

PREVIEW



NEWS AND COMMENTARY

Vale Brian Spies

Uncertainty benefits gold miners

Quality control in airborne
geophysics

Lossless vs lossy
compression

FEATURES

Don Emerson's best of
Exploration Geophysics

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FRONT COVER



The late Dr Brian Spies conducting a TEM survey for Schlumberger Doll. See Brian's obituary in this issue for more information.

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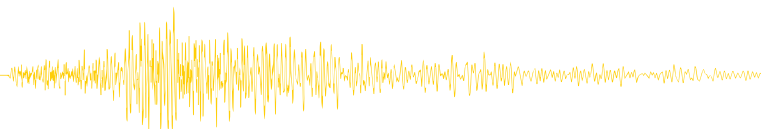
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Editor's desk

Our "best of" series, marking the 50th anniversary of the establishment of the Australian Society of Exploration Geophysicists, continues in this issue. Don Emerson, who was Editor of *Exploration Geophysics* from 1984-93 makes his choice. Again, you will have to flick through to the feature pages to find out what it was!

We are also blessed with a mini-feature; Terry Harvey (*Mineral geophysics*) has coaxed Des Fitzgerald into sharing some of his accumulated wisdom in his article on "Quality control in airborne geophysics."

Whilst we are counting our blessings, David Denham (*Canberra observed*) notes that gold miners are benefiting from the current economic uncertainty. He also introduces the new Resources Minister and surveys the Federal Government response to the COVID-19 pandemic. Mike Hatch (*Environmental geophysics*) considers how far is far enough, and no, he is not referring to social distancing. Mick Micenko (*Seismic window*) looks back 40 years, and Ian James (*Webwaves*) muses on lossless versus lossy compression.

Like many of us, you may be working from home in the hopeful expectation of slowing the spread of COVID-19. If so, there are plenty of new data available from the state and federal surveys for you to get your teeth into (*Geophysics in*

the surveys). The volume of data that is currently coming down survey pipelines is truly mind blowing. I gave a paper at the first Australian conference on Airborne Electromagnetics (AEM '98) on "Beyond bump finding – airborne electromagnetics for mineral exploration in regolith dominated terrains" and was told by the then CEO of AGSO (Neil Williams) that AGSO, or GA as it is now, would never fly AEM for mapping purposes. Well, times have changed, and I am sure that Brian Spies, who instigated that conference and was CEO of CRC

AMET between 1996 and 1999, would have been as pleased as I am to have witnessed that change. Brian died earlier this year and his obituary appears in this issue. His death is a sad loss to our community of geophysicists, and many of us feel it quite personally.

Please stay safe during these difficult times.

Lisa Worrall
Preview Editor
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The Editor in happier times - when international fieldwork was still on the agenda.

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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.



President's piece



I would like to take a moment to acknowledge our collective sadness at the news of the untimely passing on 8 February of Dr Brian Spies, one of Australia's most eminent and visionary research exploration geophysicists, an accomplished national and international science leader, inspiring geoscience innovator and inventor, research collaborator, science mentor and advocate and a great science educator.

Brian was a pioneer of transient electromagnetics (TEM). He published more than 40 scholarly papers in geoscience journals and magazines, many book chapters on exploration geophysics, and organized over 30 national and international workshops on forefront research and application in exploration technology, environmental geophysics, and reservoir characterization. Uniquely, there are 11 patents authored by Brian for the measurement and application of electromagnetic methods. He joined the ASEG in 1970 and the SEG in 1972 and was active in both societies throughout his career, including distinguished service as ASEG President in 1999 and SEG 1st Vice President 2003.

Brian and I shared our undergraduate years at the University of New South Wales, forging friendships with our geophysics student cohort that have endured and connected over the decades. My deepest sympathies and condolences are with Brian's family.

Our 50th Anniversary Year has kicked off to a great start with the publication of *Exploration Geophysics* Vol 51 Issue 1. Huge congratulations to Mark Lackie as *Exploration Geophysics* Editor in Chief and to Aaron Davis, organizer of this Special Airborne EM Issue which presents 17 papers from the 7th International Workshop in Airborne Electromagnetics, AEM 2018, held in Denmark, June 2018.

The international Special Edition Committee comprised Chair Mark Lackie (*Exploration Geophysics* Editor in Chief), Aaron Davis (CSIRO), Anders Vest Christiansen (Aarhus University, Denmark), Andi Pfaffhuber (NGI Norway) and Camilla Sorenson (SkyTEM, Denmark). The Committee handled reviews and revisions for the 17 papers submitted to *Exploration Geophysics*.

Over 90 papers were presented over three days at AEM 2018, which followed on from the successful 6th International Workshop in AEM, previously held in South Africa. The Special Airborne EM Issue from AEM 2016, also organized by Aaron Davis, appeared in *Exploration Geophysics* 2015 Vol 46, Issue 1.

Aaron Davis has provided an excellent introduction to the outstanding mix of 17 papers in this Special Issue. There are some real highlights here for me, including developments in modelling in three dimensions, improvements in near-surface AEM resolution, and advances in understanding and detection of induced polarization (IP) by today's airborne EM systems. I particularly commend the paper on AusAEM; airborne electromagnetic data collected on an unprecedented scale across the entire top end of Australia.

There is a direct line of site from the recent AEM 2018 and *Exploration Geophysics* Vol 51 Issue 1 through the history of airborne EM developments and global EM conferences to the very first International Conference on Airborne Electromagnetics hosted in 1998 in Australia. You won't be surprised when I tell you that Dr Brian Spies initiated, organized and chaired the very successful AEM 1998, the first AEM conference to be held in Australia in his role as Director of the Australian Cooperative Research Centre for Airborne Mineral Exploration Technologies. These international AEM workshops continue to bring together the latest and best international research and technical innovations in airborne electromagnetic prospecting. It seems appropriate that the next International AEM Workshop will again be hosted in Australia.

Another ASEG 50th Anniversary Year special publication, some months away, is "Measuring Terrestrial Magnetism - A History: The evolution

of the Airborne Magnetometer and the first anti-submarine and geophysical surveys operations – People, Places and Events 1100 – 1949" by Doug Morrison, well known to many of you as a frequent contributor to our *Preview* magazine. I've had the pleasure of reading the draft manuscript – it's a unique journey of science, engineering and invention and a compelling story of how the measurement of magnetism has influenced the history of the world. You'll hear more about this great new book in the coming months.

We are more than a year out from our next AIG-ASEG-PESA Australasian Exploration Geoscience Conference in Brisbane - AEGC 2021 – and everything is progressing well under the leadership of our joint Co-Chairs Rachel Kieft and Eric Battig, and the professional support of Arinex, the conference organiser for this event. A new website has just been launched; 2021.aegc.com.au I urge you to follow the announcements by signing up for the mailing list and encourage all of our ASEG Members to plan for and give priority to contributing strongly to our 28th ASEG Geophysical Conference and Exhibition.

I am preparing this piece in mid-March ahead of stepping down as President and welcoming our incoming President Dr David Annetts at our Annual General Meeting scheduled for 7 April. By the time you read this, we will have held a successful AGM, welcomed some great new Federal office bearers to the cause, completed some major initiatives for our Society and acknowledged the contributions of our high performing Federal Executive team.

In the meantime, the impact of the global COVID-19 pandemic in Australia and beyond is evolving rapidly. The latest recommendations from Government Chief Medical Officers and the latest travel and community contact restrictions and guidance that are being announced daily by the Prime Minister require our ASEG Federal and State leadership to act with an abundance of caution and care for our Members and for each other.

For the first time in the history of our Society we will no longer be holding a conventional face to face Annual General Meeting in one of Australia's capital cities. The ASEG Federal Executive has taken the initiative to

now host the 2020 ASEG AGM via online videoconferencing. We also see this as an opportunity in our 50th year to open the AGM to a wider group of our Membership. I'm sure with the best good will of our Executive and our Membership that we will make this new era of online meetings work well.

It has been a real pleasure and a privilege to share the past year as President with the great teams in our Federal and State Executives – we've all enjoyed moving our Society forward into the new decade of the 20s.

I'm very proud to welcome our incoming President, David Annetts,

and I'm personally very pleased to endorse Dr Kate Robertson as the next President Elect and ASEG Director. We also enthusiastically welcome Leslie Atkinson as the next Federal Secretary and ASEG Director. We also warmly welcome Yvette Poudjom Djomani, Suzanne Haydon and Millicent Crowe to the Federal Executive. With huge thanks and appreciation, we farewell Marina Costelloe, ASEG Past President, who steps down from the Federal Executive after six years of outstanding contributions to our Society and inspiring leadership as our President in 2018-19. I very much look forward to contributing as Past President and to working with the Federal and

State executives to support a highly successful AEGC 2021. A full report on the ASEG AGM and the new Federal Executive 2020 will follow in the June Issue of *Preview* 206.

In the coming weeks and months, the global pandemic will be truly challenging for our families, our communities and our industries and our way of life in Australia. I wish each of you and your families good health and wellbeing and a positive way forward. My wish for the ASEG in the longer term - Live Long and Prosper.

Ted Tyne
ASEG President
president@aseg.org.au

Welcome to new Members

The ASEG extends a warm welcome to 13 new Members approved by the Federal Executive at its February and March meetings (see Table).

First name	Last name	Organisation	State	Country	Membership type
Tiago	Attorre	Flinders University	SA/NT	Australia	Student
Neil	Bradbury	Raglan Mine	Newfoundland	Canada	Active
Lewis	Brothers	University of Tasmania	TAS	Australia	Student
Natalia	Valenzuela Delgado	The University of Western Australia	WA	Australia	Student
Michael	Everett	Flinders University	SA/NT	Australia	Student
Andrew	Frost	Flinders University	SA/NT	Australia	Student
Umer	Habib	University of Tasmania	TAS	Australia	Student
Youseph	Ibrahim	University of Sydney	NSW	Australia	Student
Oscar	Leon Estacio	Curtin University	WA	Australia	Student
Jennifer	Market	MPC Kinetic	WA	Australia	Active
Thusitha	Nimalsiri	Macquarie University	NSW	Australia	Student
Mahtab	Rashidifard	The University of Western Australia	WA	Australia	Student
Wai	Yong	CGG Services Australia	WA	Australia	Active

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 meeting that was held in February 2020. 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 February:

Year to date income: \$133 046

Year to date expenditure: \$29 440

Net assets: \$913 427

Membership

At the time of this report, the Society had 735 financial members, compared to 750 at this time last year. The ASEG currently has seven Corporate Members, including two Corporate Plus Members and one

International Corporate Member. A huge thanks to all our Corporate Members for your continued support in 2020. Don't forget to have a look for our Corporate Members on the contents page of *Preview* and support them as much as you can. It is great to see our Society's Members also taking advantage of the savings gained with the 5-year membership options. Please remember early and mid-career Members can join the ASEG Young Professionals Network at www.aseg.or.au/about-aseg/aseg-youngprofessionals.

Social media

Don't forget you can keep up to date with all the happenings of your Society on social media. You can connect to us on LinkedIn, Facebook and Twitter for all the latest. With 2020 marking ASEG's 50th year, the committee has lots of interesting events and promotions coming in the year ahead. It's not too late to renew, so remind your friends and colleagues, and renew today.

AGM

Don't forget our Federal AGM which is being held on 7 April 2020. For the first time in the history of our Society the ASEG AGM will be conducted via online videoconferencing. This is an opportunity, in our 50th year, for more Members to participate in the AGM. The meeting will begin at 5.30 pm. We will also have a talk by Graham Heinson, Professor of Geophysics at The University of Adelaide, titled "Training the next generations of geophysicists: Challenges and opportunities".

Nominations for all positions (except Past President) are very welcome. Please forward the name of the nominated candidate and the position nominating for, along with the names of two Members who are eligible to vote (as Proposers), to the President Elect, David Annetts at secretary@aseg.org.au.

Leslie Atkinson
ASEG Secretary
fedsec@aseg.org.au

ASEG Research Foundation: Update

Applications for grants for 2020 closed at the end of February. Eight applications were received from five Australian Universities. There were three in the category Minerals, two in the category Petroleum and three in the category Engineering/Environmental. They are currently being review by the category sub committees of the Research

Foundation Committee. Six are for PhD support for two or three years and the others are for BSc Honours and MSc support for one year. Details of the successful applicants will be announced in the next *Preview*. Support for four other projects from previous years will continue this year, subject to satisfactory progress reports.

The Foundation is also pleased to welcome eight new committee members following successful recruiting at the AEGC last year. This will assist in renewal of the foundation as several long serving members head towards retirement.

Doug Roberts
ASEG Research Foundation Secretary
dcrgeo@tpg.com.au

ASEG Technical Standards Committee: Update

The Committee has been contacted regarding best practice for mineral petrophysics. There are only two methods in widespread use, but frustration at no preferred format of recording or storage. Discussion at the latest Committee meeting revolved around the minimum of metadata and data required such

as units, device used and orders of magnitude of device readings.

Mark Duffett pointed out this is a chance for the work of the Government Geoscience Information Committee to become an industry standard in the field and archives. Technical Standards

could reinforce the standard by pointing enquiries to the GGIC site when the petrophysics template is released later in 2020.

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

ASEG national calendar

Date	Branch	Event	Presenter	Time	Venue
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All ASEG Branch events have been cancelled until further notice. Some Branches are investigating options for meeting on-line. Please monitor the Events page on the ASEG website for information about on-line events

ASEG Branch news

Tasmania

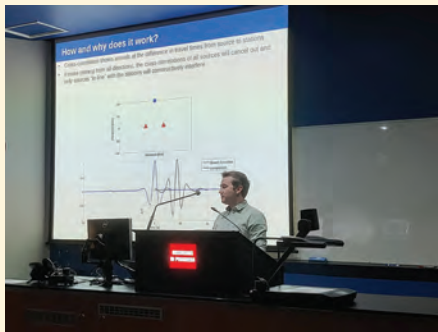
The Tasmanian Branch of the ASEG had a bumper week at the end of February, with two technical talks a couple of days apart. **Dr Esmaeli Eshaghi** gave an insider's perspective on the early days of Canada's Metal Earth project on 25 February. The project is a C\$104 million research initiative aimed at improving metal resource discovery rates through better understanding, with an initial focus on Archean volcano-sedimentary greenstone belts. Esi showcased some major data acquisition and initial integration for 3D modelling across a range of geophysical methods. There was a lunchtime audience of some 25 ASEG Members and students.

Then, only just over 48 hours later, in a joint meeting with the Geological Society of Australia's Tasmania branch, **Dr Gerrit Olivier** of the Institute of Mine Seismology delivered insights into the 2018 eruption of Kilauea Volcano from ambient seismic noise. With depictions of dynamic magma chamber and conduit development almost as spectacular as the eruptions they were driving on the surface, this was a fascinating diversion from his more usual but no less insightful application of seismic noise for imaging and monitoring in mines. The number of GSA Members who accompanied Gerrit to dinner afterwards was testament to the cross-disciplinary appeal of the presentation.

Needless to say, both speakers were rewarded not just with audience appreciation, but also a bottle from the SA Branch's excellent 2019 red wine selection.



ASEG Tasmania Branch secretary **Matt Cracknell** introduces **Esmaeil Eshaghi**.



Gerrit Olivier at the start of his presentation

An invitation to attend Tasmanian Branch meetings is extended to all ASEG Members and interested parties. When conditions return to normal Meetings will usually be held in the CODES Conference Room, University of Tasmania, Hobart. Meeting notices, details about venues and relevant contact details can be found on the Tasmanian Branch page on the ASEG website. As always, we encourage Members to also keep an eye on the seminar programme at the University of Tasmania / CODES, which routinely includes presentations of a geophysical and computational nature as well as on a broad range of earth sciences topics.

Mark Duffett
taspresident@aseg.org.au

Victoria

It seems I've invalidated Don Corleone's legendary line from the movie, *The Godfather*, where he says "I'm gonna make him an offer he can't refuse". Apparently, the prospect of collecting one million dollars by being voted the best presenter at a Victorian Branch Technical Meeting night in 2020 holds no weight to the professionals in our industry. Clearly, you're all being paid far, far much more. A 'call to arms' was launched at potential speakers early in the year and the responses the committee received were collectively akin to the sound of crickets chirping. Blasphemy! If I had sway with a hobby farm, you'd all awaken in your beds to find a horse's head lying next to you.

Alright, enough about some of my favourite *Godfather* movie scenes. Your Victorian Branch started 2020 with a bang, as we jointly hosted the annual, not-to-be-missed Summer Social that was held at Henry and the Fox in mid-February. Sadly, the event was more

of a fizzle than a bang. The Branch had anticipated record numbers of members attending, as had been the case in prior years. The turn out from ASEG Members on this particular night was woeful. I'm starting to wonder whether any hobby farm will have enough horses for me to decapitate. Interestingly, the last time I witnessed so few people attend an evening celebration was coincidentally at the premiere of the movie *Freddy Got Fingered*. Yes, I saw that movie. Yes, I regret seeing it. And, yes ... I was probably smoking something fresh at the time ... but in my defence, I did not inhale. More or less.

So, onto Autumn, and I'm wickedly chuffed to inform our Members that the Victorian Branch has not organised anything fun, entertaining nor informative for our ungrateful Members to participate in over the coming months. Nothing. Nada. Zilch. We've taken drastic steps to punish all our Members for their lack of enthusiasm and dire support for our Society. We've cancelled the Melbourne Grand Prix. How do you like that? Not much, eh? How about we lock the gates and prevent any of you from attending an AFL or NRL match either? Indefinitely. Worse yet, we'll force you to remain isolated in your residence for two weeks until cabin fever sets in. Coincidentally, the Australian Government has supported these extreme measures to help slow the spread of the coronavirus pandemic. You too can help yourself by refraining from licking too many rocks that you may find in the field. Leave your alchemist ways behind! By the way, I would have proposed similar actions to the committee in disciplining our Members ... as fallback.

On a serious note, the ASEG is very committed to your wellbeing, which is why we have cancelled all technical meeting nights for the next two to three months. Fortunately, we didn't manage to find any presenters anyway. Take care out there, boys and girls. Know the facts about the pandemic and look after one another. Lastly, think about your health and safety first before you attempt to watch *Freddy Got Fingered*.

When the situation returns to normal Victorian Branch Meetings will generally be held on the third Thursday of each month from 17:30 in the Kelvin Club, 18 – 30 Melbourne Place, Melbourne.

Meeting notices, addresses and relevant contact details can be found on the Victorian Branch page of the ASEG website.

Thong Huynh
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Western Australia

Lisa Gavin's presentation on anisotropy as SEG Pacific South Honorary Lecturer was a very big success in Perth, with 60 plus attendees, strong interest, and good end questions. Much appreciated by all who attended at the Celtic Club on 12 February.



The audience eagerly anticipating Lisa Gavin's talk (Lisa Gavin is in the front row).

And many thanks to **Partha Pratim Mandal**, our Secretary, who added and manned our booth at the Curtin University Orientation Week (Feb 17-21).



ASEG Booth at the Curtin University Orientation Week.

Well, I tried something new, 12 March Technical Night was scheduled for two authors, both on TEM, but with complimentary technologies. It was also well-attended, although the second talk had to be postponed at the last minute due to (COVID-19) travel bans, and will hopefully be scheduled for later this year.

Andrew Duncan was able to expand his talk "Case Studies from Loupe – New Technology in Portable TEM for Near-Surface Measurements", and a lively back-and-forth set of discussions ensued about the evolution and development of Loupe's new portable self-designed and engineered TEM.

Lastly, **Sergey Fomel's** Australian and New Zealand visits (Perth on 1 April) have been cancelled, as more travel bans have started to come into effect. However, VC presentations will be available (likely via Zoom), so we still expect a very good series available down-under.

When the situation returns to normal in WA monthly technical meetings will generally be held on the second Wednesday of each month and highlight topics within the geophysical fields of petroleum, mining, exploration, near-surface, and hydrogeology. Please refer to the Events page on the ASEG website for details of upcoming presentations and events.

Todd Mojesky,
wapresident@aseg.org.au

Australian Capital Territory

The ACT Branch's first technical talk of the year was held at Geoscience Australia on 11 March. **Greg Street** of Loupe Geophysics presented a talk on a portable, time domain electromagnetic (TDEM) sounding system. This is a lightweight system, fully contained in two backpacks: the first backpack houses an EM source, electronics and data storage components, and is connected by wire to a second backpack containing the horizontal receiver loop. Each backpack is said to weigh less than 12 kg and makes for ergonomic surveying with two people walking over the survey area at a steady speed. Transmitter waveforms are programmable and switch off times are 10 microseconds or less with full time series recording and real time processing. Depths of penetration, depending on the subsurface conductivity are from 25-50 m. Field test results from waste disposal and mining sites were shown, including from within an underground shaft, which point to the versatility of the system.



Greg Street presenting to the ACT Branch

On the same evening, award presentations were made for several student prizes at the ANU Research School of Earth Sciences (RSES). The reactivated Australian Society of Exploration Geophysicists (ACT Branch) Prize for Applied Geophysics was awarded to Ms **Madison Wait**, who is enrolled in the course Applied Geophysics EMSC 3033.

In light of the current situation, the ACT Branch AGM will be held after crowd restrictions are eased. Prior to this, a technical presentation will be given by Ms **Rebecca McGirr**, the successful candidate for the inaugural Dr Peter Milligan Student Award for Geophysics 2019. Rebecca's talk entitled "Mass Balance in Antarctica as Measured by Satellite Gravimetry" is based on her research that led to the award. This event is much anticipated at the Branch.

Grant Butler
actpresident@aseg.org.au

New South Wales

In February, we held our AGM and the usual suspects (**Mark Lackie**, **Steph Kovach** and **Ben Patterson**) were elected to the roles of President, Secretary and Treasurer. **Simon Williams** (GBG), and **Josh Valencic** (GHD), were elected as committee members. GBG Australia was confirmed as Platinum Sponsor for meetings for 2020.

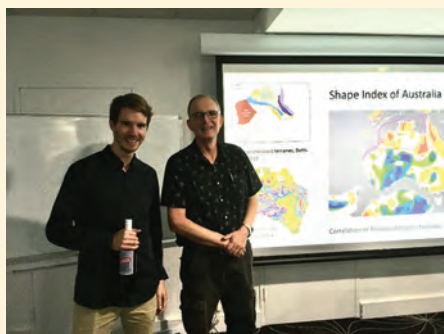


Mike Smith, ASEG Honorary Member, chairing the NSW AGM. Thanks to Mike for his exceptional chairing skills.

Also in February, **Peter Haas** (Institute for Geosciences, Kiel University, Germany) presented a talk entitled "Satellite gravity data as an important tool to decipher the lithospheric architecture of supercontinents". Peter talked us through how he developed a novel inversion, where satellite gravity gradient data is inverted for crustal thickness under

ASEG news

consideration of regional varying density contrasts between crust and mantle. This approach was then applied to the inversion of the Amazonian and West African Craton, which formed the western part of supercontinent Gondwana. Peter introduced the term for the residual gravitational field "palaeo-gravity". Using palaeo-gravity as initial data for the inversion, Peter studied the Moho depth of Western Gondwana ("Palaeo-Moho"). Palaeo-gravity and Palaeo-Moho help to get a more precise view on the anomalies connecting the cratons. Much discussion followed Peter's talk, especially his interpreted map of Australia.



Peter Haas (left) and Mark Lackie (right) enjoying beverages after Peter's presentation. The background shows one of the slides that triggered a lot of discussion.

In March, **Greg Street** (Loupe Geophysics, Perth) presented a talk entitled "Case Studies from Loupe – New Technology in Portable TEM for Near-Surface Measurements". Greg described Loupe, a portable, broadband TEM system, which has been developed for the purpose of measuring the distribution of near-surface electrical conductivity. Greg outlined how the Loupe system is designed to measure primarily in the top 25 metres of the ground. Greg walked us through trial surveys that had been conducted with Loupe in a number of near-surface applications including mineral exploration on surface and underground, geological / regolith mapping, study of groundwater around tailings storage facilities and the mapping of structural features in open-cut mines. Much discussion about the new system followed the talk.

An invitation to attend NSW Branch meetings is extended to interstate and international visitors who happen to be in town at that time. When the situation returns to normal Meetings will generally be held on the third Wednesday of each month from 5:30 pm at Club York.



ASEG NSW president, Mark Lackie (and one of his fun shirts) introducing Greg Street. A big thank you to the GBG Group for their sponsorship, which helps fund the NSW Branch monthly technical meetings.



Greg Street (Loupe Geophysics) presenting case studies from the portable TEM system.

Meetings notices, addresses and relevant contact details can be found at the NSW Branch website. All are welcome.

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

Queensland

The QLD Branch started the year with a talk by in February **Dr Lucy MacGregor**, Chief Technology Officer of Cognitive Geology, titled "Recent advances in multi-physics approaches to characterising the earth". The talk was well attended and sparked an interesting discussion and questions on the integration of different geophysical data types to get a more complete picture of the earth than seismic or others alone.

We plan to hold our Branch AGM in when conditions allow. We are still looking for speakers to fill the 2020 programme. If you have any ideas for a talk please get in touch with the QLD committee. With just over a year until the AEGC in Brisbane, we hope that everyone stays safe and that the current corona virus outbreak won't continue to disrupt everyone's life and work for too long.

Ron Palmer,
qldpresident@aseg.org.au

South Australia & Northern Territory

Hello!

On Tuesday 11 February the SA/NT Branch hosted SEG Honorary Lecturer **Dr Lisa Gavin** from Woodside Energy at the Coopers Alehouse for her talk, "Regional to reservoir stress-induced seismic azimuthal anisotropy". It is always a pleasure hosting SEG Honorary Lecturers, and this talk was enjoyed by 25 attendees and was followed by lively discussion.

On Tuesday 24 March we held our AGM virtually, for the safety of our Members. Thank you to those that 'Zoomed' in- it was great to see you all!

I would like to introduce and welcome our new branch executive, named in the table below. I would also like to thank **Adam Davey** and **Ben Kay** for their fantastic ongoing contributions to the ASEG. Thanks also to all of our Branch members who have made my time as President for the last two years so enjoyable and rewarding.

Role	2019	2020
President	Kate Robertson	Ben Kay
Treasurer	Adam Davey	Samuel Jennings
Secretary	Ben Kay	Carmine Wainman
Northern Territory Rep	Tania Dhu	Tania Dhu

For now face-to-face meetings have been suspended, but we hope to see you soon, in some way or another, and are eager to continue to deliver value to our Members in any way we can. If you have any suggestions, we would love to hear them - send an email to sa-ntpresident@aseg.org.au.

As always, a huge thank you to our sponsors, we are so grateful for your support;

Heathgate Resources, Department for Energy and Mining, Beach Energy, Santos, Terrex Seismic, Geosensor, Minotaur Exploration and Zonge Australia.

Stay safe!

Kate Robertson
 ASEG SA/NT Branch committee member
 (former President)
Kate.Robertson2@sa.gov.au

Vale: Brian R Spies PhD FTSE FRSN (1949 – 2020)



Dr Brian Spies passed away in Sydney on the 8th of February 2020, after a courageous two-year battle with cancer.

Brian was one of Australia's most eminent and visionary research exploration geophysicists, an accomplished national and international science leader, inspiring geoscience innovator, inventor and research collaborator, science mentor and advocate, and a great science educator.

He remained an active geoscience collaborator and advocate for the importance of science in our modern society, with significant late-career contributions in the field of environmental and climate science, until a few months before he died.

Brian's geoscience career and his innovations and contributions to exploration geophysics, particularly as one of the pioneers of Transient Electromagnetics (TEM) as well as his contributions to other areas of science, have been brilliant and transformative.

Brian joined the Australian Society of Exploration Geophysicists (ASEG) in 1970 and gave the strongest support to the Society over five decades including distinguished service as ASEG President in 1999-2000, using his position at that time as Director Cooperative Research Centre for Australian Mineral Exploration Technologies (CRCAMET) and his international expert standing in Transient Electromagnetics to promote Australia's innovations and breakthroughs in the science of mineral exploration geophysics.

Brian joined the Society of Exploration Geophysicists (SEG) in 1972 and was acknowledged for his outstanding service in many capacities, including a term as 1st Vice President (2003-04)

and Secretary-Treasurer (1996-97) with the award of SEG Life Membership in 1996.

Brian was an author of many scholarly papers on exploration geophysics presented in journals and at international conferences through his memberships of the ASEG, SEG, Environmental and Engineering Geophysical Society (EEGS), American Geophysical Union (AGU), Society of Petrophysicists and Well Log Analysts (SPWLA) and European Association of Geoscientists & Engineers (EAGE).

Brian grew up in Sydney, Australia, with a fondness for mineral collecting that surfaced at a young age. In high school he manufactured thin sections of Australian rocks in his father's garage and distributed them to local schools. Brian's high school offered a strong geology component in its science program, and it was here that he was first exposed to geophysics.

Brian gained a BSc from the University of New South Wales in 1971, double-majoring in geology and physics, and

went on to earn a Post-Graduate Diploma in Applied Geophysics from UNSW in 1972, supported by a Graduate Cadetship from the Australian Bureau of Mineral Resources, where he undertook applied research throughout the 1970s with a broad range of geophysical techniques in the Australian outback.

By the mid-1970s, Brian was presenting his leading BMR geophysical field research at conferences and forums and in international journals including:

- Transient Electromagnetic field surveying using an innovative new dual-loop configuration (*Geophysics*, 1975, **44**, 1051-1057),
- Derivation of absolute units in TEM scale modelling (*Geophysics*, 1976, **41**, 1042-1047)
- The TEM method in Australia (*BMR J. Aust. Geol. Geophys*, 1976, **1**, 23-32)
- Absolute electromagnetic scale modelling and its use in interpretation of TEM response (*BMR J. Aust. Geol. Geophys*, 1977, **2**, 89-96)

In 1976, Brian received the first SEG Foundation scholarship given in the



Demonstrating electromagnetic prospecting equipment at BMR Open Day for High Schools, Canberra, Australia.

southern hemisphere. This scholarship, and an Australian Public Service Board award, allowed him to commence his PhD studies at Macquarie University, under the supervision of the late Professor Keeva Vozoff.

In the 1970s the quest was really on across Australia to establish how mineral explorers could apply the latest geophysical exploration technologies – electrical, electromagnetics, magnetics, gravity, radiometrics and seismic to direct discovery of economic metal-rich ore bodies.

The discoveries at this time in New South Wales of the Elura Massive Sulphide Lead-Zinc-Copper Orebody in the northern Cobar region and of the Woodlawn Massive Sulphide Lead-Zinc-Copper Orebody near Goulburn, provided unique opportunities for researchers and practitioners of the latest exploration geophysical methods to quantify the “geophysical signature” of these orebodies and to test, develop and further refine the application of geophysics to uncover new economic metal orebodies.

Brian enthusiastically led the BMR TEM field trials over the Elura and the Woodlawn orebodies and followed with new interpretative scale model studies, presenting and publishing influential findings including:

- Scale model studies of the Elura Deposit (*BMR J. Aust. Geol. Geophys.*, 1980, **5**, 77-85)
- Interpretation and Design of TEM Surveys in Areas of Conductive Overburden (*Bull Aust. Soc. Explor. Geophys.*, **11:4**, 130-139)
- One-loop and two-loop TEM responses of the Elura Deposit, Cobar NSW (*Bull Aust. Soc. Explor. Geophys.*, **11:4**, 140-146)
- Results of experimental and test TEM surveys, Elura Deposit, Cobar NSW (*Bull Aust. Soc. Explor. Geophys.*, **11:4**, 147-152)

This BMR research under Brian’s leadership helped to further establish Transient Electromagnetics as a practical exploration method for metallic ore deposits in Australia’s conductive terrains. Brian is responsible for these and a number of other developments in the TEM technique in Australia, which was transferred to the minerals exploration industry in a campaign of field demonstrations, presentations and publications – TEM is now an indispensable geophysical technique in Australian mineral exploration.



Electromagnetic surveying at the Elura Deposit, NSW Australia

Brian presented much of this work at the 1st ASEG Biennial Conference and Exhibition in Adelaide in 1979, and was awarded the ASEG Best Paper at the Conference.

In 1979, Brian undertook a major international research study, supported by the Australian Government under the Australia-USSR Agreement on Scientific Cooperation, focussed on “use of the electrical methods MT, TEM and IP for petroleum prospecting”. Until that time, few technical details of these techniques were available in Western

countries despite a great interest in them. Brian visited the Ministry of Geology in Moscow and Novosibirsk and the Academy of Sciences in Novosibirsk.

Brian’s seminal paper, “Recent developments in the use of surface electrical methods for oil and gas exploration in the Soviet Union” (*Geophysics*, 1983, **48**, 1102-1112) explained the latest methods, many of them revealed for the first time, and included case-study examples from the Soviet Union.



Schlumberger Doll Field Research TEM survey, North America

Brian completed his doctoral studies at Macquarie University in 1980 and was awarded a PhD for an outstanding Thesis "The application of the transient electromagnetic method in Australian conditions: field examples and model studies", which still has relevance to today's exploration geophysicists.

Brian's international geoscience and leadership roles began in the USA in 1980, when he joined Exploration Data Consultants in Denver as Senior Geophysicist and in 1981, he moved to California to join Electromagnetic Surveys Inc. as Vice President and Director.

In 1984 he joined the ARCO Oil and Gas Research Center in Texas as Senior Principal Research Geophysicist. While at ARCO, he developed a new non-destructive testing technology for oil pipelines. The technique is based on focussed electromagnetic antenna arrays and is capable of measurement of metallic wall thickness to an accuracy of 0.1 mm through variable-thickness insulation and metallic cladding. The method was commercialised by a large multinational engineering organisation and is now used worldwide. In 1989

Brian was awarded ARCO's highest technical award, the Outstanding Technical Achievement Award in Research, for development of the Transient Electromagnetic Probing (TEMP) corrosion detection technique.

In 1990 Brian joined Schlumberger-Doll Research where he led the Deep Electromagnetics research program, involving theoretical and experimental investigations of new borehole electromagnetic and electrical techniques, with an emphasis on multi-scale measurements of petrophysical and reservoir properties. Fundamental to these studies was the integration of geophysical, geological and engineering data, and large-scale computer modelling of complex, realistic geological sequences. During his time in the US, Brian also took on university Adjunct Professor teaching and post-grad student supervision.

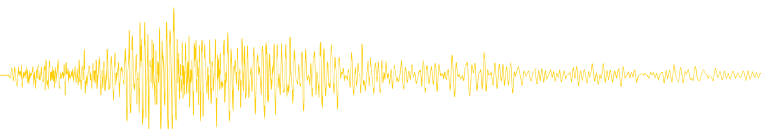
He led the team that developed a new generation of deep-imaging electromagnetic tools for the oil well environment, based on a three-component digital cross-well system capable of generating accurate 2-D images of reservoirs between boreholes separated by several hundred metres, operating at depths to 3000 m and at temperatures to 125 °C. He also helped develop the next generation of monitoring technology using instrumented oilfields.

During the period of Brian's commercial research in North America, he authored 11 patents covering some highly innovative applications of transient electromagnetics including:

- Methods and apparatus for dynamically estimating the location of



Ground TEM survey using SIROTEM, Alaska USA



- an oil-water interface in a petroleum reservoir
- Method of reducing noise in electromagnetic geophysical exploration data
- Transient electromagnetic method for directly detecting corrosion on conductive containers
- Method of reducing impulsive noise in electromagnetic data
- Method and apparatus for cancelling powerline noise in geophysical exploration
- Method of reducing noise in a borehole telemetry system

In 1996, Brian returned to Australia to take over from Dr Andy Green as Director of the Cooperative Research Centre for Australian Mineral Exploration Technologies (CRC AMET), appointed as part of the Corporate Executive of CSIRO Exploration and Mining.

CRC AMET was a collaborative joint venture of seven government, academic and industry partners, developing a new generation of geophysical exploration technologies for Australian conditions of deep and varied weathered cover. The research programs involved all aspects of airborne and ground electromagnetic exploration, instrumentation, processing, modelling and geological interpretation.

Brian assumed the position of Director in Year 4 of the CRC AMET, and successfully integrated the research programs and participants to achieve the CRC objectives, particularly commercialisation and knowledge transfer. Brian's leadership of the research partnerships delivered a new generation of broadband high-resolution airborne electromagnetic exploration techniques optimised for Australian conditions.

Following the successful delivery of the outcomes from the CRC AMET, Brian was appointed in 2000 as the Director Physics Division of the Australian Nuclear Science Technology Organisation (ANSTO).

In 2003, Brian took on the role of Chief Research Scientist, CSIRO Exploration and Mining, with major contributions to Australia's strategy and policy for the "Mineral Exploration Action Agenda", announced by the then Department of Industry, Tourism and Resources. Brian was co-leader for targeted R&D funding for mineral exploration and lead writer for the education and training programs, including increased support for science and technology in secondary and tertiary education.

Brian's leadership positions in ANSTO and then CSIRO Exploration & Mining, provided the platforms for his passion for advocacy of great science influencing good government policy outcomes.

A great example of Brian's contribution to leading strong science evidence, informing national science debate and influencing good policy outcomes was his co-leadership of the Project Review Team on "Review of Salinity Mapping Methods in the Australian Context", funded by Environment Australia and Agriculture Forestry and Fisheries Australia (AFFA) to evaluate the range of methods, including airborne and ground EM near surface systems, for mapping the extent and severity of dryland salinity – an important roadmap delivered to the National Ministerial Council of the time.

In 2004 Brian was appointed Science Manager and later Principal Scientist, Sustainability and Climate Change, in the Sydney Catchment Authority. It was during his time in SCA that Brian began working in climate science.

In Brian's later career he was highly respected as a science advocate for the broader integration of science-technology-engineering and mathematics in modern research, education and formulation of Government policy. His co-authorship in 2012 of a major report supported by the Australian Research Council under the auspices of Australian Academy of Technological Sciences and Engineering – Dr Brian Spies and Professor Graeme Dandy "Sustainable Water Management – Securing Australia's Future in a Green Economy" – produced a visionary roadmap for Australia's future water management.

During this period Brian also made huge contributions through the Australian Academy of Technology and Engineering (ATSE) and was elected as Fellow of ATSE (FTSE) in 1998. In 2003 he was awarded the Australian Centenary Medal for his contributions to geoscience. Brian also made substantial science contributions in environmental and climate science through the Royal Society of New South Wales and was elected as Fellow (FRSN) in 2016.

Above all else, Brian's most important legacy to geoscience and to successful exploration and discovery has been through his forty eminent, if not transformative, and well-cited

scholarly papers in refereed geoscience journals, many book chapters and over thirty other papers and articles in geoscience publications and conference proceedings. There are a number of major reference works and important collaborative contributions in Brian's journal papers and books including:

- Oristaglio, M. L. and Spies, B. R. (Eds), 1999, *Three-Dimensional Electromagnetics: Soc. Explor. Geophys.*, Tulsa, 709 pp.
- Spies, B. R., 1998, Earth conductivity measurements, in Bud, R. and Warner, D. (Eds.), *Instruments of Science: An Historical Encyclopedia*: Science Museum, London, and Smithsonian Institution, Garland Publishing, 199-201.
- Spies, B. R. and Macnae, J.C., 1998, *Electromagnetic Trends— Spatial, Temporal and Economic* (Invited paper), in Gubins, A. G., Ed., *Proceedings of Exploration 97: Fourth Decennial International Conference on Mineral Exploration*, 489-496.
- Spies, B. R., and Frischknecht, F. C., 1990, Electromagnetic sounding, in M. N. Nabighian (Ed), *Electromagnetic methods in applied geophysics*, **2** Soc. Explor. Geophys., 285-425.
- Spies, B. R., Hone, I. G. and Williams, J. W., 1981, Transient electromagnetic test surveys and scale model studies of the Woodlawn orebody with the MPPO-1 equipment, in *Geophysical studies of the Woodlawn orebody, New South Wales, Australia*: Pergamon Press.
- Wilt, M, L. Spies, B. R., and Alumbaugh, D., 1999, Measurement of surface and borehole electromagnetic fields in quasi two- and three-dimensional geology, in Oristaglio, M. L., and Spies, B. R., (Eds), *Three-Dimensional Electromagnetics: Soc. Explor. Geophys.*, Tulsa.
- Frischnecht, F.C., Labson, V.F., Spies, B. R. and Anderson, W.L., 1990, Profiling methods using small sources, in M.N.Nabighian (Ed) *Electromagnetic methods in applied geophysics:2*, Soc. Explor. Geophys., 105-270.
- Macnae, J. C., and Spies, B. R., 1988, Accomplishments of wide-band, high-power EM, in G. D. Garland (Ed), *Proceedings of Exploration '87*: Ontario Geological Survey, Special Volume 3, 109-121.

In addition, Brian's inspiring initiatives and leadership in establishing over 30 national and international workshops at the fore-front of research and the application in geophysical exploration technology, environmental geophysics, reservoir characterisation and trends

in science management, has produced ground-breaking conference proceedings and workshop publications that now form a core part of the industry's reference works on electrical and electromagnetic exploration geophysics.

Brian initiated and organised many specialist international workshops and conferences including:

- *Advances in Geoelectromagnetism* for EAGE, 1999;
- *3-D Visualisation for Mineral Exploration Geophysics* for ASEG, 1998;
- *Future Trends in Mineral Exploration* for ASEG, 1997; and
- *Environmental Geophysics* for SEG, 1993

Brian was also Technical Program Co-Chair and Organiser of the ASEG-SEG Joint Conference 1988 and the SEG Annual Meetings 1986, 1989, 1996.

Brian initiated, organised and chaired the AEM 1998, in Sydney, also overseeing the compilation of the proceedings – a great reference work and in hindsight, a visionary early initiative that continues to bring together the latest and best international research and technical innovations in airborne electromagnetic prospecting:

- Spies, B., Fitterman, D., Holladay, S., and Liu, G.(Eds), 1998, Proceedings of the

International Conference on Airborne Electromagnetics (AEM 98): *Exploration Geophysics*, 29(1&2) 262pp

Throughout his career Brian has earned many prestigious awards, working in research and management in the resources and energy sectors in Australia and North America and across industry, academia and government sectors. He has also held numerous eminent board and senior management positions.

Brian was particularly proud of the SEG Award of Life Membership – an excerpt from the Citation for that Award follows ...

To his colleagues, Brian's name brings to mind words like internationalism, collaboration, communication, hard work, commitment, and, most of all, zeal.

True leaders are zealots with the passion to pursue a vision with unwavering purpose, with the commitment to invest untold hours when it seems no one else cares, and with a clarity of vision that later causes the rest of us to wonder why it took us so long to jump on the bandwagon.

Brian has been zealous in leading SEG to become a truly international society, to chart new directions with its publications, and most recently to embrace the age of electronic communications.

Yet he is a zealot with humanity and humility; he approaches every job with an outrageous sense of humour and enthusiasm, and it is more important to him to achieve the vision than to get credit.

Brian leaves an extraordinary legacy of achievement beyond the science of exploration geophysics. His Australian and international science partners, friends and colleagues all speak of him with the highest praise and with reverence for his achievements and contributions and his inclusiveness and openness sharing new ideas and knowledge.

It's been such a privilege to share friendship, enthusiasm and passion for our science with Brian.

Our deepest sympathies are with Brian's family and with all of Brian's close friends.

