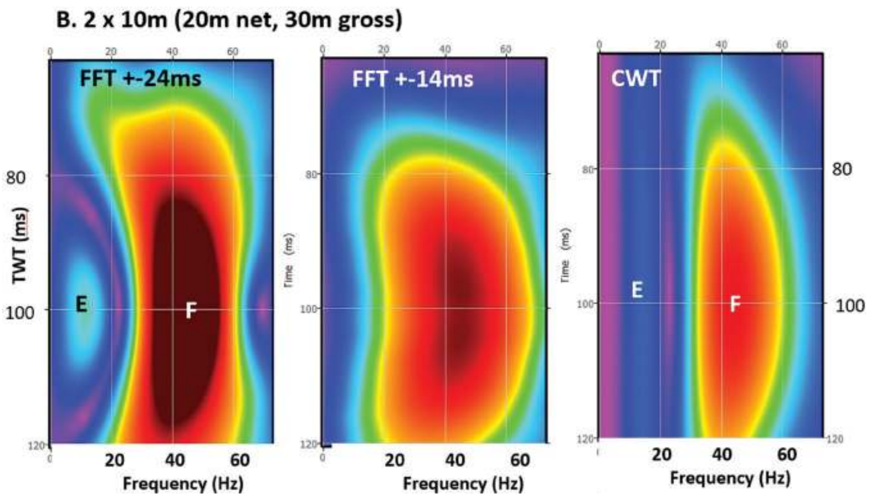

Figure 7. *Spectral Decomposition of a model with two 10 m beds separated by 10 m. Here the 10 m bed thickness can be estimated from the frequency at point F (~50 Hz). An interesting aspect is the high amplitude anomaly at point E (~17 Hz) which corresponds to the thickness of the gross interval (30 m).*

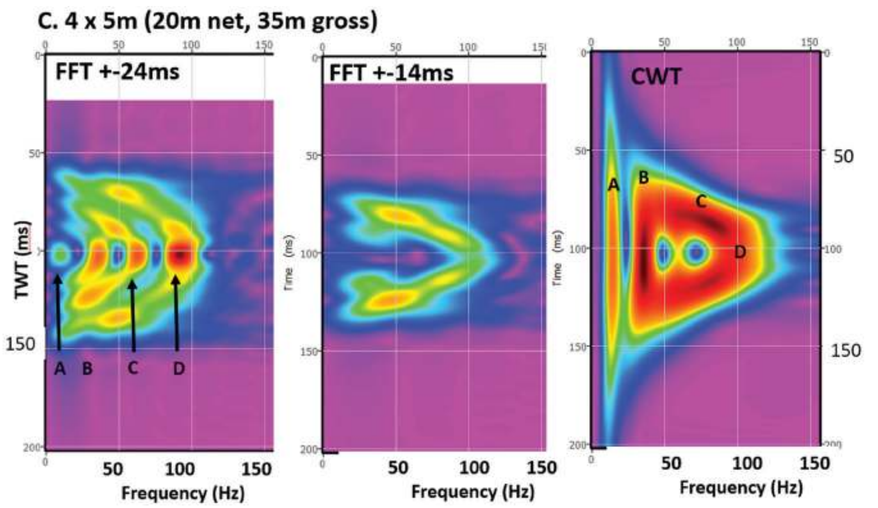

Figure 8. *NOTE change of scale. This model has four beds 5 m thick with 5 m between each bed. The response not only includes the 5 m beds (D) but also the various combinations A, B and C. These correspond to gross thicknesses of 35 m, 25 m and 15 m respectively as shown in Figure 9.*

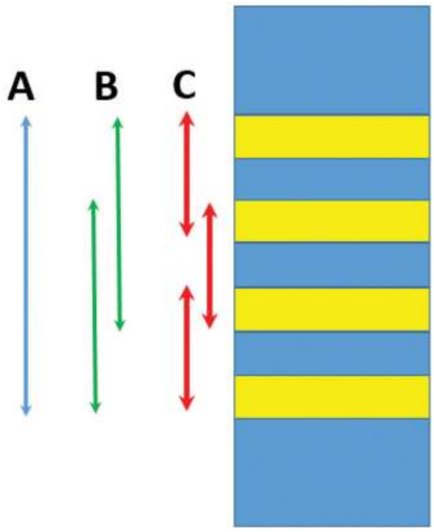

Figure 9. *Illustration of four bed model and combination of beds that give rise to multiple possible bed thicknesses. A – 35 m gross thickness, B – 25 m and C – 15 m. All these cases involve the top of a bed and the bottom of a bed but only in case D is it the same bed.*

Acknowledgment

OpendTect donated all software used to generate the figures in this article.

Data trends

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Five minute domaining

Domaining is the method of tracing the apparent boundaries of magnetic bodies and their direction/trend. Practitioners trace along the centre of anomalies in 1VD images to accentuate the trend, and use one of the edge detecting products for boundaries (Pilkington and Tschirhart, 2017). The result is a layer of lines where the direction trends within boundaries are a proxy for tectonic activity, classifying them into magnetic domains. As an overlay it may help discern spatial relationships between magnetic domains and other data types.

Automated contouring/tracing functions are common in image processing software but suffer from noise, and even the best data will not produce a convenient series of equivalent grid values for seamless contouring. Contours can halt in a series of disjointed lines and lines can double back on themselves while buffers can allow jumping that swallows neighbouring anomalies into one. Manual tracing is normal.

However, if the outlines are not an intended final product then how about near enough being good enough for the human eye? The following example cheats by not drawing lines but using pointillism – the art of using dots to build up an image.

The First Vertical and Total Horizontal Derivatives create a Tilt Derivative (Miller and Singh, 1994), which can be calculated in any program with raster maths (Figures 1 and 2). It is the quotient of the First Vertical Derivative divided by the Total Horizontal Derivative and scaled between $\pm\frac{\pi}{2}$ by an inverse tan function.

$$Tilt = tan^{-1}\left(\frac{1VD}{THD}\right)$$

"This measure has the property of being positive over a source and negative elsewhere" (Miller and Singh, 1994).

Cells equal to zero (0) theoretically mark the boundary of magnetic bodies and the highest values reflect the peak amplitudes of anomalies. To display the boundaries and trends the colour stretch of the Tilt Derivative raster in Figure 1 has been modified along the following lines:

- Black is used for values ±5% either side of 0 for anomaly boundaries
- The top 10% are coloured white for directional trend inside anomalies
- The rest are set to no data/null for transparency

It's not polished, but quickly outlines where you can draw major domain boundaries. The strongest edges are definite, while sparse dots reflect the ambiguity in the data. It implies but does not impose structure. You can play with the display ranges to suit your needs. If you still prefer boundary contours then it might be much quicker to delete rather than create. Image processing programs would allow quick erasing to eliminate dots that might confuse automated contouring.

Figure 1. *TMI RTP overlain with Tilt Derivative. Black indicates Tilt values ±5% of 0 and white highlights the highest 10% of Tilt values. Tilt Derivative cells outside those two ranges are transparent.*

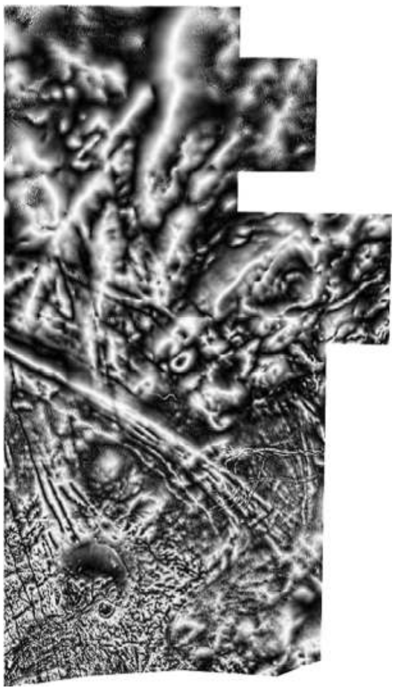

Figure 2. *Tilt Derivative with grey scale colour stretch.*

The survey data used to create Figures 1 and 2 was flown in 2015 by GPX for GA and GSSA over the Coompana area of South Australia (Kita, 2015). The survey was flown in an EW direction with a flight line spacing of 400 m with some 200 m infill.

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Webwaves

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Markdown

HyperText Markup Language (HTML) is a widely used markup language that formats content in web browsers. The first publicly available version of HTML (http://info.cern.ch/hypertext/WWW/MarkUp/Tags.html) was created by Tim Berners-Lee, the creator of the World Wide Web, in 1991. A HTML file contains the web page content as well as code contained in angle tags <> . These tags describe the context and formatting of the content.

The archetypal 'hello world' webpage could look like the following:

```
<!DOCTYPE html>
<html>
 <head>
  <title>This is a title</title>
 </head>
 <body>
  <div>
    <p>Hello world!</p>
  </div>
 </body>
</html>
```

With all the HTML tags present, there is a lot of distraction from the actual text content "Hello world!". Lightweight markup languages were created to remove the clutter and distractions associated with <> tags, while also avoiding similar issues associated with WYSIWYG rich text editors like LibreOffice Writer or Microsoft Word.

Markdown (https://daringfireball.net/projects/markdown/) is one of these lightweight markup languages. It was created in 2004 by Gruber and Swartz to be "an easy-to-read, easy-to-write plain text format". The syntax in Markdown prioritises readability and write-ability - this is what differentiates it from other lightweight markup languages. Gruber also wrote a Perl script that converts Markdown formatted text into structured HTML. This provides users an efficient way of writing easily legible content that can be seamlessly converted to valid HTML.

After 2004, numerous variants of Markdown appeared, mainly driven by efforts to extend Markdown and remove ambiguities that existed in the initial version. For example, GitHub created GitHub Flavored Markdown (GFM), which is used extensively in repository documentation.

The lack of standardisation led to the formation of CommonMark (https://commonmark.org/): a formal specification for Markdown (https://spec.commonmark.org/). CommonMark was backed by well-known figures from companies including Reddit, Stack Overflow and GitHub. However, despite the standardisation, Markdown variants continue to exist, including some that are extended versions of the CommonMark standard itself, as is the case for Github Flavored Markdown. This has resulted in over-standardisation (Figure 1).

The popularity of Markdown has led to website content management systems (such as Wordpress) integrating it to allow users to quickly write and create formatted webpages without having to use HTML. Markdown variants are also used in popular sites and apps as the default formatting syntax, including Reddit, Slack, Teams and Wikipedia. Additionally, as a plain text format, it has the flexibility to move content between applications and be opened in any text editor or terminal. Other tools, such as Pandoc (https://pandoc.org/) a universal document converter, will read markup formats such as Markdown and output other formats including LaTeX and PDF. With widespread usage, ease of use and flexibility, Markdown is a markup language worth learning.

Quick Markdown cheatsheet:

(Try using some of the following in applications like Slack and Teams. Your mileage may vary based on the Markdown variants used.)

```
*Italic*
_Italic_

**Bold**
__Bold__

# Heading 1
## Heading 2

[Link](https://aseg.org.au)

![Image](https://www.aseg.org.au/sites/all/themes/aseg_theme/logo.png)

>Blockquote

* list
* list
* list

1. numbered list
2. numbered list
3. numbered list

`inline code inside backticks`

'''

# a code block
print '3 backticks or'
print 'indent 4 spaces'

'''
```

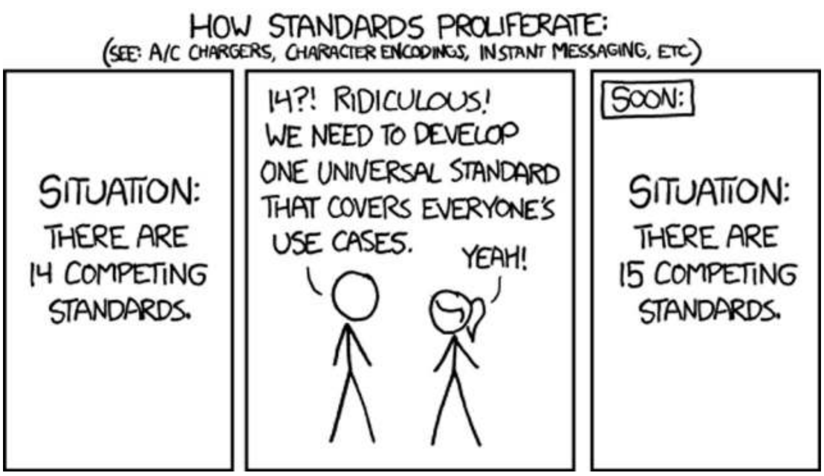

Figure 1. *Standards (from https://xkcd.com/927/)*

The Australian national differential RTP grid

Clive Foss[1], Des Fitzgerald[2] and Mike Barlow[3]

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Over the last 50 years total magnetic intensity (TMI) has been the most measured expression of the magnetic field, not for interpretational advantage but for practical and cost-effective acquisition. Since 2011, Geoscience Australia has produced a series of national TMI compilations from a minimum of 795 individual survey grids. TMI measurements are (except in regions of intense local fields) the scalar magnitude of the vector component parallel to the local geomagnetic field. There is significant variation in direction of the magnetic field across Australia, and therefore the nature of TMI also varies considerably. The shallowest geomagnetic inclination of -40° at the north coast of Queensland and the Northern Territory (Figure 1) is steeper than would normally be expected at those latitudes, and is associated with a substantial northward departure of the geomagnetic equator (the line of zero inclination) through the South China Sea. The steepest inclination of -70° is at the south coast and in Tasmania (Figure 1).