Dr Ted Tyne
ASEG President 2019-20
president@aseg.org.au

With appreciation for contributions and advice:

Roger Henderson, Chair ASEG History Committee

Dr David Annetts ASEG President 2020-21

Dr John Baxter FTSE Hon FIEAust FSAEA



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Geoscience Australia: News

Geoscience Australia, in collaboration with the Geological Surveys of Western Australia, South Australia, Northern Territory, Queensland, New South Wales, Victoria and Tasmania are soon to release several substantial airborne geophysical datasets, including the first tranches of AusAEM2, inverted data from the Cobar AEM survey, and new high resolution airborne magnetic and radiometric datasets over central NT and South Australia - just to name a few. Outlined in Figure 1, these datasets provide leading-edge continental pre-competitive datasets of ever-increasing quality and type. For March 2020, some highlights include:

Updated national gravity compilation

As reported last month, Geoscience Australia is currently updating the national gravity compilation. The new free-air compilation, combining ground, marine, satellite and airborne data for the first time into seamless stitch, will be joined by the Bouguer-reduced dataset in early May. Both grids will be available for download via Geoscience Australia's electronic catalogue: <https://ecat.ga.gov.au/geonetwork>.

AusAEM1 – additional product release

While originally released in early 2019 through GA's e-catalogue and EFTF portal, the AusAEM1 record has now been updated to include all of the 1500 line km of infill flying funded by private exploration companies. The package contains a) survey logistics and processing report, b) final processed electromagnetic, magnetic and elevation point located line data, c) processed electromagnetic, magnetic and elevation grids, d) point located conductivity estimates from EM Flow® and e) multi-plots of line data and conductivity sections. All of the products were produced by the contractor CGG Aviation (Australia) Pty Ltd.

The package also includes inversion results generated using GA's sample-by sample layered-earth (1D) inversion, a deterministic regularized gradient-based algorithm, which we call GALEISBS (Brodie, 2016). The process simultaneously inverts the vector sum of measured X-and Z-component data to produce a single smooth layered conductivity model. More details can be found in Brodie, 2016 and Ley-Cooper *et al*, 2019.

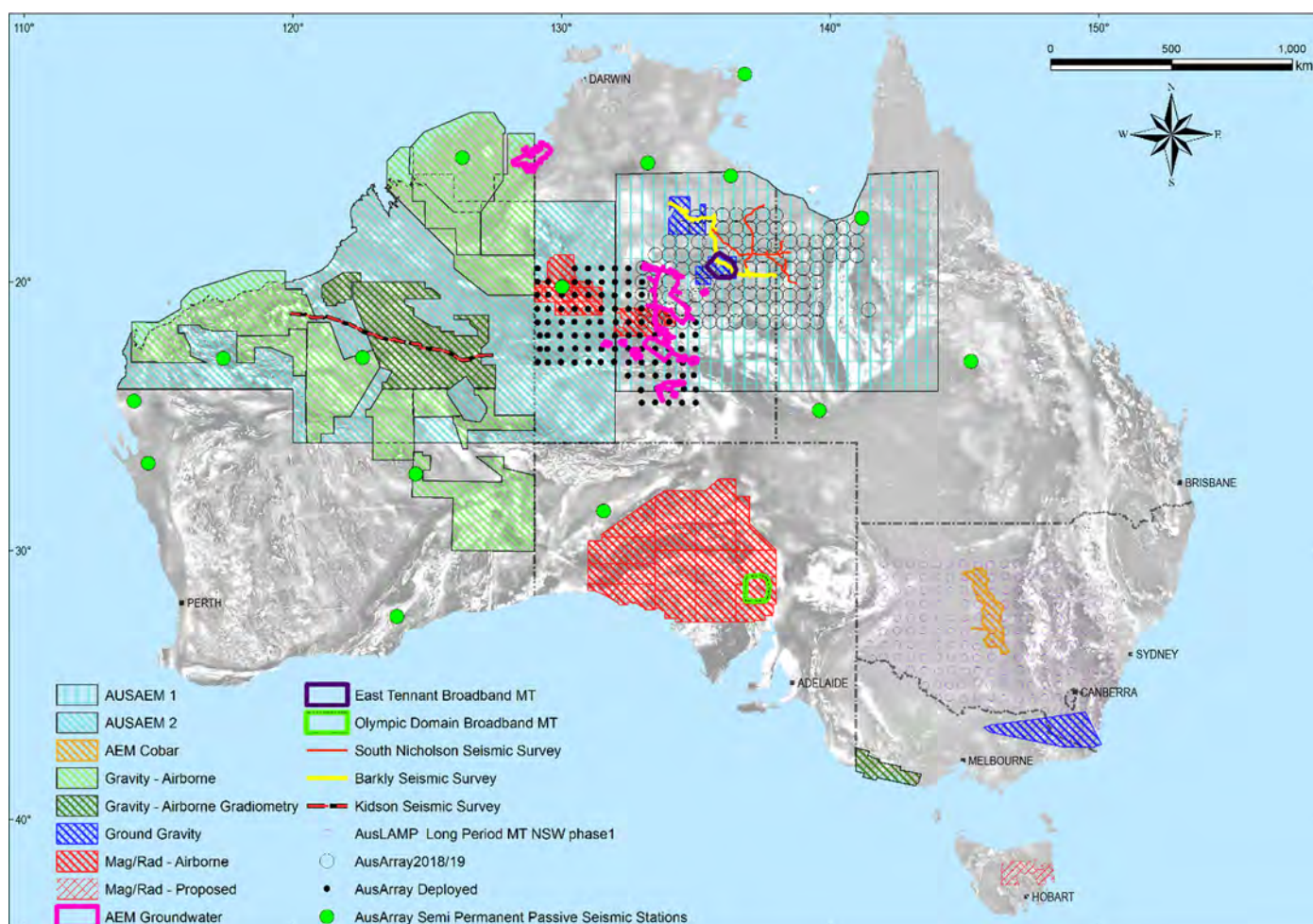


Figure 1. 2018-2020 geophysical surveys – completed, in progress or planned by Geoscience Australia in collaboration with State and Territory agencies.

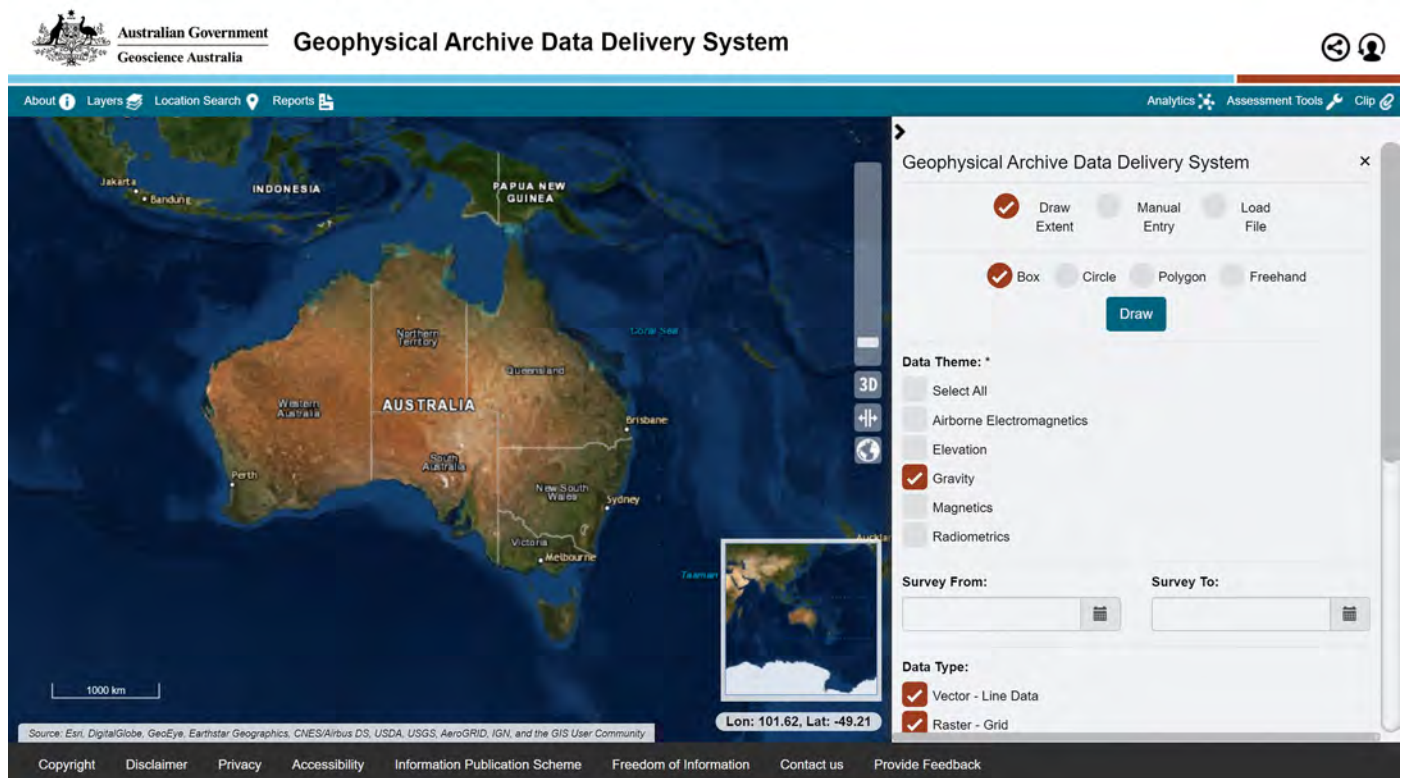


Figure 2. Screenshot of the new GADDS front end – delivered through the EFTF portal: <https://portal.ga.gov.au/>.

The AusAEM Year 1 survey was flown from 4 August 2017 – 31 July 2018, using the 25 Hz TEMPEST® airborne electromagnetic (AEM) system owned by CGG Aviation (Australia) Pty Ltd under contract to Geoscience Australia. It acquired with a 20-kilometre line separation and collected over 60 000 line kilometres of data in total. The survey area covers the Newcastle Waters and Alice Springs 1:1 Million map sheets in the Northern Territory, plus the Normanton and Cloncurry 1:1 Million map sheets in Queensland.

Geoscience Australia's GADDS

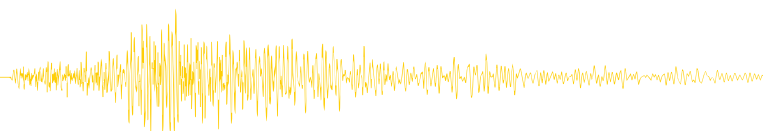
GA's new Geophysical Archive Data Delivery System (GADDS) is on track for beta release before the end of June 2020. Delivered through the Exploring for the Future (EFTF) portal, the GIS interface will make it much easier to select, clip, ship and 'zip' located and point data from GA's electronic catalogue. Beginning with magnetics, radiometric and gravity, the delivery

service will be expanded to cater for airborne EM, airborne gravity/gradiometry and other n-dimensional regular and irregular-spaced datasets (Figure 2).

For the moment, GADDS will continue to faithfully deliver located datasets for surveys archived before June 2019. For located survey data acquired afterwards, please contact GA's client services (clientservices@ga.gov.au) or Mike Barlow on mike.barlow@ga.gov.au.

References

- Brodie, R.C., GA-AEM Source Code Repository, 2016, <https://github.com/GeoscienceAustralia/gaaem>
- Ley-Cooper, A. Y., R. C. Brodie, and M. Richardson, 2019. "AusAEM: Australia's Airborne Electromagnetic Continental-Scale Acquisition Program". *Exploration Geophysics*, 51, 1-10, (doi.10.1080/08123985.2019.1694393).



News

Update on geophysical survey progress from Geoscience Australia and the Geological Surveys of Western Australia, South Australia, Northern Territory, Queensland, New South Wales, Victoria and Tasmania (information current on 18 March 2020).

Further information about these surveys is available from Mike Barlow Mike.Barlow@ga.gov.au (02) 6249 9275 or Marina Costelloe Marina.Costelloe@ga.gov.au (02) 6249 9347.

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	TBA	~Apr 2020	Up to an estimated 66 000	200 m 60 m N-S or E-W	11 000	End of 2020	TBA	TBA	Agreement between GA and MRT is in place to commence work FY 21.
Gawler Craton	GSSA	GA	Various	2017	1 670 000	200 m, various orientations depending on structure	294 000	26 Jun 2019	Aug 2019	http://www.energymining.sa.gov.au/minerals/geoscience/pace_copper/gawler_craton_airborne_survey	For release in a variety of filtered products, Apr 2020
Tanami	NTGS	GA	Thomson Aviation	14 Jul 2018	275 216	100/200 m 60 m N-S/E-W	48 267	2 Dec 2018	Jun 2019	195: Aug 2018 p. 16	Released
Mt Peake	NTGS	GA	MAGSPEC	10 Jul 2019	136 576	200 m N-S	24 748	Oct 2019	Feb 2020	Aug 2019	Released

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
Kidson Sub-basin	GSWA	GA	CGG Aviation	14 Jul 2017	72 933	2500 m	155 000	3 May 2018	15 Oct 2018	The survey area covers the Anketell, Joanna Spring, Dummer, Paterson Range, Sahara, Percival, Helena, Rudall, Tabletop, Ural, Wilson, Runton, Morris and Ryan 1:250 k standard map sheet areas	Expected release before the end of Jun 2020
Little Sandy Desert W and E Blocks	GSWA	GA	Sander Geophysics	W Block: 27 Apr 2018 E Block: 18 Jul 2018	52 090	2500 m	129 400	W Block: 3 Jun 2018 E Block: 2 Sep 2018	Received by Jul 2019	195: Aug 2018 p. 17	Expected release before the end of Jun 2020
Kimberley Basin	GSWA	GA	Sander Geophysics	4 Jun 2018	61 960	2500 m	153 400	15 Jul 2018	Received by Jul 2019	195: Aug 2018 p. 17	Expected release before the end of Jun 2020
Warburton-Great Victoria Desert	GSWA	GA	Sander Geophysics	Warb: 14 Jul 2018 GVD: 27 Jul 2018	62 500	2500 m	153 300	Warb: 31 Jul 2018 GVD: 3 Oct 2018	Received by Jul 2019	195: Aug 2018 p. 17	Expected release before the end of Jun 2020

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

Survey name	Client	Project management	Contractor	Start survey	Line km/ no. of stations	Line spacing/ station spacing	Area (km ²)	End survey	Final data to GA	Locality diagram (Preview)	GADDs release
Pilbara	GSWA	GA	Sander Geophysics	23 Apr 2019	69 019	2500 m	170 041	18 Jun 2019	Final data received Aug 2019	The survey area is in the Pilbara region in the northwest of Western Australia. Data acquired will be compiled into an update of the gravity anomaly map of Western Australia	Expected release before the end of Jun 2020
SE Lachlan	GSNSW/ GSV	GA	Atlas Geophysics	May 2019	303.5 km with 762 stations	3 regional traverses	Traverses	Jun 2019	Jul 2019	TBA	Set for incorporation into the national database by Jun 2020
TISA	NTGS	GA	Atlas Geophysics	2 Jul 2019	5719	2 km × 2 km grid	31 285	Sep 2019	Nov 2019	See Figure 1 in previous section (GA News)	East Tennant portion released. Residual for release May 2020

TBA, to be advised

Table 3. Airborne electromagnetic surveys

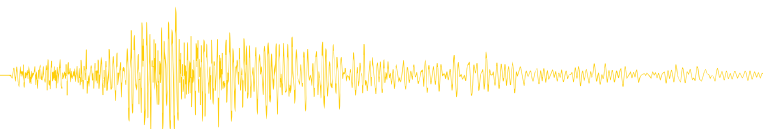
Survey name	Client	Project management	Contractor	Start flying	Line km	Spacing AGL Dir	Area (km ²)	End flying	Final data to GA	Locality diagram (Preview)	GADDs release
East Kimberley	GA	GA	SkyTEM Australia	26 May 2017	13 723	Variable	N/A	24 Aug 2017	Nov 2017	TBA	eCAT release http://pid.geoscience.gov.au/dataset/ga/130762
Surat-Galilee Basins QLD	GA	GA	SkyTEM Australia	2 Jul 2017	4627	Variable	Traverses	23 Jul 2017	Nov 2017	188: Jun 2017 p. 21	Not for release until Jun 2020
Stuart Corridor, NT	GA	GA	SkyTEM Australia	6 Jul 2017	9832	Variable	Traverses	12 Aug 2017	Nov 2017	188: Jun 2017 p. 22	eCAT release http://pid.geoscience.gov.au/dataset/ga/131098
AusAEM2, NT-WA	GA	GA	CGG Tempest	May 2019	73 005 with areas of industry infill	20 km	1 074 500	~ May 2020	~ Jun 2020	201: Aug 2019 p. 16	72% complete. Acquisition suspended. Acquired portion will be released in Jun 2020
Cobar	GSNSW	GA	NRG Xcite	30 Sep 2019	6701 with areas of industry infill	2.5 and 5 km	19 145	19 Oct 2019	Jan 2020	201: Aug 2019 p. 17	TBA
Howard East	NTGS	GA	SkyTEM Australia	23 Jul 2017	2073.6	Variable to 100 m	Traverses	8 Aug 2017	Feb 2018	TBA	eCAT release http://pid.geoscience.gov.au/dataset/ga/132400

TBA, to be advised

Table 4. Magnetotelluric (MT) surveys

Location	State	Survey name	Total number of MT stations deployed	Spacing	Technique	Comments
Northern Australia	Qld/NT	Exploring for the Future – AusLAMP	367 stations deployed in 2018-19	50 km	Long period MT	The survey covers areas of NT and Qld. <i>Ongoing</i>
AusLAMP NSW	NSW	AusLAMP NSW	270 stations deployed in 2018-19	50 km	Long period MT	Covering the state of NSW. <i>Ongoing</i>
Southeast Lachlan	Vic/ NSW	SE Lachlan	Deployment planned to commence in Oct 2020	~4 km	AMT and BBMT	~160 sites in the Southeast Lachlan
AusLAMP TAS	TAS	King Island MT	4 sites completed	<20 km	Long period MT	Covering King Island. Acquisition completed.
East Tennant	NT	East Tennant MT	131 sites completed	1.5 – 10 km	AMT and BBMT	Released
Cloncurry	QLD	Cloncurry Extension	200 stations have been acquired	2 km	AMT and BBMT	Approximately 500 sites planned in the northern Cloncurry. Data acquisition will be restarting in late Mar 2020.
Spencer Gulf GA/GSSA/ UofA/AuScope	SA	Offshore marine MT	12 stations completed	10 km	BBMT	This is a pilot project for marine MT survey

TBA, to be advised


Table 5. Seismic reflection surveys

Location	State	Survey name	Line km	Geophone interval	VP/SP interval	Record length	Technique	Comments
South East Lachlan	Vic/NSW	SE Lachlan	629	10 m	40 m	20 s	2D - Deep crustal seismic reflection	This survey covers the Southeast Lachlan Orogen crossing the Victorian-NSW border. Data acquisition was completed in Apr 2018. Raw data and processed seismic data has been released and are available via Geoscience Australia and State Geological Surveys.
Kidson	WA	Kidson Sub-basin	872	20 m	40 m	20 s	2D - Deep crustal seismic reflection	Within the Kidson Sub-basin of the Canning Basin extending across the Paterson Orogen and onto the eastern margin of the Pilbara Craton. The survey completed acquisition on 8 Aug 2018. Data released in May 2019.
Barkly/Camooweal	NT	Barkly sub-basin	812	10 m	30 m	20 s	2D - Deep crustal seismic reflection	Acquisition of 2D land reflection seismic data to image basin and basement structure in the Barkly region of the Northern Territory. Data acquisition was completed in Nov 2019. The data is expected to be released first half of 2020.

Table 6. Passive seismic surveys

Location	Client	State	Survey name	Total number of stations deployed	Spacing	Technique	Comments
Northern Australia	GA	Qld/NT	AusArray Phase 2	About 135 broad-band seismic stations	50 km	Broad-band 1 year observations	The survey covers the area between Tanami - Tennant Creek -Uluru and West Australian Border. The first public release of transportable array data is expected by end 2019. See location map in in <i>Preview 201: Aug 2019</i> p. 16
Northern Australia	GA	QLD/WA	AusArray	3 high-sensitivity broad-band seismic stations installed in Oct 2019	~1000 km	Broad-band 4 years observations	Semi-permanent seismic stations provide a backbone for movable deployments and complement the Australian National Seismological Network (ANSN) operated by Geoscience Australia, ensuring continuity of seismic data for lithospheric imaging and quality control. Associated data can be accessed through www.iris.edu

The ASEG in social media

The ASEG has just joined Instagram https://www.instagram.com/aseg_news/ – so go on, give us a follow! We'd love to share your photos too, so please email Kate Robertson at communications@aseg.org.au if you have any images you would like featured.

We know not everyone is on Instagram, but you can also find us on a variety of other social media platforms too! We share relevant geoscience articles, events, opportunities and lots more.

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

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

LinkedIn group: <https://www.linkedin.com/groups/4337055/>

Twitter: https://twitter.com/ASEG_news

Youtube: <https://www.youtube.com/channel/UC-dAJx8bXrX5BEudOQp4ThA>

Geological Survey of Western Australia: AusAEM20 - WA project

The Department of Mines, Industry Regulation and Safety's (DMIRS) Geological Survey Division and Geoscience Australia (GA) have recently entered into a new National Collaboration Framework Agreement for the Western Australian component of the Australian 20 km Airborne Electromagnetic Survey Objective (AusAEM20).

AusAEM20 is a collaborative, national goal of the Commonwealth, State and Territory geological survey agencies to acquire airborne electromagnetic (AEM) data at 20 km or closer line spacing across the Australian continent. It is a successor to the 2017–20 Geoscience Australia Exploring for the Future (EFTF) AusAEM Project, which, on completion, will have covered a substantial part of northern Australia. The AusAEM20 – WA Project, as the Western Australian agreement is referred to, will complete the 20 km AEM coverage of those parts of Western Australia that have not been surveyed as part of Year 2 of EFTF AusAEM (Figure 1).

We anticipate that acquisition of the 65 000 km of data that will be needed for this coverage will take place over the next two to three years.

GA's AusAEM EFTF surveys have demonstrated that, even at this wide line spacing, AEM data are coherent at very broad reconnaissance scales (Figure 2) and may be used to:

- determine trends in regolith thickness
- map regional variations in bedrock conductivity, within the depth of penetration of the system
- set context for and guide mineral exploration project generation by industry
- improve targeting for water resources definition
- provide input for other land-use applications in other industry sectors and land-use agencies.

However, if tendered prices are suitably attractive and if adequate funding is available, DMIRS is considering data acquisition at smaller line spacing in particular areas of interest.

For more information, please contact geophysics@dmirs.wa.gov.au.

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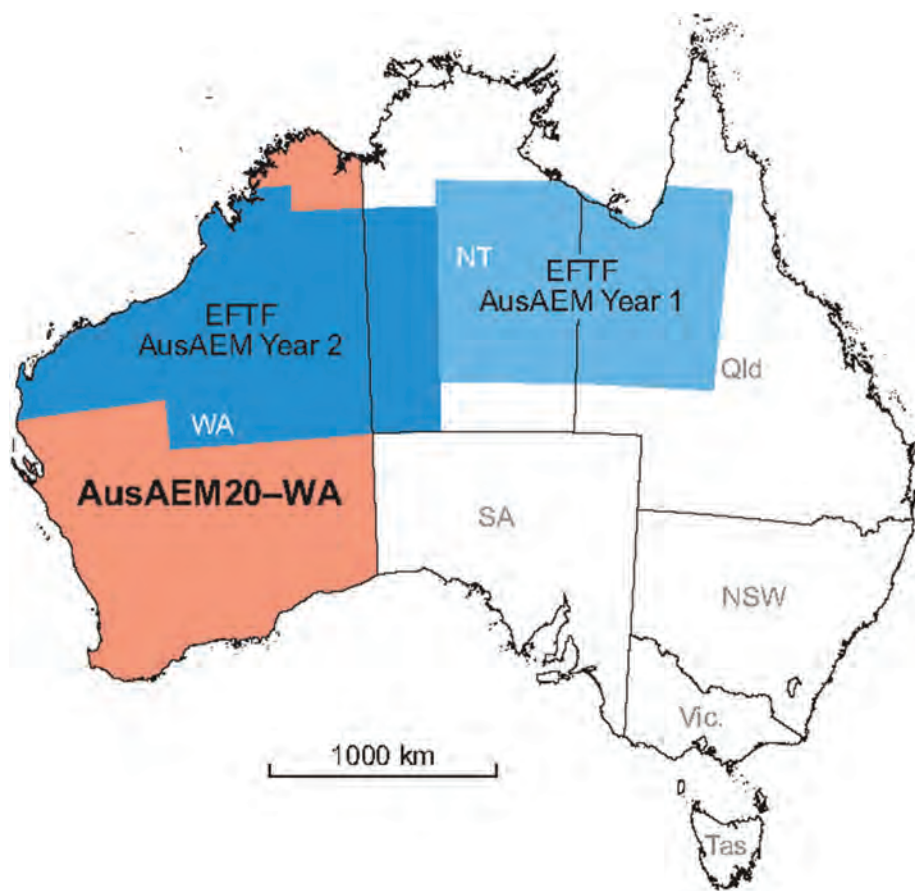


Figure 1. Location of AusAEM20-WA survey areas.

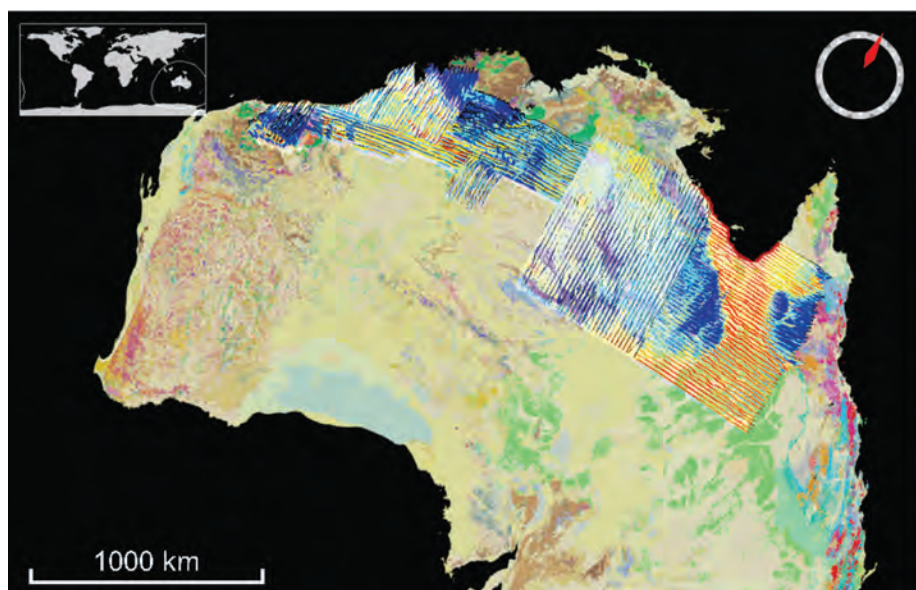


Figure 2. AusAEM profiles from 2018 and 2019 surveys (image courtesy of Geoscience Australia).

Geological Survey of South Australia: The GCAS reaches another major milestone – all survey data and value-added data packages delivered!

The 1.6 million line-kilometre Gawler Craton Airborne Survey (GCAS) began in 2017, and has been systematically delivering new high quality magnetic, radiometric and elevation data from its 16 survey regions as data acquisition and processing were completed over the past two years. February 2020 marked a significant milestone in the life of the program with the release of the final survey data package (Region 5, Streaky Bay) and on 2 March 2020 the final value-added data packages and magnetic source depth models were released.

GCAS data were captured using 200 m line spacing; half the line spacing of the previous 400 m regional data coverage. The 200 m line spacing ensures gridded data products offer a higher resolution (four times the resolution of the previous 400 m line spaced regional geophysical data) and more consistent mapping of the radiometric and magnetic field than is available from the previous multi-survey coverage. The advantages of the new survey data are clear on examination of the

total magnetic intensity (TMI) data (Figure 1), but it is on enhancement of that TMI data that the advantages are more noticeably articulated. Many of the image enhancements that are routinely performed to enhance geological interpretation are of limited application to the previous TMI data across the area because of insufficiencies and imperfections in that data together with abrupt contrasts on passing between surveys of different line spacing, flying height or flight-line orientation. The advantage of consistency and close line spacing also supports higher resolution and more confident source depth mapping from the magnetic field data (Foss *et al*, 2018). The result is an internally consistent set of geophysical datasets, creating image products that will merge seamlessly to provide high quality geological information over the Gawler Craton, South Australia's premier mineral producing region.

The Geological Survey of SA and Geoscience Australia GCAS team

has worked closely with four survey acquisition contractors engaged during the life of the acquisition and processing to ensure that rigorous data standards established nationally through Geoscience Australia and Australian state geological surveys were achieved. A number of survey specifications updated for GCAS have become the new standard, in line with technological improvements in acquisition equipment and platforms.

The Gawler Craton Airborne Survey Community Information webpage

The GCAS Community Information webpage is a dedicated resource developed to provide near-real-time information to landholders and stakeholders. It has been a valuable resource using an embedded GIS map service to show where aircraft were working during the acquisition phase of the survey; provide answers to frequently asked questions and act as a one-stop-shop for the GCAS data. The webpage continues in its capacity to deliver the

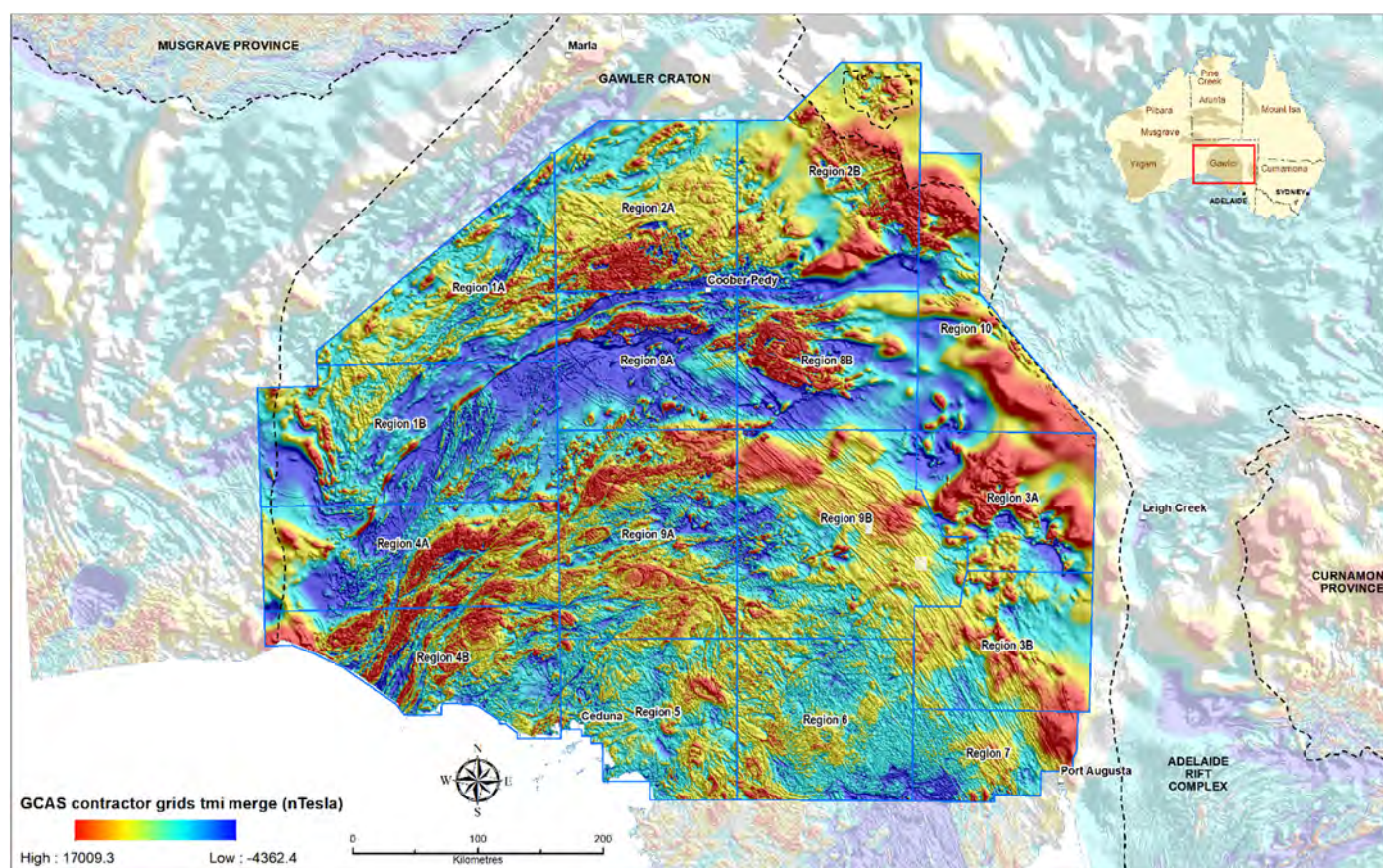


Figure 1. A preliminary total magnetic intensity (TMI) grid merge from the 16 GCAS regions, all now available online, via SARIG and the GCAS web page.

GCAS data and information on the project. A subscription service has been useful in providing subscribers with email updates when survey acquisition commences, completes or when new data is made available. The web map also has direct links to all data downloads and contact information for survey contractors.

Available data

The primary GCAS data releases consist of the deliverables from the survey contractors, which have been rigorously quality controlled by the Geological Survey of South Australia, in partnership with Geoscience Australia. These deliverables include:

- Final located data: magnetic, radiometric and elevation data.
- Gridded magnetic images: TMI, RTP TMI, RTP TMI 1VD in geodetic and projected coordinate systems
- Gridded radiometric images: Dose, Uranium, Thorium, Potassium, Ternary (RGB) with NASVD and no NASVD, in projected and geodetic coordinate systems
- Gridded radar and laser altimeter derived elevation: in geodetic and projected coordinate systems

Value-added data package releases

A major initiative to extend the GCAS body of work has been through a collaborative effort with CSIRO. Clive Foss from CSIRO, in partnership with GSSA has produced a series of enhanced geophysical imagery, magnetic source depth models and reports using the GCAS TMI data, complemented by regional gravity data. These collections of images and digital data products have been generated to facilitate geological interpretation. The products are not themselves interpretive, but provide more direct access to interpretation than the directly measured data. These products, and in particular the magnetic source depth estimates (Figure 2), are designed to provide a 'live' resource which can be progressively upgraded rather than simply replaced as further studies are undertaken in the area, the depth solution database is added to, or new drillholes are reported (Foss, *et al*, 2018).

Where to get the data

Mineral explorers, academia and community stakeholders have

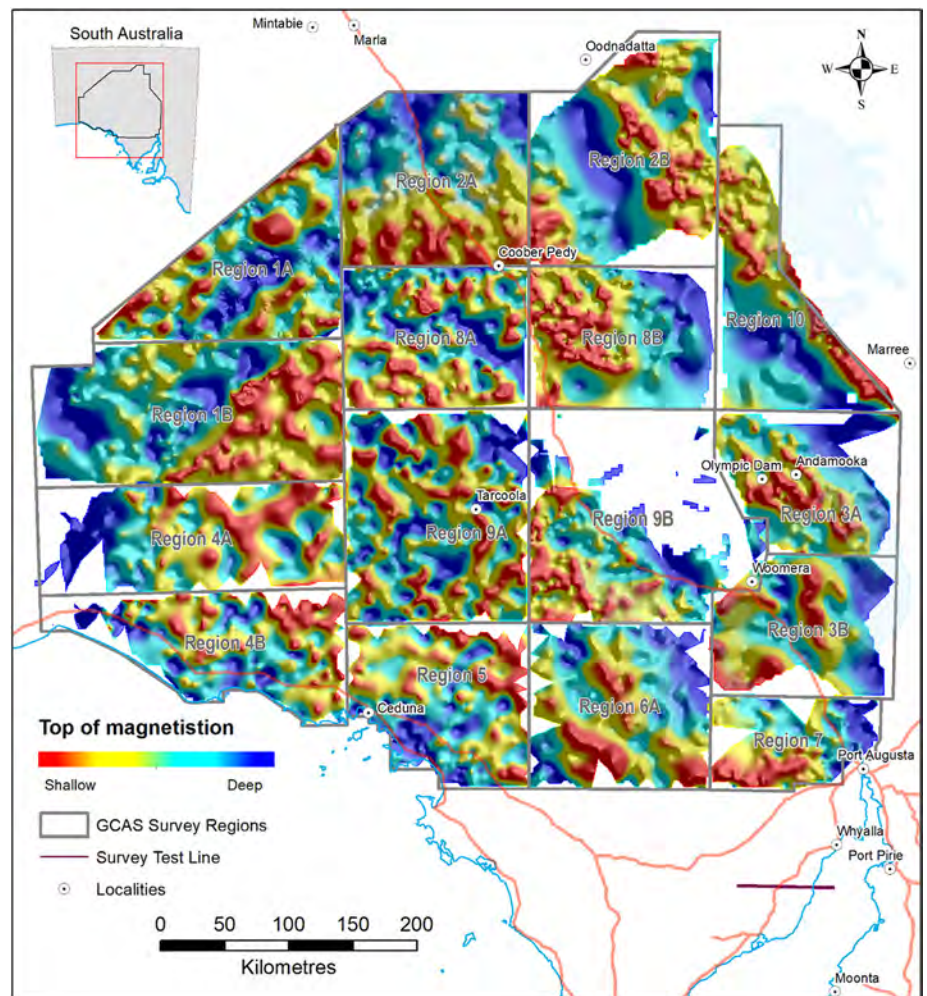
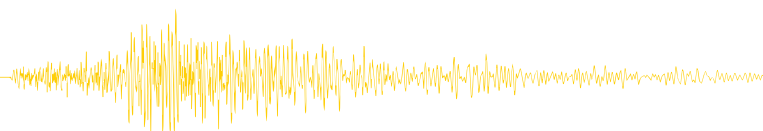


Figure 2. Elevation of magnetic source, interpolated from 4627 individually modelled magnetic source solutions, now available through the enhanced data packages produced in collaboration with CSIRO.

unfettered access to the highest quality magnetic, radiometric, and elevation data ever acquired by the Government of South Australia. There are multiple ways that the public can get the data, beginning with SARIG, where the gridded GCAS data can be viewed on screen and downloaded. From the SARIG interface links to data packages which contain the full set of deliverables listed above, for each GCAS block can be downloaded. SARIG's advanced geophysical search capability can be used to download portions of the GCAS located data or grids, plus SARIG's new airborne surveys time-slice tool provides links to direct download of the data packages. As indicated above, links to the data packages are also available via the GCAS web page. Through the use of cloud technology, these data packages are now being made available through Amazon Web Services (S3), ensuring high reliability and speed of downloads.

Next steps for the GCAS Project

The GCAS team are now preparing to merge the individual GCAS grids into sets of continuous surfaces covering the entire GCAS project area. This will involve careful re-gridding of the individual survey regions using a single, consistent set of gridding parameters with careful attention paid to the maintaining grid co-nodularity across the region. This eliminates resampling during processing to ensure an end product with minimal effects introduced by processing, which may affect the final product. This is a well understood and straightforward process for TMI and elevation grid merging but radiometric grid merging is somewhat more complicated, due to the latter requiring both shifting and rescaling in order to achieve a robust merged product. To improve the radiometric merge process, data from the Whyalla test lines (flown as part of the GCAS to enable a direct comparison of acquired data over the



same set of seven flight lines), will be used to generate scaling coefficients using the average radioelement concentrations from each aircraft to scale the data to a set of reference survey concentrations (one of the Whyalla concentration sets). This novel procedure will remove the requirement to scale all surveys to the national reference dataset – only a shift will be required to perform the final grid merge.

GCAS Final Report

A final project report will be released that encapsulates all of the activities,

data and learnings from GCAS. This report is expected to be complete in 2020.

Reference

Foss C., G. Gouthas, A. Fabris, M. Werner, L. Katona, M. Hutchens, and G. Reed. 2018. "Gawler Craton Airborne Geophysical Survey Region 3B, Torrens – Enhanced Geophysical Imagery and Magnetic Source Depth Models", Report Book 2018/00038. Department for Energy and Mining, South Australia, Adelaide.

Acknowledgements

The GCAS project team gratefully acknowledges the participation of Geoscience Australia, CSIRO and the airborne geophysics suppliers and contractors to the GCAS, including MagSpec Airborne Surveys Pty Ltd, Sander Geophysics, Thomson Aviation Airborne Geophysical and Survey, GPX Surveys, Baigent Geosciences and Minty Geophysics.

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Update from the lithospheric architecture team

Kate Robertson returned from an extended visit to the United States in February. A travel grant from the 34th IGC Travel Grant Scheme along with internal funding from the Geological Survey of South Australia (GSSA) made this trip possible. During her stay, Kate visited the SCRIPPS Institute of Oceanography in San Diego, to discuss future plans with the marine MT data acquired in November 2019 across the Spencer Gulf, South Australia. Kate then attended the AGU Fall Workshop in San Francisco to present some AusLAMP models across the Delamerian Orogen, a collaborative geophysical modelling project with Geoscience Australia for the MinEx drilling project in SA.

Kate spent most of her time at the Lamont Doherty Earth Observatory (LDEO), Columbia University in New York, applying a new 3D inversion code, Mare3DEM, to AusLAMP data in South Australia. This new code will enable modelling of marine and land magnetotelluric (MT) data together, along with anisotropic modelling in 3D. We look forward to working with Associate Professor Kerry Key and colleagues at LDEO.

Kate Robertson and Stephan Thiel of the GSSA, along with Naser Meqbel at the National Observatory of Brazil recently published a paper in the open access journal, *Earth, Planets and Space*. This paper, "Quality over quantity: on workflow and model space exploration of 3D inversion of MT data" investigates the intricacies of 3D modelling of MT data.

Seismic tomography data are being acquired across the central-eastern Gawler Craton from April 2020 until mid-2021. The GSSA will employ Dr John Paul O'Donnell for two years to acquire and model this new dataset co-located on the existing AusLAMP array across South Australia. This data will become a critical input to the ARC Linkage project, "Illuminating AusLAMP: Thermodynamics for mineral systems" with research partners at University of New South Wales, Macquarie University, Geoscience Australia, and collaborators at the Northern Territory Geological Survey, and the Geological Survey of New South Wales.

In Q3 2020, broadband MT data will be acquired in a transect across the

transition from the Nackara Arc, Flinders Ranges, east into the part of the Delamerian Orogen mostly hidden beneath sediments of the Murray Basin. Approximately 80 sites are planned for acquisition in a ~120 km transect, with 1.5 km site spacing.

Tom Wise of GSSA has recently returned from attending the Prospectors and Developers Association of Canada (PDAC) in Toronto, Canada, where he presented on "South Australia's world-class IOCGs: established and emerging prospectivity." Tom also attended the 'Deep Probing Seismics & Electromagnetics for Mineral Exploration' workshop at Laurentian University where he presented the work that he and Stephan Thiel have recently published in open-access journal *Geoscience Frontiers*, "Proterozoic tectonothermal processes imaged with magnetotellurics and seismic reflection in southern Australia."