Figure 2 shows anomalies due to an induced dipole at 1 km depth in fields of -65° and -45° inclination. Shallowing of inclination from -65° to -45° reduces the peak to trough ratio of the anomaly and shifts the anomaly peak further north away from the centre of magnetisation. North-south profiles through these anomalies and for a -90° inclination are plotted in Figure 3. For the anomaly in a vertical inclination field the TMI peak is directly above the dipole centre, the anomaly of the symmetric source is itself symmetric and the peak to trough ratio is extremely high, giving clear advantages for mapping magnetisation. A reduced-to-pole (RTP) phase transform of the field and induced magnetisation from the local geomagnetic direction to the vertical can be used to extend this advantage to other latitudes (Baranov 1957, Blakely 1995) but the conventional transform from a single TMI direction to vertical cannot span the whole of Australia.

Arkani-Hamed (1988) and Swain (2000) developed differential RTP to transform TMI of continuously variable direction, and Cooper and Cowan (2005) developed an iterative algorithm to perform the task using a spatial domain Taylor series approximation. Geoscience Australia applied this method to the Edition 4 TMI compilation (Nakamura and Milligan, 2015) using the Intrepid software product and have since updated the grid using the 2019 TMI compilation (Poudjom Djomani and Minty, 2019). The regular variation of the geomagnetic

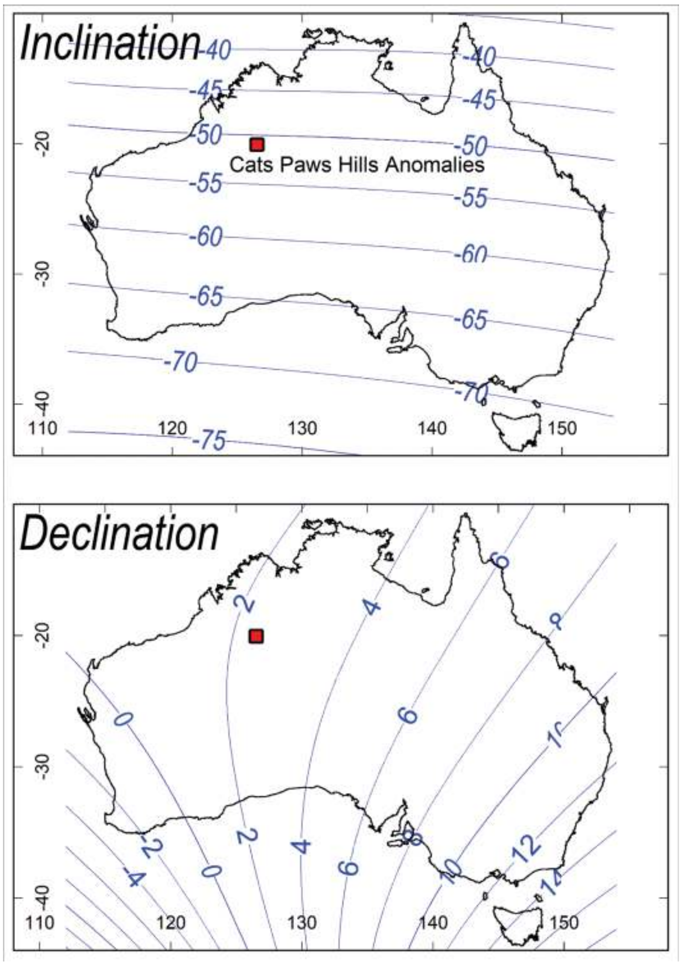

Figure 1. *Inclination and declination changes of the geomagnetic field across Australia, 2021. Red square defines the case study location.*

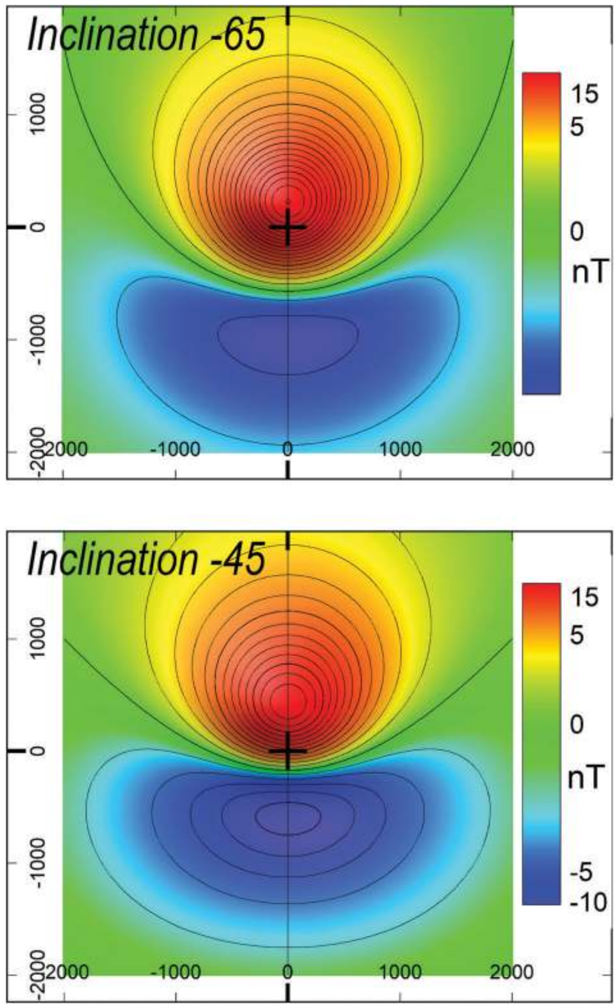

Figure 2. *Dipole TMI anomalies in (top) a steep -65° inclination towards the south coast and (bottom) a lower -45° inclination towards the north coast.*

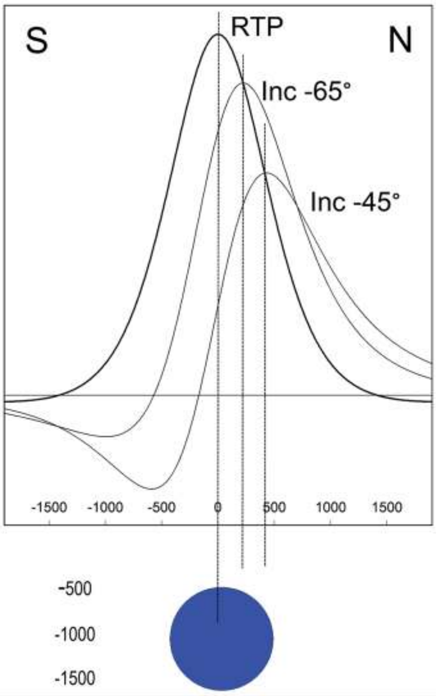

Figure 3. *South-North profile through the two TMI anomalies plotted in Figure 2 and a corresponding vertical field anomaly.*

field across Australia as mapped in Figure 1 is well described by a rapid convergence in the Taylor series for which the first 5 terms are used. Figure 4 shows the 2019 differential RTP grid of Australia which can be downloaded from Geoscience Australia's geophysical archive data delivery system (GADDS, https://portal.ga.gov.au/persona/gadds) or through Geoscience Australia's electronic catalogue (http://pid.geoscience.gov.au/dataset/ga/131533).

The quality of the differential RTP in representing the (transformed) magnetic field variation across Australia is primarily determined by the quality of the input TMI grid. The grid used is the best national compilation but includes surveys of different vintage and specifications and its reliability varies with location. A unique strength of the Australian national TMI compilation grid is constraint of long wavelength variations using the coast to coast (east-west and north-south) Australia-wide airborne geophysical or AWAGS survey (Milligan *et al.*, 2009), which eliminates the cumulative errors that would arise in levelling using multiple grid overlaps. This validity of the long wavelength TMI components contributes significantly to validity of the differential RTP grid. As can be seen from Figure 1 there is considerable variation in the magnetic field direction across most of the States and Territories and therefore any compilation across those areas will also benefit from a differential RTP (in some states they are already delivered by the state geological surveys). Those state differential RTPs will perform identically

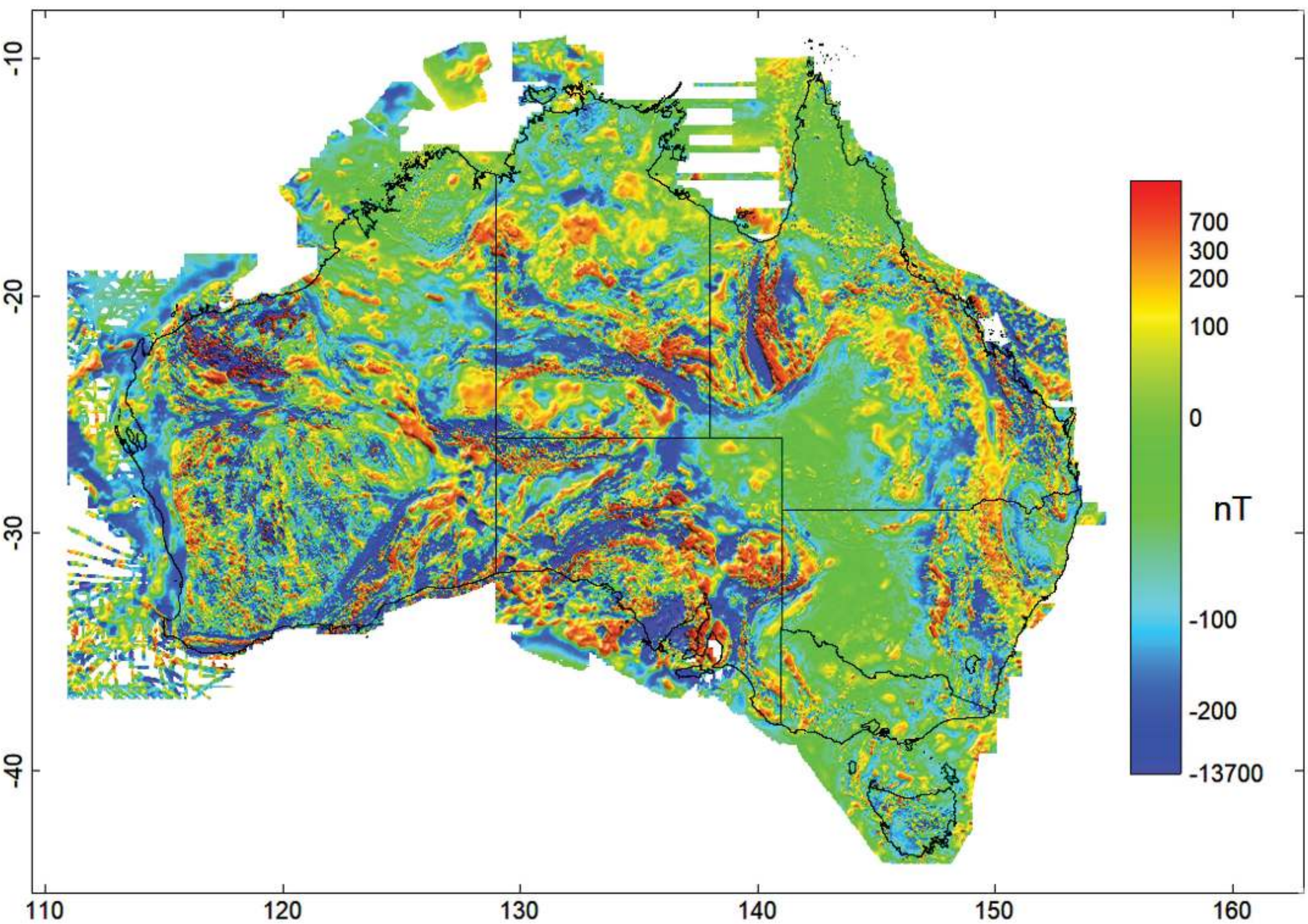

Figure 4. *Differential Reduction to Pole applied to the Australian national magnetic compilation, 2019.*

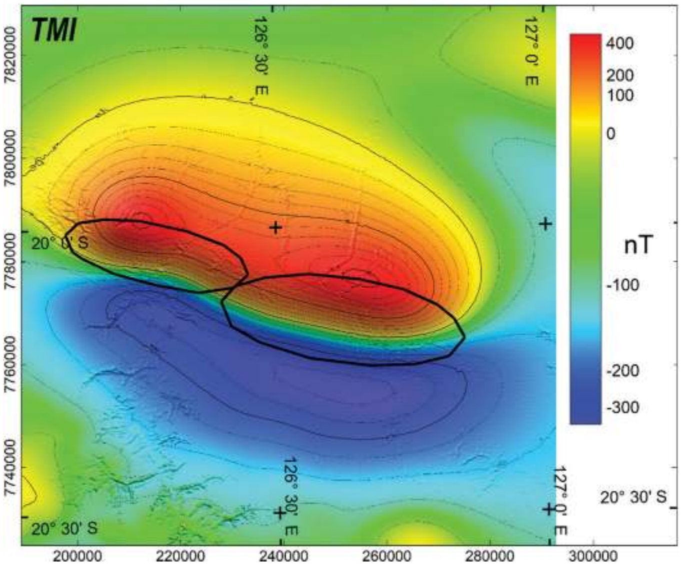

Figure 5. *Outline of inversion source bodies on TMI for anomalies in northeast Western Australia (for location see Figure 1).*

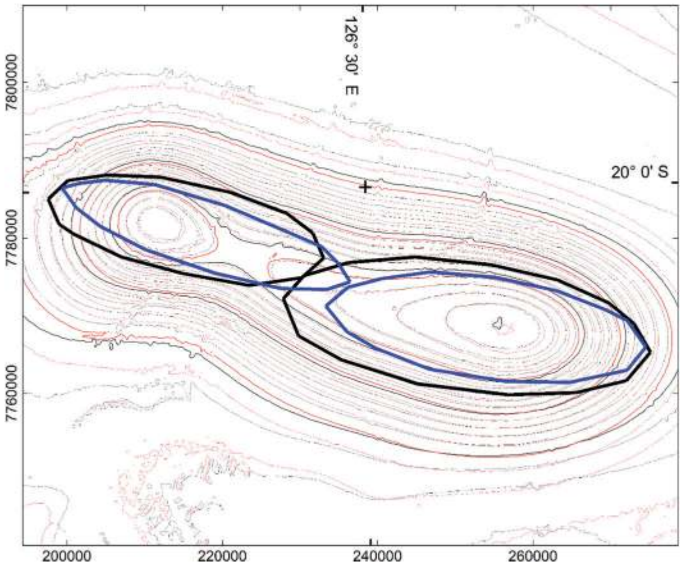

Figure 7. *Almost coincident induced (black) and free magnetisation (blue) inversion body outlines with differential (black) and standard (red) RTP contours.*

to Geoscience Australia's national differential RTP - the only differences will arise from differences in the TMI compilations that they are applied to. GSWA use over 2500 input grids to create their state super grid which locally introduce additional detail.