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Geological Survey of Queensland: Camooweal 2D seismic survey

The Isa Superbasin, South Nicholson and Georgina basins of North West Queensland are frontier basins earmarked for examination of their resource potential under the Strategic Resources Exploration Program (SREP). Little exploration has occurred for petroleum resources in these basins, although proven petroleum systems exist in both the Isa Superbasin and Georgina Basin with demonstrated flow at sub-commercial rates.

The Camooweal 2D seismic survey was acquired during July and August 2019. It was centred on Camooweal and aimed to increase knowledge of petroleum (and mineral) systems, define the extents and thicknesses of the Georgina and South Nicholson basins and the Isa Superbasin, and to examine basin architecture.

The Camooweal seismic survey ties into Geoscience Australia's 2017 South Nicholson Basin seismic survey, and the recently completed Northern Territory Geological Survey/ Geoscience Australia Barkly seismic survey, improving seismic data coverage across these frontier basins. The Camooweal seismic survey links into older regional seismic data surveys, tying into the 1994 Mount Isa seismic line, 94 MTI-01 (Figure 1).

The total length of acquisition was spread over three lines, 19Q-C1 (totalling 65.8 km in length), 19Q-C2 (173.6 km) and 19Q-C3 (60.9 km) (Figure 1). Acquisition was via vibroseis using Nodal DTCC SmartSolo receivers. The source array consisted of three Inova AHV-IV Commander PLS-364 (64 000 lb) vibroseis in single file linear arrangement (Figure 2). A single linear sweep from 4 to 96 Hz over 18 seconds was run using 1200 channels symmetrically split, with source station spacing of 30 m and receivers every 20 m. The data indicated the Moho at a depth of 30 to 40 km depth and a previously unknown sub-basin on the eastern end of line 19Q-C1.

The Camooweal seismic survey increases the coverage and improves the quality of fundamental geophysical data over the southern Isa Superbasin, South Nicholson and Georgina basins (Figure 1). The seismic survey will assist in improving the understanding of basins and basement structures and also the energy, mineral and groundwater potential of North West Queensland. The new reflection seismic data and derivative information will reduce risk for exploration companies

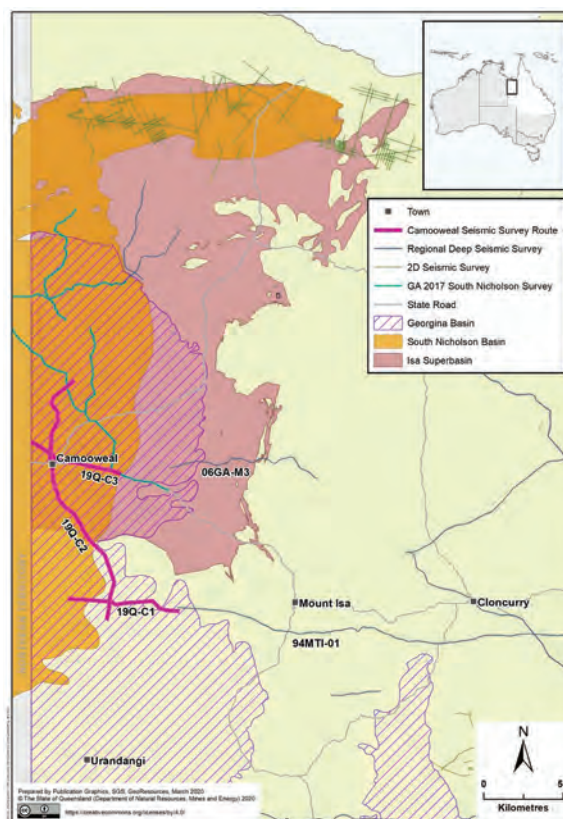


Figure 1. Location of the Camooweal seismic survey.



Figure 2. Three vibroseis trucks out on the vast expanses of the Barkly Tableland, during acquisition of the Camooweal 2D Seismic Survey.

in this underexplored area by providing information for industry to confidently invest in exploration activities.

The data is available for download from the Queensland Government's Open

Data Portal at <https://geoscience.data.qld.gov.au/seismic/95590>

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Sally.Edwards@dnrme.qld.gov.au

Geological Survey of New South Wales: MinEx CRC data acquisition kicks off in New South Wales

The Geological Survey of New South Wales (GSNSW) and Geoscience Australia (GA) coordinated the largest [airborne electromagnetic \(AEM\) survey](#) ever flown in NSW in September – October 2019. The survey was aided by near-perfect weather, so finished early and within budget.

The AEM survey was undertaken as part of the NSW commitment to the MinEx Cooperative Research Centre ([MinEx CRC](#)). This collaboration brings together industry, government, research organisations and universities to further our understanding of geology, mineral deposits and groundwater resources in covered terrains and develop new tools for exploring under cover.

In NSW, MinEx CRC focuses on five regions in the state’s central and far west, which represent the undercover extensions of known mineralised terranes ([Figure 1](#)).

As part of the overall data-acquisition strategy, GSNSW plans to collect new geophysical data over each area.

The Cobar MinEx CRC airborne electromagnetic (AEM) survey was flown in September – October 2019 and covered the greater Cobar Basin, including the North and South Cobar MinEx CRC focus areas ([Figure 2](#)). The information collected will improve our knowledge of the geology and groundwater resources of the survey

area, which will inform government, mineral explorers and farmers. The drought in NSW has increased the need to find groundwater as communities, farmers, mining companies and local government struggle to secure water supplies. AEM surveys have been flown in many parts of Australia to detect and map groundwater systems.

New Resolutions Geophysics (NRG™) acquired 7000 line km of AEM data using a helicopter-borne Xcite™ time-domain electromagnetic (HTDEM) system. The survey covered 19 000 km² which is about one and a half times the size of Greater Metropolitan Sydney. The helicopter flew along east–west lines

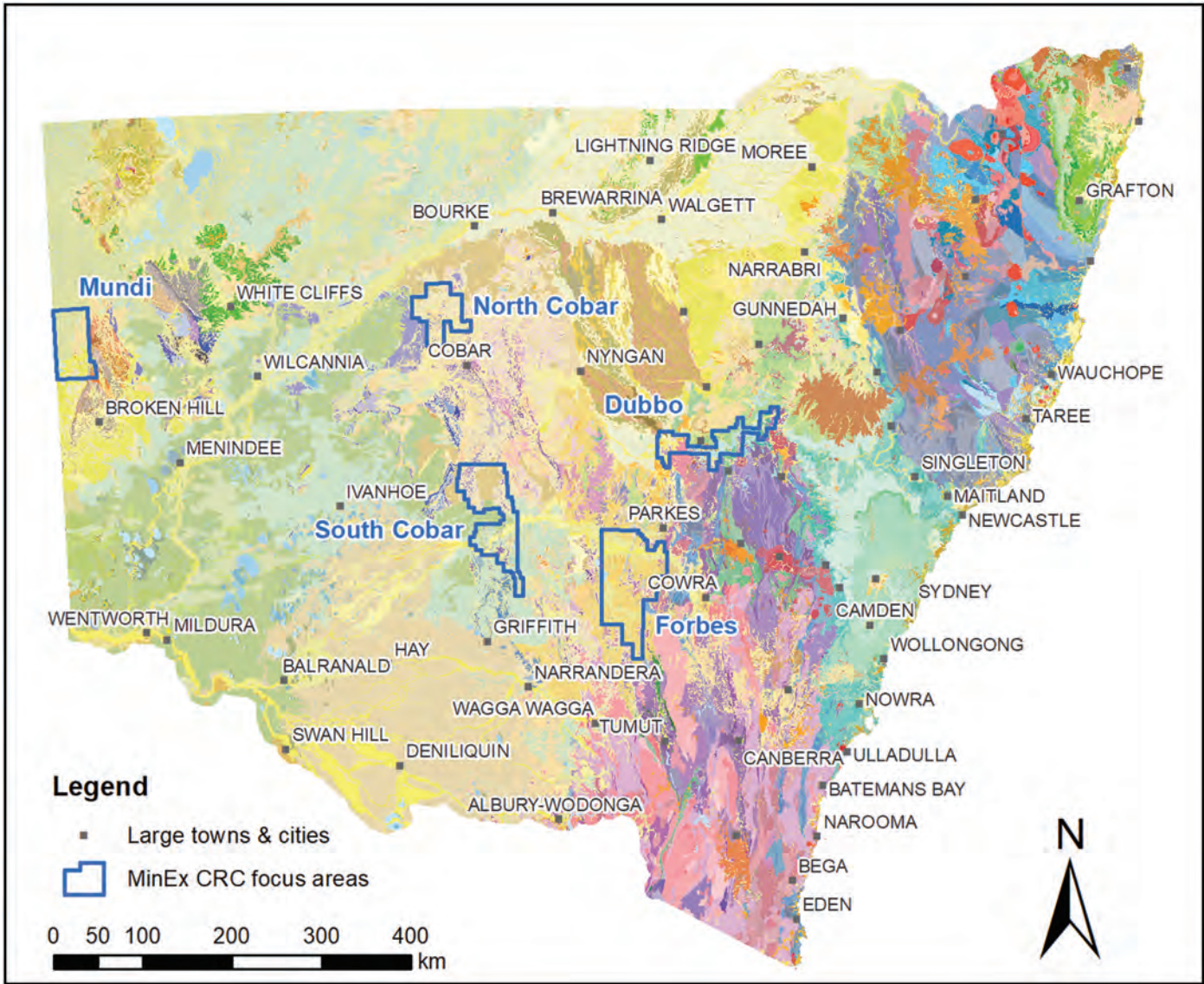
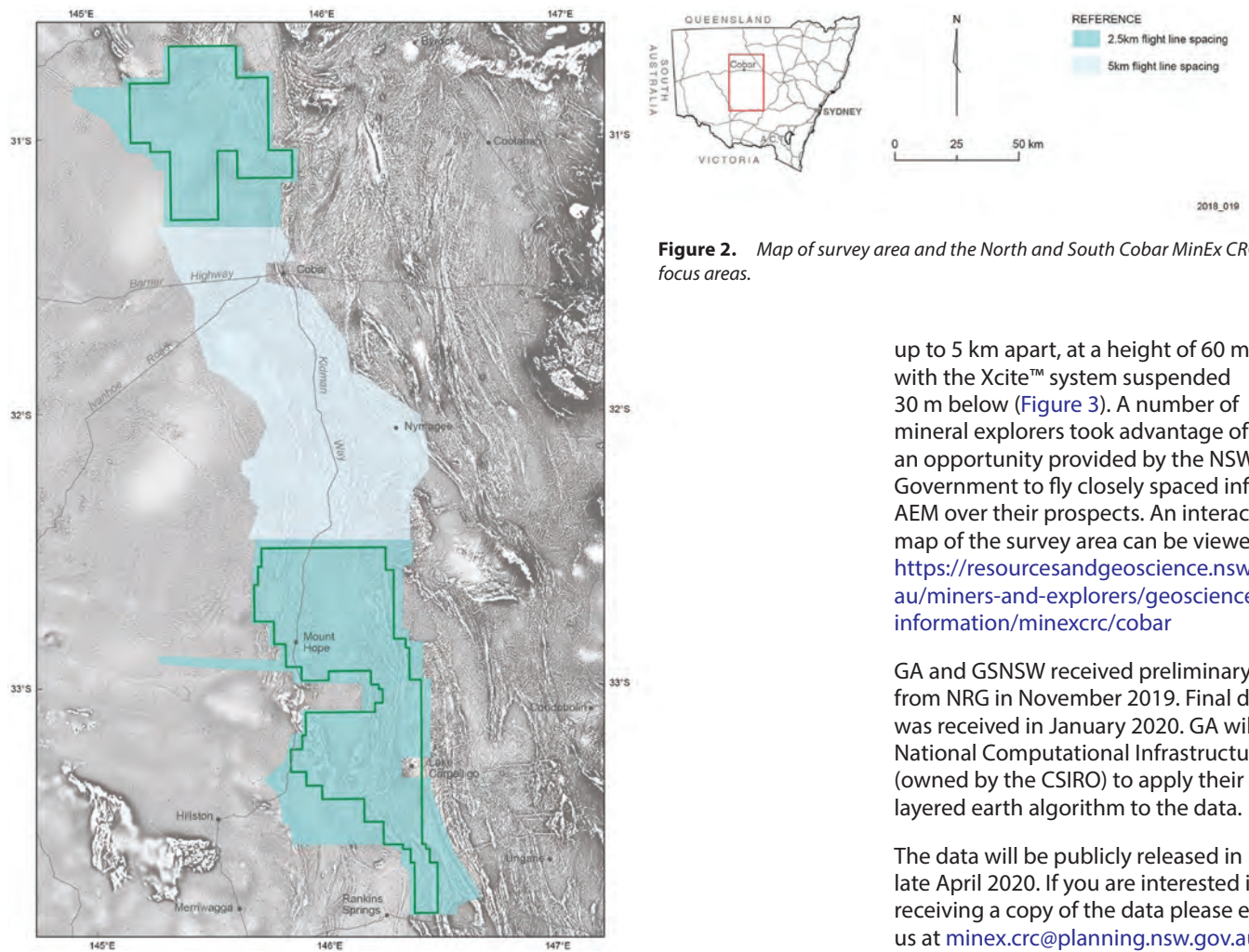


Figure 1. Map of NSW showing the five MinEx CRC focus areas in NSW.



up to 5 km apart, at a height of 60 m, with the Xcite™ system suspended 30 m below (Figure 3). A number of mineral explorers took advantage of an opportunity provided by the NSW Government to fly closely spaced infill AEM over their prospects. An interactive map of the survey area can be viewed at: <https://resourcesandgeoscience.nsw.gov.au/miners-and-explorers/geoscience-information/minexcrc/cobar>

GA and GSNSW received preliminary data from NRG in November 2019. Final data was received in January 2020. GA will use National Computational Infrastructure (owned by the CSIRO) to apply their layered earth algorithm to the data.

The data will be publicly released in late April 2020. If you are interested in receiving a copy of the data please email us at minex.crc@planning.nsw.gov.au.



Figure 3. The Xcite™ HTDEM system in use near Lake Cargelligo, NSW.

Open file company geophysics now available for download via MinView

During 2019 the Geological Survey of New South Wales (GSNSW) geophysics team initiated a project to refresh the publicly available geophysics data in New South Wales by collating, cataloguing and quality-assuring all the company geophysics acquired across the state over the past six decades. Where previously clients needed to directly contact GSNSW and request the data, now all surveys can be searched and discovered through the GSNSW MinView web-based mapping application, and can usually be immediately downloaded.

The first stage of the update was to systematically review each of approximately 800 geophysical surveys held by GSNSW, harvest technical specifications and other metadata, check that all submitted data were present and accurate, and create functional grids and images which honour the data. The harvested metadata forms the backbone of the new geophysical survey catalogue and the data delivery system.

All survey boundaries are now displayed in a set of improved MinView layers, and quality assured and consistently formatted data are readily accessible. A public release date is provided for surveys that are currently confidential, with many of these surveys scheduled for release on 1 June 2021 as part of the Sunset Clause data project. Metadata and a thumbnail image for each open file survey can be displayed at the click of the mouse, allowing clients to assess the quality of the selected survey and take a quick look before deciding to download. A great deal of forensic geophysics was required to ensure data, grids and images are fit-for-purpose and in useful form because the formats, conventions, and file structures of submitted company data varied enormously over the past 60 years. Despite the best efforts of GSNSW geophysicists, there are many company surveys for which no data, or only limited data (usually hard-copy plots), are known to exist. Clients are still able to view the boundaries and specifications of these surveys in MinView and download any reports pertaining to the data.

MinView is an excellent platform for viewing and analysing NSW geoscientific data (Figures 4–6). A number of useful features include: pre-set views for geological, geophysical and geotechnical users; spatial and text data searching options; drawing and annotation capability; and the ability for users to import their own GIS files or located data. There are also download options for a range of data including geophysics, geochemistry, drilling and geology. Another highlight is the on-line delivery of the Statewide Seamless

Geology geodatabase. This allows users to view the best available mapped surface geology and also to strip back the geological time zones and view the interpreted geology of the Permian–Triassic basins, Pre-Carboniferous orogens and the Precambrian provinces.

The final stage of the geophysics renewal project is to update the statewide geophysical imagery by merging the highest quality

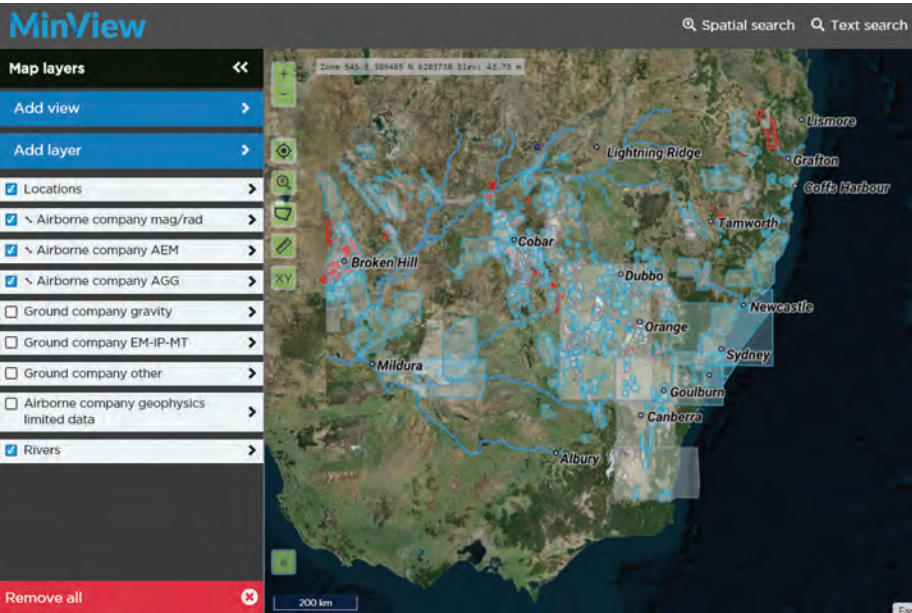


Figure 4. Screenshot of MinView company geophysics view. Survey boundaries of company airborne magnetic/radiometric (light blue), electromagnetic (red) and gravity gradiometry (dark blue) surveys are shown on the map. New South Wales towns and rivers are also shown. The available layers for company geophysics are listed on the left-hand side, including a layer for known surveys without digital data.

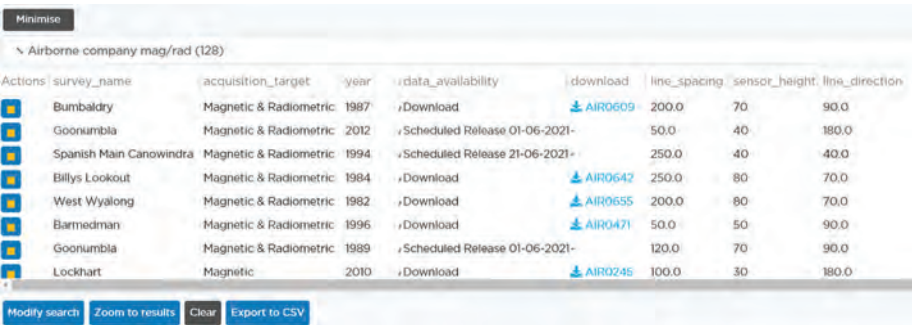
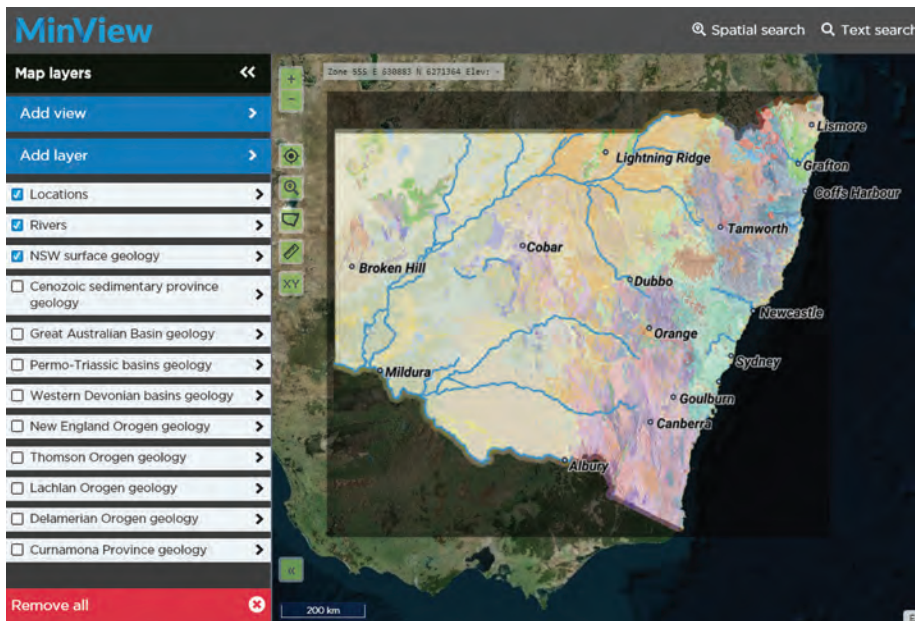


Figure 5. Output from a spatial search of the airborne company magnetic/radiometric survey layer in MinView, showing key survey specifications and the availability of data.



open-file company data with the existing and recently acquired government data. This will happen initially for the magnetic and gravity statewide images, expected to be delivered in mid-2020, and will extend to a comprehensive review and reprocessing of NSW radiometric data, which will be completed by early 2021.

The MinView portal can be accessed at <https://minview.geoscience.nsw.gov.au/>.

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Figure 6. Screenshot of MinView seamless geology view. The surface geology is shown on the map, while available layers of geology for various basins, orogens and provinces are listed on the left. New South Wales towns and rivers are also shown.



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Geological Survey of Victoria: Victorian Government is “Backing the Science”

The Andrews Labor Government [announced](#) on 17 March 2020 that it will introduce new legislation to lift the moratorium on onshore conventional gas exploration and production, and to ban fracking for good in Victoria.

The decision follows three years of detailed investigation by the [Victorian Gas Program](#), which found an onshore conventional gas industry would not compromise the state's environmental and agricultural credentials.

The restart of onshore conventional gas exploration and development will begin from 1 July 2021.

The investigation - led by Geological Survey of Victoria and overseen by Victoria's Lead Scientist Dr Amanda Caples - has identified potentially significant onshore conventional gas resources, particularly in the Otway Basin.

[Victorian Gas Program Progress Report 4](#), also released on 17 March 2020, summarises the program findings to date. The scientific studies and supporting data are being published in a series of Technical Reports available from www.earthresources.vic.gov.au/projects/victorian-gas-program.

New regional 3D geological framework models have been constructed and petroleum systems modelling has been carried out to inform gas resource estimates and prospectivity assessments in the onshore Otway and Gippsland basins.

The Geological Survey of Victoria is currently finalising prospectivity assessments that address the likelihood of particular geographic areas in the Otway and Gippsland basins (within Victorian jurisdiction; [Figures 1 and 2](#)) to host yet-to-be-discovered conventional gas accumulations.

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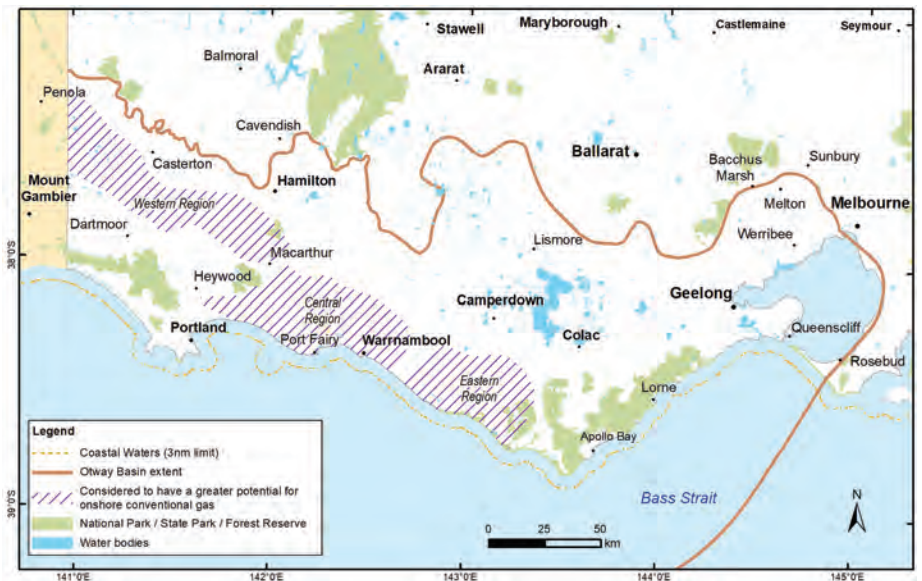


Figure 1. Map of the Otway Basin showing areas considered to have some potential for hosting onshore conventional gas

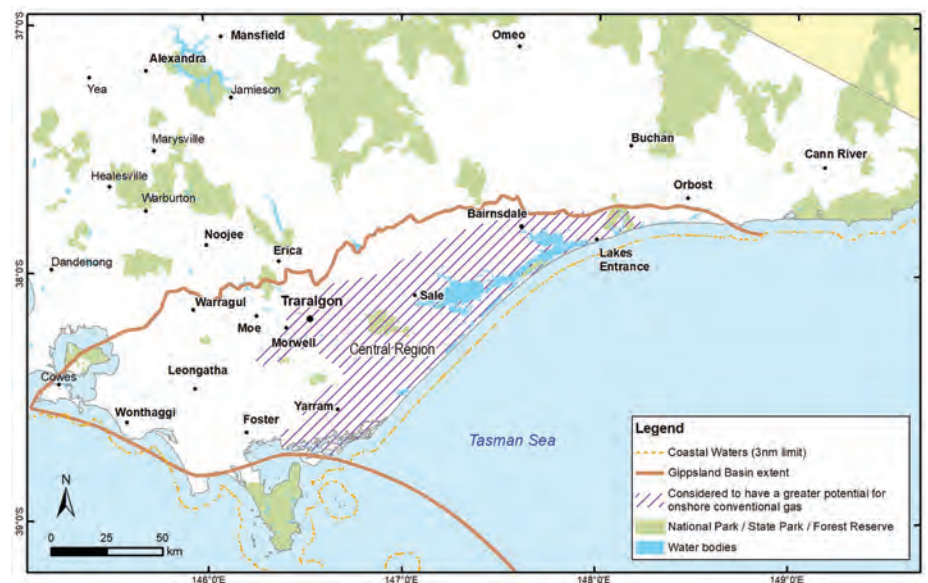


Figure 2. Map of the Gippsland Basin showing areas considered to have some potential for hosting onshore conventional gas

Canberra observed



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Keith Pitt replaces Matt Canavan as Resources Minister



Keith Pitt was sworn in as Minister for Resources, Water and Northern Australia in February this year to replace Matt Canavan, who quit Cabinet to support Barnaby Joyce's bid to lead the Nationals. Pitt was promoted from the back bench straight into cabinet. He is based in Bundaberg and has represented the seat of Hinkler since 2013, where he represents the Liberal National Party of Queensland. He graduated in computing and electrical engineering and, before entering parliament, owned two sugar cane farms.

Previously, in the parliament, he was assistant minister for trade, tourism and investment and quit in August 2018 in opposition to the government's commitment to reducing emissions by 26-28 per cent by 2030 under the Paris accord. He has consistently argued for nuclear power and has been an opponent of global action on climate change.

On nuclear power he stated:

"Australia is one of the few developed nations which is not using nuclear as an energy source, yet we mine uranium here and send it overseas. It's not just about looking at whether nuclear could be an affordable, reliable power source with virtually no emissions, it could be a new

strand to the economy with fabrication, reprocessing, mining and exporting of uranium."

He has called for: "An expansion of Australia's coal seam gas industry, including the Santos project in north-west New South Wales and more exploration of carbon capture and storage, even though CCS has not been commercially viable despite years of development." He said he was firmly technology-neutral when it came to power generation, but "coal will continue to be an important part of not only the economy, but what happens in regional areas for a long time to come".

How he manages the water part of his portfolio will be of interest. South Australian Centre Alliance senator Rex Patrick said: "It's good that the new water minister Keith Pitt's electorate is outside the Murray-Darling Basin, it must be managed in the national interest, not just the interests of large upstream irrigators." And South Australian Greens senator Sarah Hanson-Young tweeted: "Another Queensland National's politician given the job of Water Minister. RIP the Murray-Darling Basin."

He has a very important challenge, let's see what happens.

Gold miners benefit from economic uncertainty

2019 was a very good year for Australian gold producers. According to the media release from Surbiton Associates, the December quarter produced a record quarterly output of 87 tonnes. If you add this to the production numbers published by the Department of Industry Innovation and Science for the first three quarters of 2019 – (79, 83 and 78 tonnes), you get a record annual 327 tonnes. The previous best was the 312 tonnes in 2018 (<https://publications.industry.gov.au/publications/resourcesandenergy/quarterlydecember2019/index.html>).

The top three producers were Newcrest's Cadia mine in NSW, at 24.7 tonnes, followed by Newmont's Boddington in WA at 19.9 tonnes and Kirkland Lake Gold's Fosterville in Victoria at 17.6 tonnes.

The COVID-19 infection caused huge economic and social volatility throughout the world and in the first

10 weeks of 2020 the price of gold rose, on average, from about A\$2150 in

December 2019, to A\$2550 in mid-March at the time of writing. An increase of



Figure 1. Daily gold price in A\$ from 1 December 2019 - 13 March 2020 from <https://www.abcbullion.com.au/products-pricing/gold>.

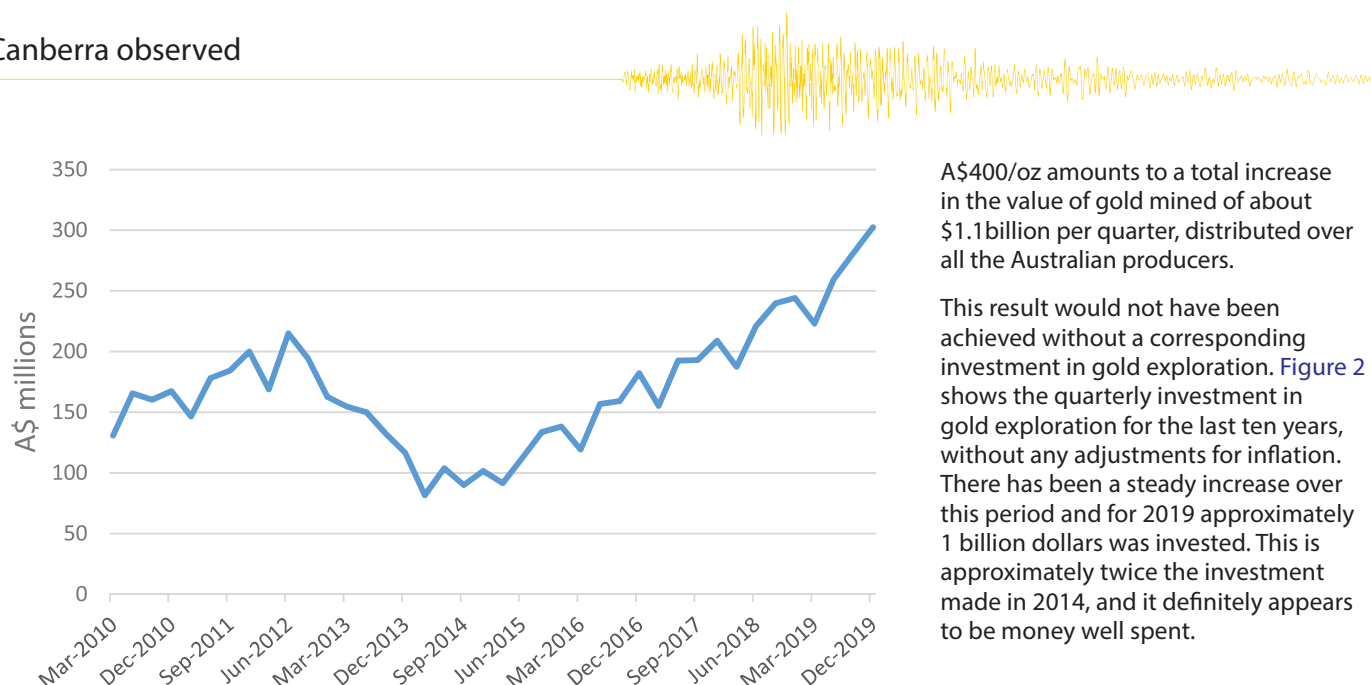


Figure 2. Quarterly investment in gold exploration from 2010-2019. No adjustment has been made for the effects of inflation. Taken from data provided by the Australian Bureau of Statistics <https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/8412.0Dec%202019?OpenDocument>.

A\$400/oz amounts to a total increase in the value of gold mined of about \$1.1 billion per quarter, distributed over all the Australian producers.

This result would not have been achieved without a corresponding investment in gold exploration. Figure 2 shows the quarterly investment in gold exploration for the last ten years, without any adjustments for inflation. There has been a steady increase over this period and for 2019 approximately 1 billion dollars was invested. This is approximately twice the investment made in 2014, and it definitely appears to be money well spent.

COVID-19 pandemic creates havoc everywhere

The word unprecedented is often over-used, but in the context of the effects of COVID-19, it is almost an understatement. This virus is affecting almost every human on planet Earth, particularly those living in the OECD countries.

In Australia COVID-19 has really affected the stock market. It is making it difficult for companies to raise fresh money. According to *The Guardian* of 14 March 2020 "two bank-funding injections totalling at least \$2.5bn were called off. And billions of dollars in other attempts to raise money have also been cancelled as investors close their wallets after two wild weeks of trading erased more than a year's worth of gains."

The market value of resource companies in the ASX's top 150 fell from \$330 billion to \$241 billion in less than a month (February – March 2020). You have to go back to the GFC in 2008 before anything comparable took place.

Petroleum stocks were particularly hard hit with Woodside falling from \$31 billion to \$20 billion in one month and Santos from \$17 billion to \$9.5 billion in the same period. Admittedly the Saudis and the Russians were playing chicken with the oil price at the same time, but essentially the global demand for liquid fuel just fell through the floor. Figure 1 shows the history over the last 10 years of

the price for West Texas Crude, adjusted to 2020 US dollars.

The enforced isolation and travel restrictions mean that many non-essential businesses are suffering. All overseas tourist activity such as cruise ships and airlines, together with sporting activities, gambling, concerts, restaurants and festivals are affected and those who work in those industries are in trouble.

The Prime Minister announced a \$17.6 billion economic package to try and stave off a recession, but I am not sure it is being spent as effectively as it could be.

The \$4.6 billion for a one-off \$750 payment to recipients of Newstart, the disability support pension, carers' allowance, youth allowance, veterans support payments, family tax benefits, the Commonwealth senior health cardholders and aged pensioners is a good move. Likewise, the \$1.3 billion for a 50% wage subsidy for apprentices and trainees in businesses with less than 20 employees is welcome. The money invested will quickly flow back into the economy, and training skills should be a high priority.

However, the \$3.2 billion for accelerated depreciation deductions and the \$6.7 billion for one-off payment to small and medium-sized businesses who employ people and have a turnover of up to \$50 million may not be very effective. I would

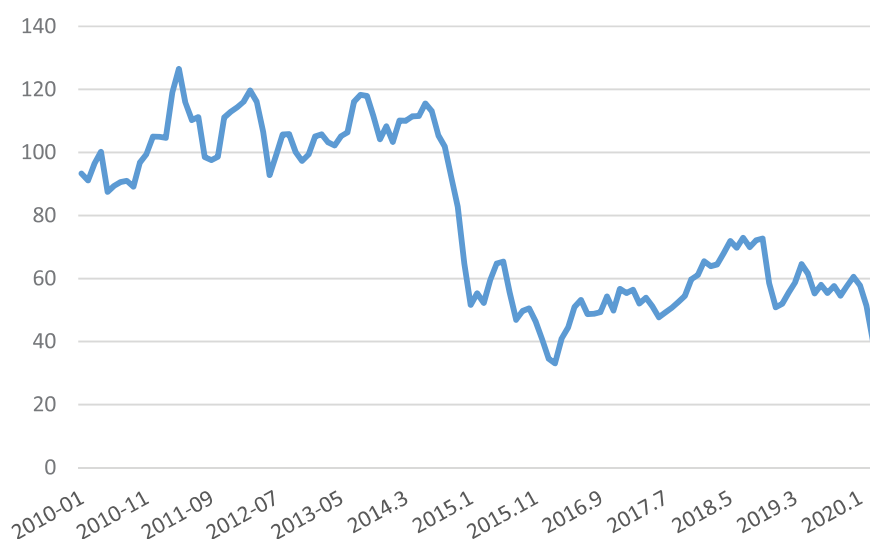


Figure 1. Monthly price for West Texas crude/bl, adjusted to US\$2020, see: <https://www.indexmundi.com/commodities/?commodity=crude-oil-west-texas-intermediate&months=120¤cy=eur>.

have thought it would have been better to put more cash into people's pocket. If this targeted the lower socio-economic groups it would be spent in Australia by those who need it the most, and would be a better way to keep businesses viable.

The Prime Minister stated that \$3 in every \$4 dollars of stimulus would go to business. If three quarters of the package went directly into people's pockets that would

have a more immediate impact. That gives the government breathing space to invest in infra structure projects that have been properly assessed, a bit later on.

Let's all hope COVID-19 wanes very quickly and we can get back to a more normal lifestyle.

Since this article was written the Australian government has provided an emergency \$130 billion stimulus package

to help cushion the blow to the economy from the coronavirus. This addresses the main concerns in the article above. The government has so far pledged a total of \$320 billion Australian dollars in fiscal support as the coronavirus pandemic infects not only people but the economy. To put this number into perspective the GDP for Australia in 2019 was approximately A\$1785 billion (<https://treasury.gov.au/coronavirus>).

Henderson byte: Multiferroics

If you haven't heard of "multiferroics" you might be forgiven. The term has only appeared in papers since 2003, and relates to a special condition of materials that have unique properties. A strict definition is that materials are multiferroic if they exhibit more than one of three primary ferroic properties. The three are "ferromagnetism", "ferroelectricity" and "ferroelasticity". What are they? Well ferromagnetism may, at least, be familiar. A material is ferromagnetic when it is magnetised by an external magnetic field. This happens when the magnetic domains become aligned in the direction of the field. Iron ore is a common ferromagnetic material. Similarly, for ferroelectricity, an electric field may be produced in a material when the individual electric dipoles are aligned by an external electric field. This is also termed electric polarisation. A material is ferroelastic when a phase change occurs from one phase to an equally stable phase by the application of stress. One change may be from cubic crystal structure to tetragonal. Nickel titanium (Nitinol) is a ferroelastic alloy. Materials with the first two properties are also called magnetoelectric multiferroics.

Until recently it was thought nigh impossible that any two of these properties could exist in the one material. For instance, it could mean a material having a magnetic field and an electric field at the same time. Because of the requirements for electrons to be free to move in one case, and to be fixed in another, the properties are almost mutual exclusive. Despite this, the search for such materials began, it is said, by the pioneering enthusiasm of one person, Nicola Spaldin (formerly Hill). Nicola developed an interest in multiferroics in 1996, during her postdoctoral research, and in 2000 published a seminal paper in the *Journal of Physical Chemistry*, the first of many that generated an avalanche of interest in multiferroics. The growth in the number of papers on multiferroics was exponential from 2000 to 2008, with over 700 published in 2008. Incidentally, Nicola went on to receive many accolades including Fellow of the Royal Society in 2017, and one of the laureates of the 2017 L'Oréal-UNESCO Awards for Women in Science. Since 2010 she has been Professor of Materials Theory at the Swiss Federal Institute of Technology (ETH), Zurich.

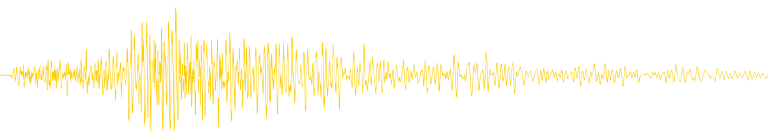
One compound found to be multiferroic in 2003 was bismuth ferrite, first studied at UC Berkeley, by Ramamoorthy Ramesh, who was inspired by Spaldin and became her collaborator. The structure of the bismuth atoms provides the ferroelectricity, and the electrons in the iron ions supply the magnetics.

Interest in multiferroics, apart from their unusual physical properties, is in their other applications, such as high-sensitivity sensors and new types of electronic memory devices. For example, while magnets are normally used to change binary "0s" and "1s" in computers, one electric multiferroic can make the changes using an electric field - which uses much less energy than a magnetic field.

More and more uses have since been found for this new class of materials. Some have a structure that makes for exceptionally efficient solar cells, and some are used as nanobots in the blood stream. These nanobots can be guided to specific locations by external magnetic fields and then cancer cells, say, are treated by their electric properties. The full potential for multiferroics is yet to be realised.

Further information on multiferroics is available from Wikipedia and *New Scientist*, 30 November 2019, pp. 43-46.

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Environmental geophysics



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Mundane applied geophysics

Welcome readers to this issue's column on geophysics applied to the environment. In this column I am going to expound on some fascinating "research" on which I have been working (is there a Nobel Prize for "Mundane Applied Geophysics"? – if so, this work would be in the running). It is actually part of a larger topic that has always interested me in applied geophysics: how far is "infinitely far"? Or more realistically, how far is far enough? For example, in a pole-dipole/resistivity survey the remote transmitter electrode needs far enough away that the roving electrode may be considered to act like a transmitting pole. "Conventional" wisdom is that

2 km from the survey area is far enough. Except when that is impractical or unsafe or ... ??? Sometimes 500 m is all you can get, and that distance probably matters less now that we can include transmitter infinite locations in at least some inversions.

In the problem at hand, I am running surveys with a terrain conductivity meter (TCM). In this case a GF Instruments CMD Explorer (similar but different to that old stalwart the Geonics EM31 or one of the DualEM devices). So, how far is "far enough?" I will need to mount and run a TCM from a ute (Australian abbreviation for a utility vehicle), as the survey area is just too large for me to walk. Or, maybe the system should be dragged behind that ute on a sled? I know that many have done this testing before, but alas I have never seen the results, so we have to keep reinventing the wheel.

In the name of mundane science, I recently borrowed a CMD Explorer from the School of the Environment at Flinders University and took a quad bike and a Toyota Hilux ute (both courtesy of Zonge Engineering) and set up some cardboard boxes and a tape measure and did the tests. [Figure 1a–c](#) shows two of the setups; [Figures 2](#) through [5](#) show the results graphically, and [Table 1](#) reviews some of the results.

First let's review the setups. All data were collected with the GF Instruments CMD Explorer instrument (<http://www.gfinstruments.cz/>) running in continuous mode, collecting "high-moment" data at one second intervals. The internal

height setting was set to zero. Remember that the CMD uses a single 10 000 Hz transmitter, and has three receiver coils fixed in the ~4.5 m long tube. The closest spacing (shallowest data – labelled in the figures and table here as con1 or inph1) is 1.48 m. The middle spacing (con2 and inph2) is 2.82 m between the transmitter and receiver coils. The longest spacing (deepest data – con3 and inph3) is 4.49 m. I tried to collect at least 100 data points per experiment. Data were collected in two configurations. First, with the CMD mounted broadside and parallel to the ute and quad bike, to simulate mounting the CMD to the side of a ute or quad bike ([Figure 1a and b](#) shows the test setup; [Figure 1c](#) shows a typical broadside setup in the field). I also collected data with the CMD on the ground behind the vehicles, to simulate mounting a TCM on a sled or other device and towing it.