To illustrate and calibrate the role of RTP we have selected a pair of adjacent anomalies in northeast Western Australia (location shown in Figure 1). The magnetic field inclination and declination at the area are -51.3˚ and +3.0˚ respectively. The TMI anomalies are shown in Figure 5. Interpretive separation of the TMI anomalies from the background field gives peak to trough amplitudes of 830 and 880 nT and peak to trough ratios of 2. 9 and 2.3 for the western and eastern anomalies respectively. The differential RTP anomalies are shown in Figure 6 with peaks 6300 and 8200 metres south of the TMI peaks. A simultaneous inversion of the two TMI anomalies assuming induced magnetisation and using horizontal-top elliptic-section bodies gives depths and apparent magnetic susceptibilities of 12700 and 13000 metres and 0.43 and 0.49 SI for the western and eastern sources (outlines as plotted in Figure 5). The apparent susceptibilities (equivalent to over 10% magnetite by volume) are high for such large volumes and may suggest contribution from remanent magnetisation. Spatial details of the sources at these depths are not reliably recovered but nevertheless the inversion bodies and differential RTP peaks are coincident as shown in Figure 6. This does not conclusively prove that both methods are correctly achieving their objectives of locating the magnetisation because they both share the common assumption that magnetisation is parallel to the local geomagnetic field. To establish the appropriate magnetisation direction, we repeated the inversion with a free magnetisation direction. This results in a slightly shallower inclination of magnetisation but the difference of less than 5 degrees is not clearly significant and location of the magnetisation does not shift substantially. Figure 7 also shows the very close match between the differential RTP contours and contours of a local standard RTP. Figure 8 shows the anomalies

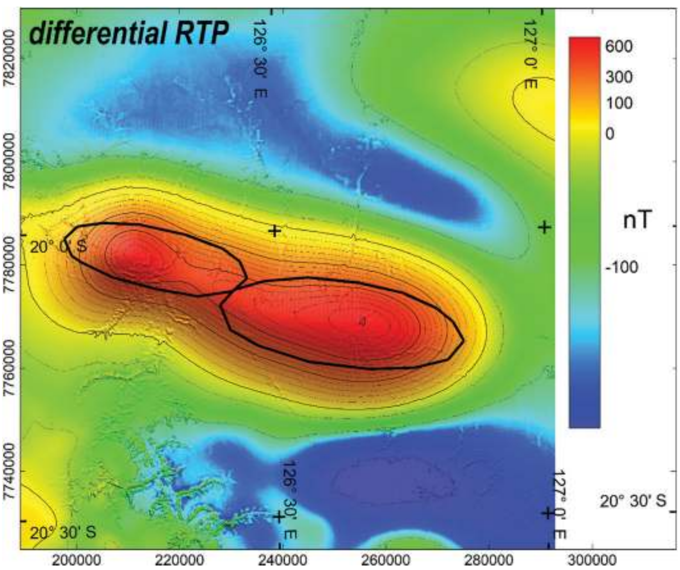

Figure 6. *Outline of inversion source bodies on the differential RTP.*

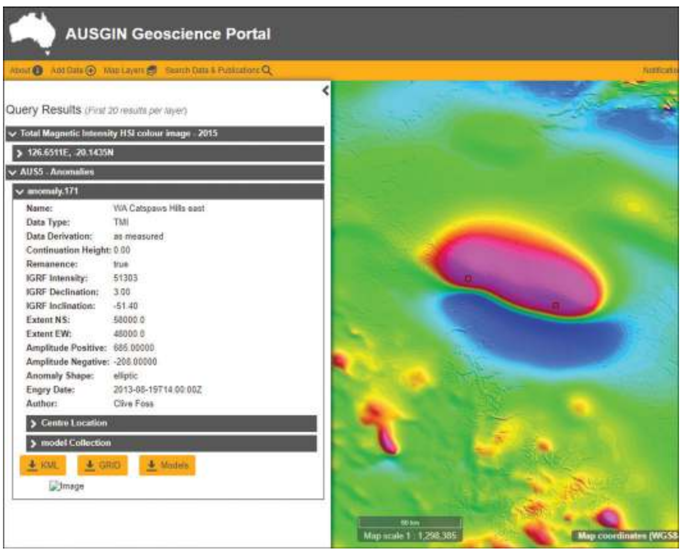

Figure 8. *Anomaly sources in the Australian Remanent Anomalies Database presented in the AUSGIN portal.*

(171 and 176) in the Australian Remanent Anomalies Database accessed in the AUSGIN portal (https://portal.geoscience.gov.au/restore/6727640b-5fb1-4e75-964a-c59c0ab5ca91) from where the models can be downloaded.

Figure 7 contours also show that differential or variable RTP changes the shape of the anomaly, and also moves the anomaly high hot-spot, in the case of the right hand "fried-egg" anomaly, around 700 m in a mostly Easterly direction.

Conclusions

The differential RTP grid is a valuable component of the national magnetic field datasets and is fit for purpose for regional geological mapping and national crustal studies. The variable RTP is also useful as an input to further transforms used for regional mapping such as vertical derivatives. For smaller scale studies well covered by a single survey it is better to use the standard RTP of the local survey. However, if an anomaly of interest crosses or lies close to the northern or southern edge of an individual survey it may be preferable to buffer the data with a merged adjacent grid rather than relying on synthetic padding.

A major concern with application of any RTP transform is the assumption that magnetisation direction is parallel to the local geomagnetic field. In the example presented here, we established that there is no significant rotation of magnetisation away from the geomagnetic field. Such rotations are more common than is generally appreciated, with anomalies due to clearly rotated magnetisations just extreme examples of a much larger population (Foss, 2021). The differential RTP is neither more nor less susceptible than a conventional RTP to distortions arising from inappropriate source magnetisations or any imperfections in the TMI data from which it is derived. Without validation of magnetisation direction, RTP transformation cannot be relied upon. It is recommended that locating or designing drillholes should always be based on modelling and/or inversion studies applied directly to TMI data (and ideally line rather than grid data).

End note: What else could go wrong in using "continental scale" geophysical processing methods to systematically locate anomalous geology?

Enter the cartographers. The standard practise for continental scale work is to use GEODETIC coordinates. One cannot use Mercator projections as there is no continuity at Zone Boundaries. Cartographers would like to produce "flat-land" maps where a scale ruler can be used. This requires a process that warps the signal from the ellipsoid to "flat-land". Only in the last 5 years, has consensus emerged on what coordinate transforms should be used so that geophysics data can be confidently passed between 3D visualisation, GIS, creation of Data Cubes and traditional map products without losing registration and while minimising resampling. The candidate coordinate projections are Lambert Conic Conformal, and Albers Equal Area. If there is a mismatch in the specification and understanding of this data warping process all the care in producing a differential RTP is wasted, and spatial location errors of several kilometres might go un-noticed for some time (this problem is not specific to the differential RTP). In response to this concern the ASEG Technical Committee has recently decided to create a table of formalised projections for use in Australia.

Acknowledgements

The national differential RTP grid was championed by Peter Milligan who played a key role in generating the national TMI compilations, acquiring and applying the AWAGS survey data and implementing the differential RTP. Peter worked on this transform and checked its implementation within the Intrepid technology product. This method of differential RTP has been used by many Australian and International geological surveys over the last 10 years. There are several other key contributors to this happy situation from times past that are not being acknowledged here.

The authors wish to acknowledge that the datasets presented here include components of the Australian national magnetic compilation. This includes surveys acquired over more than 50 years, funded, and managed by Geoscience Australia, the State and Territory Geological Surveys and industry.

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MEASURING TERRESTRIAL MAGNETISM

the evolution of the AIRBORNE MAGNETOMETER and the first anti-submarine and aeromagnetic survey operations – People, Planes, Places and Events 1100s –1949

W. D. (Doug) Morrison

This book, covering a global expanse of more than 800 years, recounts the largely untold story of 'measuring terrestrial magnetism' and of the extraordinary 'people, planes, places and events' that have contributed to the evolution of the magnetometer and the first anti-submarine and aeromagnetic geophysical survey operations. It is a unique journey of science and engineering, of inventions, new methods and instruments – a compelling story of how the measurement of terrestrial magnetism has influenced the history of the world.

This is an operational historical record rather than a history of the theory of terrestrial magnetism. The story begins at the earliest documented geomagnetic discoveries and moves on to observations of magnetic intensity and the first ground magnetic surveys. We see how the instruments used for geomagnetic observations from moving airborne platforms evolved in parallel with the evolution of flight from balloons (from 1784) to airships and eventually aircraft.

In the 1930s and 1940s there were major advances in magnetometry, in USSR, Japan and Germany as well as in USA and UK. In USA and UK these advances were applied in military surveillance systems, including in the detection of submarines. Landmark World War II induction coil and fluxgate instruments – the first of the modern technologies – enabled aeromagnetic acquisition, mapping and direct detections of ore bodies from the air from mid-1944 onwards, foreshadowing today's airborne magnetic surveys. The military developments of magnetometers were taken up, rapidly advanced and applied by the mineral exploration industry to find new economic deposits of magnetic mineral ores. Countries including Australia, Canada and the United States charged their national mining and geological survey departments with investigating and establishing programs of major aerial magnetic surveying and mapping in the search for minerals and energy.

The story explores the inextricable cross-discipline connections of terrestrial magnetism and magnetometers as used for navigation, geodesy, anti-submarine and military purposes, and their role in the geophysical oil and mineral exploration industry. Organisations, people and specific instruments and aircraft are noted, including (at times coincidental) Australian connections. The extraordinary depth and scope of research, over many decades, by the author W.D. (Doug) Morrison, as well as his collection of photos and illustrations, and his astonishing attention to detail, make this book an amazing and immersive historical reading experience and a future primary reference work. Through several decades Doug has developed an extensive 'reference' network of geophysical survey practitioners, and former experts in military, aviation and maritime matters. Through their little-known stories and personal reflections, and his access to personal and official archive material from this network, Doug's narrative brings unique insights into the evolution of the airborne magnetometer. Along that timeline he has produced details that are not available in public historical material.

Measuring Terrestrial Magnetism is a major work of 630 pages, illustrated throughout with 156 plates of figures and photos, and including comprehensive Endnotes, Appendices, References and Index.

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Metadata standards for magnetotelluric time-series data

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Introduction

Modern magnetotellurics (MT) offers a multiscale capability to image the electrical properties of Earth's crust and upper mantle. The data it provides and the models derived from it are important geophysical contributions to understanding Earth's geology and resource potential.

In Australia, MT data is acquired by the resource exploration industry, university-based research groups, and Federal, State and Territory geological surveys. To ensure this data can be used to its full potential, including by groups and individuals who may not have been involved in its acquisition, it is important that community-agreed standards be adopted for the acquired data and its associated metadata.

Metadata for field-acquired MT data

Several steps have been taken to solicit the Australian MT community's views on metadata. Kirkby (2019) sought feedback on a draft set of metadata parameters for field-acquired MT data. Rees *et al.* (2019) describe field-acquired data as Level 0 data. Intrepid Geophysics subsequently conducted a series of interviews with MT stakeholders in Australia and overseas. The results of this consultation are described in Leonard *et al.* (2020).

The key recommendations of the Intrepid Geophysics report are that:

- Australian MT practitioners adopt a standard set of metadata parameters to be recorded with acquired MT field data
- The required parameters be only those necessary to adequately represent the data
- JSON be used in preference to XML as the metadata markup language
- Geoscience Australia nominates suitable time and space reference systems for the collection of MT data in Australia
- The Australian MT community adopts an internationally accepted standard for the public release of MT time-series data.

Achieving the ultimate goal of findable, accessible, interoperable and reusable (FAIR; Wilkinson, 2016) MT data and metadata begins with the acquisition of high-quality field data and the metadata required to adequately describe and quality assure it. The metadata standard proposed by Leonard *et al.* (2020) has been developed in consultation with the Australian MT community to reflect current and possible future Australian field practices for the acquisition of MT data. This standard is the basis on which metadata for higher-level MT data products (Rees *et al.*, 2019) is founded. In this paper, Geoscience Australia recommends that Australian MT practitioners adopt the metadata standard for field data that Leonard *et al.* (2020) propose.

Leonard *et al.* (2020) identify the need for clarity on the coordinate reference frame used for MT data collection. In the proposed standard the coordinate reference frame used to locate the MT site and electric-field electrode locations is a required piece of metadata. Geoscience Australia recommends that the Geocentric Datum of Australia 2020 (GDA2020) be used. This is the current coordinate reference frame recommended by the Intergovernmental Committee on Surveying and Mapping for use in Australia (icsm.gov.au/gda2020). However, where its use is not possible, the proposed standard has the flexibility for fieldworkers to use a coordinate reference frame compatible with the GPS receivers they use.

Leonard *et al.* (2020) also recommend clarity about the time reference system to be used when recording dates and times relevant to MT surveys. The proposed metadata standard provides for either Coordinated Universal Time (UTC) and/or local time to be used. When local time is used, additional information is needed, such as the time correction to UTC and the time zone in which the measurement is made. Whereas, when UTC dates and times are recorded such additional information is not required and its omission is unlikely to result in incomplete metadata. Additionally, some MT surveys may cross state/territory borders and therefore be recorded in different time zones such that inadequately captured local-time metadata may jeopardise the correct interpretation of date and time information. For these reasons, Geoscience Australia recommends UTC as the preferred time reference system and endorses its classification as compulsory, and local time as optional, in the metadata standard.