For the broadside experiments, the CMD was set at 730 mm height, with the end labelled "T" (the transmitter end) forward. Intuitively it seems better to have the receiver as far away as possible from the running motor, and yes motors were running during all tests. For the ute experiments I ran two sets of tests, first with the CMD centred lengthwise along the ute, and then the second, with the CMD offset 1.35 m back from the centre. For the quad bike experiments, I only ran with the system centred. [Figure 1](#) shows the setups for the broadside tests.

For the towed simulation, the CMD was laid on the ground. Most of the experiments were run with the transmitter end near the vehicle.



Figure 1. a) TCM device broadside to ute; b) mounted broadside to quad bike; c) CMD mounted broadside to ute. Note proximity to carpark in a) and to overhead powerlines in b).

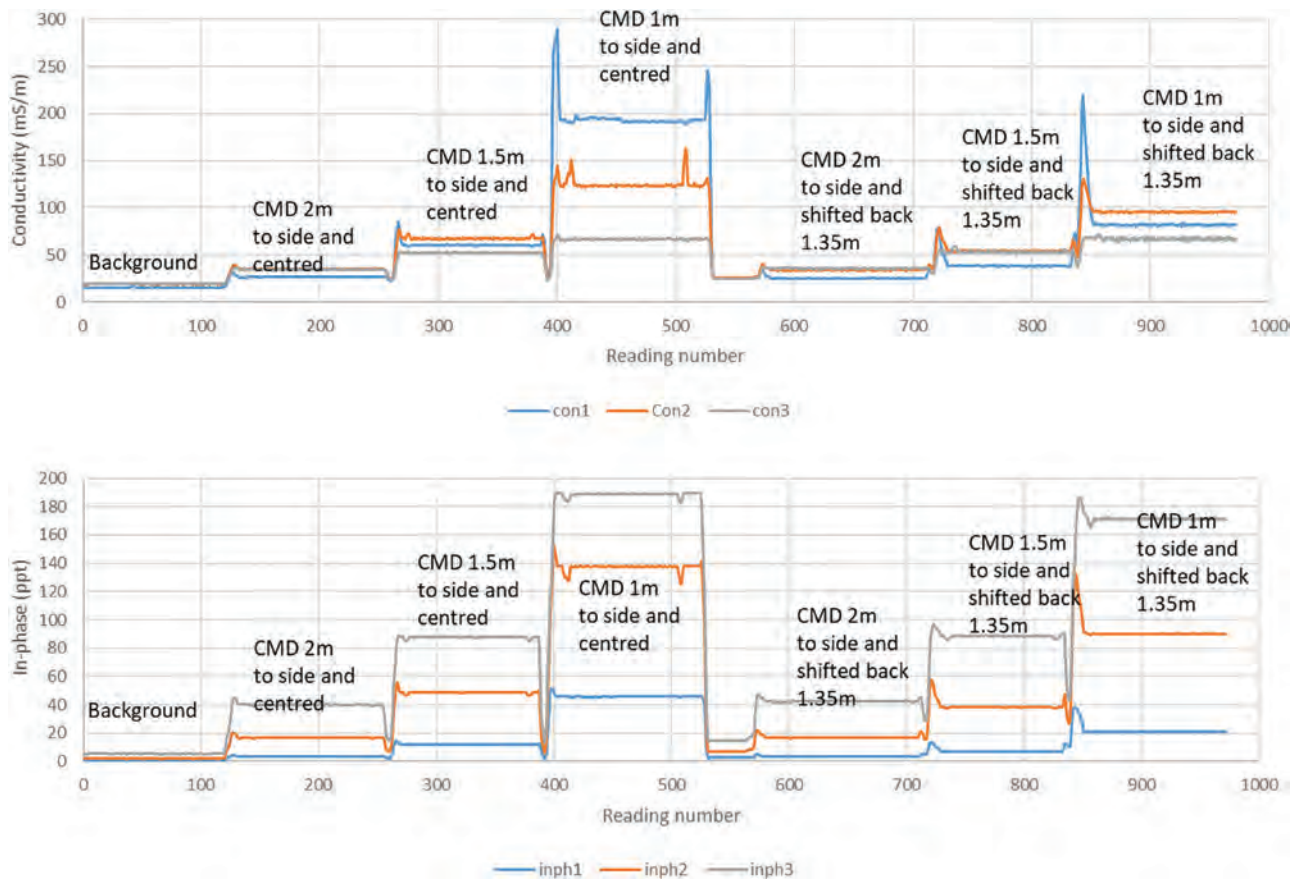


Figure 2. Results with CMD mounted broadside to ute.

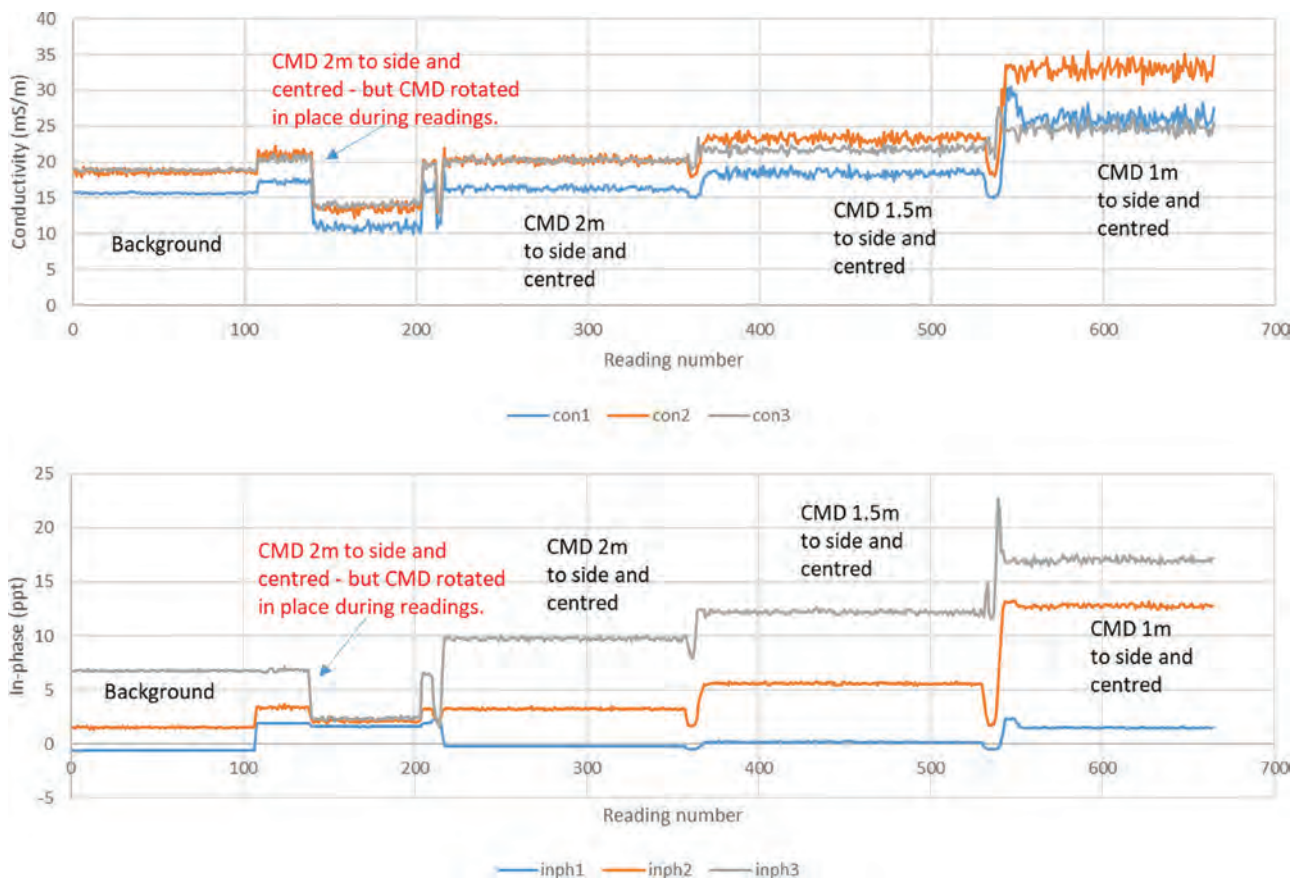


Figure 3. Results with CMD mounted broadside to quad bike.

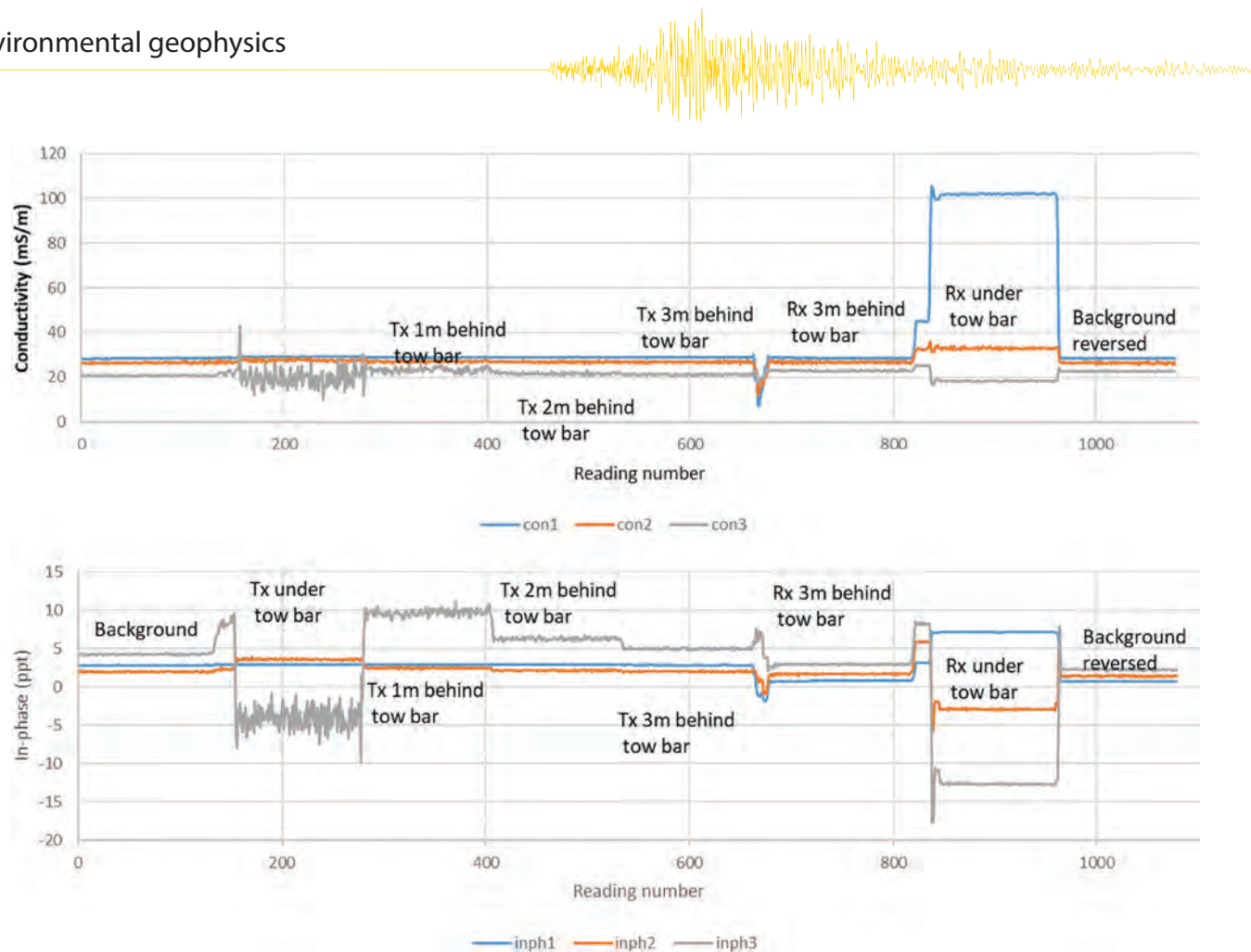


Figure 4. Results with CMD behind ute.

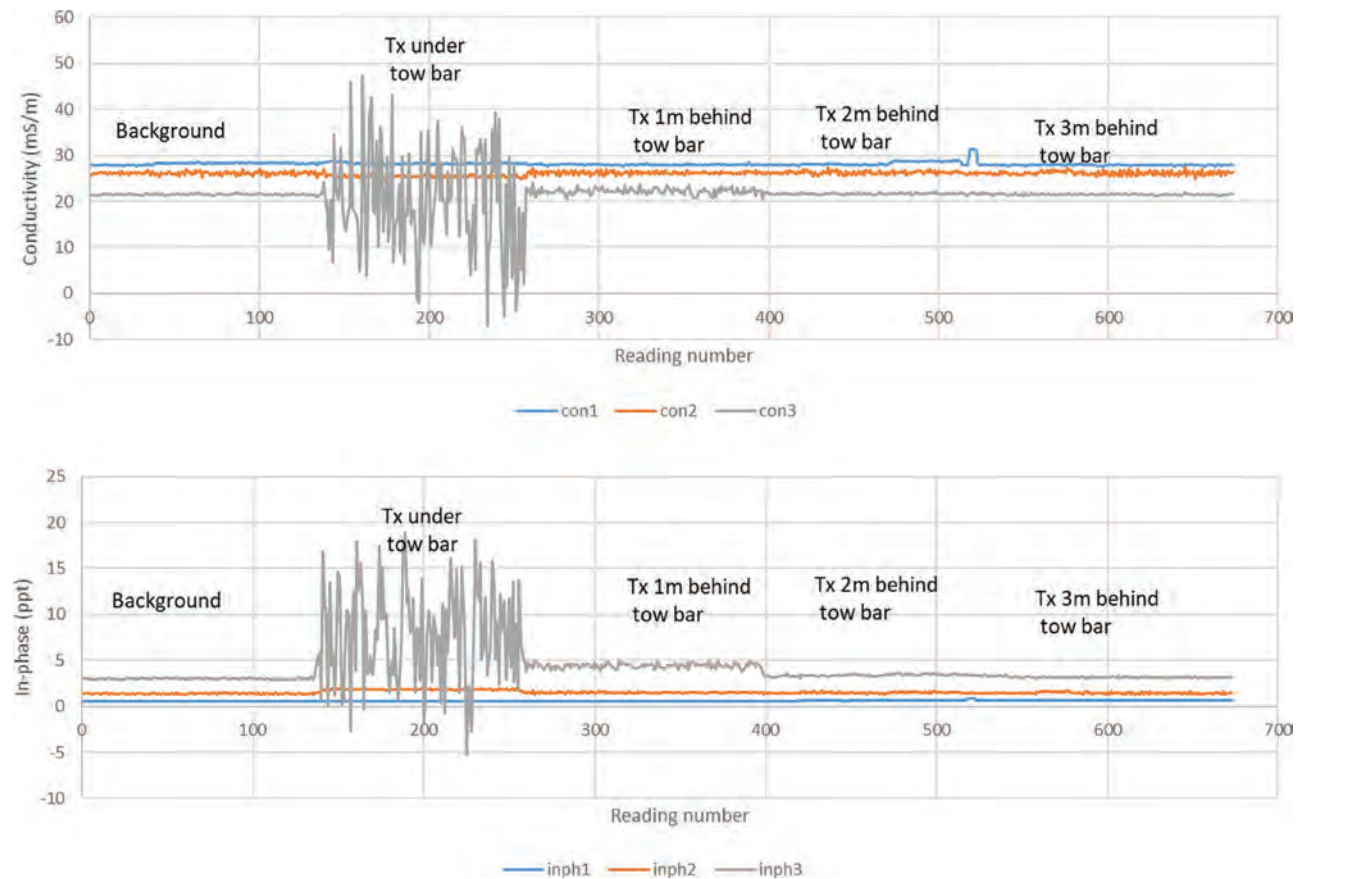


Figure 5. Results with CMD behind quad bike.

Table 1. Tabulated results for two of the tests shown in Figures 2 through 7.

	Con1 (1.48 m spacing) (mS/m)	Inph1 (ppt)	Con2 (2.82 m spacing) (mS/m)	Inph2 (ppt)	Con3 (4.49 m spacing) (mS/m)	Inph3 (ppt)
Broadside test						
Background	15.53	0.70	19.19	1.79	19.55	5.23
With TCM broadside to ute	25.04	3.16	33.91	16.67	35.70	42.45
Ratio	1.61	4.48	1.77	9.31	1.83	8.12
In-line test						
Background	28.41	2.80	26.43	1.95	20.74	4.20
With TCM behind ute	28.57	0.74	26.74	1.66	22.86	2.92
Ratio	1.01	0.26	1.01	0.85	1.10	0.69

Examination of Figure 1 shows that this site may not have been an optimal place to run this sort of test as there are large powerlines ~100 m from the test area. Then again, many field areas have no cultural noise, so maybe this situation is closer to field reality. I don't think that the powerlines affected my conclusions much at all.

The results, summarised in Figures 2 through 5, and Table 1 are pretty interesting. In nearly all cases, the in-phase response is compromised by mounting the CMD anywhere near a vehicle with the engine running – except towed 2 to 3 m behind the quad bike. For most data collection exercises this may not be important, as the in-phase supposedly is only used to help identify responses from metallic targets.

For the quadrature response/conductivity, Figure 2 (and Table 1) shows pretty categorically that it is not

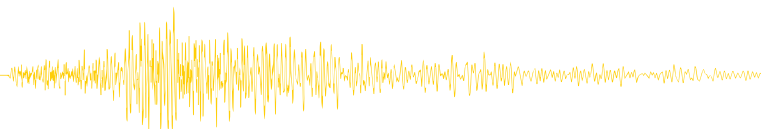
possible to mount the CMD broadside to a ute without substantially affecting the data. It appears the response is improved by mounting the CMD as far back as possible so that the receiving antenna is far from the engine. The shortest dipole spacing response with the CMD mounted toward the rear of the vehicle and 2 m from the vehicle, is 61% greater than the response with no vehicle near the CMD (i.e. “background”). The response is about 77% greater for the medium dipole and about 83% greater for the longest dipole, when compared to the background response at the same location.

Figure 3 shows that the response comparisons for the experiment where the CMD is mounted broadside to a quad bike are only slightly better. In fact, it may even be acceptable to use this configuration if the CMD is mounted 2 m from the quad bike.

The situation isn't quite so bad when the CMD is towed behind a vehicle – at least when the CMD is towed so that the nearest point is about 3 m behind the ute. The conductivities are shifted by 1% from background for the short and medium length dipoles, and 10% (not that great really) for the longest.

As an aside, isn't the response interesting when you put the transmitter end directly under the tow bar of either vehicle? And for the ute, the responses are still noticeably noisier up to 2 m separation. In Figure 4 it can be seen that the response when the receiver end is put under the tow bar of the ute is quite different from than when the transmitter end is put under the tow bar. I am not sure what to make of that. By the way, I am just about to test this type of towed rig in the field – and we are going with the towed configuration with the transmitter end 3 m behind the ute.

There are some obvious shortcomings in this set of experiments (no prizes yet Mike). For example, it might (will?) be interesting to test these results in other settings – both more resistive and conductive – to see if the changes are at least somewhat consistent (even linearly/predictably inconsistent). Also, in these tests the engine was running but the vehicle wasn't moving – there are more moving/rotating bits of metal when you move and that adds noise. I am hoping to get some results soon comparing walking the CMD over a line of data and towing it. Watch this space for those results later this year – I bet you can hardly wait ☺.



Minerals geophysics



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Preserving industry experience

In a chat Des FitzGerald and I had at the last AEGC Conference in Perth, one of the subjects we discussed was how can the accumulated practical experience of industry stalwarts be preserved and utilised. I think Des' article "Quality Control in Airborne Geophysics" in this issue of *Preview* is one such way. Des' practical experience comes to the fore in his contribution, and having ready access to the article is one way of deriving benefits from his experience. Quality control is not something I have addressed in previous issues, so the subject matter is timely.

Following up on one of the points Des makes, I have noticed that the performance of inversion software can be a *de facto* indicator of geophysical data quality. Certainly, if something is seriously awry with the data, an inversion can go off-track, and the degrees of fit may be poor. But, more subtly, the path an inversion takes can sometimes be an indicator that something is not quite right. Of course, such behaviour is more readily identified if you are familiar with the "normal" performance of the inversion process. Experience does count!

Finally, if you feel that you may have a Minerals Geophysics contribution to make to *Preview*, please get in touch.

Quality control in airborne geophysics



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Introduction

Quality control of airborne geophysics surveys is a complex subject. The discipline has continuously developed over more than 60 years. The primary checks on quality are those of common sense and the outcome of the surveyed representation of the measured field creating a geologically sensible basis for interpretation, at a scale and resolution that is required. Of the common geophysical exploration techniques, gravity, magnetics, inductive electromagnetics (EM) and radiometrics have long histories of successful development of airborne systems and applications. Large institutions have learnt from experience to always have a process of independently checking

geophysical surveys, both during the acquisition phase and also when the contractor is delivering the final versions.

Geophysical surveying practice continues to evolve at quite a rapid rate, with new and improved systems regularly coming on to the market, promising higher resolution and better accuracy and repeatability etc.

Airborne magnetics or ground gravity data collected in the 1990s is gradually being relegated to the status of legacy, and new surveys are being commissioned. Starting from the mid-2000s, airborne electromagnetics (AEM) and gradiometry can provide much superior products to interpret geology, etc. Horsfall (1997) outlines equipment calibration and field data quality checking procedures that have not altered much since then for magnetic and radiometric surveying.

All members of an airborne survey crew and client (or their representative) have a role to play in delivering a safely acquired quality product. The skill of the pilot always contributes, as the specifications for the flight path and minimisation of influences such as turbulence are critical. The field technician's role involves making sure the acquisition system and the instruments are running and producing useable data. At the start and end of each flight and each day, repeat lines might be required to be acquired to check that the instruments remain

working within specifications. The survey processing engineer typically has access to each flight of data within a few hours, and standard post-processing steps are undertaken to also check to a first order that all the data appears to be in order. This checking remains in the realm of a time series. One or more geophysicists are then tasked with preliminary processing to produce located flight lines that are de-spiked and trimmed to the required survey line specifications. This data can then have progressive grids created so that any variations from flight to flight or day to day become apparent. A diligent independent quality assurance process is then added to the process with the aim of reproducing the preliminary results, and making requests for re-flights if the data is out of specifications. A contractor should not be allowed to demobilise and leave the survey until a formal process of verifying a viable and in-specification data set has been achieved.

Influence of government regulations

Some governments require all exploration geophysics datasets to vest back with the government after an exclusive period. This then sets up a long-term archive and repurposing activity. Australia can be seen to be at the forefront of this style of activity, resulting in continental scale compilations at survey resolutions of gravity, magnetics,

radiometrics and emerging AEM. Other jurisdictions, such as the USA, leave the data in the hands of individuals, and consequently lag in an obvious way any attempts at upscaling their geological mapping and making predictions about what lies “undercover”.

There is typically a lag of many years between an initial geophysical survey and follow up drilling, ground sampling for geochemical purposes, and detail structural geology studies. So, airborne geophysics is the common path finder. As there are many competing technical and safety requirements and engineering products, there is a spread of quality produced by the available systems. Good practice is stated in terms of flying height, speed of flying, topographic drapes and line spacing. These requirements vary from one physical parameter to another - see Reid, (1980). Clifton (2016) builds on this original work and develops the arguments for flight line spacing and direction, to create survey data that is better suited for the purpose of deducing near surface buried bodies in terms of detectability. The goal posts have shifted towards not just a surface mapping outcome but finding out more about the features in the top 1000 m below the topography. Consequently, when designing a new geophysics airborne acquisition system, no one system design is optimal for all cases.

Also, commercial competition has proven to be very important as an evolutionary driver in that the value for money proposition drives one aspect of the technology, versus the requirement for highest quality and a multi-sensor system to illuminate the unknown and lead to a better geology interpretation.

When a new technology emerges and is championed by an exclusive development partner, e.g. magnetic tensor gradients, the progress of the development can struggle to progress as fast as a more competitive environment is capable of (FitzGerald, 2013).

Method and results

Field acquisition issues

Before a survey is undertaken, a process of survey design is undertaken that is affected by the weather, availability of aircraft, and fuel. Initial test flights are undertaken to verify that airborne systems are functioning by flying repeat lines.

During acquisition, the flights must meet guidelines as to height above ground, deviation from the original flight plans, speed and accelerations of aircraft, and turbulence with the continuous recording history for each instrument remaining within operational specifications. Required noise levels, calibrations, data corrections and reduction and their specifications as well as processing requirements have developed over decades mainly by government institutions and, obviously, by contractors.

Precision

As it turns out, most instruments that are used have relatively limited precision, often because data are recorded with, say, no more than 24 bits at best (so 4 or 5 digits). Some of the measures are less well constrained, particularly the instantaneous rotational state. Do not be confused by the quoted number of decimal places, as these may not reflect the actual precision of the original measurement. Gamma ray data are collected as counts/second in energy windows from 0 to 3 million electron volts (MEV). You may not get any counts at all in some of the channels, so knowledge of the Poisson distribution is used to find and recover signal amongst the noise.

If a vector or tensor gradient are being measured, or a secondary field, the rotational state of the instrumentation system is critical.

Gravity gradient acquisition systems all derive from the original Lockheed Martin GGI pack. Figure 1 shows a Falcon survey from Victoria being subjected to a noise review. In the case of AEM surveys, increasingly both X and Z components of the B-field decay curve responses are deliverables. For such systems, all important issues are calibrations of both X and Z so that they are consistent with each other, lag distances, rotational state of the bird and non-saturation of the sensors in the instrumentation.

The human factor

As many as 50% of all airborne geophysical surveys that are currently being flown have issues that are left unresolved when the survey is accepted and paid for.

There is an ever-rising specifications bar for each of the survey types that tries to counter issues that have occurred in the past, but were accepted previously and are now deemed unacceptable. If there is not an independent QA/QC process being employed on a survey using appropriate checks, it follows that there is more likelihood of inferior results even if there are the requisite pretty pictures. Airborne geophysical surveys are one of the prime techniques available to illuminate the near surface geology, even if indirectly. The various government agencies in Australia are collectively spending more than \$100m annually.

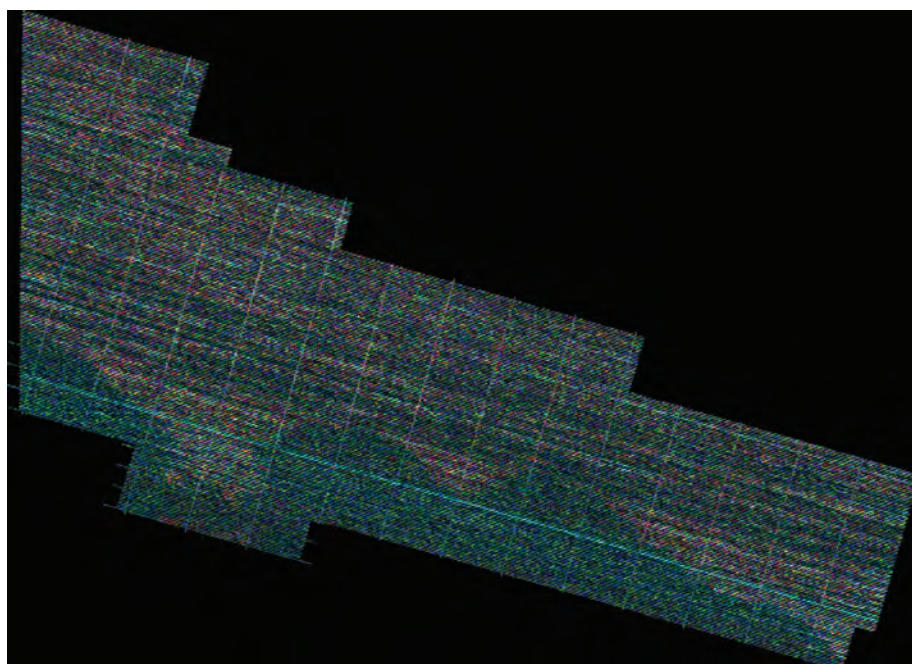
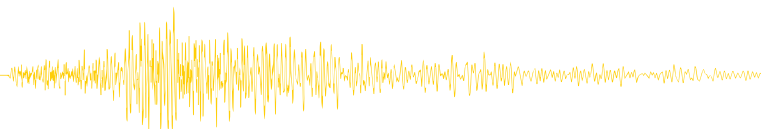


Figure 1. Falcon Gravity Gradient - 3 channel noise image: Local StdDev (600 m) of AB_NE-diff, AB_UV-diff and Turbulence in R-G-B



A government agency that undertakes acquisition of many geophysical surveys can also undertake a very thorough effort to keep up with the quality control aspects while the data are being collected and before acceptance.

The private sector, especially in minerals, is not always as organised, as the activity of getting a new survey is not as common an activity in any one company.

Post-acquisition

Most of the work done after flying, and before final data delivery, involves a correction for systematic errors or adjustments for known factors such as magnetic compensation, altitude corrections, spike removals, radon corrections, de-stripping, de-corrugation and cross-over analysis.

Terrain

In almost all cases, terrain effects are the dominant component of any newly recorded airborne geophysical survey. It follows that a terrain dataset of appropriate resolution should be available before assessing the quality of the newly recorded survey. Up to 80% of the recorded signal can be directly attributed to terrain effects for gravity gradiometry for instance.

Gridding

Gridding of an acceptable final version of the measured field, after all the conditioning steps and production of a residual anomaly estimate, to reveal how the local geology is influencing the measures, is the principal deliverable to clients. This follows from the reality that the ultimate client is usually an interpreting geologist, not a geophysicist. The very act of gridding immediately rejects, or does not use, around 80% of the acquired data due to the fact that flight line data are aliased in the direction of acquisition and poorly sampled between the lines. Honouring the 20% of the data that is being used, while a representation of the field in the grid is created, is critical. The common practice is to have just 4 cells between lines. As an aid, the physics that the measured field is known to obey can be used to constrain the gridding algorithms, hence the use of minimum curvature and bi-cubic splines for potential field components or scalar measures. It is a limitation of the minimum curvature smoothing convolution operator that the 11, 25, and 49 terms that might be used here in

various flavours of the implementation, are first order errors, second order, or third order errors, when judged from a finite difference perspective. The actual width of this operator, each time it is applied needs, at some point, to access original observations that are being honoured to constrain the curvatures to observations. It is for this reason, as much as anything else, that scalar airborne surveys have come to use 4 cells between lines.

A grid contains the summary information content of a survey, whereas an image is a reduction of that information using a look up table colour stretch. The colours and their transitions do not signify a change of geology or a boundary, but are an arbitrary assignment so that the eye can better detect the information content. It is important to note that while honouring the gridding cell size chosen, most commercially available gridding packages actually display on the screen an over interpolated, aesthetically pleasing version of the

gridded data and thus could tempt the unwary processor to use an inappropriately smaller cells size than the line spacing could ever justify.

Higher dimension signal observations

Gradient gridding and tensor gridding change this processing practice quite a bit, as greater than 70% of the measured signals can make it into the grid, producing a higher resolution grid of the field. In this case the quality control issue shifts even more critically to the gridding algorithm and its ability to honour locally all the trends that have been measured. The technical objective here for instance, is to produce from magnetic gradient tensor data a grid with a cell size that is one tenth of the line spacing while honouring the observations. This leads to twice the resolving power, as a minimum, to traditional TMI surveys. For instance, a 5-metre cell size or less can routinely be achieved with this technology. [Figure 2](#) shows a model study of a dyke-like

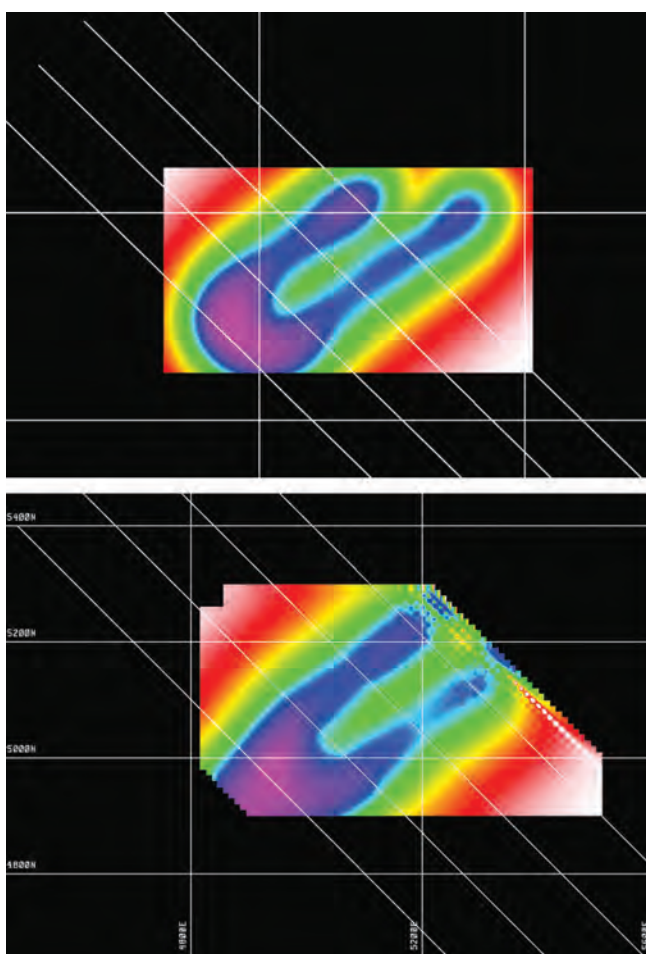


Figure 2. Magnetic Tensor gridding, synthetic data trials. (a) The forward model of a highly folded dyke body and its magnetic tensor default visual enhancement "Cube Root of the Determinant", without any noise. The four flight lines at right angles to its strike are shown. Sample observation is made back to the flight lines. (b) A tensor grid created, in this case with 12 cells between each pair of lines, recovering the correct geology object signature. The top edge is unconstrained, so some artefacts are coming in.

Most Southern line - Waddikee Line 60280

Fitting the observed data and Noise analysis

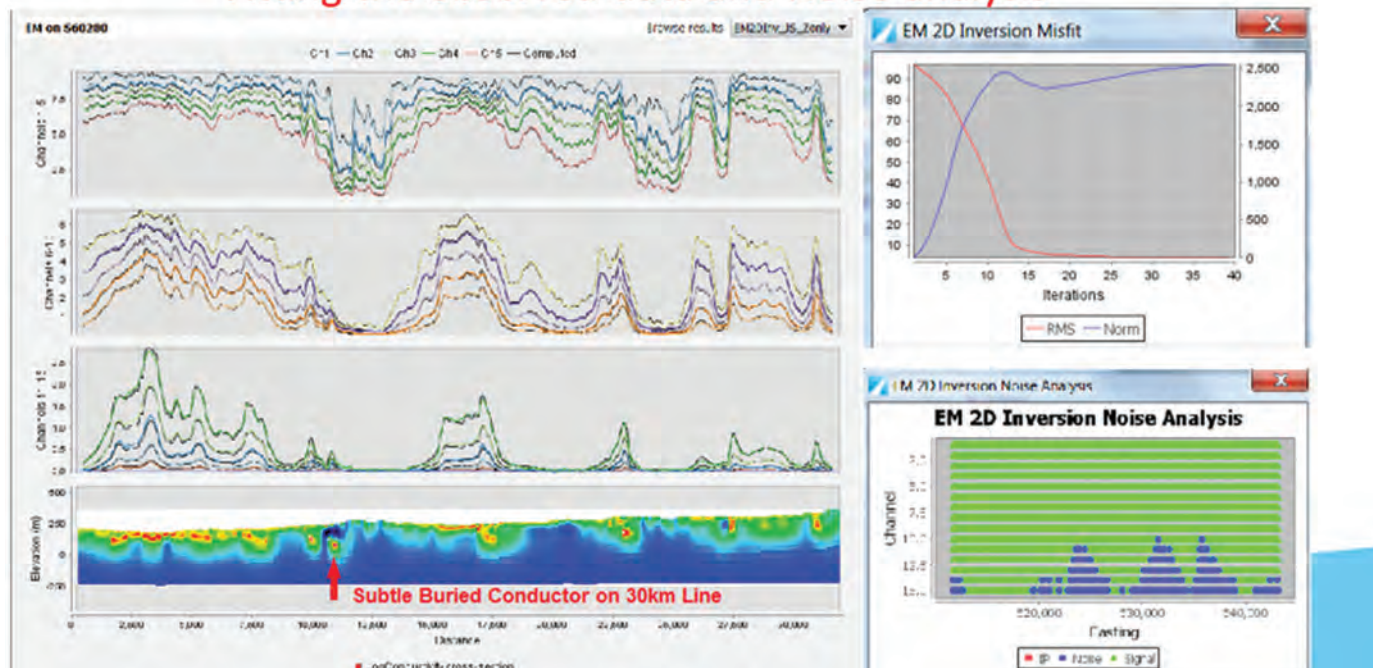


Figure 3. Use of 2.5D AEM inversion as a quality control checking tool. In South Australia, the Waddikee Tempest survey shows what portion of the measured signal is useable and what is below the noise floor.

structure buried below the surface, with a quite ambiguous TMI signal when sampled along four lines that cross it. If a tensor magnetic gradient signal is acquired, or in this case calculated (Holstein et. al. 2009), most of the ambiguity disappears and the challenge then is to push the resolution to the upmost. A sensor may have up to 6 degrees of freedom in its trajectory through space. The three rotational states have not been routinely measured with the required accuracy nor corrected for. This has now become a requirement for these high rate, higher dimensional acquired signals. Of course, the presence of noise and non-ideal flying directions also can be investigated once this framework is available.

Turning to AEM data sets, gridding also presents some quality control challenges. Typically, the magnetic B-field component decay curves of the secondary response are the principal delivered data from an airborne survey. As it is easy to do, grids of these early time and late time values can be generated. These grids are not directly interpretable as a geological response, but rather an indication of local coherence between soundings. It is the cross-sections of the log conductivity after an inversion that has more geological significance, and that is what the geologist needs.

Inversion

The 2.5D inversion technique has a place to play in quality control for AEM surveys. The method is very exact and reports all difficulties with the delivered data from a contractor with ease. Figure 3 shows an example where the quality of the survey data is being tested. In particular, the inversion requires correct calibration of X & Z channels, proper compensating for bird motion, validation of the noise model and a lack of late time correlated noise. When the data are not processed correctly, any or all these factors are easily detected.

If 1D inversion, or CDI production is all that is attempted by the team checking the delivered AEM data, there is much less quality control being applied for a coherent and properly calibrated signal. The characteristic “pants-leg” artefacts from 1D often are interpreted as an anticline by a geologist, when in fact they often reflect a steeply dipping conductor or an off-end effect associated with a fault.

Longer Term Factors

As geophysical surveys have been acquired over more than 50 years, there are generations of workers and instruments that make for a non-homogeneous patch work of spatial coverage, which in turn has an impact on regional dataset quality. Regional surveys about each other and

further quality control issues which were never anticipated at the outset emerge. Each of the geophysical signal types seem to have their own unique issues, once this scenario is discussed.

Gravity

Older gravity stations set out on up to a grid of 11 km have issues with XY location, and of more concern the height as a barometric pressure method was used historically. This means the elevation estimate in older datasets has much larger errors that typically cannot be fixed, compared to more modern survey observations. This means merging older data of this nature with a modern airborne gravity survey is almost a pointless exercise, except there may be no choice.

Radiometrics

In earlier times, calibration of the crystals and the processing coefficients used may either be lost or poorly executed. At times flight lines need to be re-occupied with a view to re-establishing what coefficients might have been used to produce the “final” multi-channel data and the standard four channel products. Unless this process is followed there is almost no chance of harmonizing the old survey data with a next generation. Figure 4 shows a newly developed

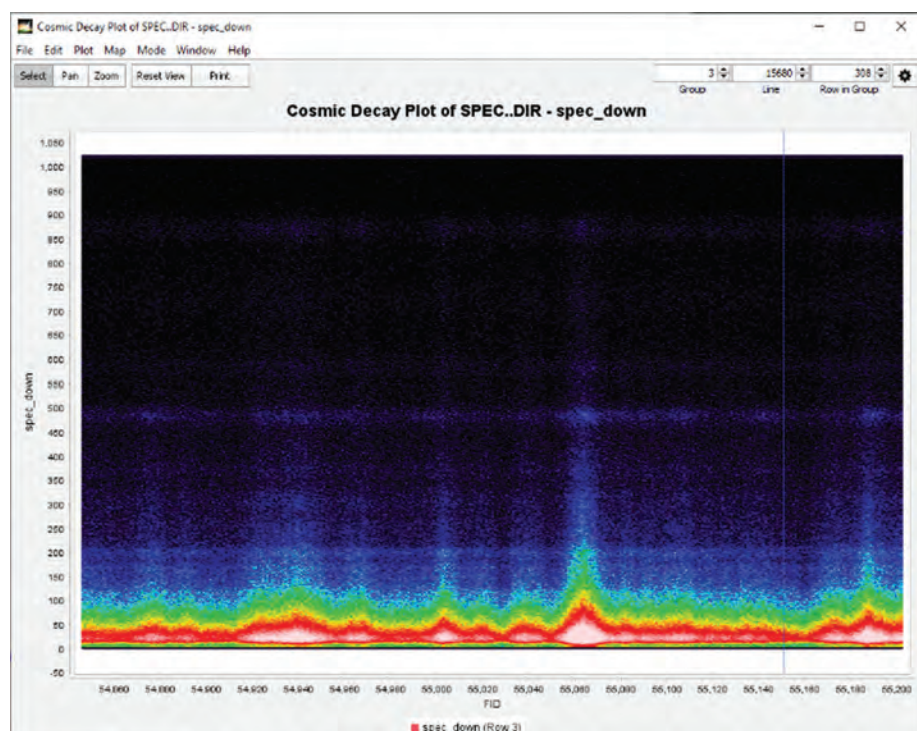
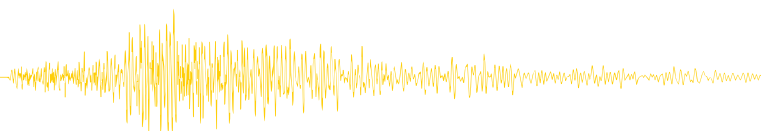


Figure 4. Image processing methods to QAQC 1024 channel Gamma Ray records by flight line. A pseudo colour histogram stretch is applied to each recorded spectra, displayed by fiducials.

capability to not only visualise all of the measured values by fiducial, but by using a differencing arithmetic operation, a before and after capability, to check processing operations on the data.

Magnetics (TMI)

These data are also not without issues. What was the diurnal correction applied and what trends were removed from the survey data? Are there enough overlaps between surveys to figure out an adjustment that the physics of the situation might find acceptable, i.e. first order trend and a DC shift. The push to mix poor survey data with high quality modern surveys to create the illusion of a coherent continental coverage does a disservice for the interpreting geologist as Clifton (2016) points out. East-west flown lines with a spacing of greater than 200 m have a poor chance of being able to characterise near surface magnetic sources in the geology.

Practical implementations of these quality control adjustments show up in the use of the GridMerge tool, (Minty, 2011) where routinely more than 5000 prior TMI surveys are re-adjusted and remerged to make a new coherent representation of the magnetic field. Figure 5 is typical of what is behind most magnetic gridded products in

Australia at present. Some states in Australia over-grid their survey data in an effort to not de-sample their high-resolution data. This exposes users who are un-aware of this, thinking that there is little benefit to be had in flying a new magnetic survey if the cell size is reported to be 40 m etc.

Future needs

Intrepid Geophysics has many tools that have evolved over the years to provide tailored abilities to check and if necessary correct geophysical survey data. Often the processes involved are completely non-trivial, and require a good understanding of typical measuring systems and the physics involved. Typically, creating visual plots to check data quality is the standard means of going about QA/QC, rather than relying on group statistics. Often, the outlier errors mostly show up statistically in the kurtosis, if at all.

As many geologists and other interpreting geoscientists rely on the further processed

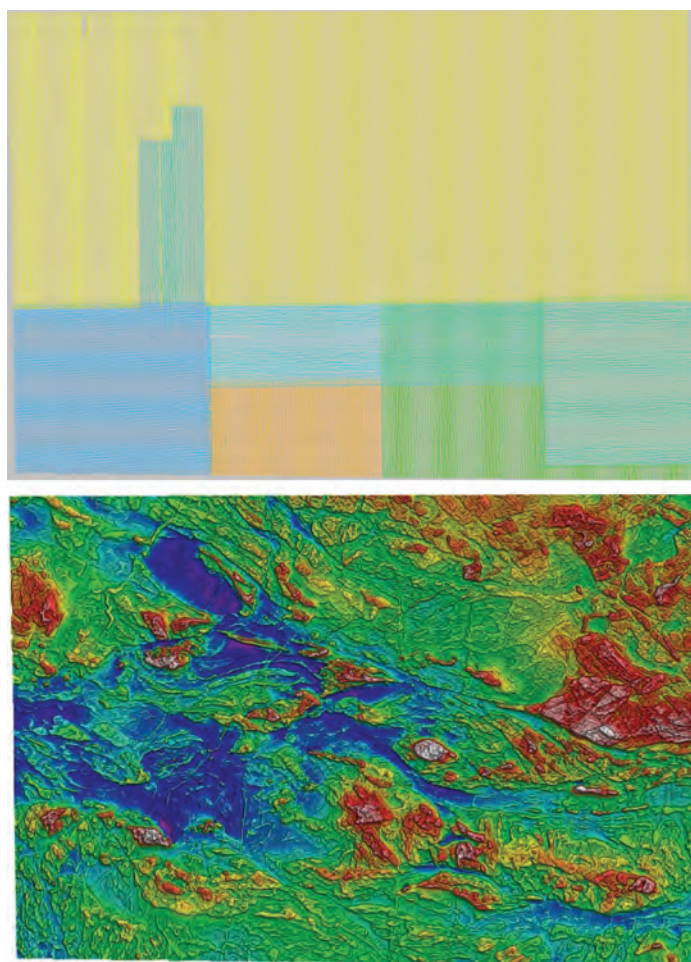


Figure 5. a) Typical generations of magnetic survey, with differing line spacing and flight directions, flying height, IGRF etc. b) GridMerged product, showing best efforts at a unified prediction of the magnetic anomaly field.

gridded form of the geophysical survey datasets, or indeed, just images of this data, there is a big duty to prepare best efforts and also check the efforts of others, as any error that remains in the data undetected can have large implications and cause a lot of unnecessary miss-direction and expenditure.

Conclusions

The critical step of ensuring that high quality geophysics data are both acquired and then reduced via established processing methods to a coherent and consistent representation of an element of a field cannot be taken for granted.

Quality control should not be restricted to ticking all the boxes, rather it should become a cooperation between contractor and technical inspector to provide the client with the best possible data under the given circumstances!

2.5D AEM inversion provides an exacting quality control check on survey data, as all aspects of the

components of the B-field measured signal are rigorously tested for coherence. Airborne gravity and gravity gradiometry also require a high level of quality control procedures, especially involving terrain factors. An emerging magnetic tensor gradient survey technology presents even further challenges for quality control, as many of the established shorthands and rules of thumb no longer apply.

The QC technology applied across the industry is not uniform, and sometimes inappropriate for new datatypes being acquired. Government contract specifications can help. Also improved software tools being generally available and having trained operators are emerging requirements.

In time, consistent and coherent regional compilations of airborne geophysical data open up a new range of applications for these data. Large regional anomalies can now be better appreciated and interpreted. A significant benefit is the ability to apply quantitative modelling and data

processing techniques to large areas. These methods have the potential to provide significant new insights into the geology and prospectivity of continental scale compilations.

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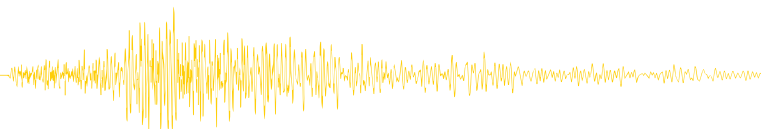
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Seismic window



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40 years of change

My favourite geophysicist retired earlier this year – that's right, Interpreter Sam will no longer be gracing the back page of *The Leading Edge*. This got me thinking about the last 40 years since I started in the oil industry with Delhi Petroleum in Adelaide. After spending the late 70s taking field measurements for minerals companies and the SA Department of Mines my first experience with Delhi was a real eye opener - I received a 20% pay increase between the job interview and my first day. The job interview consisted of a morning answering questions in a "psych test" and then being taken to lunch by the exploration team. If you survived the afternoon you got the job. There was not an HR person in sight and the Exploration Manager never looked at the nut test results.

So, what else has changed since 1980? Seismic data was supplied as paper sections and interpreted with colour pencils. Derwent were preferred over Staedler by most of my colleagues. The exploration group had a single Tektronix computer (total RAM 8 Kbyte) that was used to digitise interpreted horizons and sonic logs, the latter being used as input to calculate synthetic seismograms which took several hours. Delhi was one of the few companies in Australia that could create these useful overlays. Being a progressive company, we soon had a VAX/VMS computer and

a terminal on most desks so we could plot posted maps for hand contouring. The Delhi mapping software was at the forefront of technology and I recall a team from Esso travelling from Sydney to check it out.

Of course, support staff were abundant. We had technical assistants, draftspersons, surveyors and secretaries so we could spend our time looking at seismic data rather than making power points, which weren't invented yet, typing memos or digitising. The company bought the first fax machine in Adelaide, but had to wait for someone else to buy one before they could use it. Actually, it was mainly used to receive logs from the well site. Prior to this we would charter a jet to fly to Moomba, pick up the logs and return them to Adelaide the next day. Today we get real time logs displayed on our desk top while drilling.

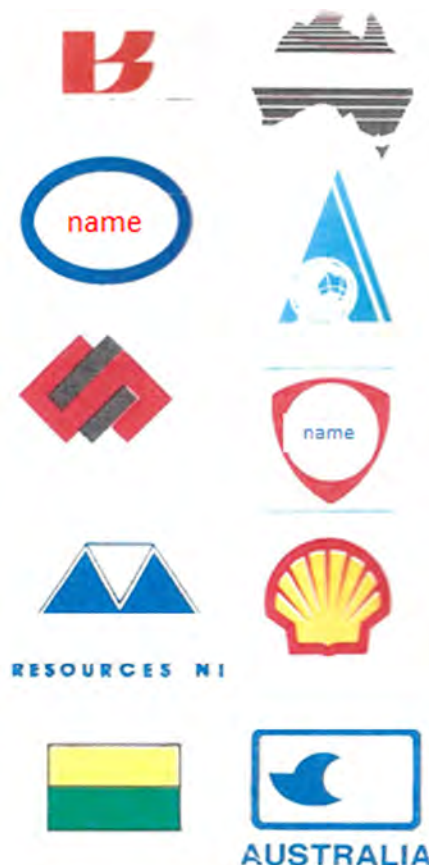


That's enough reminiscing so let's move on to asking what has been the most significant improvement over the last 40 years. I could say 3D seismic and everyone would probably agree but I will stick my neck out and go with velocity modelling. An accurate velocity model is crucial to obtaining a good image of the subsurface. It does no one any good to have a 3D volume of multiples and noise. Processing companies spend a huge effort to obtain the best velocity model possible because an accurate velocity model results in good time to depth conversion, multiple removal, flat gathers and the best possible migration.

Full Waveform Inversion (FWI) has become a mainstream process and can

produce detailed velocity profiles that conform to geological features. There are limitations such as the restricted depth of investigation and cost although the latter is being reduced as computing power becomes cheaper and faster. Another velocity related issue is anisotropy or variations in velocity dependent on the direction of travel. The inclusion of anisotropy parameters in the velocity model improves well ties and extends the number of useful traces at far offsets which possibly results in a better stack and constrains AVO inversion possibilities.

So, there you have it – there have been huge changes in the industry since I started but I think the most important change is the ability to create detailed and accurate velocity models.



Name the logo quiz - a bottle of red to the first person to correctly name the companies that used these logos. Hint: they were active at least 25 years ago. Reply to my email above.

Webwaves



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Lossless vs lossy compression

In the high bandwidth world, we find ourselves in today, you could be forgiven if you ignored data compression. However, with video streaming and social media viewing consuming internet traffic, data compression is just as important today as it was in the dial-up days of yesteryear.

There are two commonly used terms in data compression: lossless compression and lossy compression. Lossless compression uses a group of algorithms that allows the original data to be accurately reconstructed from the compressed. Lossy algorithms do not facilitate accurate reconstruction of the original data and there is some loss of information in the compression.

With compression, there is no right answer for how best to compress the data, with advantages and disadvantages of both lossy and lossless approaches. An approach can be considered based on the acceptable quality and size of the output data. For instance, on the web, priority may be given to lower resolution, lossy data formats to accelerate viewing. But repeated compression and decompression can result in information loss.

One of the most widely used lossy compression algorithms is the discrete

cosine transform (DCT), which was first published by Ahmed, Natarajan & Rao in 1974. The DCT uses a sum of different frequency cosine functions to express a finite sequence of data points. To those of us used to looking at seismic data, a good analogy is Fourier transforms and their uses. The JPEG image format uses DCT in a similar approach to resampling seismic data, with frequencies of interest retained and other frequencies rejected. Other lossy approaches include using discrete wavelet transforms (DWT) and modified discrete cosine transforms (MDCT).

Lossy compression is widely used both on the internet and on local machines. Multimedia files are commonly compressed with lossy compression algorithms, and file formats like JPEG, MP3, MP4 and MKV all represent files that have used a lossy algorithm. The benefit of lossy algorithms is that, when used judiciously, minimal degradation of the end product will occur, while being able to encode the data in a significantly smaller file. This has obvious benefits on the internet, resulting in faster loading times, and reduced network requirements. In this respect, some loss may be desirable to improve performance for the end user.

When it comes to lossless compression, text files are useful to consider. In a standard ASCII file, an 8-bit code is assigned to each character, resulting in a constant and expected file size based on the number of characters. Contrast this with Morse code, where common letters have fewer dots and dashes to be encoded. This naturally leads us to Huffman coding, whereby symbols are encoded based on the frequency of occurrence, with higher frequency symbols having shorter sequences, as in Morse code.

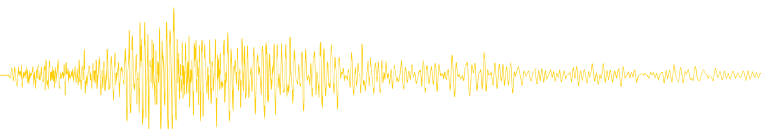
Should you have data in a lossy data format, converting the data to a lossless format offers limited gains, with no real benefit over keeping the data in the lossy format. Similarly, conversion between lossy formats results in increased loss of data if different algorithms are used.



Figure 1. a) Image from the 2018 photo competition, and featured on the Preview page of the website. Compressed as JPEG, file size of 116 KB. Minimal loss in the image is observed at this scale. b) Further compressed version of a). Format JPEG, file size 20 KB. Considerable loss of detail is observed by the additional compression.

In contrast, conversion between lossless formats performs well as the data is able to be reconstructed perfectly within the compression. For example, when the Microsoft Office suite moved to the *.x file extensions (e.g. .docx, .pptx), the files became compressed as a zip archive. As a result, compression of Microsoft Office documents offers little advantage in terms of file size.

On the ASEG website we use a variety of lossless and lossy compression algorithms in our media. With high quality imagery provided via the photo competition, some images are displayed at high resolution using lossless file formats, while other, non-critical content, is displayed using highly compressed lossy formats (see Figure 1). Videos hosted via YouTube, such as the talks that are published online, will also be compressed using Google's algorithms, with users able to choose their desired resolution when streaming them.



Don Emerson's best of *Exploration Geophysics*



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Memories. While admiring the detail of pixelated perfection in some recent magnetic images, I recalled some comments I made at the Applied Magnetic Interpretation Symposium held 42 years ago at the University of Sydney. I convened this meeting, which was well attended by over 100 geophysicists and geoscientists.

The Proceedings were published in 1979 in the *ASEG Bulletin* **10** (1) p 3-139. This is the first part of my introductory comments:

The subject of applied magnetism in hard rock environments has interested me for many years. Magnetic data are cheap and are employed by geophysicists and geologists in a variety of investigations including ore search, regional studies and lithological/structural elucidation. Most earth scientists, even academics, are familiar with magnetism. On reviewing the literature and perusing open file exploration company reports, one cannot help being struck by the imbalance between methodology and interpretation.

Let us look at interpretation; it is indeed a sad situation, a barren field. Often data are simply 'eyeballed' into a qualitative interpretation. Quantitative interpretations where attempted, often owe more to geometry than geology. They have an air of geological unreality about them as there is commonly little in the way of auxiliary control, corroboration and checking. It is unfortunate for geophysics in general and magnetism in particular that hypotheses are rarely tested. This leads to some very brave predictions or to inferences so qualified as to be useless or tautological. My comments, of course, do not apply to all interpretations. Examples of worthwhile published and unpublished interpretations are numerous, but overall they are in the minority. Let us consider what two eminent mathematical geophysicists have said about interpretation:

*"Although aeromagnetic data have been collected all over the world for the past 30 years at a total astronomical cost, it is safe to say that practically nothing is known of the physical characteristics of the rocks that produce the magnetic anomaly. The unpredictability of observed magnetic field over rocks where geology is 'known' reinforces this observation. In our opinion, one of the most significant studies that ought to be made in the immediate future is the relationship between mineralogy and petrology, rock magnetism and aeromagnetic anomalies". (I. Zietz & B.K. Bhattacharyya, Rev. Geophys. Space Phys., **13** (3), p 178-9, 1975)."*

*On the other hand, the methodological/computational side of magnetism is in a very healthy state. Indeed, magnetism seems to be suffering from computobabble; it is in danger of becoming a mausoleum of irrelevant methodologies. Instead of being concerned with eliciting meaningful geological information from field and laboratory magnetic measurements, many publishing geophysicists appear to devote themselves to methods and variations on computational themes rather than interpretation improvements. I wish to make it quite clear that I am not advocating censorship or discouragement of this type of study. Scientists, quite rightly, follow their own inclinations in their work and researches. Furthermore, without some of the brilliant recent methodological/computational advances, magnetism would be a very backward and limited discipline. What I do advocate is that geophysicists with a data interpretation bent be actively encouraged to publish and discuss their work. After all, that is what applied geophysics is all about - the solution of geological problems in understandable and meaningful terms. There is a great need to remedy the imbalance between interpretation and computation. The imbalance can be demonstrated by considering 136 hard rock magnetic papers published in *Geophysics* (a journal of very high standard) between 1962-1977.*

Twenty seven per cent of the papers were of the fundamental theoretical type - they were without exception, excellent and worthwhile. Also, twenty seven per cent comprised trivial, "me-too", elegant, mathematical variations on computational or methodological themes. Next, twenty six per cent consisted of good interpretation and case history papers tied into the geology. Then thirteen per cent comprised miscellaneous (instrumental etc.) papers. Finally, the very important petrophysical topics (susceptibility and remanence) accounted for only seven per cent. So it can be seen clearly that only one third of the papers were concerned directly with the true task of magnetism - solving or clarifying geological problems. I say categorically that such a proportion is far too low, and this is the reason for the Applied Magnetism Interpretation Symposium.

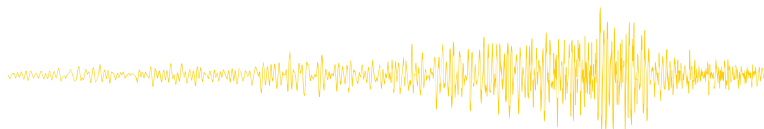
How things have changed with the substantial progress since then! Australian geophysicists feature prominently in the vanguard of excellent professionals who have advanced the practice of magnetism in data acquisition, presentation, and interpretation. Outstanding work has been carried out over the years by magnetic laboratories and groups in CSIRO, universities, government agencies, AMIRA projects, and companies.

The insightful work carried out by the CSIRO rock magnetisation group is especially significant. From their series of publications one, to me, is particularly noteworthy, namely: Dave Clark's contribution to meaningful interpretation of the magnetic petrology of igneous intrusions. A masterly overview (David A. Clark, 1999, Magnetic petrology of igneous intrusions: implications for exploration and magnetic interpretation, *Exploration Geophysics*, **30**:1-2, 5-26, DOI: 10.1071/EG999005). This is my BEST PAPER choice; it is a CLASSIC PAPER.

I commend it as refreshing re-reading to all interested in magnetic anomaly interpretation.

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Magnetic petrology of igneous intrusions: implications for exploration and magnetic interpretation

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Abstract

Magnetic petrology integrates rock magnetism and conventional petrology in order to define the processes that create, alter and destroy magnetic minerals in rocks. By relating magnetic mineralogy, bulk magnetic properties, petrology and geochemistry to observed magnetic anomalies an understanding of the geological factors that control magnetic signatures is obtained, which can be used to improve *geological* interpretation of magnetic surveys.

The magnetic properties of igneous intrusions, and hence the magnetic anomalies associated with them, reflect bulk rock composition, redox state, hydrothermal alteration and metamorphism. These geological variables are in turn controlled by tectonic setting, composition and history of the source region, depth of emplacement and nature of wall rocks. The fundamental control on magnetic mineralogy and bulk magnetic properties is partitioning of iron between silicate and oxide phases, which is strongly influenced by oxidation ratio. This paper reviews and synthesises information on relationships between the chemistry, mineralogy and metallogenic associations of igneous intrusions and their magnetic properties. Although links between magnetic properties and broad rock names are tenuous, refined rock classification enables magnetic properties to be predicted with reasonable confidence.

Oxidised, magnetite-series, and reduced, ilmenite-series granitoids have quite distinct metallogeny. Cu, Mo and Au are associated with oxidised granitoids and Sn with reduced granitoids. Fractional crystallisation, which has a distinctive magnetic expression, plays an important role in generating magmatic-hydrothermal ore deposits. Hydrothermal alteration profoundly affects magnetic properties, in a generally predictable fashion. Implications for interpretation of magnetic anomalies associated with igneous intrusions and recognition of magnetic signatures of potential intrusive-related ore deposits are adduced.

Keywords: magnetic petrophysics, magnetic petrology, magnetic anomalies, rock magnetism, interpretation of magnetic surveys, igneous intrusions, granitoids, granitoid-related mineralisation

Introduction

The magnetic method has been widely used in mineral exploration for decades. Recent improvements in magnetic data acquisition, processing and presentation and reduced airborne acquisition costs have increased the utility and importance of magnetic surveys, particularly high resolution aeromagnetic surveys. Increasingly, high quality surveys of large areas are becoming available at reasonable cost. This has led to increasing emphasis on magnetic methods in area selection and regional mapping, as well as prospect-scale mapping and drill targeting.

The mineral exploration industry has now reached a stage where the ability to acquire, process and present magnetic survey data far outstrips capacity to interpret the surveys. There is often far more geological information in these very large data sets than can be presently extracted in the time available for interpretation. Better understanding of the relationships between magnetic signatures and geology can facilitate the interpretation process and produce more reliable geological interpretations.

A crucial limitation of interpretation of magnetic surveys arises from the fundamental non-uniqueness of potential field source distributions. This ambiguity in source geometry can only be addressed by constraining models. The most important control on the reliability of magnetic models is information on magnetic properties. Understanding of the factors that determine magnetisation intensities and directions for the geological units within the survey area is essential for resolving geological ambiguity in order to produce a reliable interpretation of subsurface geology.

Igneous intrusions comprise a substantial portion of many geological provinces and intrusive-related mineralisation is a major exploration target. Information on the magnetic petrology of igneous intrusions should therefore assist geological mapping and an understanding of the relationships between magnetic properties and metallogenic associations of intrusions is important in exploration for intrusive-related ore deposits. Extensive background material that cannot be included in this summary paper can be found in Clark *et al.* (1992a).

Principles of magnetic petrology

What is magnetic petrology?

Magnetic petrology integrates rock magnetism and conventional petrology to characterise the composition, abundance, microstructure and paragenesis of magnetic minerals in order to define the processes that create, alter and destroy magnetic minerals in rocks. By relating magnetic mineralogy, bulk magnetic properties and petrology to observed magnetic anomalies an understanding of the geological factors that control magnetic signatures is obtained, which can be used to improve geological interpretation of magnetic surveys. Dunlop and Ozdemir (1997) have provided a comprehensive and up-to-date overview of rock magnetism. There is no corresponding textbook on magnetic petrology. Useful reviews of magnetic petrological principles have been given by McIntyre (1980), Grant (1985) and Frost (1991a). Clark *et al.* (1992b) presented several magnetic petrological case studies. Clark and Emerson (1991) summarised magnetic properties of rocks and some principles of rock magnetism and

magnetic petrology. Clark (1997) tabulated magnetic properties of rock-forming minerals, and reviewed general aspects of magnetic petrophysics and magnetic petrology.

Magnetic properties of rocks reflect the partitioning of iron in the rock between strongly magnetic oxides and/or sulphides and weakly magnetic phases (silicates, carbonates etc.). This partitioning depends on chemical composition, oxidation ratio of the iron, and petrogenetic conditions. Thus a host of geological factors influence magnetic properties and simplistic correlations between magnetic properties and lithotype are generally unreliable. It is dangerous to extrapolate empirical correlations between mapped geology and magnetics in one area to another area, ignoring changes in depositional environment, metamorphic grade or structural setting.

For the purposes of subsequent discussion, an informal classification scheme, based on rock susceptibility (k) is used. Igneous rocks are classified as

1. diamagnetic (DIA) if $k < 0$,
2. paramagnetic (PM) if $0 < k < 1260 \times 10^{-6}$ SI (100 $\mu\text{G}/\text{Oe}$),
3. weakly ferromagnetic (WFM) if 1260×10^{-6} SI $\leq k < 3770 \times 10^{-6}$ SI (300 $\mu\text{G}/\text{Oe}$),
4. moderately ferromagnetic (MFM) if 3770×10^{-6} SI $\leq k < 37,700 \times 10^{-6}$ SI (3000 $\mu\text{G}/\text{Oe}$),
5. strongly ferromagnetic (SFM) if $k \geq 37,700 \times 10^{-6}$ SI (3000 $\mu\text{G}/\text{Oe}$).

Diamagnetic igneous intrusions are extremely rare. The approximate magnetite contents corresponding to the ferromagnetic classes are: 0.02 vol % to 0.1 vol % for WFM intrusions, 0.1 vol % to 1 vol % for MFM intrusions and greater than 1 vol % for SFM intrusions. Rocks that have susceptibilities low enough to fall into the paramagnetic class contain at most trace amounts of ferromagnetic (*sensu lato*) minerals, such as magnetite or monoclinic pyrrhotite. In these rocks, the measured susceptibility is generally dominated by contributions from paramagnetic minerals. Because paramagnetic minerals do not carry any remanent magnetisation, the remanent magnetisation of PM intrusions is very weak. Ferromagnetic intrusions, on the other hand, may carry significant remanence.

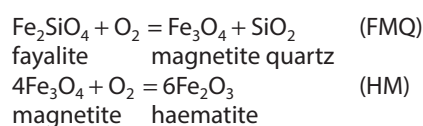
The concept of oxygen fugacity

Standard textbooks on petrology treat the concept of oxygen fugacity in a geological context. Oxygen fugacity ($f\text{O}_2$) is measured in units of pressure and is formally defined as the chemical activity of oxygen. Apart from a small correction due to departures from ideal gas behaviour, $f\text{O}_2$ is equal to the partial pressure of oxygen gas. It should be noted that the abundance of free oxygen is vanishingly small in magmas and hydrothermal fluids. Nevertheless, $f\text{O}_2$ is a well-defined thermodynamic variable that can be controlled in the laboratory and can be deduced from mineral assemblages. Frost (1991b) has recently clarified some common misconceptions about oxygen fugacity and given an unusually clear and succinct treatment of the subject.

Iron, which is the fourth most abundant element in the Earth's crust, exists in three oxidation states: metallic (Fe^0), ferrous (Fe^{2+}) and ferric (Fe^{3+}) iron. Oxygen fugacity is a variable that strongly influences the propensity for iron to occur in a particular oxidation state. At very low oxygen fugacities, such as in the Earth's core, in some serpentinised ultramafic rocks, and in a few exceptionally reduced lavas that have reacted with carbonaceous material, iron occurs as the native metal. Iron

occurs in the divalent ferrous state at higher oxygen fugacities. In silica-bearing systems the ferrous iron is incorporated mainly into silicate minerals. With increasing oxygen fugacity, iron occurs in both the divalent and trivalent states and is incorporated into magnetite as well as silicates. At still higher oxygen fugacities, iron occurs in the ferric state and is incorporated into haematite. Note that the relative terms "low" and "high" $f\text{O}_2$ depend strongly on temperature (T). At 500°C an oxygen fugacity of 10^{-15} bar is strongly oxidising for most minerals, but at 1000°C the same $f\text{O}_2$ would correspond to very reducing conditions.

In the system Fe-O-SiO₂, the fayalite-magnetite-quartz (FMQ) buffer marks the lower oxygen fugacity limit for the stability of magnetite and the haematite-magnetite (HM) buffer marks the upper oxygen fugacity limit (Figure 1). The corresponding reactions are:



Whether or not magnetite is precipitated from an igneous melt that is cooling along a particular T - $f\text{O}_2$ path depends on the overall composition of the melt. For example, substitution of Mg for Fe in silicate minerals stabilises them to higher oxygen fugacity (Frost and Lindsley 1991). In particular, addition of Mg reduces the activity of fayalite in olivine, thereby shifting the equilibrium in the FMQ reaction to the left. As a result, small amounts of magnetite and quartz react to produce fayalite, thereby partially restoring the fayalite activity, plus oxygen, which increases the oxygen fugacity. Thus the olivine-magnetite-quartz buffer is displaced upwards from FMQ and the stability field of magnetite is restricted. At higher Mg contents, this simple picture is complicated by reaction of Mg-rich olivine with quartz to produce orthopyroxene + magnetite. Thus, as shown in Figure 2, at high temperatures the oxygen fugacity of the Mg-rich Fe-O-SiO₂-MgO system is defined by either a quartz-orthopyroxene-magnetite buffer curve (if the melt is saturated in quartz) or an olivine-orthopyroxene magnetite buffer curve (if the melt is olivine-

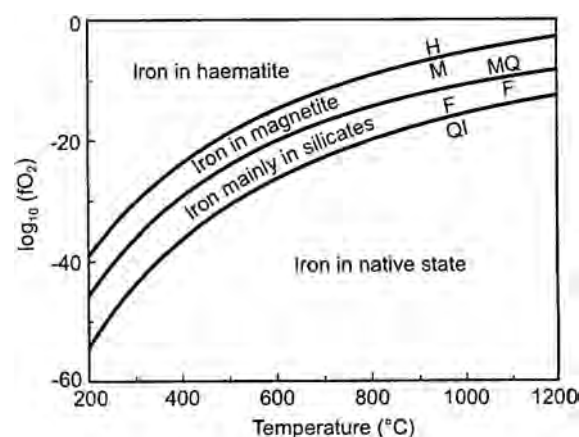


Figure 1. Plot of oxygen fugacity, expressed as $\log_{10}(f\text{O}_2)$, versus temperature showing the relative stabilities of the various oxidation states of iron in the system Fe-Si-O (after Frost 1991b). Below the quartz-iron-fayalite (QIF) buffer iron is present as Fe^0 ; between IQF and the fayalite-magnetite-quartz (FMQ) buffer iron occurs in the ferrous (Fe^{2+}) oxidation state; between FMQ and the haematite magnetite (HM) buffer iron occurs in both ferrous and ferric (Fe^{3+}) oxidation states; and above HM iron is in the ferric state.

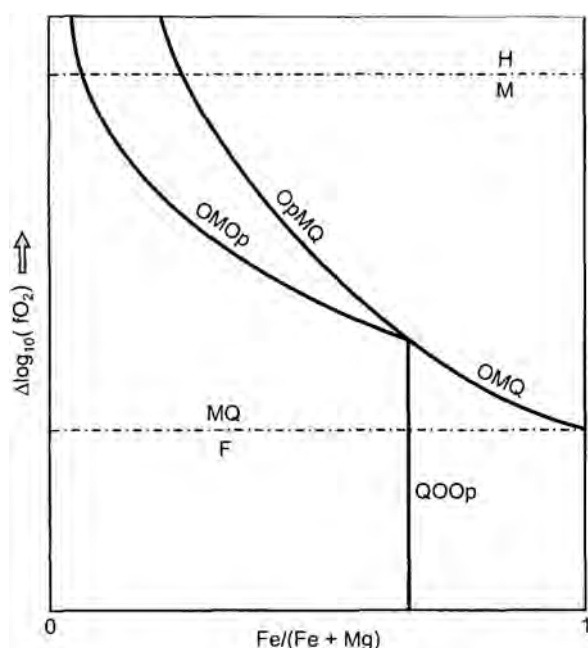


Figure 2. Schematic $\Delta\log_{10}(fO_2)$ versus $Mg/(Fe + Mg)$ diagram showing effects of adding MgO to the Fe-Si-O system at a fixed temperature (after Frost and Lindsley, 1991). OMQ=olivine-magnetite-quartz, QOOp=quartz-olivine-orthopyroxene, OpMQ=orthopyroxene-magnetite-quartz, OMOp=olivine-magnetite orthopyroxene, OHQ=olivine-haematite-quartz, OHOp=olivine-haematite-orthopyroxene. The parameter $\Delta\log fO_2$ is defined as $\log_{10}(fO_2) - \log_{10}(fO_2: FMQ)$. The values of $\Delta\log_{10}(fO_2)$ for the FMQ and MH buffers are shown for reference. Note that these equilibria become displaced towards higher absolute fO_2 as $Mg/(Mg + Fe)$ increases, because Mg preferentially enters olivine over magnetite and magnetite over haematite.

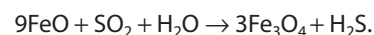
saturated). It is evident from Figure 2 that higher Mg content of a melt tends to restrict the occurrence of magnetite to higher oxygen fugacities.

On the other hand, substitution of ferrous iron + titanium for ferric iron in titanomagnetite reduces the activity of magnetite and displaces the fayalite-titanomagnetite-quartz equilibrium downwards with respect to FMQ. Thus, titanomagnetite is stable in igneous rocks at lower oxygen fugacities than is end-member magnetite. Similarly, because Ti substitutes even more readily into haematite than into magnetite, addition of Ti to the system displaces the HM buffer to lower fO_2 .

For many plutonic rocks that behave essentially as closed systems during their history, in particular many tholeiitic rocks, the Fe/Mg ratio of the silicates, plus the Ti content and the ferrous/ferric ratio of the oxides, monitor and, in effect, control the oxygen fugacity. In this case the cooling history of the rock is characterised by a path in fO_2 -T space that is approximately parallel to the standard mineral-buffered curves. In turn the oxygen fugacity influences the composition of the fluid phase and the stability of graphite and sulphides in such igneous rocks.

Fluid buffering, rather than mineral buffering, of oxygen fugacity is evidently important during hydrothermal processes that have large fluid-rock ratios. Fluid buffering may also play a role in some magmatic processes. If the initial volatile content of the magma is sufficiently high, the oxygen fugacity may be largely controlled by the fluid phase, rather than by the ferric and ferrous iron contents of the melt and the crystallising minerals. Takagi and Tsukimura (1997) suggest that the SO_2 - H_2S buffer may be important in the evolution of oxidised granitic

rocks, provided the initial SO_2 content of the magma is greater than 250 ppm. Because this buffer curve lies below the FMQ buffer at high temperatures, but intersects FMQ at $\sim 850^\circ C$ and lies well above FMQ at lower temperatures, it represents a relatively oxidising cooling trend that in principle can oxidise ferrous iron in silicates to magnetite via the reaction:



in silicates

Takagi and Tsukimura (1997) calculate that initial SO_2 contents of 250-1900 ppm by weight as the dominant sulphurous species are required to precipitate 0.2-1.5 vol % magnetite from granitic melts and show that other fluid buffers, e.g. H_2 - H_2O , CO_2 - CH_4 , or CO_2 - CO , cannot produce the oxidising trends that are inferred for many calc alkaline granitic rocks. The general relevance of sulphur dioxide buffering of melts is still an open question, however, because the primary contents of sulphur species and other volatile phases in magmas is poorly known (P. Blevin, pers. comm). Reported sulphur contents in granitoids are lower than the values that are required to produce substantial magnetite, but this may reflect significant late-stage loss of sulphur carried away by hydrothermal fluids, which sometimes produce related sulphide ore deposits.

Frost (1991b) points out that there can be no *unique* correlation between fO_2 during rock formation and Fe^{3+}/Fe^{2+} of the rock. For example, rocks that contain the same mineral assemblages must have formed at similar fO_2 , but if they have very different abundances of the iron bearing minerals, they may have very different absolute and relative abundances of ferrous and ferric iron. However, oxygen fugacity of melts and glasses is simply dependent on chemical composition, in particular the relative abundance of ferrous and ferric iron. Similarly, in the case of volcanic rocks that are relatively free of cumulate minerals fO_2 can be calculated at a given temperature and pressure, corresponding to crystallisation conditions midway between the liquidus and solidus for the rock, from the whole rock chemical composition, including ferrous and ferric iron. Kress and Carmichael (1991) show that the Fe^{3+}/Fe^{2+} ratio is by far the most important term in the relationship between fO_2 and chemical composition of volcanic rocks.

Blevin (1994) has shown that ferric/ferrous iron ratios in granitoid rocks are also very highly correlated with oxygen fugacity as calculated from the chemical composition (and confirmed by mineral assemblages that are dependent on oxygen fugacity). Thus Fe^{3+}/Fe^{2+} , often measured as $Fe_2O_3/(FeO + Fe_2O_3)$, can in practice be used as a proxy for oxygen fugacity in granitoids, in spite of the theoretical possibility that the nexus between oxidation state and fO_2 might be broken for rocks that formed under very different conditions or that have exotic compositions.

Figure 3(a) plots isopleths in fO_2 - T space for various titanomagnetite and ilmenite compositions, with the FMQ and HM buffers shown for comparison. Titanomagnetites are solid solutions of magnetite, i.e. $Fe^{3+}[Fe^{2+}Fe^{3+}]O_4$, and ulvöspinel, $Fe^{2+}[Fe^{2+}Ti^{4+}]O_4$, whereas natural ilmenites invariably incorporate some haematite, $Fe^{3+}_2O_3$, in solid solution with ilmenite, $Fe^{2+}Ti^{4+}O_3$. The square brackets indicate octahedral cations in the spinel phases. Note that the titanomagnetite isopleths are quite oblique to the oxygen buffer curves, whereas the ilmenite isopleths are subparallel to the buffers. This implies that as an igneous melt cools and solidifies along a trajectory that is approximately parallel to FMQ, the stable

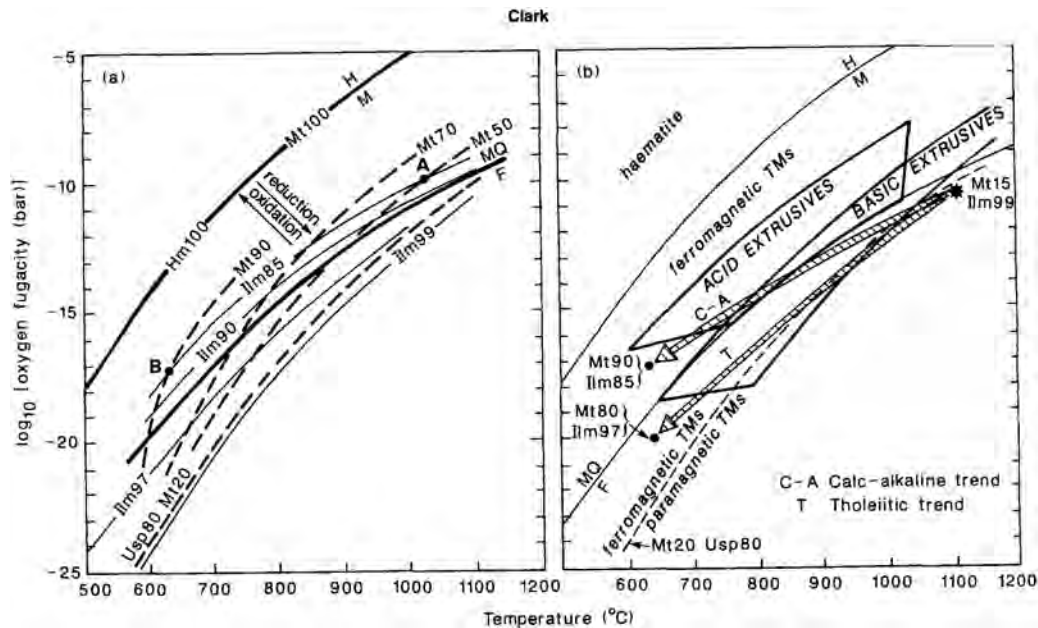


Figure 3. (a) Isoleths for various titanomagnetite and ilmenite compositions, plotted in fO_2 -T space. The FMQ and HM buffers are shown for comparison. (b) Contrasting tholeiitic and calc-alkaline cooling trends in fO_2 -T space for an initially reduced ($\log_{10}[fO_2] = FMQ - 1$), high temperature magma that is in equilibrium with Mt15 and Ilm99. The re-equilibrated Fe-Ti oxide compositions at $\sim 600^\circ\text{C}$ for the two cooling trends are indicated. The dashed line indicates the boundary between the stability fields of ferromagnetic (sensu lato) and paramagnetic titanomagnetites. The fields representing fO_2 -T conditions recorded by Fe-Ti oxides in basic and acid extrusive rocks (Haggerty 1976) are also shown.

titanomagnetite composition evolves from very ulvospinel-rich at high temperatures to magnetite-rich at subsolidus temperatures. Corresponding changes in ilmenite composition are less pronounced. For example, a relatively oxidised melt at $\sim 1000^\circ\text{C}$ (point A in Figure 3(a)) may be in equilibrium with Fe-Ti oxide compositions of 50 mole % magnetite-50 mole % ulvospinel (Mt50) and 85 mole % ilmenite-15 mole % haematite (Ilm85). If this magma cools slowly along the Ilm85 isopleth, which almost parallels FMQ, the ilmenite composition remains unchanged, but the equilibrium titanomagnetite composition at $\sim 600^\circ\text{C}$ (point B) evolves to Mt90.

The final titanomagnetite composition found in the rock depends on the initial redox state of the magma (relatively oxidised magmas initially crystallise titanomagnetites with lower Ti than more reduced magmas) and the temperature at which the titanomagnetite composition is "frozen in", which depends on cooling rate. Rapidly cooled volcanic rocks quench in relatively titaniferous compositions that are metastable at low temperatures. On the other hand, in slowly cooled intrusions, oxide mineral compositions continue to re-equilibrate well below the solidus, producing titanomagnetites with progressively lower Ti, until the increasingly sluggish kinetics of Fe and Ti exchange between oxide phases inhibits further change. Furthermore, slowly cooled titanomagnetites tend to exsolve into intergrowths of magnetite-rich and ulvospinel-rich phases.

The magnetic properties of titanomagnetites depend on composition. Titanomagnetites with more than 80 mole % ulvospinel are paramagnetic at ambient temperatures and have very low susceptibility. Compositions with less Ti are ferromagnetic *sensu lato*. Consider a reduced ($\log_{10} [fO_2] = FMQ - 1$), high temperature magma that is in equilibrium with Mt15 and Ilm99. If this magma were cooled very rapidly by being extruded onto the ocean floor, for example, the quenched titanomagnetite would be

paramagnetic. However, if the magma is emplaced at depth and cools slowly, following a typical tholeiitic fO_2 -T cooling trend as shown in Figure 3(b), the Fe-Ti oxides re-equilibrate attaining compositions of Mt80 and Ilm97 by $\sim 600^\circ\text{C}$. If this titanomagnetite composition is metastably stranded upon further cooling, the titanomagnetite is ferromagnetic at ambient temperature and greatly enhances the susceptibility of the rock. Thus, ferromagnetic titanomagnetites may form even under relatively reducing conditions, provided the cooling is sufficiently slow. Figure 3(b) also shows an alternative, more oxidised, cooling trend that is characteristic of calc-alkaline magmas. Even though fO_2 decreases strongly with falling T, the calc-alkaline path falls more slowly than the FMQ buffer, so the system evolves to a relatively oxidised state that is in equilibrium with more oxidised mineral assemblages. In particular, the equilibrium Fe-Ti oxide compositions at $\sim 600^\circ\text{C}$ are Mt90 and Ilm85 for the calc-alkaline trend. Figure 3(b) is schematic, because initial magmatic conditions and cooling paths can vary substantially, but it serves to illustrate qualitative trends. Initial conditions of calc-alkaline magmas are generally more oxidising than those of tholeiitic magmas, so the final Fe-Ti oxide compositions may be even more oxidised than indicated in Figure 3(b). The fields representing fO_2 -T conditions recorded by Fe-Ti oxides in basic and acid extrusive rocks (Haggerty 1976) are also shown in Figure 3(b).