Rees *et al.* (2019) describe various levels of time-series data depending on the amount of processing it has undergone. The Leonard *et al.* (2020) metadata standard is recommended for use in the acquisition of raw and Level 0 MT time-series data. This data is not typically released publicly but is the foundation for a range of higher-level data products that have been processed to varying degrees and can be made publicly accessible on delivery platforms managed by the acquiring organisation and by domain-specific platforms managed by others.

Metadata and data formats for higher-level MT data products

There is significant overlap between the metadata that should be recorded for field-acquired Level 0 time-series data and the metadata that should accompany published Level 1A and 1B time-series data; there are also distinct differences (Figure 1). Level 0 metadata should be sufficient to identify, quality assure and later process the field-acquired data without being too onerous for field parties to record. Level 1A and 1B metadata should record much of this information and add further information about what processing the data has undergone, who has been responsible for the processing and archiving of the data, assigned DOIs, papers published using the data, etc. Much of this additional metadata is not known at the time of field acquisition. Figure 1 gives some examples of this overlap and these differences using a Venn diagram representation.

The similar but different metadata requirements for the different levels of data suggest the need for different standards – one for field-acquired data and another for data that is ultimately made publicly available. The first could feasibly be a locally or nationally agreed standard, the second should preferably be an internationally accepted standard.

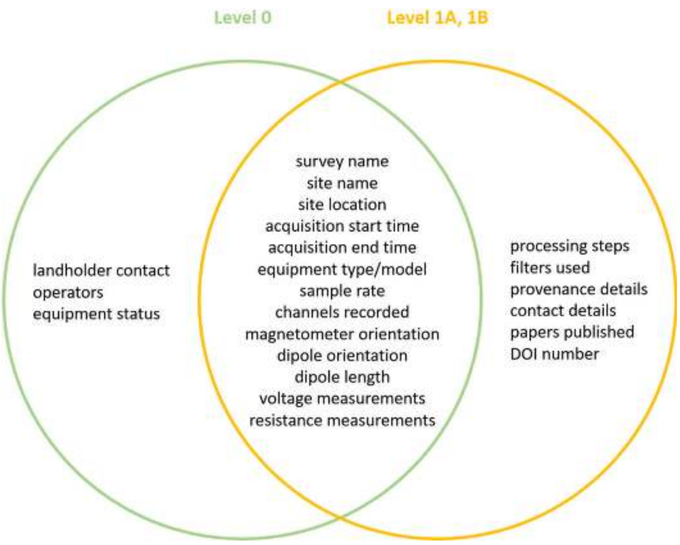

Figure 1. *Examples of metadata for Level 0 and Level 1A and 1B MT time-series data*

Currently, there is no widely adopted international standard for MT data or metadata. Notwithstanding, the renaissance of the MT method in Australia and internationally, the expected continued acquisition of significant amounts of MT data for the foreseeable future, and the growing interest in the availability of FAIR MT data, suggest that a solution, even an interim solution, should be adopted promptly. Otherwise MT data will remain "in the drawer" (Kelbert *et al.*, 2018) and its full potential will not be realised.

High-performance data requirements suggest that a preferred solution for an MT data standard should:

- Be self-describing, keeping metadata with data
- Handle big data flexibly
- Permit fast input/output
- Be platform independent and open format
- Handle heterogeneous data.

Additionally, for ease of implementation within workflows, the solution should:

- Provide interfaces and utilities in a range of software languages to accommodate users' differing work environments
- Have an established and wide user base
- Offer scope for user support in their implementation and use.

Table 1 sets out some metadata and data options that have been developed which may offer solutions to the Australian MT community until an internationally-agreed standard is developed.

The EMERALD scheme for MT data has been developed by the GFZ German Research Centre for Geosciences (Ritter *et al.*, 2015). It stores MT data and metadata in file pairs – a usually binary file containing the MT time series, spectra and

Table 1. Metadata and data format options for publicly accessible MT data. Rows shown in bold text are the metadata and time-series formats recommended in this article.

	Reference	Summary	Pros	Cons
Metadata				
EMERALD	Ritter *et al.* (2015)	ASCII XML metadata files	Mature Human readable	Metadata files separate to data files XML a dated format
IRIS	Peacock and Frassetto (2020)	JSON metadata files usable as self-describing headers in binary data files	Self-describing JSON an efficient format	Immature format
Data formats				
ASCII	Wyborn *et al.* (2020)		Mature format Human readable	Space inefficient Inefficient I/O Not self-describing
SEG EDI	Wight (1988)	ASCII-based SEG standard format for MT and other EM data	Mature format Human readable	Space inefficient Inefficient I/O Not self-describing
EMERALD	Ritter *et al.* (2015)	Stores MT data and metadata in file pairs; related utilities are in C++, C and FORTRAN, with interface functions in Matlab and Powershell	MT-specific Mature format	
HDF5	https://www.hdfgroup.org/	High-performance, big data-capable, flexible, n-dimensional scientific data format	Self-describing Mature format Widely used to archive large datasets	Not MT-specific
netCDF4	https://www.unidata.ucar.edu/software/netcdf/ Ip *et al.* (2019)	HDF5-based data format developed for atmospheric data; programming interfaces for C, Java, Fortran, Python, C++, IDL, MATLAB, R, Ruby, Perl	Self-describing Mature format Utilities and toolkits widely available Extensive user community	Not MT-specific
MTH5	https://mth5.readthedocs.io Peacock (2018)	HDF5-based data format adapted for MT time series	MT-specific Self-describing	Immature format
GeoHDF	Wyborn *et al.* (2020)	netCDF4-based generalised container format for geophysical time-series data	netCDF4-based Geophysics-specific Self-describing	Under development
ASDF	http://seismic-data.org/ Krischer *et al.* (2016) Duan and Kirkby (2018)	HDF5-based data format adapted for seismic data	Mature format Adaptable to MT Used in MTpy Efficiencies where both seismic and MT data are managed	Seismic-specific No efficiencies where seismic data is not managed

calibration data and a plain ASCII file containing the related metadata in XML format. Related utilities are in C++, C and FORTRAN, with interface functions in Matlab and Powershell.

As part of its PASSCAL program, the IRIS option provides a comprehensive list of metadata parameters recommended for implementation using the JSON file format (Peacock and Frassetto, 2020). These metadata may be written as headers to binary data files of varying formats.

IRIS has also commissioned work to develop MTH5 (Peacock, 2018), an MT-specific self-describing, modern, HDF-based time-series format, as well as additional work to develop a series of utilities and tools to support the format and integrate it in MT data workflows.

IRIS is working with suppliers to deliver data acquisition platforms that provide time-series data in an accessible non-proprietary format. These suppliers would include those supplying the Australia market.

Due to the compatibility of the standard recommended herein for field-acquired metadata with the IRIS-developed standard for published metadata, and its compatibility with the IRIS-developed time-series format, Geoscience Australia recommends the adoption by the Australian MT community of the metadata standard in Peacock and Frassetto (2020) and time-series format in Peacock (2018) for the delivery of publicly accessible time-series data. In making this recommendation, we recognise there are risks associated with it – for example, there is no guarantee that the IRIS standards will be internationally embraced, a different international standard may be adopted down the track, and there will be challenges implementing this standard in existing workflows. Also, the IRIS Working Group for Magnetotelluric Data Handling and Software (https://www.iris.edu/hq/about_iris/governance/mt_soft) plans to deliver an MT data processing and analysis workflow by the end of September 2021, which may have implications for these recommendations. Nevertheless, we are of the view that it is preferable to make a recommendation now so that high-performance Australian MT data is available to the research community, even if this recommendation may need to be revisited in light of future international developments.

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Geoscience Australia thanks the Australian MT community for contributing the advice, insights and suggestions that have underpinned the development of this metadata standard, and Intrepid Geophysics for the preparation of its reports.

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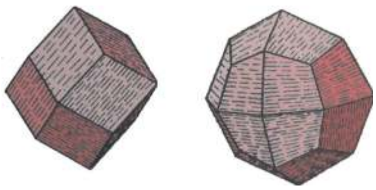
Garnet: The colourful silicate, a speciality mineral



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Introduction

Non-metallic silicate minerals, and silica, are dominant in the earth's crust, but do not receive as much published attention from exploration geoscientists as do the rarer metal and fuel resources, and groundwater. However, non-metallics also constitute an important resource. They are indispensable; sand, for instance, is the world's most consumed commodity after water. Sand, on the whole, is too vast a topic for a short article. Rather, a particularly impressive non-metallic silicate, the garnet, which can occur as a sand, is the focus here.

The name garnet comes from the Latin for pomegranate. *Pomum granatum ie*, seeded fruit. Small common garnets were likened to its reddish seeds. Garnets are a common mineral mainly found in regional and contact metamorphics, and in the detritals shed from them. They are present in some granites and pegmatites, also in ultramafics ejected volcanically from the depths of the earth and upper mantle. They have an interesting history: being prized in human culture as a semi-precious gem, being used (by believers) in crystal therapy, acting as pathfinders in diamond exploration, providing information on the deep earth and upper mantle[1], and forming an actual resource in deposits of the garnet sands much preferred as an abrasive (instead of quartz) in many industries. Owing to their colour and sharp crystal forms they are also sought by mineral collectors, even if the garnets are not of the transparent gemmy variety. Gem garnets are sought and sold in affordable jewellery the world over.

Garnets abound in the metamorphic terrain of Broken Hill NSW. Many years ago, in the pub there, after a day's field work, my friend Thirsty the geologist opined "Mate! Garnets are great, they got grunt, they grate, and you can trouser a few dollars by flogging any good ones you find!" The recollection of Thirsty's earthy wisdom inspired this article, written, as usual, discursively, and subjectively.

Garnets

Of the twenty or so recognised garnets only five are important here: pyrope, almandine, spessartine (the pyralspites); grossular and andradite (the calcic ugrandites). Almandine is the common garnet. Rare uvarovite, occurring as tiny green crystals, and the greenish garnetoid hydrogrossular are often added to the main five types, see Table 1. Garnets are found in all colours except blue; some can be colourless, though commonly they are a dark reddish brown. Colour in garnets results from traces of transition metals such as chromium, iron, manganese, vanadium, and titanium. Deer *et al* (1992) provide an excellent mineralogical review of garnets.

Table 1. Garnet groups; chemical formulae, densities and magnetic susceptibilities.

Group	Species	Compositions	Density (g/cm³)	Mag k SI x 10^{-5}
Pyralspites	pyrope	$Mg_3Al_2(SiO_4)_3$	3.58	0
	almandine	$Fe_3Al_2(SiO_4)_3$	4.32	369
	spessartine	$Mn_3Al_2(SiO_4)_3$	4.19	474
Ugrandites	grossular	$Ca_3Al_2(SiO_4)_3$	3.59	0
	andradite	$Ca_3Fe_2(SiO_4)_3$	3.86	291
	uvarovite	$Ca_3Cr_2(SiO_4)_3$	3.85	(~90?)
	hydrogrossular	$Ca_3Al_2(SiO_4)_{3-x}\,OH_{4x}$ [x ~ ½]	3.1 – 3.6	0

Notes to Table 1:

- Garnets are nesosilicates comprising stacked SiO_4 tetrahedra linked by interstitial cations: $A_3B_2(SiO_4)_3$ where A may be Ca, Mg, Fe^{++}, Mn^{++} and B may be Al, Fe^{+++}, Cr^{+++}.
- Hydrogrossular is really a jade-like garnetoid often intergrown with idocrase (a jade-like complex silicate). Uvarovite occurs as tiny, very pretty, green crystals and is rare. Accordingly, these two types will not be considered further in the text, being only listed here for completeness.
- The ideal ("pure") formula, densities, and magnetic volume susceptibilities (k) are given for the main species. Note that within two broad groups (pyralspites & ugrandites) there are frequent gradations of composition owing to solid solution miscibility, but less between the groups.
- The densities are for pure synthetic garnets prepared using high pressure techniques. Pure garnets do not seem to occur much, if at all, in nature so the use of these theoretical densities needs to consider the effect of each garnet molecule on the properties of the mixed types encountered in nature (Anderson & Jobbins, 1990).
- The paramagnetic & magnetic susceptibilities of garnets are a moot point, the values in the above Table have been taken from Bleil & Petersen (1982).
- The susceptibilities of almandine, spessartine, and andradite will vary in natural garnets owing to solid solution mixing e.g., spessartine with almandine, almandine with pyrope, andradite with grossular, and other possibilities (as for densities).
- Pyrope and grossular are most likely to be diamagnetic, displaying a small negative susceptibility, however, for convenience in plotting they have been ascribed a value of zero in Figure 5.
- Uvarovite's susceptibilities does not seem to have been documented. Limited tests I have carried out on unsatisfactory material suggests ~ 90 x 10^{-5} SI.
- Spessartine's mag k seems high to me, but I cannot check it as I cannot acquire a pure spessartine. However, many Mn compounds have well established high paramagnetic susceptibilities e.g., rhodochrosite, $MnCO_3$, 480 x 10^{-5} SI

The five main garnets are variably dense (3.6 – 4.3 g/cc, see Figure 1), hard (Moh's hardness ≤ 7 ½), variably paramagnetic (up to ~500 x 10^{-5} SI), insulating (virtual dielectrics), moderate in thermal conductivity (~3 to 7 W/m°C), high in Pwave velocity (~8500 m/s), and generally inert (resist alteration). Garnets lack cleavage and fracture (sub) conchoidally or unevenly. Crystallisation is in the cubic system usually as dodecahedra (12 rhomb faces) or trapezohedra (24 trapezoid faces). Figure 2 shows some dodecahedral garnets collected in the field. Figure 3 shows small translucent gemmy almandine garnets cut and polished into various shapes popular in the gem industry.