Figure 4 plots the range of titanomagnetite compositions found in the major types of igneous rock. Note the tendency for decreasing Ti content of titanomagnetite, i.e. more magnetite-rich compositions, for more felsic compositions. There is also a clear tendency for lower Ti contents in titanomagnetites from intrusive rocks than for their extrusive analogues, reflecting greater re-equilibration during cooling for intrusive rocks. Paramagnetic titanomagnetite compositions are rare and are only found in a few mafic extrusive rocks with primitive compositions. The inferred primary magnetite composition of the Skaergaard gabbros,

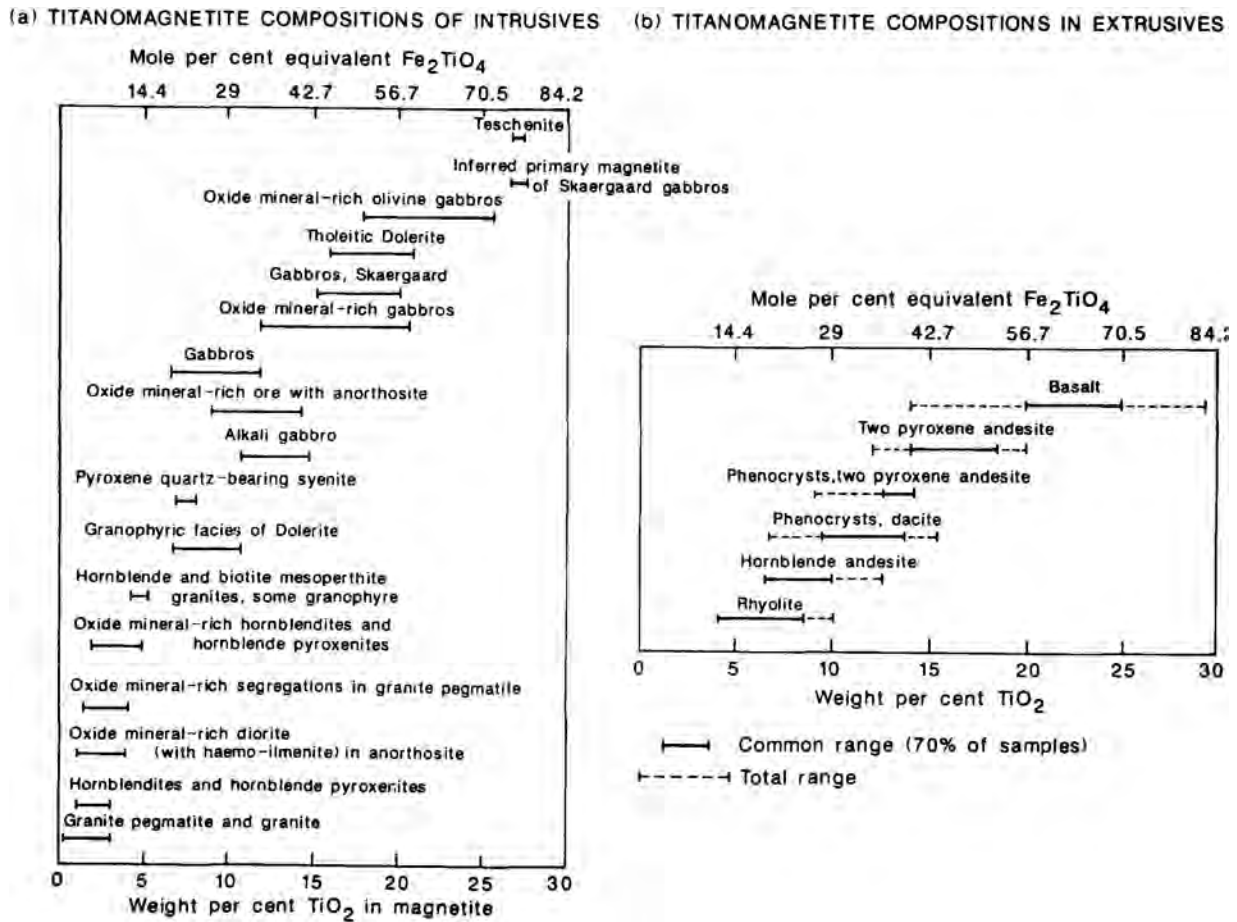


Figure 4. Range of titanomagnetite compositions found in the major types of igneous rock (after Buddington and Lindsey 1964).

derived by reconstituting magnetite-ulvospinel intergrowths within single grains, is very Ti-rich and is close to a paramagnetic composition. However exsolution of primary titanomagnetite into relatively Ti-poor magnetite, which is ferromagnetic, and paramagnetic ulvospinel (or ilmenite, if oxidation-exsolution occurs) during slow cooling produces grains that are ferromagnetic overall. Although the saturation magnetisation of titanomagnetites depends strongly on composition, decreasing almost linearly from 480 kAm^{-1} for pure magnetite to zero for Usp80, the susceptibility is only weakly dependent on Ti content for ulvospinel contents of less than ~70% (Clark 1997). Thus the titanomagnetites carried by igneous rocks, ranging from gabbroic to granitic compositions, are almost invariably ferromagnetic and the susceptibility of the rock is essentially proportional to the modal titanomagnetite (allowing for intergrown paramagnetic phases in composite grains) and only weakly dependent on titanomagnetite composition. This conclusion differs from that of Grant (1985), who assumed that titaniferous magnetites have much lower susceptibilities than Ti-poor magnetite.

Relationship between lithology and magnetic properties

The data of Figures 5 and 6 are based on magnetic property measurements at the CSIRO Division of Exploration and Mining over the last 18 years and published studies and compilations. The systematic collection of petrophysical data by the geological surveys of Scandinavian countries, in particular, has greatly expanded the quantity and scope of the information available. It is evident from Figure 5 that each rock type exhibits a wide range of susceptibilities and that susceptibility values are not generally diagnostic of lithology. Classical rock names

are in fact much too broad to be useful for classification of magnetic properties. This is because the susceptibility of most rocks reflects the abundance of accessory minerals, particularly magnetite (*sensu lato*), which are generally ignored in petrological classification.

Koenigsberger ratios (Q) can also vary quite widely (see Figure 6), but useful rules-of-thumb can be stated. Ferromagnetic intermediate to felsic granitoid rocks contain multidomain magnetite, which is associated with Koenigsberger ratios less than unity (usually $Q < 0.5$, typically $Q \sim 0.2$). Furthermore, the remanence carried by such grains is generally unstable and is dominated by viscous remanence acquired in the recent field. However some, but not all, gabbros, norites and mafic diorites contain ultrafine pseudosingle domain to single domain magnetite hosted within silicate minerals, such as pyroxenes, olivine or plagioclase, as well as discrete multidomain grains. The ultrafine ($< 10 \mu\text{m}$) grains are capable of carrying intense remanence and these rocks may accordingly exhibit Q values substantially greater than unity. Thus, magnetisation by induction can be assumed as a first approximation for the more felsic granitoids, whereas remanent magnetisation, possibly oblique to the present field, may be significant for mafic plutonic rocks.

Bimodal susceptibility distributions reflect ferromagnetic and paramagnetic populations

A notable feature of Figure 5 is that the magnetic susceptibilities of a number of rock types have distinctly bimodal distributions.

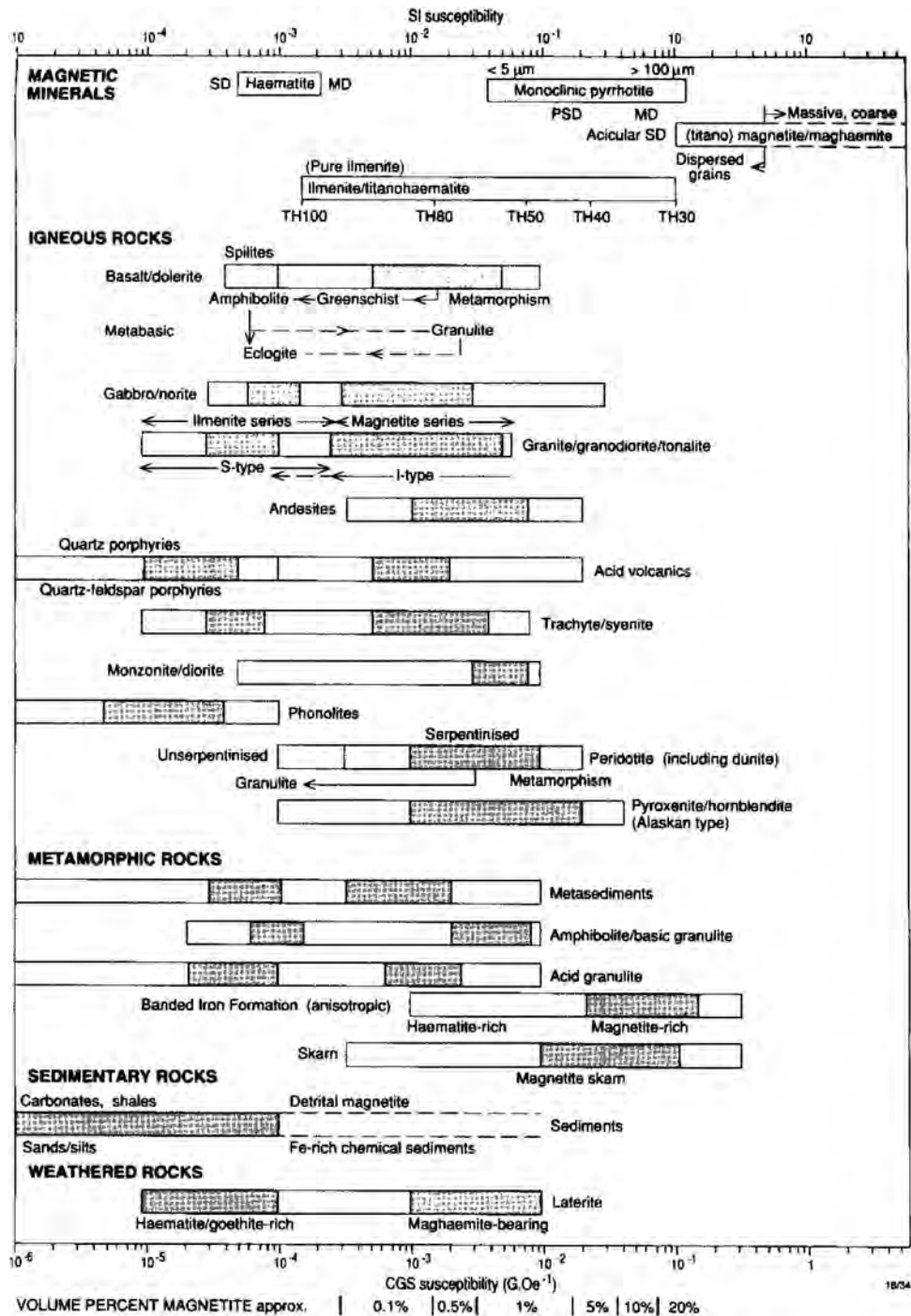


Figure 5. Range of magnetic susceptibilities for important magnetic minerals and major rock types. Stippled portions of bars indicate common susceptibility ranges for various lithologies. Note the bimodal susceptibility distributions for many rock types.

Puranen (1989) presented results from very large petrophysical sampling programs in Finland. His data confirmed that all broad field names, such as "granite," "gabbro," "mica schist," "amphibolite" etc., exhibit distinctly bimodal susceptibility distributions. Figure 7 shows frequency distributions of susceptibility for major intrusive rock types, based on Puranen's data. The two modes of the frequency distribution correspond to distinct paramagnetic and ferromagnetic populations, with a pronounced intervening gap. Iron in the weakly magnetic subpopulation is incorporated into paramagnetic silicate minerals, predominantly as Fe^{2+} , whereas similar rocks that are moderately to strongly magnetic contain significant Fe^{3+} , which is incorporated into magnetite.

Very highly oxidised rocks, however, tend to contain haematite rather than magnetite and are therefore also weakly magnetic. Within each of the subpopulations, the modal and mean values of susceptibility are much more closely related to rock type than for the total susceptibility distribution. For the paramagnetic subpopulation, in particular, the susceptibility is directly related to the chemical composition, which tends to have a restricted range for each lithology. Clark and Emerson (1991) give the relationship between iron content and susceptibility for paramagnetic rocks and between magnetite content and susceptibility for rocks that contain more than ~ 0.1% magnetite by volume.

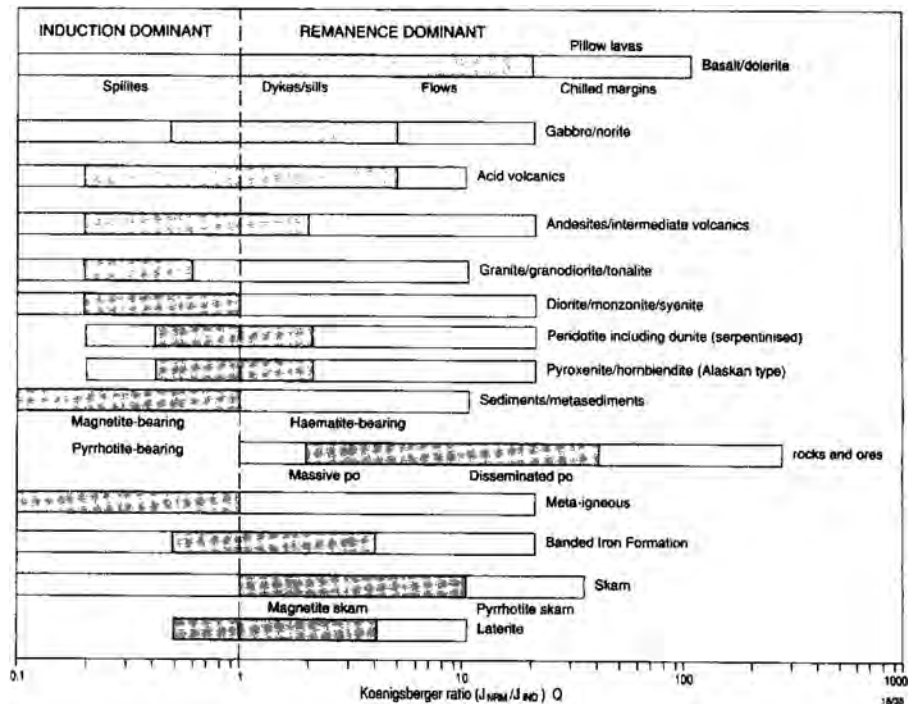


Figure 6. Range of Koenigsberger ratios for common rock types. Stippled portions of bars indicate common ranges.

When varietal mineralogy is incorporated into a refined rock classification, the bimodal susceptibility distribution tends to resolve into a paramagnetic subpopulation and a ferromagnetic subpopulation, each associated with a distinct mineralogy. Bimodality often also reflects the fact that important geological factors, such as geochemical affinity, alteration and metamorphic grade are not considered in the simple classification schemes used for most petrophysical summaries. A truly meaningful magnetic petrological classification scheme must include chemical and/or mineralogical data for protoliths, plus information on metamorphic grade and environment, and/or alteration.

Similarly, when susceptibility distributions are considered on progressively smaller scales, the range of susceptibilities becomes more restricted. Within different geological provinces, the relative proportions of paramagnetic and ferromagnetic subpopulations differ from those of other provinces. It is often found that within sufficiently small areas, e.g. within a particular geological environment or simply within a single outcrop, all susceptibilities fall exclusively within one of the subpopulations. Thus, the distinct susceptibility subpopulations tend to reflect differing geological conditions, which are not considered in the primary rock classification schemes.

Classification of intrusive igneous rocks

IUGS classification of plutonic rocks

The internationally accepted IUGS classification of mafic to felsic plutonic rocks (Le Bas and Streckeisen 1991) is simply based upon the relative proportions of three major rock forming minerals: plagioclase ($> \text{An}5$); alkali feldspar (K-feldspar and albite); and either quartz (in oversaturated rocks) or a feldspathoid mineral, most commonly nepheline, in the case of an undersaturated rock. Figure 8 shows the fields and rock names on the QAPF double triangle. Ultramafic rocks, for which mafic minerals constitute 90% to 100% of the rock, are classified separately.

Given the fact that, in extreme cases, up to 90% of the mineral content of the rock may be ignored in the first-order classification, it is little wonder that magnetite abundance, for instance, is weakly correlated with rock name. It is also clear that there can be no unique correlation between rock name and bulk chemistry, given the wide range and variety of minor minerals that can be present within any one of the rock type fields. Of course, the classification is so useful and widely accepted because there are coherent patterns of mineralogical and chemical variation among plutonic rocks. Figure 9 illustrates some aspects of this coherency. A generalised plot of mineral composition for the full range of plutonic rock types is shown in Figure 9(a). Figure 9(b) shows average trends in plagioclase composition, mafic mineral contents and hornblende/biotite ratio in granitoid rocks, showing systematic variation with position in the QAP diagram.

Spatially related plutonic rock series show clear mineralogical and chemical correlations with tectonic environment and relative time of emplacement, as shown in Figure 10. These various rock associations are characterised by different metallogeny and can be related to magnetic petrology much more reliably than to the broad IUGS rock names. This has implications for exploration, as use of magnetic methods for locating intrusion-hosted or intrusion related mineralisation requires better understanding of the relationship between rock magnetisation and the geological factors that influence mineralisation.

Chemical classification of plutonic rocks

The following summary of chemical classification schemes for plutonic rocks is largely based on the excellent textbook by Hughes (1982).

Feldspars are the commonest minerals in igneous rocks, in which they constitute more than 50%, on average. Alumina occurs in a 1:1 ratio with oxides of the alkali metals or alkaline earth elements in feldspars. Thus departures

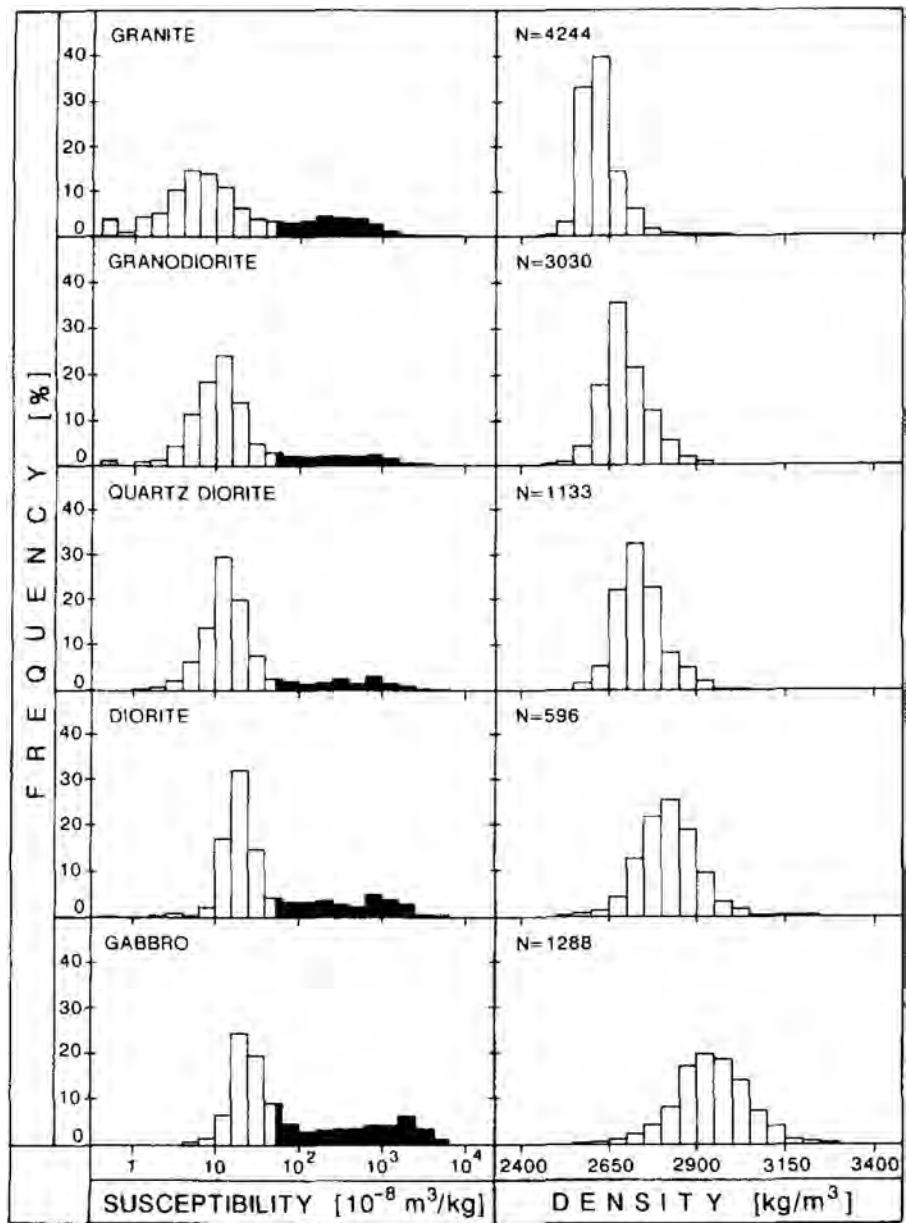


Figure 7. Histograms of SI mass susceptibility and density for plutonic rock types from Finland (after Puranen 1989). Note the unimodal density distribution contrasting with the bimodal susceptibility distribution. The ferromagnetic subpopulation is shown as black; the small proportion of diamagnetic samples is shown hatched. To convert mass susceptibility to SI volume susceptibility, multiply by the density in kg/m³.

from this ratio cannot be accommodated by varying the feldspar compositions or relative proportions, but must be expressed in the varietal mineralogy. Peraluminous rocks are oversaturated with respect to alumina, i.e. molar Al_2O_3 (A) exceeds the sum of $\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO}$ (denoted $\text{A}/\text{CNK} > 1$), and are characterised by aluminous minerals, such as corundum (rarely), andalusite, sillimanite or kyanite, almandine garnet or, most commonly, muscovite. *Peralkaline* rocks, on the other hand, contain insufficient alumina to consume all of the sodium and potassium in feldspars, i.e. molecular Al_2O_3 is less than $\text{Na}_2\text{O} + \text{K}_2\text{O}$ ($\text{A}/\text{NK} < 1$). Such rocks are characterised by minerals of the aegirine, riebeckite, arfvedsonite or aenigmatite classes. *Metaluminous* rocks are intermediate in alumina saturation, such that all the alumina, soda and potash can be accommodated in feldspars, with excess calcium appearing in the norm as diopside and in the mode as calcium-bearing pyroxene, amphibole etc. Peraluminous chemistry may result either from high Al content, or from low levels of Na, K or Ca.

For example, mature sedimentary rocks, their metamorphic equivalents, and granitic rocks derived from partial melting of the metasediments are peraluminous because of the severing of the nexus between alumina and Na+Ca during the sedimentary cycle. Sodium is partitioned strongly into seawater and calcium into carbonates, leaving sedimentary rocks with excess alumina.

Quartz is a major constituent of many igneous rocks, and its presence or absence is a very significant petrological characteristic. Many minerals exhibit a clear sympathetic or antipathetic association with quartz. *Oversaturated* rocks contain free quartz, together with oversaturated (compatible) minerals (e.g. Al- and Ti-poor pyroxenes, feldspars, amphiboles, micas, fayalitic olivine). *Undersaturated* rocks contain undersaturated minerals that are antipathetic to quartz (e.g. nepheline, magnesian olivine, sodalite, leucite, Al- and Ti-rich augite).

The abundance of Na and K exerts a strong influence on the silica saturation state. In feldspars, every molecule of soda or

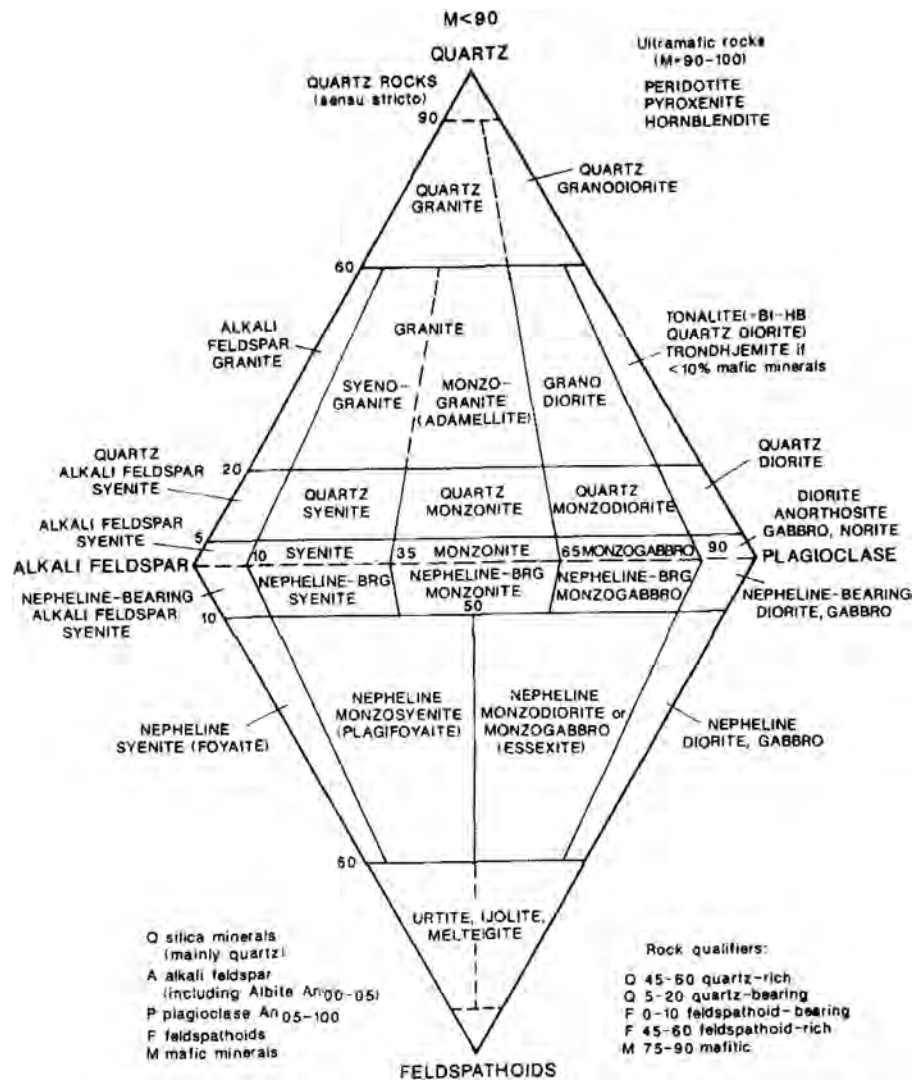


Figure 8. IUGS classification of plutonic rocks, based on the QAPF double triangle (Le Bas and Streckeisen, 1991). Q=quartz, A=alkali feldspar, P=plagioclase, F=feldspathoid (foid), M=mafic minerals, BI=biotite, HB=hornblende. Rock qualifiers are specified in terms of modal percentages. Ultramafic rocks, for which mafic minerals constitute 90% to 100% of the rock, are classified separately.

potash in feldspars consumes six molecules of silica, whereas CaO only consumes two. Thus alkaline rocks, with relatively high Na and/or K for their silica content, have no excess silica to form a free silica phase and are undersaturated. The thermodynamic parameter, silica activity, is strongly dependent on the alkali content for this reason. As an example, alkali basalts are silica undersaturated and are characterised chemically by normative nepheline. Undersaturated magnesian olivine is relatively abundant in these basalts, whereas tholeiitic basalts are silica saturated, with hypersthene in the norm. Olivine, if present, is in a reaction relationship to ferromagnesian pyroxene and was therefore out of equilibrium with the tholeiitic magma.

An important geochemical classification of igneous rock series is based upon Peacock's (1931) alkali-lime index (ALI), which is a measure of the relative alkalinity of a rock series derived by igneous differentiation from a parental magma. With increasing differentiation, accompanied by increasing silica content, CaO decreases while Na₂O and K₂O increase. There is a value of silica content, therefore, where the trend of CaO plotted against SiO₂ intersects the trend of Na₂O + K₂O versus SiO₂. This SiO₂ value (in weight per cent) is the alkali-lime index, and is lower for more alkaline rock series. Rock series are classified on the basis of their

alkali-lime index into one of four categories: alkalic (ALI < 51), alkali-calcic (ALI = 51-56), calc-alkalic or calc alkaline (ALI = 56-61) and calcic (ALI > 61), as shown in Figure 11(a).

Examples of igneous rock series representing each of the ALI categories include: tholeiitic basalts (calcic); basalt andesite-rhyolite series (calc-alkalic); alkali basalt-phonolite series (alkali calcic), and alkali syenite complexes (alkalic). The ALI provides a measure of the maturity of volcanic arcs, with igneous rock series tending to evolve from early mantle derived, calcic magmatism, through calc-alkalic orogenic magmatism, reflecting crust-mantle interactions, to post orogenic alkali-calcic or anorogenic alkalic magmatism.

Figure 11(b) shows a major difference in the behaviour of iron during differentiation of tholeiitic and calc-alkaline magmas. On a ternary plot of MgO, total iron and alkalis (AFM diagram) tholeiitic magmas show a pronounced initial iron enrichment trend, reflecting early crystallisation of Mg rich olivine and pyroxenes. This trend is typical of many layered mafic complexes (e.g. the Skaergaard, Stillwater and Bushveld Complexes), for which the parental mantle-derived magma is anhydrous and relatively reduced. The initial oxygen fugacity in such magmas

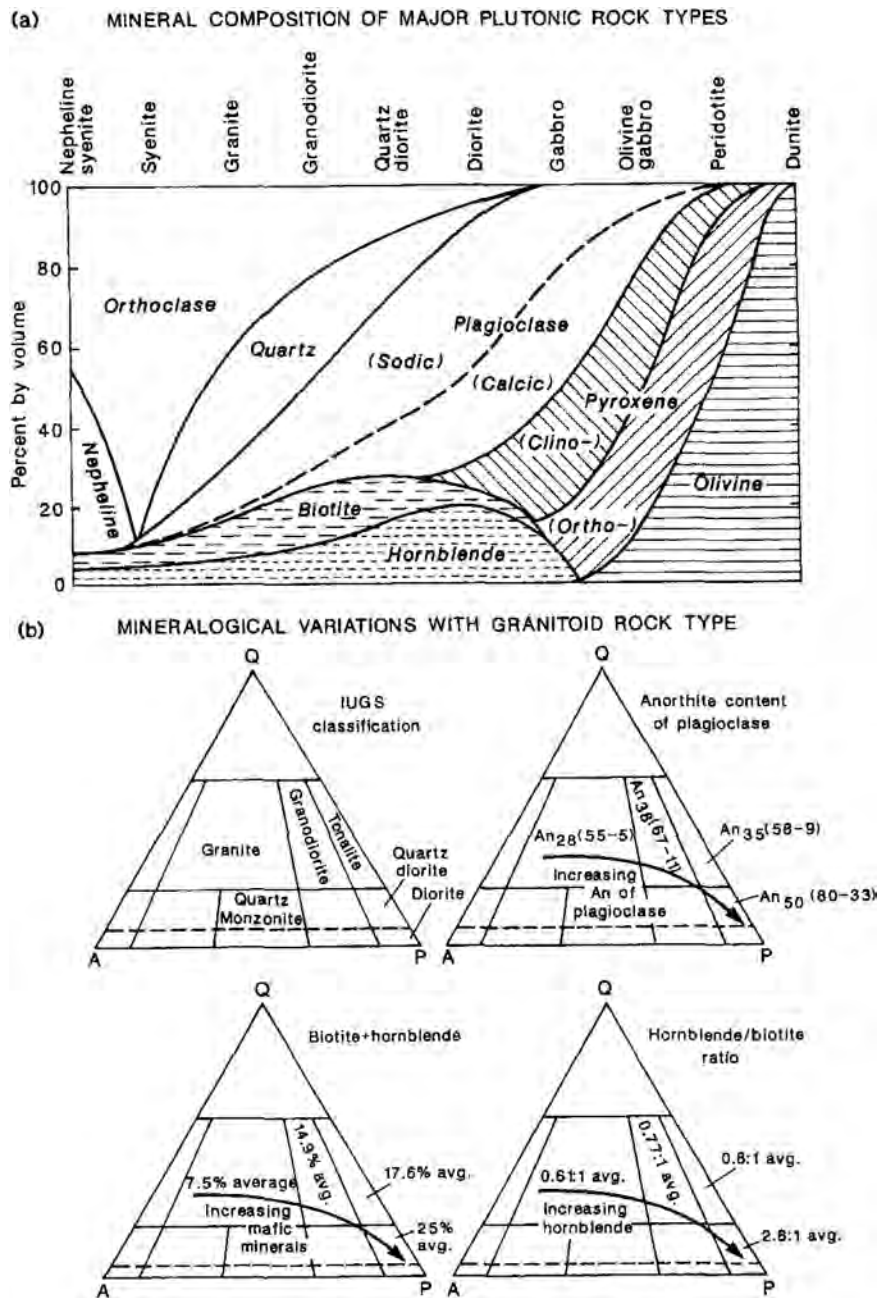


Figure 9. (a) Generalised plot of mineral composition for the full range of plutonic rock types (after Washington and Adams 1951). (b) Average trends in plagioclase composition (expressed as average and range of anorthite contents (%)), mafic mineral contents and hornblende/biotite ratio in granitoid rocks, showing systematic variation with position in the QAP diagram (after Hyndman, 1972).

is too low to precipitate magnetite. The early-crystallising spinel phase in these intrusions is chromite. As fractional crystallisation proceeds, ferrous iron is increasingly sequestered in silicates and removed from the residual melt, whereas nearly all the ferric iron remains in the melt as the magma composition evolves along the iron-enrichment trend. Thus the $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio steadily increases in the melt until the point is reached when magnetite can precipitate. The differentiation trend then turns towards the alkali apex of the AFM diagram as iron is removed from the melt in magnetite. In layered complexes, therefore, the primary ultramafic rocks near the base and the overlying lower gabbros are magnetite-free and have susceptibilities in the paramagnetic range. Overlying, more differentiated, gabbros, norites and anorthosites have higher susceptibilities, increasing upwards, due to the presence of intercumulus magnetic and the upper ferrogabbros and ferrodiorites are very strongly

ferromagnetic due to copious amounts of cumulus magnetite. Although the unaltered ultramafic cumulates are paramagnetic, serpentinisation, particularly of olivine-rich layers, frequently produces secondary magnetite and produces susceptibilities in the MFM range.

Calc-alkaline series, typified by orogenic andesites and their plutonic equivalents, and minor related mafic and silicic rocks, show a quite different trend, with early depletion in iron and pronounced silica enrichment. This is thought to reflect more hydrous magmas associated with crust-mantle interactions in a subduction zone, with more oxidised parental magma and early, and continuing, crystallisation of Fe-Ti oxides and hydrous phases, such as hornblende. This leads to a pronounced depletion in iron in the more evolved members of a calc-alkaline series, whereas fractionated rocks derived from

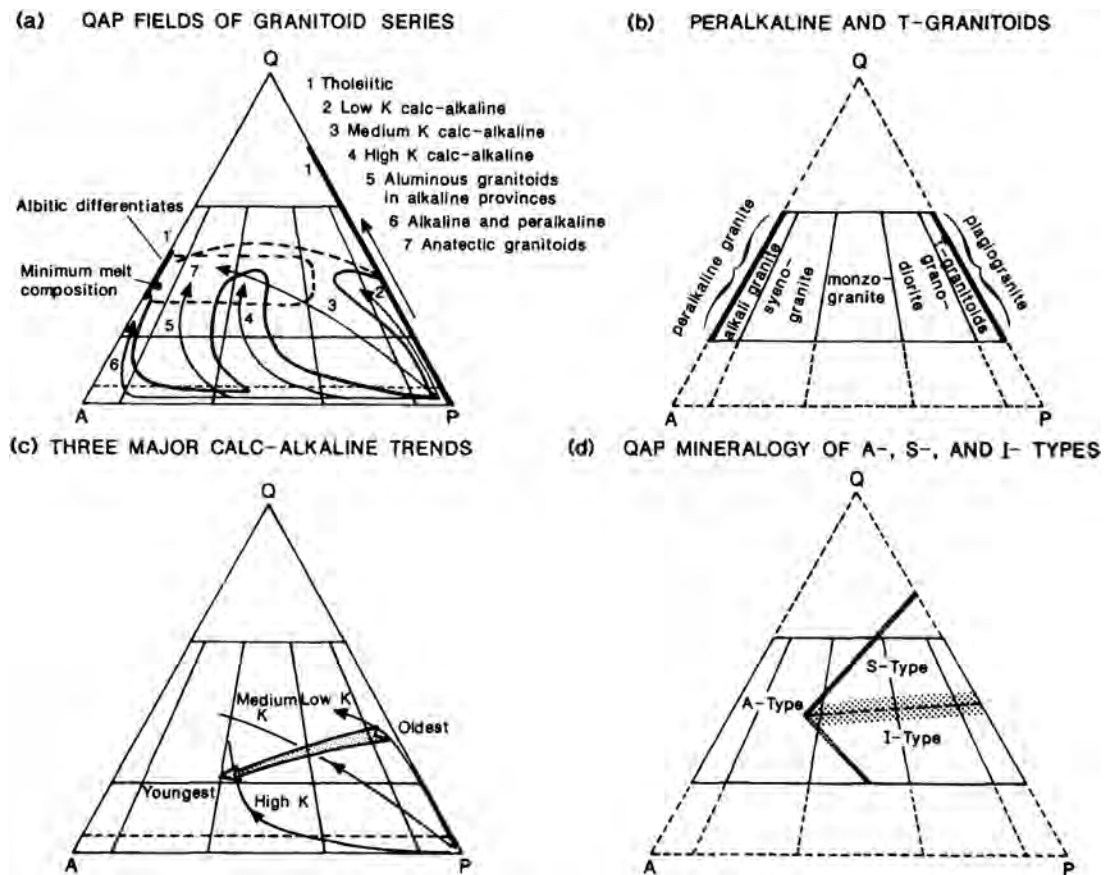


Figure 10. (a) QAP fields and differentiation trends for seven distinctive plutonic rock series. (b) QAP fields of peralkaline granites, plagiogranite and T-granitoids (tonalite/trondhjemite). (c) Spatially related plutonic rock series show clear mineralogical and chemical correlations with tectonic environment and relative time of emplacement e.g. evolution of calc-alkaline series in orogenic belts from the oldest (low-K tonalitic series) through the medium-K granodioritic series to the youngest (high-K monzonitic series). (d) Fields of the QAP plot typically occupied by I-, S- and A-type granitoids (after Bowden *et al.* 1984).

tholeiitic magma are relatively iron-rich. While calc-alkaline volcanics are subduction-related, calc alkaline granitoids are not necessarily directly associated with subduction, but are often derived from partial melting of calc-alkaline source rocks produced during an earlier tectonic cycle. Tholeiitic magmas are associated with a variety of tectonic settings. These mainly, but not always, correspond to tensional regimes and include: mid-ocean ridges; mantle plume-related intraplate oceanic islands; and anorogenic continental settings, including flood basalts, major dolerite dyke or sill swarms and layered gabbroic complexes.

Source rock classification of granitoids

Chappell and White (1974) recognised two categories of calc-alkaline granitoids with very distinctive mineralogical, chemical and geological features, which were interpreted as reflecting different source rocks. S-type granitoids are derived from partial melting of (meta)sedimentary rocks, and I-type granitoids from igneous source material. S may also stand for "Supracrustal" and I may represent "Intracrustal". S-type granitoids are characterised by metasedimentary inclusions (microgranitoid enclaves), whereas I-types contain hornblende-rich, mafic inclusions of igneous appearance. Chappell and White interpret these inclusions as "restite", residual source material. Linear inter-element variation trends are regarded as due to restite unmixing. Alternative interpretations involving magma mixing have been suggested, but are not relevant to the present topic. This first order

classification based on source rock has been extended to include M-type (mantle-derived) granitoids and A-type (anorogenic, alkaline, anhydrous and, somewhat cynically, "ambiguous") granitoids, with distinctive characteristics. A-type granitoids are inferred to be derived by partial melting of F and/or Cl-enriched dry granulitic residue remaining in the lower crust after earlier extraction of an orogenic granitic melt (Whalen, Currie, and Chappell 1987).

Selected characteristic features of these four granitoid types can be drawn from Pitcher (1983) and Bowden *et al.* (1984). They include:

I-type: metaluminous; calc-alkaline to alkali-calcic, relatively quartz-poor monzogranites, granodiorites and tonalites; 53% to 76% SiO_2 ; high Na/K, high Ca for mafic varieties; hornblende-bearing (except most felsic members).

S-type: strongly peraluminous; alkali-calcic to calc alkaline, relatively quartz-rich monzogranites, granodiorites and tonalites; 65% to 74% SiO_2 ; low Na/K, Ca and Sr; with peraluminous minerals (muscovite, cordierite, garnet or andalusite); often biotite-rich.

A-type: peralkaline to metaluminous; alkalic to alkali calcic syenogranites, alkali granites and quartz syenites; mostly 70% to 78% SiO_2 ; high Na + K, Fe/Mg, F + Cl and low Ca, Sr; accessory minerals such as fayalite, hedenbergite, ferrohastingsite, annite, fluorite, sodic pyroxenes, perthitic or rapakivi-textured feldspars.

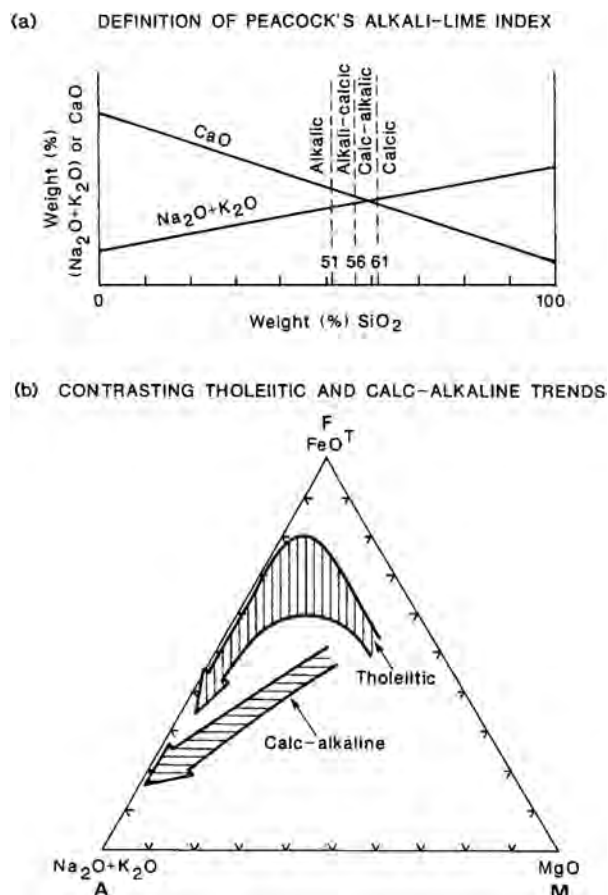


Figure 11. (a) Classification of comagmatic igneous rock series as alkalic, alkali-calcic, calc-alkalic and calcic on the basis of the alkali lime index (Peacock 1931). (b) Contrasting trends on the ternary plot of alkalis, total iron and MgO (AFM diagram) for differentiating tholeiitic and calc-alkaline magmas.

M- type: metaluminous; calcic gabbros, diorites, quartz diorites, tonalites and plagiogranites; 45% to 78% SiO_2 ; little or no K-feldspar.

Refinements of the I-S classification have been suggested. Pitcher (1983) recognised 1-Cordilleran and 1-Caledonian granitoids, each with distinctive composition and mineralogy, based on their tectonic setting. His data suggest that the tonalite-dominant 1-Cordilleran granitoids tend to be relatively magnetite-rich, whereas the granodiorite dominant 1-Caledonian type granitoids tend to have less magnetite. Chappell and Stephens (1988) proposed that progressively more felsic and chemically evolved I-type granitoids result from successive remelting of older mafic rocks that have underplated the crust. M-types comprise gabbros to mafic granites derived directly from the mantle or mantle wedge, I-tonalite types are derived from fusion of M-type material and I-granodiorite types represent remagmatised products of I-tonalite rocks. This classification allows for both I-tonalite and I-granodiorite types to occur in the one tectonic setting, although typically one subtype will predominate.