[1] Petrologists find garnets useful in lower crust and upper mantle research. The detailed nature of pyrope found in ejected eclogitic rock can be very informative as to pressure and temperature conditions at depth. Pyrope from eclogite inclusions in a basic breccia pipe at Delegate NSW indicated crystallisation in 7-15 kbar, 700 – 1200°C range (Deer *et al*, 1992).

Figure 4 shows a finished faceted pyrope, pyrope-almandine (rhodolite) rough, and gemmy striated spessartine rough.

Garnet in earlier times

Precious and semi-precious stones were long prized in antiquity for their beauty and supposed medicinal and magical properties. In the Old Testament of The Bible (6th BC) garnets were listed as part of the adornment of princes (Ezechiel: 28, 13).

A seminal treatise "On Stones" was produced in the 4th century BC by Theophrastus, a pupil of Aristotle. This work recognised the red garnet by the generic term ό ἄνθραξ, anthrax, a glowing live coal, because a garnet held up to the sun seemed similar. Anthrax also could have meant red spinel and ruby. Theophrastus noted anthrax's use a seal-stone. Many red garnet seal-stones from this era now reside in museums, but none of red spinel or ruby (both harder than garnet), so anthrax was red garnet in Hellenistic time (Caley & Richards, 1956). Garnet, with its less than extreme hardness (H ≤ 7 ½), was readily carved intaglio (sunken design) and cameo (raised design) by the technology of the period – various drills and wheels coated with powdered emery (impure corundum) or pulverised diamond.

Garnets were sourced mainly from Asia after the 4th Century conquests of Alexander. They were a popular stone in rings and for ornamental use (Hornblower and Spawforth, 2012).

Pliny the Elder (AD 23-79) discussed garnets at length in Book 37 of his Natural History (Eichholz, 1971). Pliny called garnet the *carbunculus* because good quality reddish gem garnet, probably of the pyrope-almandine variety, looked warm, suggestive of burning *carbo*, charcoal/coal.

Garnets vary in lustre. Pliny (37, 92-3) commented on this two millennia ago:

> *.. (carbunculi) praeterea in omni genere masculi appellantur acriores et feminae languidius refulgentes..*

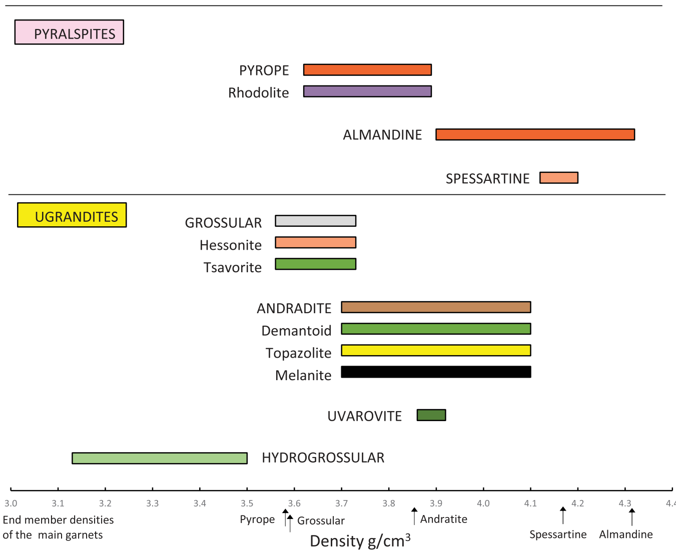

Figure 1. *Ranges in garnet densities, based on Gemmological Institute of America (GIA) data 1995 and Schumann (2006). Rhodolite is a 2:1 pyrope – almandine solid solution mix. Grossular with Fe is hessonite and with V, Cr is tsavorite. Andradite with Cr, Fe is demantoid, with Fe is topazolite, and with Fe, Ti is melanite. Colours depicted are approximate and do vary in each type. The natural density variations are due to solid solution mixing in the garnet mineral series (e.g., pyrope and almandine), and to mineral inclusions. See Table 1 for formulae of the main garnets.*

Figure 2. *Five dodecahedral garnets with rhomboid faces: (back left) almandine from the Thackaringa area to the southwest of Broken Hill NSW, weight 963 g; (back right) almandine from Harts Range NT, 201 g; (front left) almandine from India, 57 g; (front middle) almandine Harts Range, 11 g; (front right) grossular from Mexico, 25 g. Specimens such as these, although not gemmy, are popular with collectors. The largest garnet shown is worth ~ $150, the grossular ~ $10 (scale in cm).*

> *Furthermore, in each variety (of garnets) the more brilliant stones are called male and those of weaker lustre female*

There is a reason for this. Lustre is an important quality for any gem and especially so for garnet: brightish vitreous lustre stones are common; brilliant sub-adamantine lustre stones are not and are far more valuable. The percentage of light reflected from a smooth silicate or oxide surface depends on the material's refractive index (velocity of light in vacuum / velocity of light in material, R.I. always > 1). Through the Bohr Equation (see Bloss, 1971): the higher the R.I. the higher the reflectivity. The R.I.'s for grossular, almandine – pyrope, and andradite – demantoid are 1.73, 1.77, and 1.89 respectively (diamond is 2.42). The high R.I.s for andradite-demantoid impart a lively reflectivity attractive to the eye.

Figure 3. *Translucent gem garnets variously cut and polished. These are of the common vitreous lustred almandine – pyrope low value type, and it is thought that they derive from India. The single stone in the centre foreground weighs 0.28g (1.4 carat) and has lateral dimensions 9 x 6 mm, it is worth ~ $10. Most gem garnets are small, weighing between 0.2 and 2.0g (1 to 10 carats).*

Figure 4. *Faceted backlit pyrope from Kenya, National Museum Washington (top), CC BY SA 2.5 / Thomas Ruedas/ https://commons.wikimedia.org/wiki/File:Pyrope.jpg. Orange striated gemmy spessartine on smoky quartz crystals, ~60 mm lateral view, Wushan Mine, Fujian province, China (middle) Rob Lavinsky, iRocks.com – CC-BY-SA-3.0. Sharp edged rhodolite eluvial floaters from Rift Valley Province Kenya (bottom) Rob Lavinsky, iRocks.com – CC-BY-SA-3.0. These pyrope-almandine (2:1) sharp edged rough specimens are rosy red when frontlit (as here) and are cherry red when backlit, each ~20mm lateral dimension and ~7ct mass (bottom).*

Pliny continued to elaborate on particularly attractive garnets, especially what seems to be the violet tinged almandine, apparently from Myannmar:

> *in masculis quoque observant liquidiores aut flammae nigrioris et quosdam ex alto lucidos ac magis ceteris in sole flagrantes, optimos vero amethystizontas, hoc est quorum extremus igniculus in amethysti violam exeat.*
>
> *also, among the male stones, one makes special note of those that: are quite transparent, glow with more dusky character, and some that shine from inside, become quite fiery in the sun, and for sure the best are those with an amethyst tinge being the type where a violet glitter develops at the edge of a (red) stone.*

Modern connoisseurs of gemmy garnets could only agree with Pliny's preferences.

Garnet gems were admired in the Middle Ages. Marbod (1035 – 1123), Bishop of Rennes in Brittany, celebrated (and somewhat exaggerated) the merits of garnets in the 23rd Latin poem of his famous lapidary (compiled by Beckmann, 1799):

> *De Carbunculo.*
> *Ardentes gemmas superat carbunculus omnes;*
> *Nam velut ignitus radios iacit undique carbo,*
> *Nominis unde sui causam traxisse videtur,*
> *Sed Graeca lingua lapis idem dicitur anthrax.*
> *Huius nec tenebrae possunt extinguere lucem;*
> *Quin flammas vibrans, oculis micet aspicientium.*
>
> *On the carbuncle.*
> *The carbuncle outdoes all the flashing gems*
> *For it emits rays in all directions as if a glowing ember*
> *From which effect it seems to have acquired the name.*
> *In Greek it is called the anthrax.*
> *Darkness cannot extinguish the light of this stone*
> *Indeed it twinkles, to gleam in the eyes of observers.*

In 16th century Europe garnets were admired minerals, particularly in Germany. Georgius Agrocola (1494-1555), the German Georg Bauer, was born in Saxony during a time of the European revival of classical learning. His mineralogy book *De Natura Fossilium* established him as the "Father of Mineralogy" (DNF, 1546; translated by Bardy and Bandy, 2004). Book 6 of DNF devotes several pages to garnets, their properties and localities. Brilliant red carbunculi were particularly esteemed.

In England gemmy garnets were known as carbuncles during and after the rein of Elizabeth I (1558-1603). It was believed that carbuncles illuminated themselves when in darkness. So in Shakespeare's Hamlet (1603) and Milton's Paradise lost (1667) the eyes of unsavoury scary characters glow like carbuncles (Satan/Milton, Pyrrhus/Shakespeare). In this period affordable garnet was a favourite gemstone especially for rings and inlays. These garnets came from Bohemia where they still reside in extensive alluvials shed from a peridotite host (Voynick, 2021).

Garnet's reputation as a popular semi-precious gem continues today. Reddish almandine and pyrope are still referred to as the carbuncle stones in some quarters (Schumann, 2006).

Garnet – density and magnetic susceptibility

Garnets are much studied by solid earth geophysicists and petrologists whose interests lie in the deep crust and upper mantle where garnets are a significant constituent. Electrical and thermal conductivity, P and S wave velocities, mechanical properties have received considerable laboratory attention, under high temperature and pressure conditions. However, for near surface garnets the two basic properties of interest to exploration geoscientists should, in my view, be density (D) and magnetic susceptibility (k). The relationship between these two basic properties has received little attention. Garnets are variably dense, and some display a moderate paramagnetic susceptibility. Table 1 gives nominal values of these quantities. Figure 1 shows densities and the variability which results from any garnet having at least part of another garnet in its structure owing to isomorphous mixing, and also owing to the inclusion of other silicates and oxides. For example, a nominally almandine garnet, from thermal metamorphism of a pelite, could actually be $Alm_{78}Py_{15}Sp_4Gro_3$ by solid solution mixing (Deer *et al* 1992) and include rutile needles (TiO_2, 4.25 g/cc) and zircon grains ($ZrSiO_4$, 4.68 g/cc). So, the resulting density will not be almandine's Table 1 value, 4.32 g/cc. Hence the variability shown in Figure 1 for natural garnets. The Table 1 nominal values have been used in data cross-plotting (following) but the heterogeneity of any garnet needs to be kept in mind in any assessment. For similar reasons magnetic susceptibilities will vary too.

Table 2. Garnet physical properties

Sample no.	Type & colour code	Density D, g/cm^3	Magnetic susceptibility k, SIx10^{-5}
1	Almandine	3.91	142
2		4.07	238
3		4.10	274
4		4.05	216
5		4.06	254
6		4.17	308
7		4.02	197
8		3.95	145
9		4.04	244
10		4.03	251
11		4.01	224
12		4.11	245
13		4.06	237
14		4.02	235
15		4.02	234
16		4.11	248
17		4.09	241
18		4.09	229
19		4.10	231
20		4.11	217
21		4.11	227
22		4.18	274
23	Spessartine	4.16	383
24		4.18	388
25	Andradite	3.74	137
26		3.68	128
27	Grossular	3.59	32
28		3.58	26
29		3.59	29
30		3.58	31
31		3.58	22
32	Andradite	3.67	92
33		3.75	182
34		3.76	261
35		3.72	215
36	Cut and polished	4.03	162
37	Small and gemmy	3.86	138
38		3.70	95
39		4.14	234
40		3.77	118
41		3.86	124
42		3.94	154
43		4.01	219
44		3.84	146
45		4.17	276

Notes to Table 2:

- Samples #1 – 35 natural stone crystals mm → cm diameter; #36 – 45 small dimension cut, faceted gems; sample #1 from Kenya (reputedly pyrope); #2, 3 Harts Range NT; #4, 5, 7 Broken Hill NSW; #6 Massachusetts USA; #8 – 10 Turkey; #11 – 17 India; #18 – 21 China; #22 Broken Hill NSW; #23 – 24 Brazil; #25 – 26 Mali; #27 – 31 Mexico; #32 Mali; #33 Japan; #34 Hampshire Tasmania; #35 – 45 provenances uncertain
- Densities measured by Archimedes principle following Emerson (1990) to 3 decimal places for smaller mm size specimens, porosities generally low (0.1 to 1.0% range) and associated with fractures; magnetic volume susceptibility (k) measured by change of inductance when sample inserted into test coil following Yang and Emerson (1997)
- Four other samples tested thought to be from either Broken Hill NSW or Harts Range NT, are not cited in Table owing to high magnetic susceptibilities arising from included magnetite octahedra up to 2mm in size [data: 4.08, 875; 4.11, 811; 4.10, 2550; 4.15, 5906; gm/cm^3 and SI x 10^{-5}, respectively]

- Other minerals that may be confused with or passed off as natural garnets include: red-orange spinel $MgAl_2O_4$ (3.60 g/cm^3, k = 0, H ≤ 8); synthetic orange corundum Al_2O_3 (4.0 g/cm^3, k = 0, H = 9); synthetic reddish garnet YAG $Y_3Al_5O_{12}$ (4.55g/cm^3, k = 0; H = 8.25); red-brown zircon $ZrSiO_4$ (≤ 4.7g/cm^3,k = 0, H ≤ 7.5); and coloured glass doped for higher densities (2.3 – 4.5 g/cm^3, if no Fe or Mn k = 0, H ≤ 6). [H is Moh's hardness, which for garnets is ≤ 7.5]
- See also Mavko *et al* (1998)

Forty five garnets that I collected or acquired over the years from a wide variety of locations were used in trial measurements of density and susceptibility. The data are given in Table 2 and plotted in Figure 5. The results are informative. Almandines plot along the almandine – pyrope trend; the two high density spessartines have the highest susceptibilities (but fall short of the Bleil & Peterseon (1982) values, see Table 1); andradites plot, more or less, along around the andradite – grossular trend; and the gems, which when purchased (cheaply) were only labelled as garnet, appear to be of the common almandine – pyrope type as would be expected for such material. Simple susceptibility – density plots would seem to be quite useful in garnet identification, complementing optical measurements of refractive index and absorption spectra. There is ambiguity in estimating garnets types with low susceptibility and relatively low density i.e. grossular and pyrope. Other tests may be required. Natural pyrope does tend to have a distinctive reddish colour whereas grossular is usually green/yellow, or off white (as in Figure 2 front right). For translucent specimens the absorption spectra, determined with a spectroscope, are different: pyrope absorbs transmitted light in a band around 564 nm wavelength, grossular does not. The five Mexican samples #27 – 31 in the lower left of the k-D plot were confirmed as grossulars by colour, and also by thermal conductivity tests. Grossular is reported as having a higher thermal cond. than red garnet (Clark, 1966).