Granitoid classification based on tectonic setting

Pitcher (1983) has related other granite classification schemes to tectonic environment. Maniar and Piccoli (1989) have proposed an independent granitoid classification scheme, based on tectonic setting. A first order orogenic category is subdivided into island arc granitoids (IAG), continental arc granitoids (CAG), continental collision granitoids (CCG) and post-orogenic

granitoids (POG). Anorogenic granitoids fall into three categories: Rift Related Granitoids (RRG); Continental Epeirogenic Uplift Granitoids (CEUG); and Oceanic Plagiogranites (OP). Although the occurrence and abundance of magnetite was not noted by these authors, the detailed information on chemistry and mineralogy allows broad conclusions on likely magnetite contents to be inferred by comparison with other studies.

Granitoid classification based on Fe-Ti oxide mineralogy

Ishihara (1977) instigated a descriptive classification of calc-alkaline granitoids into a magnetite-series and an ilmenite-series, based on their characteristic iron-titanium oxide mineralogy. This classification can be directly related to magnetic properties and has important exploration implications, because of the association between metallogeny and the magnetite-series/ilmenite-series classification (Ishihara 1981). The characteristic accessory mineralogies of the two categories of granitoid are:

magnetite-series—0.1-2 vol % magnetite ± ilmenite; plus haematite, pyrite, sphene, oxidised Mg-rich biotite; and

ilmenite series—magnetite absent, ilmenite (< 0.1 vol %) pyrrhotite, graphite, muscovite, reduced Fe-rich biotite.

Thus magnetite-series granitoids are ferromagnetic (MFM to SFM), with susceptibilities in the approximate range $3800\text{--}75,000 \times 10^{-6}$ SI ($300\text{--}6000$ $\mu\text{G/Oe}$), whereas ilmenite series granitoids are paramagnetic. Pyrrhotite is present in ilmenite-series granitoids in very minor amounts and cannot contribute significantly to the susceptibility, particularly since much of the pyrrhotite present in ilmenite-series granitoids is the hexagonal variety (Whalen and Chappell 1988), which is weakly magnetic. Magnetite-series granitoids are significantly more oxidised than ilmenite series granitoids. This is thought to reflect upper mantle/lower crustal generation of the magnetite-series, involving minimal interaction with carbonaceous material, whereas the ilmenite-series is interpreted to have been generated in the middle to lower crust and to be significantly contaminated by C-bearing crustal rocks.

Fershtater, Borodina, and Chashchukhina (1978) and Fershtater and Chashchukhina (1979) have devised a "Ferrofacies Classification" of granitoids. The ferrofacies concept has been applied to a wide range of granitoids from the former USSR and can be regarded as an extension of the magnetite-series and ilmenite-series classification. The categories in that classification are: the magnetite ferrofacies; the magnetite bearing ferrofacies; the magnetite-"free" ferrofacies; and the titanomagnetite ferrofacies - each with distinctive mineralogical characteristics. This classification does not appear to have been used by other workers, but may form the basis for a refined magnetic petrological classification with metallogenic implications.

Suites, supersuites and basement terranes

Hine *et al.* (1978) showed that granitoids of the Lachlan Fold Belt can be grouped into suites using petrographic, chemical and isotopic criteria. Members of a suite are interpreted to be derived from similar source rocks. Suites with similar character can be grouped into supersuites. Chappell, White, and Hine (1988) demonstrated that granitoids within specific provinces tend to exhibit common geochemical character. Since the compositions of the granitoids largely reflect compositions of their source regions, the distribution of granitoid suites and supersuites can be used to define terranes, within each of which

the lower crust has distinctive geochemical characteristics. These basement terranes are often poorly correlated with the tectonostratigraphic terranes that are defined from the surface geology.

Geological factors that control magnetisation of intrusions

Iron content and oxidation ratio

Many petrological studies of intrusive igneous rocks have been made that are relevant to the problem of defining the geological controls on magnetic properties in these rocks. To a good approximation, the magnetic susceptibility of intrusive igneous rocks is simply proportional to their magnetite content. The directly relevant chemical parameters are the total iron content of the rock, which constrains the theoretical maximum attainable susceptibility, and the oxidation ratio (ferric/total iron), which essentially determines the partitioning of iron between silicates and oxides (mainly magnetite, in fresh igneous rocks). Figure 12(a) shows the typical trend for major elements with increasing silica for a series of igneous rocks derived from a basic parental magma. Total iron tends to decrease steadily, but it is important to note that even the most felsic members of common igneous rock series would contain sufficient iron to make them at least moderately to strongly ferromagnetic, provided that all the iron was contained in magnetite. Figure 12(b) gives an example of a total iron versus differentiation index trend for a comagmatic suite of granitoids, showing that even the most evolved members of this suite have at least 0.5 wt %, and generally more than 1 wt %, total iron.

Much of the iron, however, is always sequestered within paramagnetic silicate minerals. If the rocks are paramagnetic, the susceptibility decreases monotonically with increasing silica content. This occurs if the iron oxidation ratio of the rocks is low, particularly in the more evolved rocks. In that case, silicates take up the predominantly ferrous iron and the relatively small amounts of ferric iron can also be accommodated in silicates, mainly in hydrous phases. As the Fe oxidation ratio of the rocks increases, the silicates are obliged initially to take up more ferric iron. Once the oxidation ratio exceeds the maximum amount of ferric iron that can be accommodated in silicates, the excess ferric iron is forced to appear as magnetite.

Figure 12(c) shows, for the same suite of granitoids considered in Figure 12(b), how the Fe oxidation ratios of hornblende and biotite are correlated with oxidation ratio of the whole rock, indicating that these phases start to become saturated with ferric iron at rock oxidation ratios above ~20%. Maximum ferric iron contents in these silicates are attained when the oxidation ratio of the rock is ~30%. When this ratio is exceeded, there is a steady increase in magnetite content, until it constitutes ~20% of the mafic minerals, as the oxidation ratio increases up to ~70%. Above this value, the whole rock ferric iron would be in surplus for forming magnetite, especially when the large proportion of ferrous iron in silicates is considered, and haematite or maghemite would be present in addition to magnetite.

In mafic anhydrous rocks without amphibole or mica, however, the anhydrous silicates can accommodate much less ferric iron than hornblende and biotite, and magnetite appears in such rocks at lower oxidation ratios. This explains why many gabbros and norites are strongly magnetic, in spite of lower oxidation ratios than for the granitoids considered in Figure 12(b)-(d).

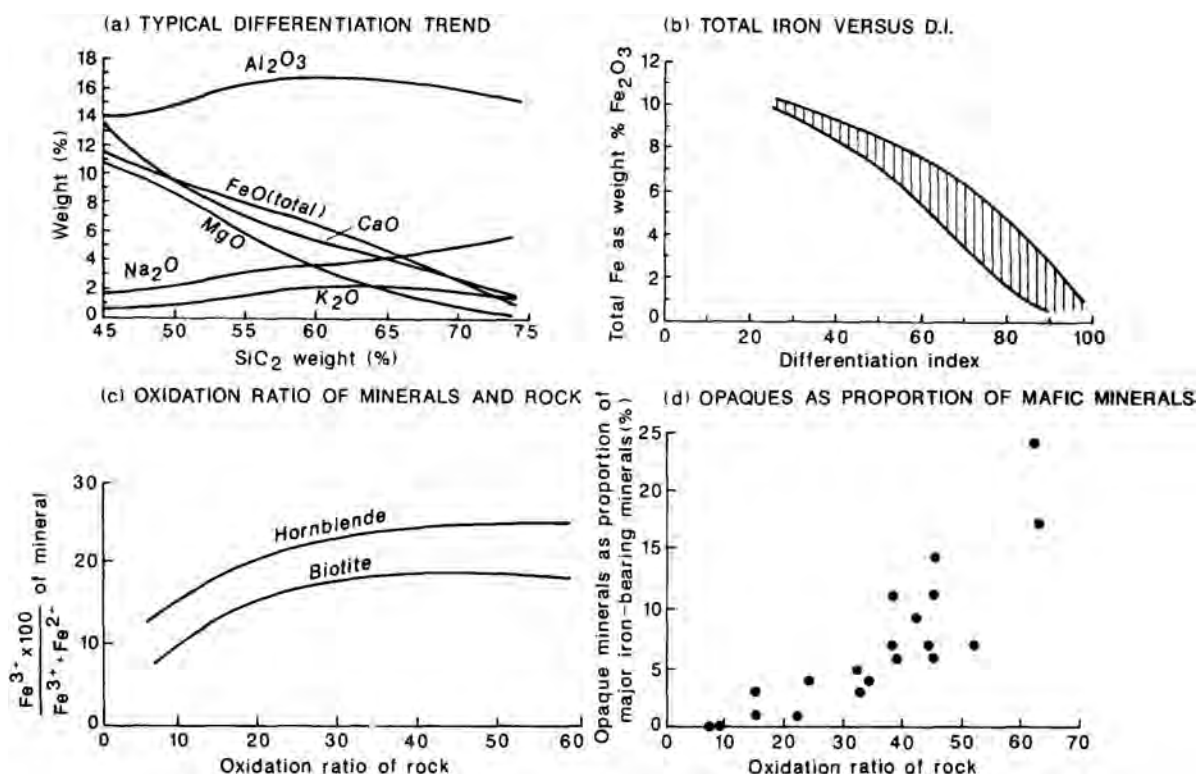


Figure 12. (a) Harker diagram showing typical differentiation trends for major elements in a comagmatic igneous rock suite. (b) Total iron versus differentiation index for a suite of granitoids from the Sierra Nevada Batholith (after Dodge 1972). (c) Oxidation ratio (%) for hornblende and biotite from the Sierra Nevada granitoids versus oxidation ratio (%) of whole rock. (d) Opaque mineral (essentially magnetite) contents as proportion of total iron-bearing mineral assemblage of the Sierra Nevada granitoids versus oxidation ratio of rock.

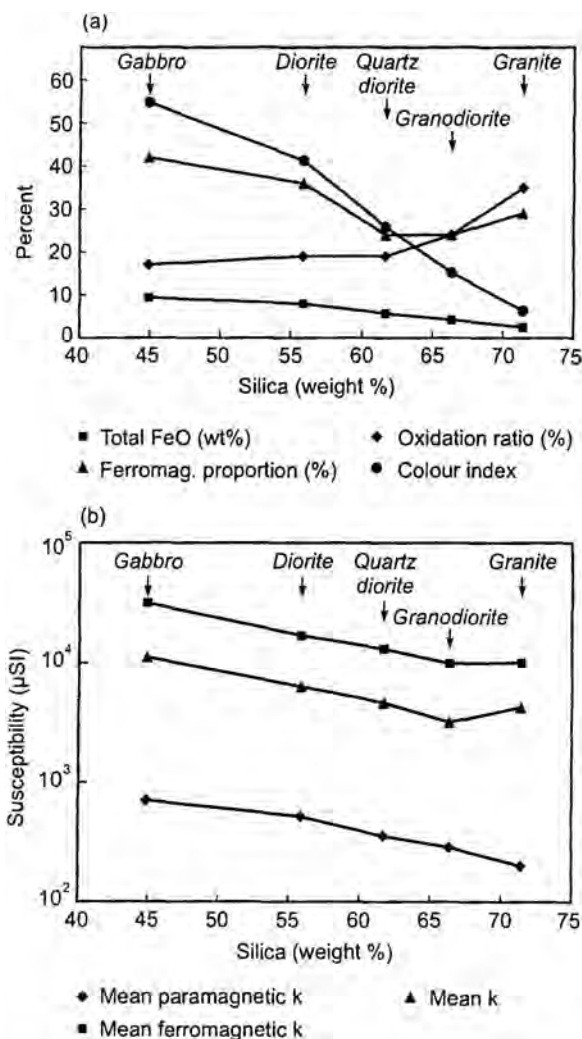
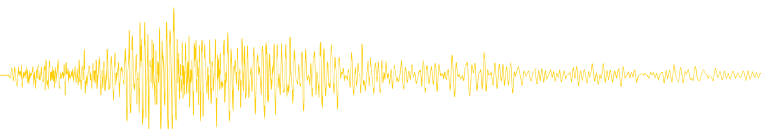


Figure 13. (a) Total iron as FeO (wt%), oxidation ratio (%), and percentage of the total sample for each rock type that is ferromagnetic versus SiO₂ for Finnish gabbros, diorites, granodiorites and granites. (b) Mean susceptibility of paramagnetic subpopulations, mean susceptibility of ferromagnetic subpopulations, mean susceptibility of total population, and colour index (volume % mafic minerals) versus SiO₂ for Finnish gabbros, diorites, granodiorites and granites (data from Puranen 1989).

Data on intrusive rocks from Finland, taken from Puranen (1989), are plotted in Figure 13. Figure 13(a) shows the average total iron, oxidation ratio, and percentage of ferromagnetic rocks for compositions ranging from gabbro to granite. There is a systematic increase in oxidation ratio with silica content, offsetting the effect on susceptibility of the decrease in total iron. This produces an increased proportion of ferromagnetic rocks at the felsic end of the spectrum, with a slight increase in average susceptibility for granites, compared to granodiorites, as a result (see Figure 13(b)). Note that these data, which are derived from a very large petrophysical sampling program by the Finnish Geological Survey, refer to all sampled units within the appropriate QAP field, irrespective of geological setting, metamorphic grade, varietal mineralogy etc. Although systematic trends tend to be smoothed out by this geological and petrological variability, a clear correlation between chemistry and magnetic petrology is still evident. This indicates that there are strong underlying trends, when specific geological provinces, tectonic settings, geochemical characteristics or mineralogical varieties are considered.

Blevin (1994, 1996) has analysed a large collection of samples for relationships between susceptibility, oxidation state, granitoid type and composition. There is a distinct susceptibility gap between two main trends in the susceptibility-SiO₂ plot. The ferromagnetic trend, representing magnetite-bearing granitoids, exhibits a gradual decrease in susceptibility in both the maximum and average susceptibility values with increasing SiO₂, up to ~ 72 wt % SiO₂, and then plunges rapidly at higher silica contents. The paramagnetic trend lies two to three orders of magnitude below the ferromagnetic trend and also exhibits a gentle systematic decrease in susceptibility with increasing SiO₂. Oxidised granitoids generally have susceptibilities greater than 2000×10^{-6} SI (160 μG/Oe), with a maximum of $80,000 \times 10^{-6}$ SI (~ 6000 μG/Oe), whereas reduced granitoids have susceptibilities ranging from $\sim 500 \times 10^{-6}$ SI (~ 40 μG/Oe) at the low silica end to $\sim 130 \times 10^{-6}$ SI (~ 10 μG/Oe) at the highest silica contents.

For a given silica content, which generally implies similar total iron contents, there is pronounced increase in susceptibility with increasing oxidation ratio. Granitoids that plot in the gap between the main ferromagnetic and paramagnetic trends are either so felsic (SiO₂ > 72 weight %) that the iron content is too low to crystallise significant magnetite, irrespective of oxidation state, or show evidence of alteration of magnetite. There is little correlation between susceptibility, SiO₂ and Fe₂O₃/FeO for the latter group of granitoids, indicating that the processes of magnetite alteration are not systematically related to granitoid composition.

Geochemical and mineralogical associations with magnetite

The clearest correlations between geochemical or mineralogical factors in granitoids and magnetite content are the general increase in magnetite abundance with increasing oxidation ratio (except for the most oxidised haematite bearing rocks), for a given iron content, and the increase in maximum magnetite content with increasing total iron, for a given oxidation ratio. However, the occurrence and abundance of magnetite is clearly correlated with other geochemical characteristics. Metaluminous granitoids are much more likely to be ferromagnetic than peraluminous or peralkaline granitoids, and igneous rocks with extreme alumina saturation are almost always paramagnetic. Within each Ishihara series, there is a general correlation of decreasing susceptibility with increasing silica content.

Hornblende + pyroxene or olivine (except fayalite) in mafic varieties is favourable for the presence of magnetite, as is hornblende + biotite in more felsic rocks. Fayalitic olivine, however, indicates reducing conditions and is found only in magnetite-poor granitoids. Mg-rich hornblende and biotite indicate relatively oxidising conditions, with removal of iron into magnetite and consequent enrichment of the mafic silicates in magnesium, particularly when the Mg/Fe ratio increases with increasing rock SiO₂. When ilmenite is present, its composition is correlated with magnetite content. Granitoids without magnetite have relatively reduced ilmenite (< 8 mol % Fe₂O₃), whereas magnetite-bearing granitoids have either more oxidised ilmenite, or Mn-rich ilmenite. High Mn-ilmenite is favoured by oxidising conditions because Fe is preferentially incorporated into magnetite rather than ilmenite.

Figure 14(a) shows the correlation between opaque mineral content and susceptibility for Japanese granitoids and gabbroic rocks, showing an essentially proportional relationship (Ishihara 1981). This reflects the dominance of magnetite over other opaque phases in magnetite-series plutons and the

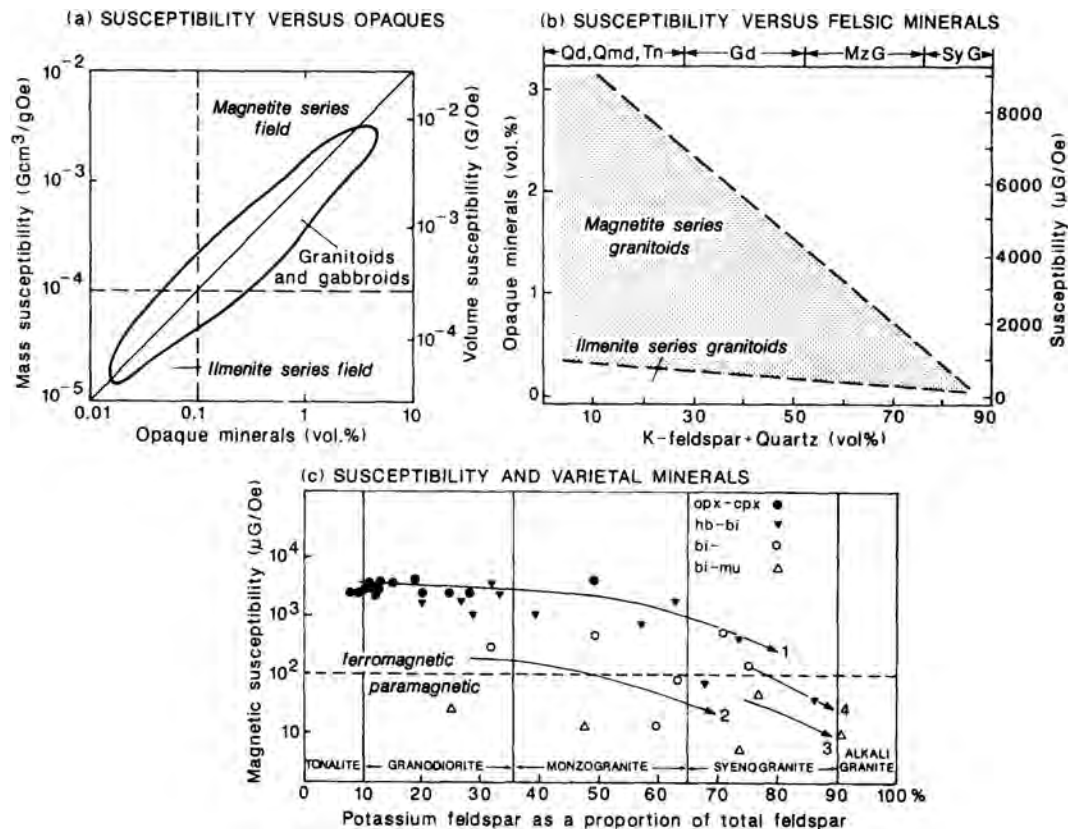


Figure 14. (a) Correlation between opaque mineral content and susceptibility for Japanese granitoids and gabbroids, showing an essentially proportional relationship (after Ishihara 1981). Ilmenite-series granitoids have very low opaque mineral contents (< 0.1 vol %). (b) Range of susceptibilities for magnetite-series and ilmenite-series granitoids versus quartz + K-feldspar (after Ishihara 1981). (c) Relationships between susceptibility, lithology and varietal mineralogy for granitoids from central Australia (after Mutton and Shaw 1979).

proportionality of susceptibility and magnetite content for normal ferromagnetic rocks. Figure 14(b) indicates that there is a wide range of susceptibilities for mafic magnetite-series granitoids, with many strongly ferromagnetic examples, but the maximum magnetite content, and hence the maximum susceptibility, decreases linearly with increasing quartz + K-feldspar, so that the most felsic members of the series (syenogranites) are only weakly to moderately ferromagnetic. Ilmenite-series granitoids have very low opaque mineral contents (< 0.1 vol %) and there is still a distinctly lower average susceptibility for the ilmenite-series syenogranites than for their magnetite-series equivalents. There is also a general trend to decreasing paramagnetic susceptibility in more felsic ilmenite-series granitoids, as expected.

Figure 14(c) shows the relationships between susceptibility, lithology and varietal mineralogy for granitoids from central Australia (Mutton and Shaw 1979). This confirms the decrease in maximum susceptibility for more felsic rocks, and the association of magnetite with pyroxene and hornblende (indicative of M- or I-type affinities) and the apparent antipathetic relationship of magnetite with muscovite, which is a mineral characteristic of peraluminous, usually S type, granitoids.

Blevin (1994, 1996) has established a useful relationship between feldspar colour and susceptibility for calc-alkaline granitoids. For granitoids with white plagioclase there is a distinct increase in average oxidation ratio and susceptibility with increasing pinkness of K-feldspar. Salmon pink K-feldspars tend to be most oxidised and have the highest

susceptibilities. White K-feldspar indicates a reduced rock with low susceptibility. Brick red K-feldspars, on the other hand, which are most common in very felsic rocks, indicate hydrothermal alteration and are generally associated with lower susceptibilities than pink K-feldspars. Green plagioclase is generally indicative of alteration that tends to be magnetite-destructive and is correlated with variable, generally lower, susceptibilities that are poorly correlated with rock composition and oxidation state. Yellowish feldspars usually indicate weathering and such samples are not representative of the fresh rock. Overall, there is a reasonably predictable relationship between susceptibility and the field-observable features: colour index (percentage of mafic minerals), which provides a proxy estimate of silica and iron contents, and K-feldspar colour (provided the plagioclase is white).

Source rock

Whalen and Chappell (1988) showed that most I-type granitoids of the Lachlan Fold Belt are magnetite-series and most S-types are ilmenite-series, although exceptions to the rule are found. Blevin (1994, 1996) has shown that ~80% of I-type granitoids from the Lachlan and New England Fold Belts have susceptibilities greater than 1000×10^{-6} SI (80 μ G/Oe), mostly greater than 2000×10^{-6} SI (160 μ G/Oe), whereas nearly all S-types have susceptibilities less than 1000×10^{-6} SI (80 μ G/Oe). Exceptions to these generalisations occur within specific suites or supersuites and are confined to particular basement terranes.

Blevin (1994, 1996) has also shown that within each granitoid suite there is generally a systematic decrease in

susceptibility with increasing SiO_2 . This decrease becomes very rapid above ~74 wt % SiO_2 . M-types from the southwest Pacific have the highest susceptibilities in this extensive collection of granitoid rocks from eastern Australia and Oceania, unless they are altered. Both carbonate and pyrite-pyrrhotite-chalcopryrite alteration are magnetite-destructive in the M-type rocks. For silica contents of 70% to 74% by weight, A-type granitoids exhibit a bimodal distribution of susceptibilities, similar to those of oxidised and reduced I-types with equivalent SiO_2 . Above ~74 wt% SiO_2 the A-types exhibit a broad unimodal susceptibility distribution, reflecting a rapid decrease from WFM to PM levels as SiO_2 increases from 74 wt% to 78 wt%.

Average susceptibilities for M-, I- and S-type granitoids are $40,000 \times 10^{-6}$, 8900×10^{-6} and 410×10^{-6} SI ($3200 \mu\text{G}/\text{Oe}$, $700 \mu\text{G}/\text{Oe}$ and $30 \mu\text{G}/\text{Oe}$) respectively. The corresponding medians are $32,500 \times 10^{-6}$, 5600×10^{-6} and 270×10^{-6} SI ($2600 \mu\text{G}/\text{Oe}$, $450 \mu\text{G}/\text{Oe}$ and $20 \mu\text{G}/\text{Oe}$). The median susceptibility of the limited set of A-type granitoids studied by Blevin (1994) is $\sim 1000 \times 10^{-6}$ SI ($\sim 80 \mu\text{G}/\text{Oe}$). For the ferromagnetic subpopulation of the slightly less felsic (70 wt % to 74 wt % SiO_2) varieties of A-type, the median susceptibility is an order of magnitude greater.

Magnetite contents of granitoids show distinct provinciality, along with other mineralogical and chemical characteristics, reflecting distinctive compositions of lower crustal source regions (Chappell, White, and Hine 1988; Blevin 1994). For example, in most basement terranes I-type granitoids are relatively oxidised magnetite-series rocks. In the Melbourne Basement terrane, however, the I-type granitoids are reduced and belong to the ilmenite-series. The infracrustal protolith from which these rocks have been derived is therefore inferred to be more reduced than elsewhere in the Lachlan Fold Belt. Granitoids belonging to individual suites, which are derived from fairly homogeneous source rocks, exhibit a systematic correlation between magnetic susceptibility and composition that is much better defined than global relationships between these variables.

Overall, mantle-derived granitoids, I-types derived from mafic crustal underplates and second-generation I-types derived from oxidised I-type source rocks are magnetite series, whereas I-types derived from reduced igneous rocks are ilmenite-series. A-types resemble felsic I-types and have subequal magnetite-series and ilmenite-series populations. Most S-types are reduced ilmenite series granitoids, probably reflecting presence of carbon in their lower to middle crustal source material.

Lithology

The overall proportion of ferromagnetic rocks within a given geological province or within a particular igneous rock series decreases from gabbro through to granite. This trend is apparent from Figure 13(a), which combines data from a wide range of areas and rock series, but is more clearly expressed within particular provinces or rock series. Mafic to felsic and intermediate to felsic associations are much more likely to be magnetite-series throughout, than compositionally restricted felsic associations. Alkaline intrusive rocks are often magnetite-series, with the exception of extreme compositions, such as peralkaline granites and agpaitic (peralkaline, undersaturated) nepheline syenites. In tholeiitic layered complexes, less evolved lower gabbros are paramagnetic to weakly ferromagnetic, whereas sufficiently evolved upper ferrogabbros and ferrodiorites, and associated granophyres, are usually strongly ferromagnetic.

Emplacement depth

Pecherskiy (1965) noted a strong correlation between shallow emplacement depth and occurrence of magnetite for a wide variety of granitoids in northeastern Russia. Figure 15 shows the percentage of moderately and strongly ferromagnetic granitoids versus estimated depth of emplacement for a large number of plutons. There is a systematic increase in ferromagnetic proportion with decreasing depth of emplacement. The ferromagnetic proportion rises to 70% for subvolcanic/epizonal granitoids. This interesting observation does not appear to have attracted much attention, but other studies lend some indirect support. Czamanske, Ishihara, and Atkin (1981) explain a similar correlation in Japan by invoking onset of second boiling in the residual melt in epizonal plutons. Dissociation of water and preferential diffusion of hydrogen out of the pluton into fractured country rock is the oxidation process that is postulated to produce the high magnetite contents of these plutons. However, Candela (1986) has shown that dissociation of water can only be an important oxidising process for iron-poor (<1 wt % FeOT) granitoids. This mechanism may operate in Climax-type Mo porphyries, which are very felsic, but interaction with oxygenated meteoric waters is a more probable explanation for the relatively oxidised nature of at least some epizonal granitoids.

There is also a general correlation between the source rock, depth of generation and depth of emplacement of granitoids, which probably explains much of the empirical trend shown in Figure 15. Deep-seated, high temperature, anhydrous magmas rise to shallow crustal levels, whereas lower temperature, hydrous magmas (produced by partial melting of muscovite-rich pelitic metasediments, for example) do not rise very far from their source regions, producing catazonal granitoids. The former type of magma is more likely to produce magnetite-series granitoids, whereas the latter generally produces ilmenite-series granitoids, for reasons already explained.

Tectonic setting

Referring to Maniar and Piccoli's (1989) classification, most island arc and oceanic plagiogranites, and more mafic continental arc granitoids, are ferromagnetic. Nearly all continental collision and post-orogenic granitoids are

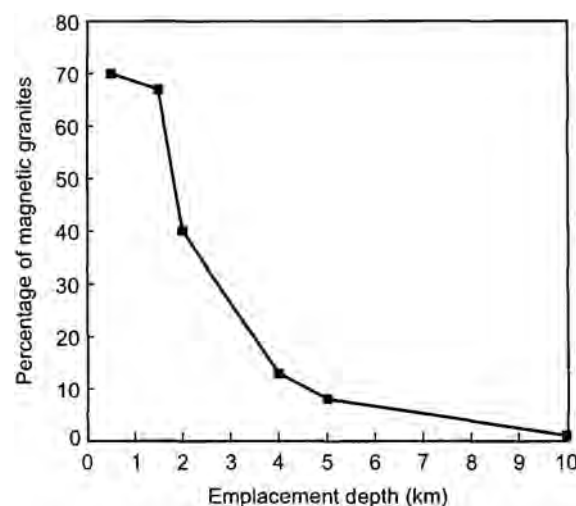


Figure 15. Proportion of ferromagnetic granitoids versus estimated emplacement depth for granitoids from NE Russia (Pecherskiy 1965).

paramagnetic. Rift-related granitoids and continental epeirogenic uplift granitoids have an inferred bimodal distribution of susceptibilities, with the mafic compositions tending to be ferromagnetic and the felsic compositions generally paramagnetic.

Crustal contamination and contact aureoles

Ishihara, Terashima, and Tsukimura (1987) presented evidence that local contamination of a I-type tonalitic pluton by sulphur and carbon derived from sedimentary country rocks produced a vertical zonation from low magnetic susceptibility ilmenite series tonalite at lower levels to magnetite-series tonalite at higher levels. There was less contamination at higher levels. Similar effects have also been observed in the Lachlan Fold Belt, but only within a few metres of the granitoid margin (Blevin 1994). More generally, Blevin (1994) argues that crustal contamination effects on oxidation state of Lachlan Fold Belt granitoids are negligible and that in the vast majority of cases the oxidation state of these granitoids is inherited from the source region.

On the other hand, Ague and Brimhall (1988) suggest that substantial contamination of granitoid magmas by country rocks has occurred in Californian batholiths. Where strongly contaminated by graphitic pelites, the I-type tonalites are reduced ilmenite-series, otherwise they are magnetite series. Pecherskiy (1965) estimates that the nature of the country rocks has significant effects on the magnetic properties of granitoids in NE Russia in at most 20% of cases (probably much less).

As well as the country rocks affecting the magnetic properties of the granitoid, emplacement of granitoids frequently has a pronounced effect on the magnetic properties of country rocks that are metamorphosed and metasomatised by the intrusion. Often the magnetic signature of the contact aureole is more pronounced than that of the granitoid itself. Speer (1981) studied the mineralogical changes, including production of secondary magnetite, within the contact aureole of the Liberty Hill pluton, South Carolina. For that granitoid, there is a very clear relationship between the detailed magnetic signature of the aureole and changes in metamorphic grade of the metapelite country rocks, as shown in Figure 16. There are smooth variations in magnetite content, correlated with changes in mineral modes and mineral chemistry, within metamorphic zones, with inflections at metamorphic isograds. The susceptibility of the metamorphic magnetite zone is substantially greater than that of the magnetite-series pluton. Outside the aureole, the susceptibility of the country rocks is very low. The magnetic signature of the granite and aureole comprises a relative magnetic high (~ 200 nT above regional background) over the granite, rimmed by a strong, narrow high (~ 500 nT above background) centred on the magnetite-rich middle to outer aureole, dropping to the regional background level outside the aureole.

Contact aureoles around granitoids that intrude pyritic sediments may exhibit substantial magnetic anomalies due to breakdown of pyrite to monoclinic pyrrhotite (the ferromagnetic variety of pyrrhotite). Monoclinic pyrrhotite generally carries a relatively strong remanent magnetisation, characterised by $Q \gg 1$.

Magnetic petrology and metallogeny of intrusions

Mineralisation in layered mafic/ultramafic complexes

Differentiation of reduced mafic magmas within large, essentially closed system, slowly cooled magma chambers

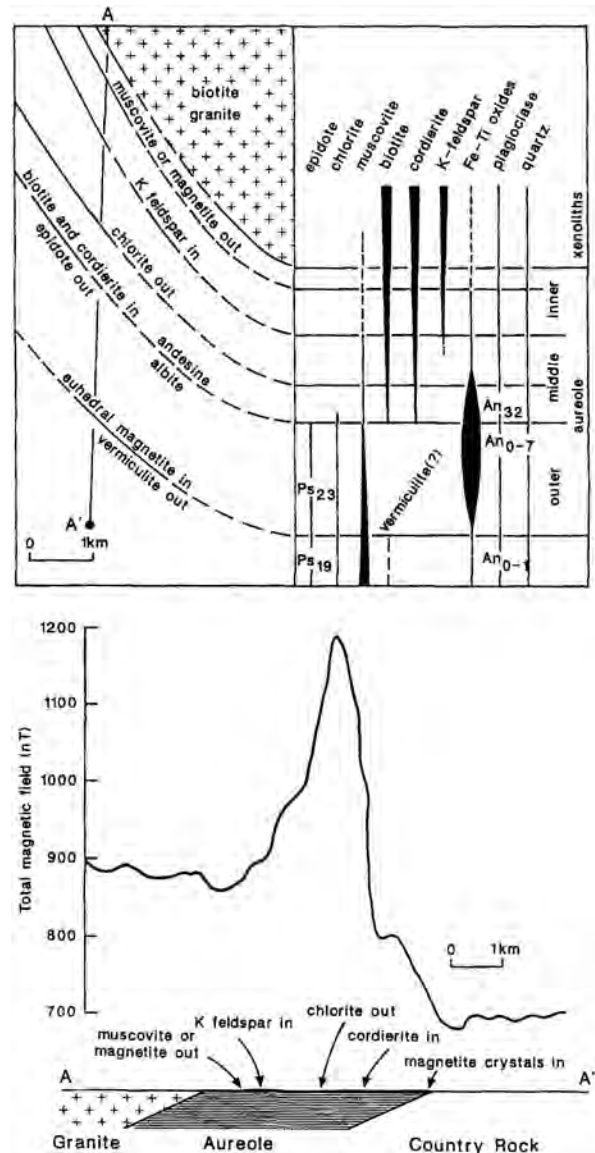


Figure 16. Magnetic expression of metamorphic magnetite formation in the contact aureole of the Liberty Hill pluton, South Carolina (after Speer 1981).

proceeds according to the tholeiitic trend discussed above, with initial iron-enrichment and late iron-depletion, producing zoned complexes with basal ultramafic layers, overlain by paramagnetic mafic rocks, then by increasingly more magnetic mafic rocks, grading finally to MFM granophyres. Cr-mineralisation occurs as chromite bands towards the top of the ultramafic zone, which contains no primary magnetite, but may be MFM due to secondary magnetite produced by serpentinisation of olivine. The paramagnetic mafic rocks that overlie the ultramafic zone may host platinum group element and Cu-Ni mineralisation. In the upper portions of the zoned complex, the SFM upper ferrogabbro and ferrodiorite zones host bands of titanium and vanadium-bearing cumulus magnetite, which may constitute economic ore deposits of Ti and V. The Bushveld Complex, which hosts the world's greatest repository of magmatic ore deposits, may be regarded as the type example of such mineralised layered mafic/ultramafic intrusions.

An idealised model of the magnetic stratigraphy can be developed from this generalised picture of layered mafic/ultramafic complexes. Clark *et al.* (1992a, 1992b) have used

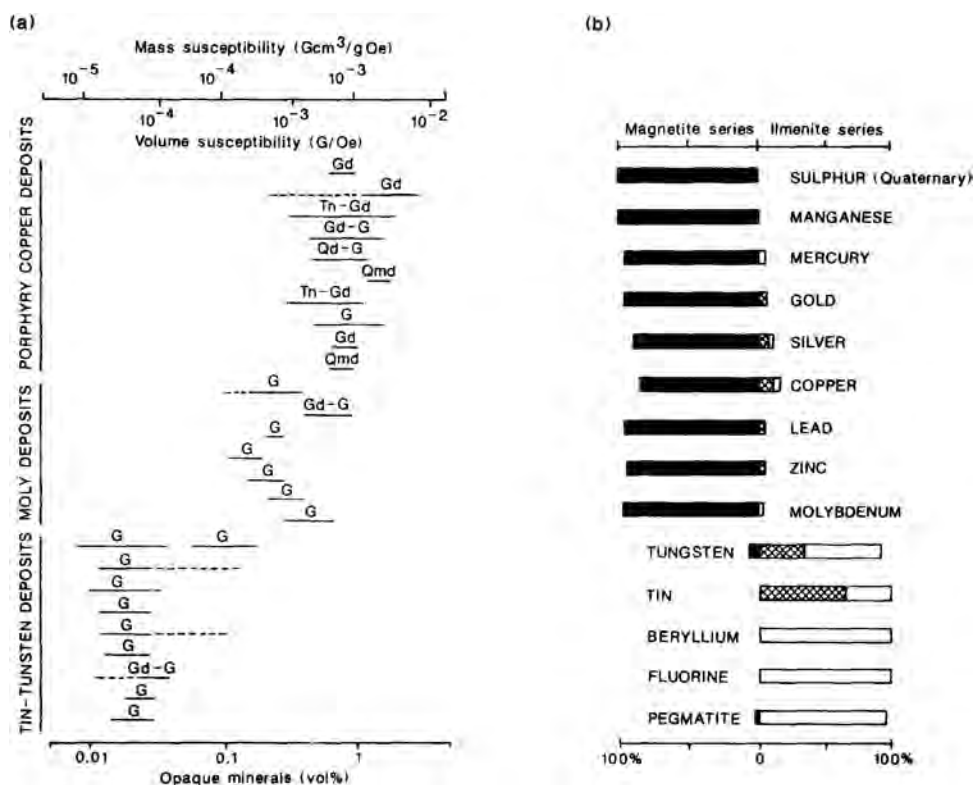


Figure 17. (a) Range of CGS mass and volume susceptibilities and opaque mineral contents for granitoids associated with porphyry Cu, granitoid related Mo deposits and granitoid-related Sn-W deposits (Gd=granodiorite, Tn=tonalite, G=granite, Qmd=quartz monzodiorite). (b) Proportions of mineral deposits, of a variety of commodities that occur within magnetite-series and ilmenite-series granitoid belts. Hatched regions represent WFM magnetite-series granitoids. The mineral deposits are inferred to be genetically related to granitoids or to their associated volcanics. Pegmatite refers to stanniferous pegmatite deposits. SI volume susceptibility = CGS volume susceptibility (G/Oe) $\times 4\pi$; mass susceptibility = volume susceptibility/density (after Ishihara 1981).

this model to predict magnetic anomalies over tilted Bushveld-type complexes.

Oxidation state and metallogenic associations

More than 30 years ago Pecherskiy (1965) noted an empirical association of granitoid-related gold deposits with ferromagnetic granitoids and tin deposits with paramagnetic granitoids. Ishihara (1981) established the important correlation between his magnetite- and ilmenite-series granitoid classification and granitoid-related mineralisation. For example, copper and molybdenum porphyries are almost always magnetite-series, whereas tin granites are invariably ilmenite-series. It has become apparent in recent times that this relationship is not just empirically based, but can be related to redox conditions in the magma. Ishihara's data on metallogenic associations with granitoid series and with susceptibility are reproduced in Figure 17.

The compatible or incompatible behaviour of multivalent metals such as Cu, Mo, W and Sn in the melt depends on their valency, which is a function of redox conditions. For example, tin occurs in two oxidation states in magmas: stannous (Sn^{2+}) and stannic (Sn^{4+}). The oxidised stannic species fits easily into the structures of minerals such as magnetite and sphene, which are diagnostic of oxidising conditions in the magma, and is therefore dispersed throughout an oxidised granitoid. On the other hand, the reduced stannous ion is too large to be accommodated readily within mineral structures and is accordingly concentrated in the residual melt. Thus, reduced, and therefore paramagnetic, granitoids are potential sources of tin mineralisation, whereas magnetite-bearing granitoids are

too oxidised to be associated with tin deposits. Development of an exsolved fluid and partitioning of ore elements into hydrothermal liquids or vapour phases also depends strongly on the nature and concentrations of volatile species. The ratios $\text{SO}_2/\text{H}_2\text{S}$ and CO_2/CH_4 depend on oxygen fugacity and therefore oxygen fugacity exerts a major influence on hydrothermal evolution, concentration of ore elements into mineralising fluids, and transport and deposition of ore elements.

Khitrunov (1985) has attempted a general explanation of the empirical relationships between oxidation state of granitoids and associated Cu, Mo, W or Sn mineralisation, concluding that magmatic conditions are progressively more reduced for Mo, Cu, W and Sn mineralisation. Cameron and Carrigan (1987) and Hattori (1987) have pointed out the association between oxidised felsic magmas, magnetic granitoids and Archaean gold deposits. They have given a detailed discussion of the factors favouring incorporation of gold from sulphide minerals in source rocks, concentration into a CO_2 -rich melt at mesothermal levels and deposition after development of an immiscible fluid phase. Sillitoe (1979) pointed out the association between gold-rich porphyry copper deposits and oxidised, magnetite-rich plutons with a magnetite-rich potassic alteration zone. Kwak and White (1982) distinguished between reduced porphyry tin and W-Sn-F skarn deposits and more oxidised W-Mo-Cu skarn deposits and Cu porphyries (Figure 18).

Blevin and Chappell (1992, 1995) have published thorough analyses of the metallogenic implications of granitoid chemistry, oxidation state and magmatic differentiation, based mainly on studies of the Lachlan Fold Belt. Sn mineralisation is associated with both S- and I-type granites that are reduced and

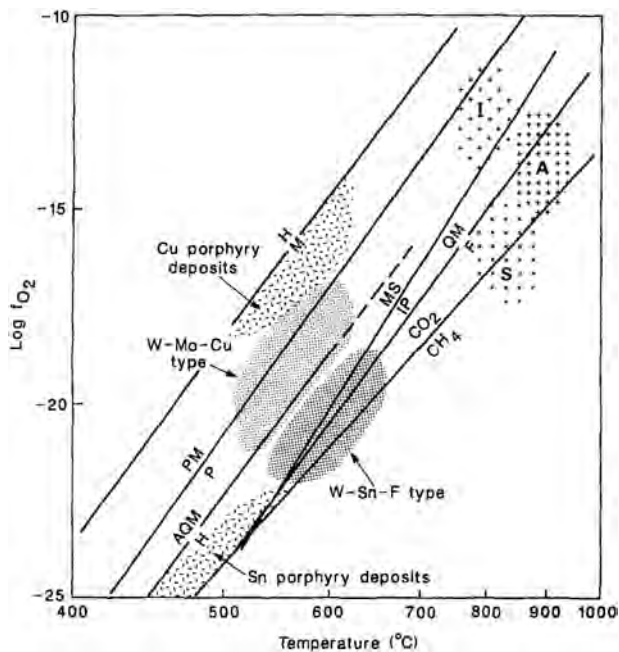


Figure 18. Oxygen fugacity versus temperature fields for typical I-, S and A-type granitoids and for porphyry Cu, W-Mo-Cu skarn, W-Sn-F skarn and porphyry Sn mineralisation, together with a number of standard oxygen fugacity buffers (after Kwak and White 1982). Mineral and fluid oxygen fugacity buffers that may be important controls on the magnetic mineralogy of the igneous intrusions and their associated mineralisation include ($\text{CO}_2\text{-CH}_4$; PMP=pyrite magnetite-pyrrhotite; AQMH=andradite-quartz-magnetite-hedenbergite; MSIP=magnetite-sphene-ilmenite-pyroxene) as well as the FMQ and HM buffers.

have undergone fractional crystallisation. Such granites contain negligible magnetite and are paramagnetic. On the other hand, Cu and Au mineralisation is associated with oxidised, magnetite- and/or sphene-bearing, intermediate I-type suites. Mo is associated with similar granites that are more fractionated and oxidised. W does not appear to show a close relationship to granitoid type and is an opportunistic ore element, occurring in association with a number of other metals. Within mineralised granitoid suites, ore element ratios are simply related to relative oxidation state and degree of fractionation.

The importance of fractional crystallisation

Blevin and Chappell (1992, 1995) point out that fractional crystallisation of magmas is a powerful mechanism for concentration of ore elements into the residual melt, which is a prerequisite for formation of intrusive-related mineralisation. Late stage fractional crystallisation leads to quasi exponential increases of concentration for incompatible elements in the residual melt, which may then partition the ore elements into late stage fluids and ultimately deposit them in a suitable trap to form economic mineralisation. Fractionated granitoids can be recognised, for example, by high Rb content and high Rb/Sr, which are sensitive indicators of fractional crystallisation. Other causes of chemical variation within granitoid suites, such as restite unmixing, magma mingling or crustal contamination cannot produce the enormous concentration factors required to form an ore deposit. Magmatic differentiation by fractional crystallisation is characteristic of melt-rich magmas. Thus mineralisation is associated with granitoids that are derived from hot magmas (very hot magmas if the source region is relatively anhydrous) or with felsic granitoids that have undergone extensive fractionation after all restite has separated from the melt.

The Tuolumne intrusion, California, represents a classic zoned pluton that grades from quartz diorite at the margin through progressively more felsic hornblende- and biotite bearing granodiorite phases, to a core of biotite monzogranite porphyry (Bateman and Chappell 1979). The normal zoning pattern, from mafic margin to felsic core, represents fractional crystallisation within the magma body as it cooled from the outside in.

Figure 19 shows the compositional variations across the Tuolumne intrusion. Note the general slow decrease in opaque mineral (mainly magnetite) content from the margins towards the centre, with a pronounced dip in modal magnetite within the felsic core. The expected magnetic signature of fractional crystallisation is gradation or zoning of susceptibility, where the most fractionated phase, which is most likely to be intimately associated with the mineralisation, has the lowest susceptibility. Figure 19 provides an example of this pattern. In the case of an oxidised comagmatic suite, the susceptibility contrast between less evolved and more evolved phases should be large, whereas the effect will be subtle for a reduced paramagnetic suite.

Large increases in radio element concentrations and changes in radioelement ratios in the most fractionated rocks may also be detectable radiometrically. Airborne radiometric data can complement magnetic survey data in this environment, because the radiometric signal is best developed over the most felsic and fractionated intrusive phases, which are the phases that have the most subdued magnetic signature.

The Tuolumne pluton is unmineralised, probably because this intrusion, at least at the current level of exposure, was a sealed system during emplacement and cooling, precluding escape of late metal-bearing hydrothermal fluids, and because fractionation of the magma did not quite proceed to the stage required to concentrate metals into an ore-bearing fluid. However, a slightly more evolved variant of the Tuolumne intrusion, emplaced at a shallower depth or in a more favourable structural setting for tapping off hydro thermal fluids should be quite favourable for development of Cu-Au mineralisation.

Effects of sulphur saturation and halogen contents of magmas

Wyborn and Sun (1994) suggested that most magma types are generally sulphur-saturated and are unlikely to produce gold or copper-rich fluids after fractional crystallisation. Au and Cu partition strongly to sulphide phases and sulphur saturation leads to precipitation of sulphides and early removal of these metals from the melt. For development of a magmatic Cu-Au deposit, the magma must remain sulphur undersaturated throughout most or all of its magmatic evolution. Oxygen fugacity has a large effect on sulphur saturation. Under oxidising conditions, sulphur becomes more soluble in the magma, dissolving as an anhydrite component. Thus oxidised magmas are more likely to be sulphur-undersaturated and are more likely to generate Cu Au mineralisation.

The most favourable magma source for formation of high gold sulphur-undersaturated magmas is lithospheric mantle that has already been depleted in sulphur by removal of sulphur-saturated basaltic melt, leaving behind small amounts of sulphide enriched in Cu, Au and other precious metals. If this refractory mantle is metasomatised, its liquidus temperature is lowered and it can subsequently undergo partial melting more readily, in appropriate tectonic conditions. The magmas generated often have shoshonitic affinities and have characteristics that are favourable for generation of magmatic-hydrothermal mineralisation. Less potassic magmas (i.e. those within the normal K-SiO₂ field for calc-alkaline magmas) that

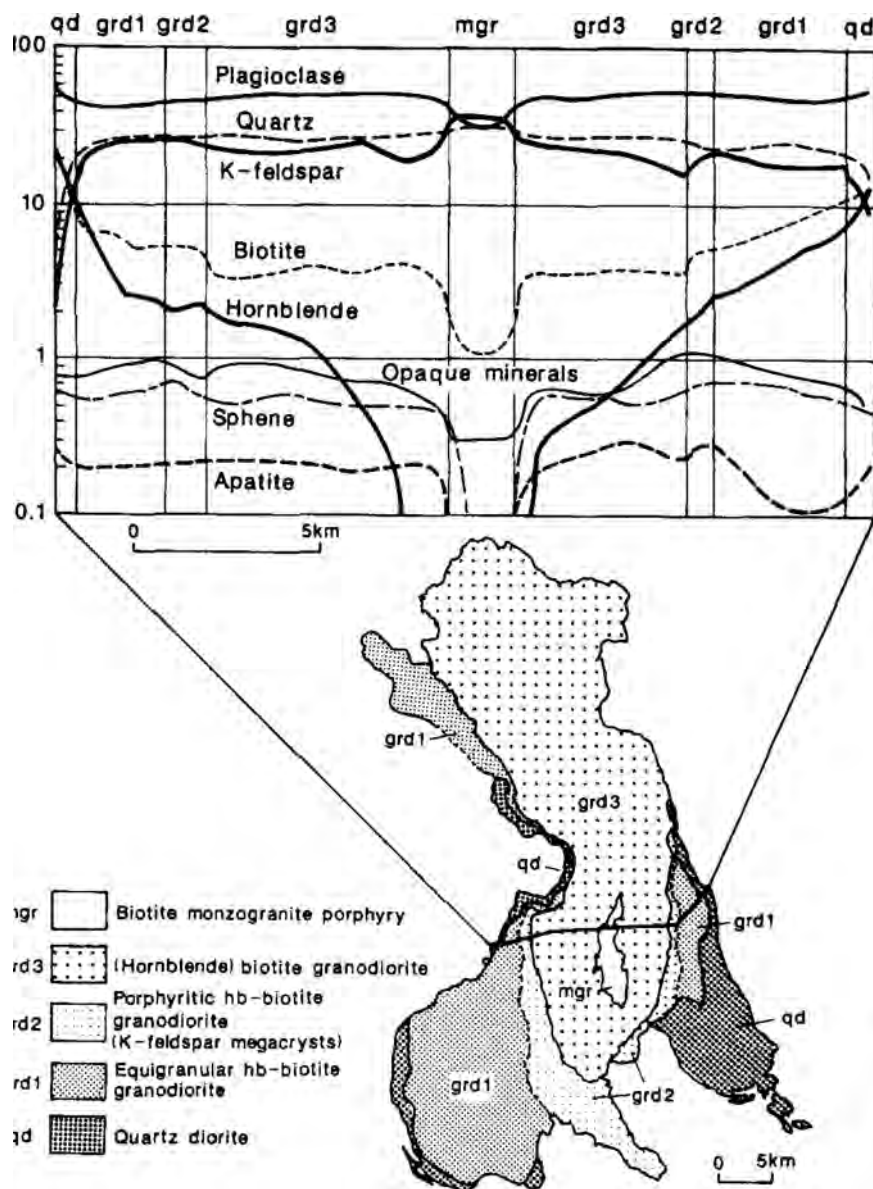


Figure 19. Compositional variations across the oxidised I-type Tuolumne intrusion, California, which shows a classic normal zonation from relatively mafic margin to felsic core, produced by fractional crystallisation (after Bateman and Chappell 1979). Modal amounts of major, varietal and accessory minerals are plotted as a function of position along the profile indicated, which passes through all mapped phases of the pluton. Magnetite is the dominant opaque mineral.

are derived from less metasomatised mantle can also give rise to large Cu-Au deposits, provided the mantle source is sulphur undersaturated. Relatively low water and sulphur contents of these mantle-derived magmas produce rather inconspicuous alteration halos with restricted potassic zones and little iron sulphide. However, the oxidised nature of the magmas and high K^+ , which boosts Fe^{3+} content, encourages formation of both magmatic and hydrothermal magnetite.

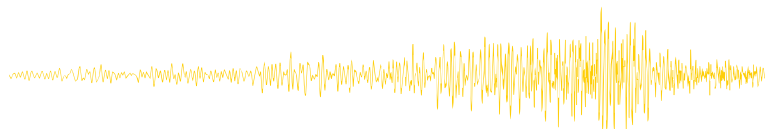
Halogens are important complexing agents for metals in hydrothermal fluids and Cl and F contents of magmas influence development of intrusive-related mineralisation. Cl decreases and F increases with fractional crystallisation in both I- and S-type granitoids (Blevin and Chappell 1992). Cl contents of I-type granitoids are higher than for S types. When a hydrothermal fluid exsolves from a silicate melt Cl partitions strongly to the aqueous phase, accompanied by chloride-complexed metals such as Fe, Mn, Cu, Mo, Pb, Sn and S. However, if a sulphur-enriched magmatic vapour phase forms,

sulphide-complexed Cu and Au preferentially partition into the low viscosity vapour, which can travel considerable distances before deposition, whereas Fe, Mn, Pb and Zn preferentially partition into the brine and tend to be deposited closer to the intrusion from which they emanate.

Effects of hydrothermal alteration

Studemeister (1983) pointed out that the redox state of iron in rocks is a useful indicator of hydrothermal alteration. Large volumes of fluid or high concentrations of exotic reactants, such as hydrogen or oxygen, are required to shift Fe^{3+}/Fe^{2+} ratios. When reactions associated with large water/rock ratios occur, the change in redox state of the rocks produces large changes in magnetic properties due to creation or destruction of ferromagnetic minerals.

Criss and Champion (1984) studied the southern Idaho batholith. They showed that intense hydrothermal alteration

**Table 1.** Petrological and geological characteristics of ferromagnetic and paramagnetic igneous intrusions

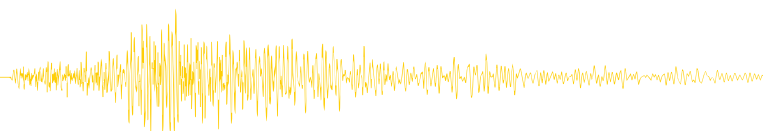
FERROMAGNETIC INTRUSIONS	PARAMAGNETIC INTRUSIONS
Source Rock Mantle Mafic crustal underplate Oxidised intermediate-felsic igneous rocks	Metasediments (particularly pelites) Reduced igneous rocks
Lithology Gabbro>diorite>tonalite>granodiorite>granite Hornblende ± biotite granitoids and biotite granites with high Mg, low Al biotite Pyroxene ± hornblende granitoids Many monzonites, quartz monzonites, syenites, quartz syenites and miaskitic nepheline syenites Most alkali gabbros, essexites, ijolites etc. Ferrogabbros, ferrodiorites and granophyres, within upper levels of layered mafic complexes	Predominantly granite and granodiorite Muscovite and two mica granitoids, most leucogranites, biotite-rich granitoids Cordierite, corundum or aluminosilicate-bearing granitoids Peralkaline granites, syenites or nepheline syenites Lower gabbros in layered mafic complexes
Mineralogy Generally higher colour index Biotite ± hornblende in felsic calc-alkaline granitoids; hornblende± pyroxene± olivine (except fayalite) in more mafic varieties Fe ³⁺ and Mg-rich biotite and hornblende; biotite colour is brown, black or olive green Sphene (> 0.1 vol %) ± hemoilmenite (8 mole % to 20 mole % Fe ₂ O ₃) or Mn-rich ilmenite (up to 30 mole % MnTiO ₃) ± epidote ± allanite ± pyrite as accessories White plagioclase + pink K-feldspar Intermediate to Fe-rich olivine and pyroxenes + intermediate to sodic plagioclase ± hornblende ± apatite in upper ± middle levels of tholeiitic layered intrusions Zoned plagioclase (> 60 %) + quartz + biotite and/or hornblende in M-type oceanic/ophiolitic plagiogranites Nepheline + alkali feldspar + plagioclase + calcic pyroxene + hastingsite + biotite in silica-undersaturated metaluminous (miaskitic) rocks Nepheline + alkali feldspar + sodic pyroxene and amphibole ± biotite without aenigmatite or astrophyllite in mildly peralkaline undersaturated rocks	Generally lower colour index Biotite + muscovite, cordierite, garnet or aluminosilicate in calc-alkaline granitoids. Fe ²⁺ and Al-rich (annite/siderophyllite-rich) biotite, often with "foxy red" colour; occasionally Fe ²⁺ -rich hornblende or fayalite "Reduced" ilmenite (< 8 mole % Fe ₂ O ₃ , usually Mn-poor) ± pyrrhotite (predominantly hex po) ± spinel ± graphite as accessories, primary sphene absent White plagioclase + white K-feldspar or sometimes brick red K-feldspar; sometimes green plagioclase + pink K-feldspar Mg-rich olivine and pyroxenes, calcic plagioclase ± chromite in lower to middle zones of tholeiitic layered intrusions Quartz + alkali feldspar + sodic pyroxene and/or sodic amphibole ± aenigmatite ± astrophyllite ± biotite in oversaturated peralkaline (ekeritic) rocks Nepheline + sodic pyroxene + aenigmatite ± astrophyllite in silica-undersaturated peralkaline (agpaitic) rocks
Chemistry Predominantly metaluminous, but also weakly peraluminous or weakly peralkaline granitoids ($0.9 \leq A/NK < A/CNK \leq 1.1$) Moderate-high ferric iron (Fe ₂ O ₃ > 0.8 wt%, typically 1-3 wt%) and moderate-high total iron (> 2 wt% FeO ^T) Moderate oxidation ratio (mean Fe ³⁺ /Fe ²⁺ ~ 0.6 at 60% SiO ₂ , Fe ³⁺ /Fe ²⁺ ~ 0.9 at 75% SiO ₂ , i.e. molar Fe ₂ O ₃ /(FeO+Fe ₂ O ₃) ~ 0.2-0.3) Normative (diopside ± olivine ± acmite) plus > 1 wt% normative magnetite ± haematite Relatively anhydrous	Strongly peraluminous (A/CNK > 1.1) and strongly peralkaline (A/NK < 0.9) granitoids, some metaluminous granitoids Low ferric iron (Fe ₂ O ₃ < 0.8 wt%) or very low total iron (< 1 wt % FeO ^T) Low oxidation ratio (mean Fe ³⁺ /Fe ²⁺ ~ 0.1 at 60% SiO ₂ , Fe ³⁺ /Fe ²⁺ ~ 0.4 at 75% SiO ₂ , molar Fe ₂ O ₃ /(FeO+ Fe ₂ O ₃) = 0.05-0.2) or very high oxidation ratio Normative corundum or normative acmite+sodium metasilicate Relatively hydrous
Emplacement depth Predominantly epizonal, particularly subvolcanic, some mesozonal and catazonal	Predominantly mesozonal or catazonal, some epizonal
Associated rocks Associated volcanics common Gabbro-diorite-trondhjemite associations (Gabbro)-diorite-granodiorite-monzogranite associations Diorite-monzonite-quartz monzonite-monzogranite associations Syenite-alkali syenite-alkali granite associations	Associated volcanics uncommon Syenogranite-monzogranite-granodiorite associations Quartz syenite-syenogranite associations
Tectonic setting Andinotype (subduction of oceanic plate beneath continental margin, generating Cordilleran I-type batholiths) Island arc plagiogranites, gabbros and quartz diorites Alpinotype (tectonically emplaced serpentinised peridotites, gabbros and plagiogranites) Caledonian-type post-closure uplift and tensional regimes with major faulting Anorogenic, rifting-associated moderately evolved granitoids	Hercynotype (continental collision, e.g. Himalayan and Hercynian leucogranites) Encratonic ductile shear belts with thickened continental crust Late tectonic/post tectonic catazonal migmatites and mesozonal granitoids associated with regional metamorphism Compressional regimes Anorogenic, rifting-associated highly evolved granitoids

A/NK = atomic Al/(Na + K); A/CNK = atomic Al/(Ca + Na + K)

around Tertiary plutons generally reduced the susceptibility of magnetite-series Mesozoic tonalites and granodiorites over substantial areas. However, hydrothermal alteration with a lower water/rock ratio locally produced secondary magnetite within ilmenite-series granitoids, enhancing their susceptibility.

Hollister (1975) distinguished between the Lowell and Guilbert (1970) quartz monzonite model of porphyry copper deposits and a diorite model. The Lowell-Guilbert model

incorporates a core potassic zone, surrounded successively by phyllic, argillic and propylitic zones arranged in concentric but incomplete shells. This model is typically most applicable to calc-alkaline granodiorite-quartz monzonite porphyries (often associated with quartz diorite intrusions) with copper and molybdenum mineralisation, but negligible gold. In the diorite model the phyllic and argillic zones are absent and the propylitic zone adjoins the core potassic zone. Sulphides are less developed in the diorite model

**Table 2.** Magnetic petrophysical classes of intrusive rocks and alteration zones associated with mineralisation:

TYPE OF MINERALISATION	MAGNETIC PETROPHYSICAL CLASSIFICATION
Au-rich (> 0.4 g/t) porphyry Cu within MFM mafic intermediate igneous host rocks	SFM granitoid (M- or I-type)+ SFM potassic alteration zone± PM phyllic zone + WFM to MFM propylitic zone
Porphyry Cu within MFM mafic-intermediate igneous host rocks	MFM to SFM granitoid ± SFM potassic alteration zone + PM phyllic zone + PM argillic zone + WFM to MFM propylitic zone
Porphyry Mo	WFM granitoid directly associated with mineralisation, zoned to MFM less fractionated granitoid phase WFM to MFM granitoid
Au-scheelite-quartz exogranitic plutonic vein (scheelite contains Mo)	
W-Mo-Cu skarn	MFM to SFM granitoid + SFM skarn PM granitoid
W-Cu-Sn veins. Tungsten mineral is wolframite or Mo-free scheelite	
W-Sn-F skarn	PM granitoid + WFM to SFM skarn PM granitoid
Sn-W greisen	PM to WFM gabbros overlying PM unserpentinised ultramafics or, more commonly, MFM to SFM serpentinised ultramafics SFM gabbros PM granitoid
Cr, PGEs, Ni-Cu in lower levels of layered mafic complex	
Ti, V in upper levels of layered mafic complex	
Sn-W, Be, Li and U associated with peraluminous two-mica granites	PM granitoid ± MFM to SFM carbonatite
Nb-Ta, REE mineralisation associated with peralkaline anorogenic ring complexes	

PM = paramagnetic; WFM = weakly ferromagnetic; MFM = moderately ferromagnetic; SFM = strongly ferromagnetic; VSFM = very strongly ferromagnetic (see text)

and lower pyrite contents in the altered host rocks allow some of their magnetite to survive alteration. The diorite model is applicable usually to syenite monzonite porphyries associated with diorites and often contain gold, as well as copper, but no economic molybdenum mineralisation.

Phyllic alteration, argillic alteration and intense propylitic alteration associated with porphyry intrusions tend to destroy magnetite within the intrusion and in surrounding rocks. Weak to moderate, but pervasive, propylitic alteration may leave most of the magnetite in host rocks relatively unaffected. On the other hand, the potassic alteration zone associated with oxidised, magnetic felsic intrusions is often magnetite-rich. This is commonly observed for Au-rich porphyry copper systems (Sillitoe 1979). It is evident from the above descriptions of the Lowell-Guilbert and Hollister's diorite models that the magnetic signatures of the two types of system should differ substantially. Clark *et al.* (1992a; 1992b) presented a theoretical magnetic signature of an idealised gold-rich porphyry copper deposit, based on the Sillitoe (1979) model and magnetic petrological concepts. Early potassic (biotite-rich) alteration around the gold-mineralised Mount Leyshon Complex (Queensland), which is comprised of intrusive breccias and trachytic to rhyolitic porphyry plugs and dykes, produced abundant magnetite in metasedimentary and doleritic host rocks that adjoin the southern half of the Mount Leyshon Complex. That alteration is therefore largely responsible for the Mount Leyshon magnetic anomaly (Sexton *et al.* 1995). However, the equivalent alteration within felsic, iron-poor, granitic host rocks, around the northern portion of the complex, produces K-feldspar alteration with little or no secondary magnetite. Thus, the Mount Leyshon magnetic anomaly is centred over the southern portion of the complex and its adjoining metasomatised aureole, rather than being symmetrically distributed around the complex.

In most porphyry systems, both primary magmatic magnetite and hydrothermal magnetite are generally in the multidomain size range. Multidomain magnetite boosts susceptibility but is not an efficient or stable carrier of remanent magnetisation. Thus, most of the magnetic signature of such porphyry systems is attributable to induced magnetisation, perhaps slightly enhanced by viscous remanence. However, alteration of certain

country rocks can produce substantial quantities of fine-grained magnetite that is capable of carrying intense and stable remanence.

The magnetic anomaly at Mount Leyshon is a pronounced low that arises from reversed remanent magnetisation ($Q \gg 1$) of the biotite-magnetite altered metasediments and dolerites. Magnetite-bearing skarns with reversed remanence are also responsible for negative anomalies at the Red Dome Au deposit in NE Queensland (Collins 1987). Monoclinic pyrrhotite may also carry intense remanence and produce large magnetic anomalies. Therefore, pyrrhotite skarns may produce strong magnetic anomalies that are dominated by remanent magnetisation.

Magnetite-rich alteration zones around calc-alkaline porphyry copper deposits have been extensively discussed by Clark and Arancibia (1996). These authors argue that magnetite-rich vein systems in and around some porphyry systems are often early (pre-mineralisation) and are distinct from magnetite-biotite potassic alteration that is associated with sulphides and Cu-Au mineralisation. The magnetite ± amphibole plagioclase alteration, with very little sulphide, represents the initial stage in the evolution of a subclass of porphyry copper deposits. Deposition of this assemblage is favoured by host rocks of mafic-intermediate composition. Host rocks influence deposition of magnetite around these systems, but iron metasomatism effected by magmatic conditions is also demonstrably important. The early strongly magnetic alteration appears to be associated with strongly oxidised intrusions that contain magnetite + sphene rather than the less oxidised assemblage magnetite + ilmenite.

Wall and Gow (1996) recognise a magnetite-rich Cu-Au class and a haematite-rich Cu-Au (U, REE) class of deposits associated with Proterozoic felsic plutons. Magnetite precipitation may be an important chemical control on sulphide precipitation in granitoid roof zones. The haematite association overprints the magnetite-rich bodies and results from highly oxidised lower temperature fluids with major meteoric component. La Candelaria-type magnetite mineralisation in Chile and Peru has some similarities and may be related to Mesozoic granitoids. The granitoids associated with these types of mineralisation are oxidised, high temperature, magnetite-series plutons.

Influence of country rocks

The nature of the country rock is crucial in the case of magmatic-hydrothermal skarn deposits, which develop in carbonate rocks that have been metamorphosed and metasomatised by the mineralising intrusion. In most cases emplacement of the intrusion into non-carbonate rocks would not have resulted in economic mineralisation. The review of Einaudi, Meinert, and Newberry (1981) contains much useful information relevant to magnetic petrology of skarn deposits. Magnetite contents of magnesian skarns developed in dolomite are generally higher than those of calcic skarns developed in limestone, because Fe-rich calc-silicates are not stable in a high-Mg system. However both island arc type calcic skarns (associated with gabbros and diorites in volcano-sedimentary sequences) and Cordilleran-type magnesian skarns (associated with quartz monzonites or granodiorites intruding dolomites) have been mined for magnetite. Such deposits are evidently associated with very large magnetic anomalies.

Cu skarns (mostly associated with epizonal quartz monzonite and granodiorite stocks in continental settings) are associated with oxidised assemblages, including magnetite haematite, with the less common magnesian skarns exhibiting higher magnetite and lower sulphide contents than calcic skarns. Tungsten-bearing skarns (associated with mesozonal calc-alkaline quartz monzonite to granodiorite intrusions) have a more reduced calc-silicate and opaque mineralogy than Cu-skarns, but typically contain minor magnetite and/or pyrrhotite and would therefore be expected to exhibit a relatively weak, but nevertheless detectable, magnetic signature in most cases. Calcic Zn-Pb skarn deposits associated with granodioritic to granitic magmatism and Mo skarns associated with felsic granites appear to contain relatively little magnetite. Sn skarns are associated with reduced ilmenite-series granites and have relatively low sulphide contents. The skarns themselves contain magnetite \pm pyrrhotite and exhibit a substantially larger susceptibility than the paramagnetic granite and unaltered host rocks. Massive sulphide replacement tin orebodies in dolomite (e.g. Renison and Cleveland deposits, Tasmania) are rich in monoclinic pyrrhotite and have high susceptibilities, with substantial remanent magnetisation. This type of orebody may represent the low temperature distal analogue of magnesian Sn skarns.

Webster (1984) analysed magnetic patterns over a number of granitoids associated with tin mineralisation in the Lachlan Fold Belt and contrasted these with unmineralised and Cu-Mo-W mineralised granitoids. The characteristic magnetic signature of granitoid-associated tin mineralisation is: a granitoid with low magnetic relief, surrounded by a more magnetic aureole, with significant magnetic anomalies associated with the mineralisation.

Wyborn and Heinrich (1993) and Wyborn and Stuart-Smith (1993) have suggested that particular host rocks favour deposition of Au mineralisation from oxidised fluids that emanate from felsic granitoids and move up to 5 km from the granitoid contact. Graphite-, sulphide- and magnetite-bearing lithologies are capable of reducing the fluids and depositing Au and Cu, whereas Pb and Zn are preferentially deposited in carbonate rocks. Au-only mineralisation will preferentially be deposited within graphite-bearing but magnetite- and sulphide-poor rocks, whereas magnetite and or iron sulphide-rich rocks tend to precipitate Cu and Au together. These relationships appear to have been observed in the eastern

Mount Isa Inlier and the Pine Creek Inlier. Thus a rock unit that is strongly magnetic, indicative of high magnetite content, may be a favourable site for deposition of Au-Cu mineralisation sourced from a nearby granitoid.

Conclusions

Relationships between magnetic properties of igneous intrusions and their mineralogy, chemical composition, geological setting and history are complex. However, clear patterns can be discerned and much progress has been made in recent years in understanding the geological factors that control their magnetic properties. Although magnetic properties are not predictable with any reliability from first order rock names, a more detailed classification of intrusive igneous rocks does correlate well with magnetic properties, because there are many links between magnetic properties of igneous intrusions and their geological, chemical and mineralogical characteristics. These patterns arise directly in some cases, e.g. the correlation between oxidation ratio and magnetite content, but in many cases they are indirect.

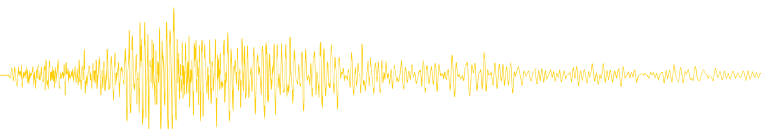
One example of an indirect relationship is the strong association between paramagnetic ilmenite-series granitoids and S-type granitoids. The magnetite-poor nature of most S type granitoids arises from their reduced character, which reflects incorporation of crustal carbon. Carbon content is an incidental, rather than a defining, characteristic of an S type granitoid.

Data on geological, geochemical and mineralogical associations with magnetite in granitoids are summarised in [Table 1](#).

Of particular importance to exploration is the clear, albeit indirect, relationships between a number of important types of intrusive-related mineralisation and the magnetic properties of the associated intrusions and their alteration systems ([Table 2](#)). There is now sufficient knowledge to develop and test improved magnetic exploration models for intrusive-related mineralisation. Key elements that need to be incorporated into magnetic exploration models include:

1. Regional-scale links, summarised in [Table 2](#), between intrusive-related mineralisation of a given type and the magnetic petrology of the associated intrusions.
2. The magnetic expression, at regional to deposit scale, of structural controls on location of intrusions or fluid pathways, and of lithological controls on deposition of mineralisation.
3. The magnetic expression of fractional crystallisation (zoned magnetic properties or complex patterns that suggest multiple comagmatic intrusions of varying fractionation) at a district to deposit scale.
4. Use of magnetic petrological principles and magnetic petrophysical data to predict the magnetic properties of intrusive phases, host rocks and alteration zones for each deposit type.
5. Incorporating predicted magnetic properties into conventional ore deposit models to enable calculation of theoretical magnetic signatures of deposits for a range of geological settings.

Clark *et al.* (1992b) showed some examples of simple magnetic exploration models. Although such models are inevitably simplistic, if they are based on petrophysical data and magnetic petrological principles they should improve the utility of magnetic surveys in exploration.



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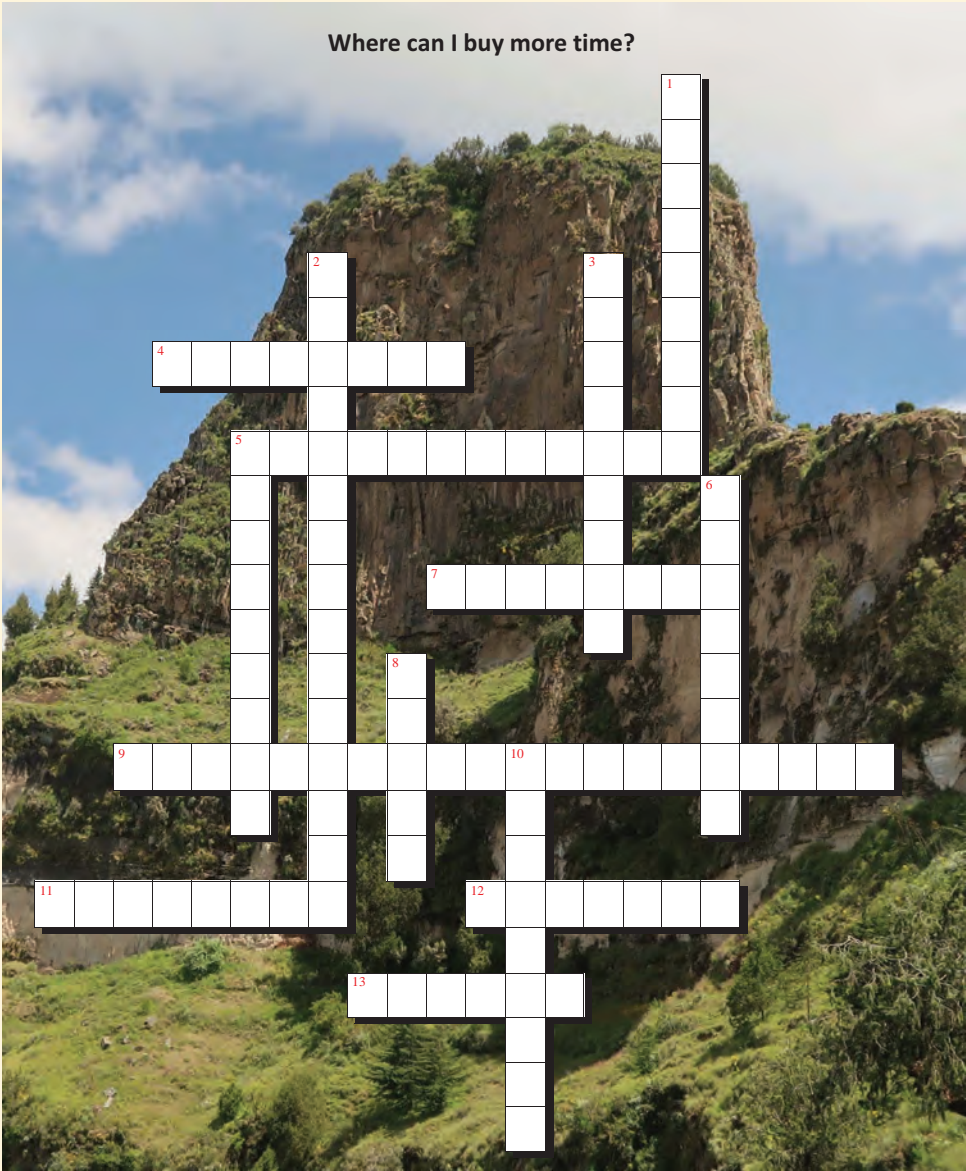
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Preview crossword #7



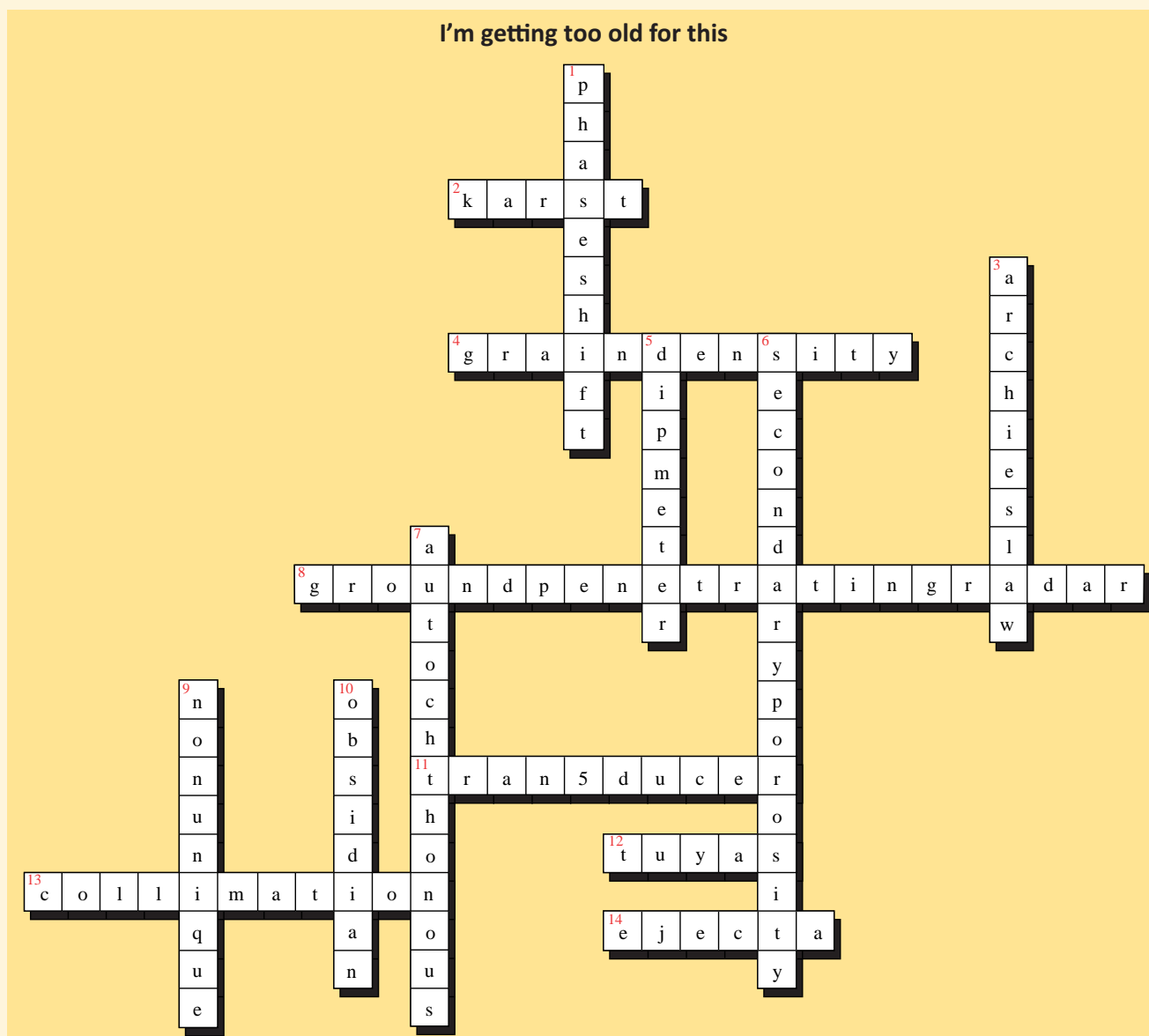
Across	Down
4. A form of crossbedding characterised by cross-laminations which have both concave and convex-upwards forms.	1. The study of the tracks, burrows and other traces made by living organisms on and within a substrate.
5. The study of a source by dispersing light into a spectrum of different wavelengths.	2. A series of convex-upward thrust or reverse faults found in transpressional strike-slip zones.
7. A great circle passing through the poles of a sphere.	3. The closest spiral galaxy to our own Milky Way.
9. The use of measurements of the magnetisation of strata for absolute or relative dating purposes.	5. Lithium bearing pyroxene.
11. Carrot-shaped volcanic vent that has formed by explosive action.	6. The commonest mercury mineral
12. The area of geophysics concerned with determining the detailed shape and mass distribution of a body such as Earth.	8. A unit of magnetic flux equal to one weber per square meter.
13. Fractures in the Earth's crust across which there has been no relative motion.	10. The transport of a physical property by entrainment in a moving medium.

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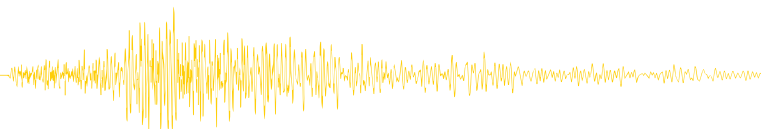


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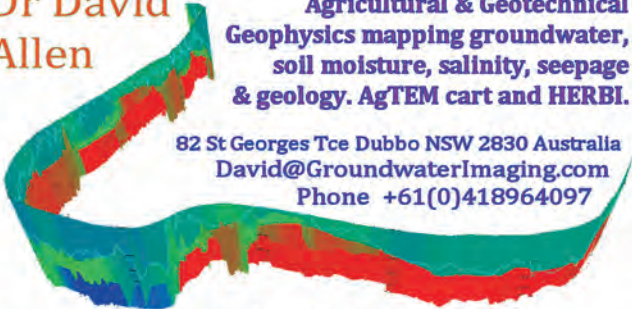
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19–21	AI Earth Exploration Workshop: Teaching the Machine How to Characterize the Subsurface Postponed https://seg.org/Events/artificially-Intelligent-Earth-Exploration	Muscat	Oman	
20	Generalized sampling and gradiometry: Changing the rules of the information game https://www.knowledgette.com/p/generalized-sampling-and-gradiometry-changing-the-rules-of-the-information-game			Webinar
22	Automating seismic data analysis and interpretation https://www.knowledgette.com/p/automating-seismic-data-analysis-and-interpretation			Webinar
24–27	Offshore Technology Conference asia (OTC asia) Postponed http://2020.otcasia.org/welcome	Kuala Lumpur	Malaysia	
30	Biogeophysics: Exploring Earth's subsurface biosphere using geophysical approaches https://www.knowledgette.com/p/biogeophysics-exploring-earth-s-subsurface-biosphere-using-geophysical-approaches			Webinar
May	2020			
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8–11	82nd EaGE annual Conference and Exhibition Postponed https://eage.eventsair.com/eageannual2020/	Amsterdam	The Netherlands	
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September	2020			
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21	Biogeophysics: Exploring Earth's subsurface biosphere using geophysical approaches https://www.knowledgette.com/p/biogeophysics-exploring-earth-s-subsurface-biosphere-using-geophysical-approach			Webinar
28–02 Oct	Advanced Earth Observation Forum 2020 https://earthobsforum.org/	Brisbane	Australia	
28–02 Oct	Australian and New Zealand Geomorphology Group Conference Postponed https://www.anzgg.org/conferences	Alice Springs	Australia	
October	2020			
11–16	SEG International Exposition and 90th annual Meeting https://seg.org/aM/2020	Houston	USA	
December	2020			
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19–22	Australasian Exploration Geoscience Conference (AEGC 2021)	Brisbane	Australia	

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EMIT

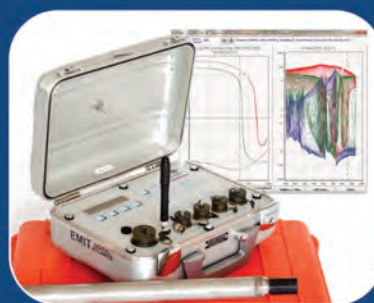
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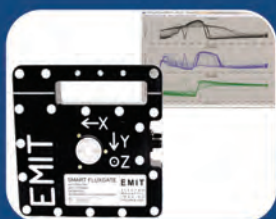
SMARTem24

Rugged and reliable PC-based, 16 channel, 24-bit electrical geophysics receiver system with time-series recording, powerful noise rejection, GPS sync and an optional separate Transmitter Controller. Works seamlessly with a wide range of transmitter systems and most sensors for EM and IP. The SMARTem24 application plots decays, profiles, maps and pseudo-sections providing powerful QC capabilities. Hot-swappable batteries, touch-screen, solid-state HDD and water/dust protection make this an instrument for serious electrical geophysics. Compatible with EMIT's Transmitter Multiplexer and other tools for increasing productivity.



DigiAtlantis

3-component digital borehole fluxgate magnetometer system in a 33mm tool for EM and MMR with simultaneous acquisition of all components, time-series recording and powerful noise rejection. Compatible with a wide range of transmitter systems and EMIT's Transmitter Multiplexer for increasing productivity. Samples the whole waveform providing on and off-time data. Magnetometer DC signals are recorded to give 3-component and total-field geomagnetic data. Orientation data gives hole inclination and azimuth in real-time without additional surveys. Designed to be used with industry-standard winches with 2-core and 4-core cable.



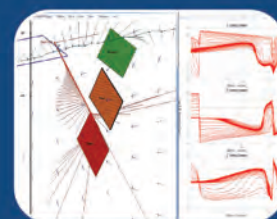
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Rugged, low noise, calibrated, 3-component fluxgate magnetometer with recording of geomagnetic fields, digital tilt measurement and auto-nulling.



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Intelligent and safe 3.6 kW transmitter for EM surveys using standard generators. Clean 40A square wave output, inbuilt GPS sync and current waveform recording.



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