Industrial garnets

Garnet, physically, is a tough stone. Small stones of the appropriate (bloody) colour were used by Asiatic tribes as missiles in slingshots and muzzleloaders, being deemed more deadly than lead. They were so used by the Kashmiri Hanza in 1892 in frontier conflict with the British.

Garnet, in our time, has found a niche as a specialty mineral for use in abrasive blasting media, waterjet cutting, abrasive powders, water filtration plants, and other uses. Garnet's inertness and resistance to chemical attack account for its use in final stage under-draining beds in water purification. However, most garnet is used in sub mm grainsizes for abrading operations of one sort or another. Table 3 attempts to summarise the characteristics, availability, and cost of garnet compared to quartz, which has most of the market. Compared to quartz, garnet is denser, tougher, harder, and stronger (see Table 3 velocities, and Young's (stiffness) modulus). It is also safer and recyclable. A key quality is fracture which, for a good abrasive garnet, results in edges self-sharpening with continuing use. Not all garnets have this splintering facture necessary for continuing abrasion.

Garnets sands are mined in only a few locations around the world. Australia has a mine in mineralised sand dunes near Geraldton W.A. Garnet is far more valuable than quartz and it would seem that there is ample scope in Australia for

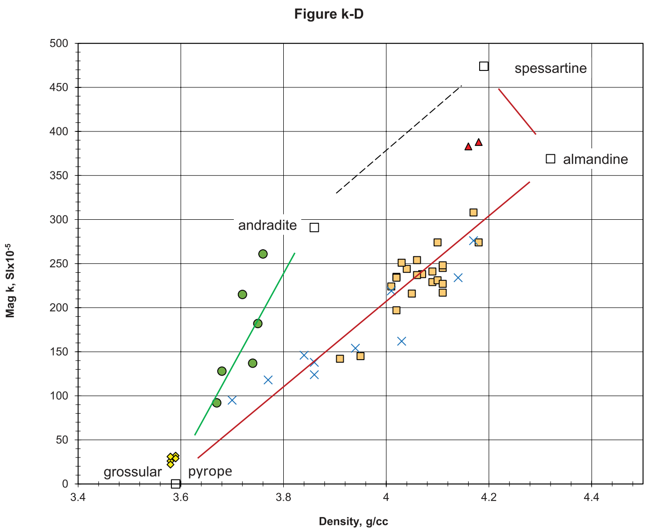

Figure 5. *Plot of susceptibility against density for 45 test garnets. Data for the 45 samples listed in Table 2 are plotted here. The open boxes give the nominal positions for the five main garnets whose paramagnetic susceptibilities are based on the Bleil & Petersen (1982) values. The cross plot suggests that density and magnetic susceptibility are useful in characterising garnets. Most of the garnets tested here belong to the almandine – pyrope isomorphous mixture series; a few plot in the andradite – grossular field. The two spessartines from Brazil have the highest susceptibilities of any tested in this batch. Using this method of plotting, pyrope and grossular with similar densities (~ 3.6 g/c) and low magnetic susceptibilities (→ 0) cannot be resolved. However, the Mexican grossulars (#27 – 31) plotting here near the pyrope / grossular reference are identified as true grossulars by other means (offwhite-yellowish colour, and thermal conductivity: grossular exceeds that of reddish garnet (Clark, 1966)).*

garnet exploration with a target, say, of 50 million tonnes of mineralised sand containing about 2 million tonnes of recoverable garnet, and possibly other heavy minerals too e.g., ilmenite. The usual suite of near surface geophysical techniques could be applied in indirect exploration i.e., to locate and define subsurface topographical features that could presumably contain garnets e.g., palaeochannels. Magnetics may be of some limited use. Paramagnetic garnets in alluvial drainage or shoreline sediments are often associated with ferrimagnetic magnetite and paramagnetic ilmenite.

Pathfinder garnet

Over 100 million carats of natural diamond rough are produced each year mainly from Russia, Canada, Southern Africa, and Australia until recently with the closure of the Argyle mine in the East Kimberly region of Western Australia. Natural diamonds are big business and exploration programs for host pipes and alluvials continue in many locations worldwide.

Garnet mapping is carried out in the first stage of diamond pipe exploration, prior to the application of detailed geophysical techniques. High pressure pyrope and other indicator minerals indicate the likelihood of possibly diamondiferous kimberlite or lamproite pipes occurring somewhere in a drainage network in which such heavy minerals have been mapped. Garnet trails can indicate localities for detailed geological and geophysical follow up even if a heavy mineral halo around a pipe has not been identified. Figure 6 shows indicator minerals found in a kimberlite exploration program in Wyoming where electrical

Table 3. Garnet and quartz (compiled from various sources including Mavko *et al*, 1998 and Voynick, 2019).

Property	Garnet	Quartz
Density g/cc, t/m^3	3.58 – 4.32 Garnet has higher unit mass and greater momentum in jet blasting	2.65
Moh's hardness (scriber scratch)	7 ½	7
Knoop hardness (diamond indentation)	1360	820
Pwave velocity m/s	8510	6050
Swave velocity m/s	4770	4090
Young's Modulus GPa	242	94
Fracture (a key quality)	(Sub) conchoidal, uneven best varieties tend to break into blocky angular fragments that under abrasive stress form new cutting edges	Conchoidal rounds with use, not self-sharpening
Recyclable	Yes, ~ 5 times	No
Health	Dust thought to be non-toxic	Debilitating silica dust -> lung silicosis
Industrial type	Mainly almandine – pyrope (but with requisite fracture characteristics, not all deposits have this)	α (low temp) quartz
Deposits	Garnet grains shed from parent rocks accumulate in palaeochannels, dunes, beach sands, alluvials, eluvials, flood plains (some hard rock mining in Adirondacks USA)	Alluvials and ocean front sands sought for their angularity – copious desert sands' grain shapes too rounded
Mines	Only a few, in India, China and Australia (WA: ~200 000 t p.a.)	Countless extraction sites around the world
Production worldwide tonnes p.a.	1 200 000 Refined concentrate sub mm grainsizes	50 000 000 000 Sands of various quality and grainsizes for many purposes including abrasives
Value $/t (AUD)	800 Milled, graded, bagged	75 Washed truckload
Resources	Promising	Stretched
Prospects	Excellent opportunities for increased production, garnet will never replace quartz sand but demand is there, because it is the best quality, natural abrasive	Sands of the favoured angularity & grain size getting harder to find but large tonnages available in the foreseeable future
Exploration for deposits	Indirect, in garnet terrain: resistivity, seismic refraction, magnetics (both magnetite and ilmenite likely to be present), to map favourable subsurface topography, then drilling	Direct, airborne imagery for drainage systems (recent and palaeo), then sampling and drilling

resistivity, magnetics, and seismic refraction were employed successfully after heavy mineral alluvial and eluvial sampling programs (Hausel *et al*, 1979, see also Jenke 1983, and Smith *et al* 1990).

Gem garnets

Apart from diamonds, gemstone mining is a multi-billion-dollar industry worldwide. Ruby, opal, jade, lapis lazuli, sapphire, and emerald are most valuable and hence have been the main exploration targets, but gems of lower value, such as garnet, are still sought and sold.

Garnets have a long history as semi-precious gems, used in adornments, and plentiful in many colours. Nowadays they are still fancied as one of the cheaper gems, although many consider them old fashioned. Gem garnet was never more popular than in the Victorian era when countless rings, bracelets, necklaces, and brooches were fashioned from Bohemian reddish-brown pyrope-almandine. Many survive to this day in antique and bric-a-brac shops and as household hand-me-downs (Figure 7). Garnet is still collected for jewellery purposes in several countries, often as water worn pebbles in alluvials, or extracted from a host rock matrix, to be cut into various shapes, then to be marketed and sold (Figure 8). While small gemmy garnets usually are not of high value, they are more valuable than the garnet crystal trophy specimens sought by collectors, museums, and researchers. For such single crystals of the common almandine type, in fair to good condition, prices can range from \$10 for a small specimen (~10mm diameter) to over \$100 for a large rhombic or trapezoidal faced crystal (~100mm diameter) i.e., roughly ~ \$0.1 per gram. Gemmy rough of any type can be worth around \$50 per gram (\$10 per carat) or more. Cutting and polishing rough into an attractive stone can increase the value by an order or orders of magnitude. Some stones can be extremely valuable (Figure 9).

Good quality andradite and its rare green variety demantoid (Cr chomophore) have dispersion coefficients (0.057) exceeding that of diamond (0.044). Dispersion gives a stone “fire” or colour flashes; the coefficient of dispersion being the difference between the refractive indices of red and violet light. Strong colouring in andradite and demantoid tends to diminish the effect, but it can be seen in weaker tints. The andradites are ‘lively” as they have the highest R.I. of any garnet and hence better reflectivity and a strong sub-adamantine lustre compared to the duller vitreous lustre of common almandine. Demantoid, found in serpentinites, is the most precious garnet – a good specimen would rival emerald in value.

In the last resort the value of a garnet will depend on the buyer’s appreciation of a stone’s clarity, colour, and character. No other mineral has garnet’s range of colour; only a few surpass it in character. The point of all this is to make geophysicists aware that garnet could be a nice little supplementary earner if, in any spare personal time they have in their travels, they care to browse around garnet areas, to meet and deal with local fossickers, and attend local gem shows. There are bargains to be had and good material can be on sold especially if, as geoscientists, they can add to the information about a stone with a simple density measurement and observations such as geological provenance. A big garnet with good rhombic dodecahedral geometry could weigh ~ 1 kg and be worth ~ \$100, so too would be the value of a couple of grams of good gemmy garnet rough.

A strong light source, a 10x loupe, a scriber, and a good magnet are indispensable tools to employ in inspecting any mineral or rock, anywhere. However, when looking at gems these may not be enough to distinguish “paste” i.e. glass imitation of minerals and gems passed off as the genuine article to unsuspecting buyers. Pliny commented on the skill and cunning of glassworkers in making counterfeit carbunculi in first century Rome. Some glass garnets were even made with internal flaws to simulate real mineral inclusions. Pliny pointed out that this could be detected because glass is

Figure 6. *Diamond indicator minerals from drainage sampling in kimberlite exploration Colorado, USA: purple pyrope, red almandine and orange spessartine garnet, emerald green chromian diopside, coated metallic picroilmenite, and metallic octahedral chromite. The finding of mineral suites such as these lead to follow up geophysics in diamond exploration programmes https://gem-garnet.blogspot.com/.*

Figure 7. *Red-brown almandine garnets with fair colour and moderate lustre are here set in a bracelet and pendant cross. Inexpensive jewellery of this type was and is still popular. It is readily available and sold worldwide (scale - cm).*

Figure 8. *Gemmy alluvial pyrope – almandine garnets (up to 15 mm lateral dimension) from Horse Gully, New England region NSW. These pebbly rough garnets are believed to have been shed from a volcanic host, possibly from a basic breccia pipe (top). Faceted pyrope – almandine garnets from Horse Gully (bottom) Specimens and photos R. Coenraads in: Webb & Sutherland (2002), thanks for facilitating the use of these images here to George Laking of The Mineralogical Society of New South Wales Inc., and Ross Pogson of the Australian Museum.*

Figure 9. *Andradite and demantoid: collector and gem grade andradite [$Ca_3Fe_2(SiO_4)_3$]. The single dark brown red andradite crystal (42mm wide) is a collector grade stone from Mali which could be worth ~ $100 (top) CC BY SA 4.0 / Didier Descouens / https://commons.wikimedia.org/wiki/File:Andradite-Mali.jpg. The substitution of Cr in the andradite imparts a green colour. This rare variety of andradite is called demantoid – the most valuable variety of garnet. The crystal cluster shown (middle) is thought to be from the Ural Mountains in Russia and could be worth ~ $1000 Rob Lavinsky, iRocks.com – CC-BY-SA-3.0. A batch of small demantoid gem garnets is shown (bottom) CC BY SA 3.0 / Elke Wetzig / as modified / https://commons.wikimedia.org/wiki/File:Demantoid_bobrowa_mineralogisches_museum_bonn.jpg. Demantoid gems are rare, very good specimens rival emeralds in price.*

softer than and not as heavy as real garnet. But today glasses are now made with a wide range of colours and properties ranging from colourless 'crown' (2.30 g/cc) to emerald green 'flint' (4.25 g/cc) and some with Moh's hardness approaching that of quartz (Anderson & Jobbins, 1992). Nevertheless, one property glass cannot readily mimic is thermal conductivity, which for glass is usually low ~ 1 W/m°C. Garnets are rather inert minerals and their thermal conductivities are not high, ~3 to 7 W/m°C, but they do exceed most glasses. Compare this with quartz, corundum, and diamond with values ~ 12, 25, 125 W/m°C respectively [all values approximate – they can vary, a good summary of thermal conductivity values is given by Schön (1996)]. Thermal conductivity needle probes are now readily available for diamond testing (Figure 10). These qualitative devices are small and inexpensive. They indicate relative thermal conductivity on an illuminated scale (12 gradations, on the model shown in Figure 10). Diamonds give a maximum reading i.e., 12 or off-scale; a piece of glass can be used as an arbitrary base reference, and a piece of metal, in lieu of diamond, to check the highest reading. Garnets, in my experience, illuminate between the third and fifth gradations, with quartz, corundum and diamond all giving higher responses. These small meters are a handy tool in the kit of any geoscientist.

Many are the chapters of book and numerous are the articles and papers on gem garnets. The interested reader is advised to consult them for further information e.g. see GIA (1995) and Schumann (2006).

Healing garnets

Mineral crystals and medicine have long been linked by folklore. Garnets have some character, but not much charisma. Nevertheless, these squat, heavy angular stones allegedly have therapeutic uses. This belief has persisted from antiquity to the present day. Such claims are based on them functioning by skin contact or as objects of meditation.

Someone presented with, or finding, a garnet may attempt to optimise its lithotherapeutic powers by "discharging" the stone i.e., washing with water or burying it for a while, presumably to dampen or delete malevolent effects. Garnet according to one source is good for gonads, and for arthritis. Another source claims such benefits as time travel (life regression), dream recall and realisation, relief of depression, and purification of the blood. Yet another maintains that garnet is an energy booster, and has stabilising power over chaos whether internal or external, and

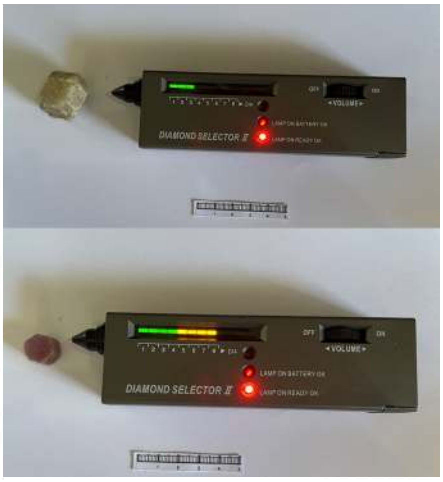

Figure 10. *Cheap diamond testers give rapid, relative indications of thermal conductivity by a needle point technique. To check whether a material is glass (paste) or garnet, the tester is set to zero when touching a piece of glass, which usually has a very low thermal conductivity, ~1 W/m°C. Garnets do not have a high thermal conductivities, they are low, in the 3-7 W/m°C range. The Mexican grossular (top) give an indication of 3 on the scale, and so, by an easy qualitative thermal measurement, we can say it probably is not glass. Ruby (Al_2O_3 + Cr) sometimes looks like garnet; it has a much higher thermal conductivity, ~25 W/m°C. The hexagonal prism section of very low-grade pink ruby (bottom) gives an indication of 8 on the scale. Diamond (not shown) goes off scale and the meter beeps. Of course, a nice ruby would be preferable to a garnet. Ruby's density (~ 4.0 g/cc) is similar to red-brown garnet, but it is much harder (H = 9). However, it is not generally a good idea to hardness test scratch a good quality specimen.*

ensures survival in crisis or trauma. Garnet is said to release bad karma and to promote success in lawsuits. Some stone! One could expand on all this, exponentially, but to no real purpose. Suffice it to say that I think the link to medicine is imaginary, and if garnet does help a person it is, in my view, a placebo effect (see Harris, 2016). The magic, fantasy and wish list aspects are just part of the folkloric litho-therapy show (and not just for garnets).

Concluding remarks

This article has presented some aspects of the history and mineralogy of the garnet. It also discussed physical properties. Although pure garnet varieties probably only exist in synthetic form, magnetic susceptibility – density plots can supply some information on a garnet's mixed solid solution composition, provided that ancillary magnetites are not present as inclusions. Simple thermal measurements may be useful in distinguishing garnet from paste or other unwanted minerals such as quartz. Garnet itself may present some exploration opportunities for the gem and abrasive industries, but it is not a vitally important economic mineral such as nickel or copper sulphide. The account of garnet given here is by no means a complete narrative. If interested in a mineral that can show grunt and (sometimes) grace, readers can easily access additional information in the science literature, and in popular publications (which sometimes lack accuracy).

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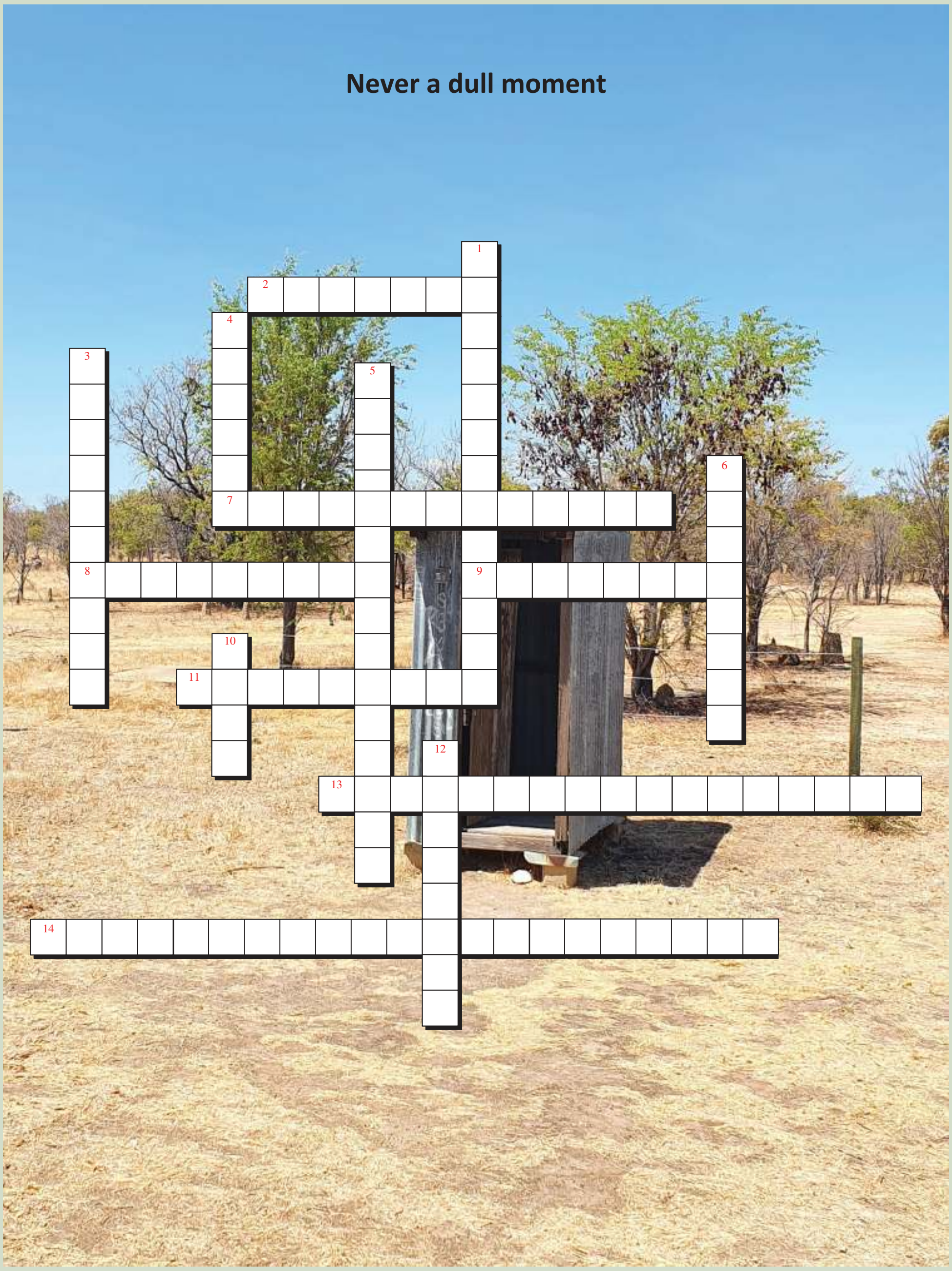
Don Emerson is a geophysical consultant specialising in the physics of minerals and rocks, he also has an interest in ancient and medieval geoscience.

Preview crossword #17



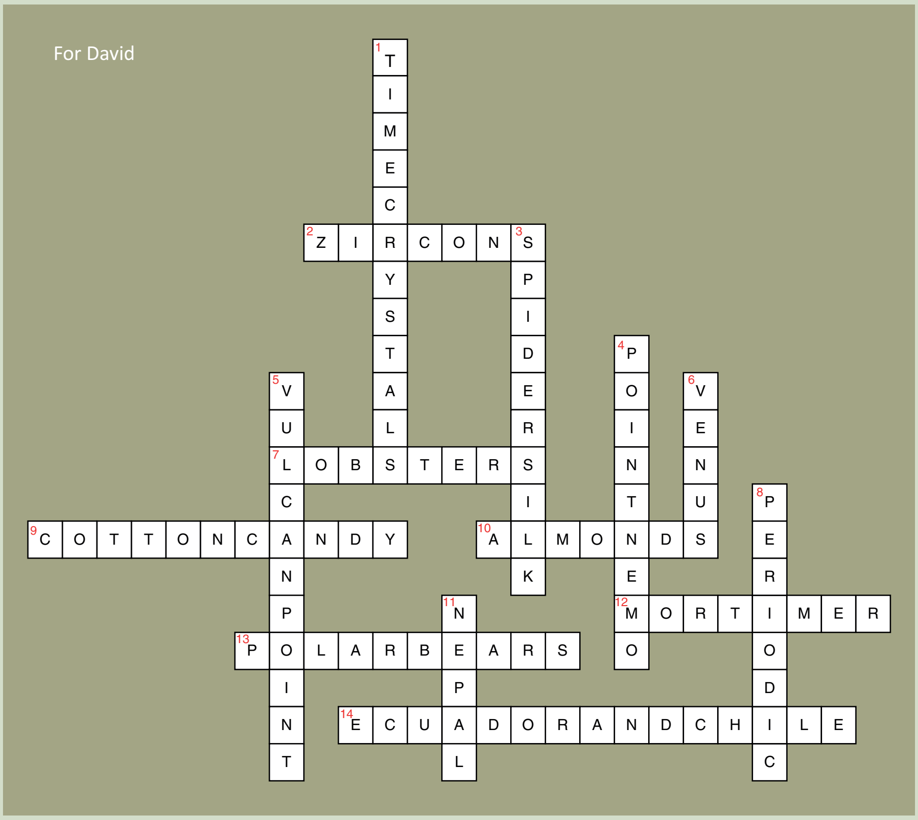
Across	Down
2. A sandy isthmus	**1.** Behemoth of a grotto [3,5,4]
7. Colossal cataclysm, the greatest killer that ever was [8,5]	**3.** A South American rodent
8. Island mountain	**4.** Fertile desert spots
9. Dinosaurs walking up walls [3,5]	**5.** Liquid used in explosives
11. Exterminate	**6.** Small scale variations in the height or roughness of a surface
13. Famed, iconic image of the Eagle Nebula [7,2,8]	**10.** Darling of the Canadian investment community during the mid-1990s…until the scandal broke
14. Some of the largest and most revered elder natives of the Seychelles atoll [7,5,9]	**12.** An organism that cannot swim effectively, so it drifts with the currents

Play to win!!

Send your answers to *previeweditor@aseg.org.au*. The first correct entry received from an ASEG Member will win two Hoyts E- CINEGIFT passes. The answers will be published in the next edition of *Preview.*

Good luck!

Preview crossword #16 solution



Business directory

AUSTRALIAN SOCIETY OF EXPLORATION GEOPHYSICISTS
A.B.N. 71 000 876 040
PO BOX 576, CROWS NEST NSW 1585 AUSTRALIA
Phone: +61 2 9431 8691 Fax: +61 2 9431 8677
Email: secretary@aseg.org.au Website: www.aseg.org.au

Application for Active & Associate Membership 2022

INSTRUCTIONS FOR APPLICANTS

1. Determine the membership level you wish to apply for, according to the eligibility criteria outlined in Section 2.
2. Fill out the application form. Note that applicants for Active Membership must nominate a proposer and a seconder who are Active Members of ASEG. Under exceptional circumstances the Federal Executive Committee may waive these requirements.
3. Submit the two pages of your application to the Secretariat at the address shown on the top of this page, retaining a copy for your own records. The Secretariat will generate an invoice for payment that includes payment instructions.
The invoice will be sent electronically so please check your email inbox and spam folders.

Section 1. Personal identification

Surname		Date of Birth
Given Names		Mr / Mrs / Miss / Ms / Other (list)
Address		
Country	State	Post Code
Organisation		
E-mail		
E-mail (alternate)		
Mobile	Phone (W)	Phone (H)

Section 2. Choice of Membership grade (Active or Associate)

- ❑ Active — Please complete all sections
- ❑ Associate — Please complete all sections
- ❑ Graduate — Please complete Active or Associate application and also check this box
- Student — Please complete the separate Student Membership Application Form

Active – an applicant must be actively engaged in practising or teaching geophysics or a related scientific field. Conditions for Active Membership include a relevant academic qualification. Any person who does not have such qualifications, but who has been actively engaged in the relevant fields of interest of the Society for at least five years, shall also be eligible for Active Membership upon the discretion of the Federal Executive Committee.

Associate – an applicant must be actively interested in the objectives of the Society. Associate Members are automatically eligible for election to Active Membership after five years as an Associate Member.

Graduate – Active or Associate Membership is subsidised by 50% for no more than two years after completion of studies. Members accepting the graduate grant are expected to contribute to Society activities and publications with the goals of raising their profile in the Society and showing ASEG's support of young professionals.

Student – an applicant must be a full-time graduate or undergraduate student in good standing, registered at a recognised university or institute and working towards a degree in geophysics or a related field. Eligibility for Student Membership shall terminate at the close of the calendar year in which the Student Member ceases their graduate or undergraduate studies. The duration of a Student Membership is limited to five years.

Section 3. Academic and professional qualifications

Month/Year (From – To)	Organisation/Institution	Position/Degree (incl. Major)	Professional Record Only: Years of Independent Work

Section 4. Nominators (must be ACTIVE Members of ASEG)

Nominator	Name	Postal or e-mail address	Phone/Fax
Proposer			
Seconder			

Section 5. Membership of other societies

Australian:

- ❑ Aus IMM Grade ________ ❑ AIG Grade ________ ❑ GSA Grade ________ ❑ PESA Grade ________

International:

- ❑ AAPG Grade ________ ❑ EAGE Grade ________ ❑ SEG Grade ________ ❑ SPE Grade ________
- ❑ Others ____

Section 6. ASEG Member record

Include me in the ASEG Member Search on the Secure Member Area of ASEG's Website (search is only available to current ASEG Members who opt-in)

❑ **Yes** ❑ **No**

Please complete this section for the ASEG Membership database.

Employment area:

- ❑ Industry
- ❑ Education
- ❑ Contract/ Service Provider
- ❑ Consulting
- ❑ Government
- ❑ Other ___________________
- ❑ Student

Type of Business:

- ❑ Oil/ Gas
- ❑ Minerals
- ❑ Solid Earth Geophysics
- ❑ Ground Water/ Environmental
- ❑ Petrophysics/ Log Analysis
- ❑ Archaeology/ Marine Salvaging
- ❑ Coal
- ❑ Research/ Education
- ❑ Computer/ Data Processing
- ❑ Survey/ Geotechnical/ Engineering
- ❑ Data Acquisition
- ❑ Other___________________

Section 7. Membership grades and rates

❑ Active/Associate (Australia) - $182.00	❑ Active/Associate 5 Year Membership (Australia) - $910.00
❑ Active/Associate (Group IV Countries) - $165.50	❑ Active/Associate 5 Year Membership (Group IV Countries) - $827.50
❑ Active/Associate (Group III Countries) - $49.70	❑ Active/Associate 5 Year Membership (Group III Countries) - $248.50
❑ Active/Associate (Group I & II Countries) - $18.20	❑ Active/Associate 5 Year Membership (Group I & II Countries) - $91.00
❑ Associate-Graduate (Australia) - $91.00	

Section 8. *Preview* & *Exploration Geophysics*

The ASEG produces a magazine called *Preview* and a peer-reviewed journal called *Exploration Geophysics*. Please read and agree to the following in order to receive ASEG publications:

1) I grant permission for the ASEG to provide my email and postal address to the Taylor & Francis Group so that I can receive copies of the ASEG publications. Taylor & Francis will not use the Member list for any purpose other than advertising and for distributing *Exploration Geophysics* and *Preview*.

2) I understand and agree that online access to *Exploration Geophysics* is for my private use and the articles shall not be made available to any other person, either as a loan or by sale, nor shall it be used to substitute for an existing or potential library or other subscription.

3) I understand and agree that *Exploration Geophysics* articles shall not be networked to any other site, nor posted to a library or public website, nor in any way used to substitute for an existing or potential library or other subscription.

4) I understand and agree that any Member who is discovered by the publisher to be in breach of these conditions shall have their subscription access immediately terminated, and the publisher shall have the right to pursue recompense at its discretion from that Member.

❑ **Yes** ❑ **No**

Section 9. Promotional opportunities

The ASEG provides opportunities for special category listings (eg. Consultants, Contractors) from the ASEG Internet Web Page.

- ❑ I (or my business) am interested in having a link from the ASEG Internet page. Rates will be advised when links are implemented. (Corporate and Corporate Plus Members get a complimentary link.)
- ❑ I (or my business) am interested in advertising in ASEG's publications.

Section 10. Declaration

I, ____ (name), agree for the Australian Society of Exploration Geophysicists to make all necessary enquiries concerning my application and suitability to become a Member. By lodging this Application and upon being accepted in my membership, I agree to be bound by the Constitution of the Australian Society of Exploration Geophysicists, including its ethical and professional standards.

*Signature:*________________________________ *Date:*_______________

ASEG CODE OF ETHICS

Clause 4 of the Articles of Association of the ASEG states that "Membership of any class shall be contingent upon conformance with the established principles of professional ethics":

1. A Member shall conduct all professional work in a spirit of fidelity towards clients and employees, fairness to employees, colleagues and contractors, and devotion to high ideals of personal integrity and professional responsibility.
2. A Member shall treat as confidential all knowledge of the business affairs, geophysical or geological information, or technical processes of employers when their interests require secrecy and not disclose such confidential information without the consent of the client or employer.
3. A Member shall inform a client or employer of any business connections, conflicts or interest, or affiliations, which might influence the Member's judgement or impair the disinterested quality of the Member's services.
4. A Member shall accept financial or other compensation for a particular service from one source only, except with the full knowledge and consent of all interested parties.
5. A Members shall refrain from associating with, or knowingly allow the use of his/her name, by an enterprise of questionable character.
6. A Member shall advertise only in a manner consistent with the dignity of the profession, refrain from using any improper or questionable methods of soliciting professional work, and decline to accept compensation for work secured by such improper or questionable methods.
7. A Member shall refrain from using unfair means to win professional advancement, and avoid injuring unfairly or maliciously, directly or indirectly, another geophysicist's professional reputation, business or chances of employment.
8. A Member shall give appropriate credit to any associate, subordinate or other person, who has contributed to work for which the Member is responsible or whose work is subject to review.
9. In any public written or verbal comment, a Member shall be careful to indicate whether the statements or assertions made therein represent facts, an opinion or a belief. In all such comments a Member shall act only with propriety in criticising the ability, opinion or integrity of another geophysicists, person or organisation.
10. A Member will endeavour to work continuously towards the improvement of his/her skills in geophysics and related disciplines, and share such knowledge with fellow geophysicists within the limitation of confidentiality.
11. A Member will cooperate in building the geophysical profession by the exchange of knowledge, information and experience with fellow geophysicists and with students, and also by contributions to the goals of professional and learned societies, schools of applied science, and the technical press.
12. A Member shall be interested in the welfare and safety of the general public, which may be affected by the work for which the Member is responsible, or which my result from decisions or recommendations made by the Member, and be ready to apply specialist knowledge, skill and training in the public behalf for the use and benefit of mankind.

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Application for Student Membership 2022

INSTRUCTIONS FOR APPLICANTS

1. Student Membership is available to anyone who is a full-time student in good standing at a recognised university working towards a degree in geophysics or a related field.

   Eligibility for Student Membership shall terminate at the close of the calendar year in which the Student Member ceases their graduate or undergraduate studies.

   Student Membership must be renewed annually.

   The duration of a Student Membership is limited to five years.

2. Fill out the application form, ensuring that your supervisor signs Section 2.

3. Submit your application to the Secretariat at the address shown on the top of this page, retaining a copy for your own records.

Section 1. Personal details

Surname		Date of Birth
Given Names		Mr / Mrs / Miss / Ms / Other (list)
Address		
Country	State	Post Code
E-mail		
E-mail (non-University alternative)		
Mobile	Phone (W)	Phone (H)

Section 2. Student declaration

Institution	
Department	
Major Subject	Expected Year for completion of studies
Supervisor/Lecturer	Supervisor Signature

Section 3 Membership grades and rates

❑ Student (Australia & Group IV Countries)	FREE
❑ Student (Group III Countries)	FREE
❑ Student (Group I & II Countries)	FREE

Section 4 *Preview* & *Exploration Geophysics*

The ASEG produces a magazine called *Preview* and a peer-reviewed journal called *Exploration Geophysics*. Please read and agree to the following in order to receive ASEG publications:

1) I grant permission for the ASEG to provide my email and postal address to the Taylor & Francis Group so that I can receive copies of the ASEG publications. Taylor & Francis will not to use the Member list for any purpose other than advertising and distributing *Exploration Geophysics* and *Preview*.

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4) I understand and agree that any Member who is discovered by the publisher to be in breach of these conditions shall have their subscription access immediately terminated, and the publisher shall have the right to pursue recompense at its discretion from that Member.

❑ **Yes** ❑ **No**

Section 5 Declaration

I, ________________________________ (name), agree for the Australian Society of Exploration Geophysicists to make all necessary enquiries concerning my application and suitability to become a Member. By lodging this Application and upon being accepted in my membership, I agree to be bound by the Constitution of the Australian Society of Exploration Geophysicists, including its ethical and professional standards.

Signature: ________________________________ Date: ________________

ASEG CODE OF ETHICS

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2. A Member shall treat as confidential all knowledge of the business affairs, geophysical or geological information, or technical processes of employers when their interests require secrecy and not disclose such confidential information without the consent of the client or employer.
3. A Member shall inform a client or employer of any business connections, conflicts or interest, or affiliations, which might influence the Member's judgement or impair the disinterested quality of the Member's services.
4. A Member shall accept financial or other compensation for a particular service from one source only, except with the full knowledge and consent of all interested parties.
5. A Member shall refrain from associating with, or knowingly allow the use of his/her name, by an enterprise of questionable character.
6. A Member shall advertise only in a manner consistent with the dignity of the profession, refrain from using any improper or questionable methods of soliciting professional work, and decline to accept compensation for work secured by such improper or questionable methods.
7. A Member shall refrain from using unfair means to win professional advancement, and avoid injuring unfairly or maliciously, directly or indirectly, another geophysicist's professional reputation, business or chances of employment.
8. A Member shall give appropriate credit to any associate, subordinate or other person, who has contributed to work for which the Member is responsible or whose work is subject to review.
9. In any public written or verbal comment, a Member shall be careful to indicate whether the statements or assertions made therein represent facts, an opinion or a belief. In all such comments a Member shall act only with propriety in criticising the ability, opinion or integrity of another geophysicists, person or organisation.
10. A Member will endeavour to work continuously towards the improvement of his/her skills in geophysics and related disciplines, and share such knowledge with fellow geophysicists within the limitation of confidentiality.
11. A Member will cooperate in building the geophysical profession by the exchange of knowledge, information and experience with fellow geophysicists and with students, and also by contributions to the goals of professional and learned societies, schools of applied science, and the technical press.
12. A Member shall be interested in the welfare and safety of the general public, which may be affected by the work for which the Member is responsible, or which my result from decisions or recommendations made by the Member, and be ready to apply specialist knowledge, skill and training in the public behalf for the use and benefit of mankind.

December	2021		
2	Tasmanian Geoscience Forum https://www.ausimm.com/conferences-and-events/community-events-details/tasmania-branch---geoscience-forum-2021/	Tullah, Tasmania	Australia
5–9	23rd World Petroleum Congress https://wpc2020.com/	Houston	Texas
13–17	AGU Fall Meeting	New Orleans	USA
February	**2022**		
1–3	EAGE Digitalization Conference 2022 https://eage.eventsair.com/digital2022/	Vienna	Austria
March	**2022**		
7–9	Prospectors and Developers Convention (PDAC) Face-to-face https://www.pdac.ca/convention	Toronto	Canada
10–11	Prospectors and Developers Convention (PDAC) Online https://www.pdac.ca/convention		Virtual
20–23	Geo-Congress 2022 https://www.geocongress.org/	Charlotte	USA
April	**2022**		
3–8	EGU General Assembly 2022 https://www.egu22.eu	Vienna	Austria
5–6	Annual Geoscience Exploration Seminar (AGES) https://resourcingtheterritory.nt.gov.au/news-and-events/ages	Alice Springs	Australia
11–14	International Geological and Geophysical Conference and Exhibition https://eage.eventsair.com/saint-petersburg-2022/	St Petersburg	Russia
May	**2022**		
9–13	8th Mines & Wines Conference 2022 https://www.aig.org.au/events/8th-mines-wines-conference-2022/	Orange	Australia
June	**2022**		
5–9	83rd EAGE Annual Conference & Exhibition https://eage.eventsair.com/eageannual2022/	Madrid	Spain
12–17	19th International Conference on Ground Penetrating Radar https://learn.mines.edu/gpr2022/	Denver	USA
August	**2022**		
1–3	Diggers and Dealers https://www.diggersndealers.com.au/	Kalgoorlie	Australia
15–19	12th International Kimberlite Conference https://12ikc.ca/	Yellowknife	Canada
28 Aug–02 Sept	International Meeting for Applied Geoscience & Energy (SEG | AAPG IMAGE 2022) https://imageevent.org/2022/Save-the-Date	Houston	USA
September	**2022**		
18–22	Near Surface Geoscience Conference & Exhibition 2022	Belgrade	Serbia/Virtual
27–29	AIG Symposium: Structural Geology and Resources 2022 https://www.aig.org.au/events/aig-symposium-structural-geology-and-resources-2022/	Kalgoorlie	Australia
26–30	Australian and New Zealand Geomorphology Group Conference https://www.anzgg.org/conferences	Alice Springs	Australia
November	**2022**		
28–30	Sub 22 https://research.csiro.au/dei/sub22/	Adelaide	Australia
March	**2023**		
13–18	Australasian Exploration Geoscience Conference (AEGC 2023)	Brisbane	Australia

Preview is published for the Australian Society of Exploration Geophysicists. It contains news of advances in geophysical techniques, news and comments on the exploration industry, easy-to-read reviews and case histories, opinions of Members, book reviews, and matters of general interest.

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Single copies of *Preview* can be purchased from the Publisher.

All proposed contributions should be submitted to the Editor by email at previeweditor@aseg.org.au

For style considerations, please refer to the For Authors section of the *Preview* website at: https://www.tandfonline.com/toc/texp20/current

Preview is published bimonthly in February, April, June, August, October and December. The deadline for submission of material to the Editor is usually the second Friday of the month prior to the month of issue. The deadline for the February issue is 14 January 2022.

For the advertising copy deadline please contact the Publisher on advertising@taylorandfrancis.com.au