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Australian Society of Exploration Geophysicists

PREVIEW

NEWS AND COMMENTARY

FEATURES

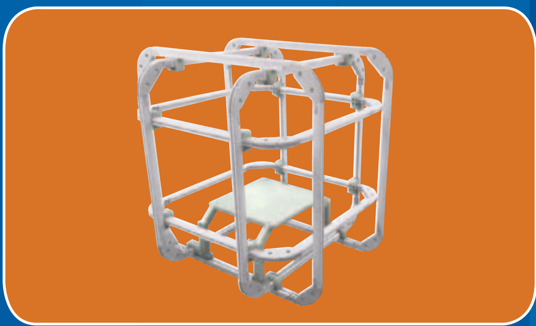
Magnetic Field Instrumentation

Three-Axis Magnetic Field Sensors

- For TDEM and airframe compensation
- Measuring ranges from ±60µT to ±1000µT
- Noise levels down to < 4pTrms/√Hz at 1Hz
- Bandwidth to 3kHz; wide bandwidth version to 12kHz

Helmholtz Coil Systems

- For downhole tool and sensor calibration
- 500mm and 1m diameter coils
- Power Amplifier and Control Unit available



Grad-13 Digital Three-Axis Gradiometers

- For shallow archaeology and UXO surveys
- Baselines of 500, 750 and 1000mm
- Measuring range of ±100µT
- Incorporates accelerometers and temperature sensor

PREVIEW

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2015 ASEG CORPORATE MEMBERS

CORPORATE PLUS MEMBERS

Velseis Pty Ltd

CORPORATE MEMBERS

Beach Energy
Geotech Ltd
Papuan Oil Search Limited
Petrosys Pty Ltd
Quantec Geoscience Pty Ltd
Rio Tinto Exploration Pty Ltd
Santos Ltd
Seismic Asia Pacific Pty Ltd
Southern Geoscience Consultants Pty Ltd
Terrex Seismic
Wireline Services Group
Zonge Engineering

FRONT COVER

University of Melbourne student Taylor Ogden performs a survey using a Scintrex CG3 gravity meter, near Wulgulmerang in the high country of north-east Victoria, on the northern fringes of the Snowy River National Park. Taylor won the ASEG Vic/Tas Branch Prize for best student presentation of his work (see Education Matters).

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Lisa Worrall

A bumper issue of *Preview* for Christmas – what more could you want? A reading feast is on offer. I invite you to nibble on news and commentary (is there anything Bob Smith can't do?) before tucking into one of the main courses: a summary of postgraduate research in Australia in 2015, an essay on the first gravity meter, which was built in Australia in the 1890s, and finally, and most deliciously, a consideration of the role that lapis lazuli has played in human history.

It is always astonishing to contemplate the scope of postgraduate research in geophysics in Australia. What is particularly heartening this time around is that much of the research is cross-disciplinary and that students are problem solving by integrating analysis of disparate data. As Michael Asten (Education Matters) says, if universities can consistently produce students of this quality then the future of the industry is bright. Just in case students, and Dave Annetts (Webwaves), are tempted to think they are doing it tough, then the piece by Roger Henderson on the trials and tribulations of the physicists who build the first gravity meter in Sydney in the 1890s is a salutary reminder of just how, in relative terms, we have it easy. If the advances in quantum computing discussed by Guy Holmes (Data Trends) come to fruition then the next generation might be equally surprised at what we managed to achieve, given what we had to work with!

One of the aims of this magazine, your magazine, is to foster and facilitate interaction between geophysicists in Australia and the Asia Pacific region. I hear on the grapevine that *Preview* articles are prompting discussion and I have seen some of your letters to the Associate Editors, so it would seem that the Editorial team, particularly the Associate Editors, are hitting the mark. The Associate Editors put themselves and their ideas out there on a regular basis – which is not an easy task – and they really do appreciate your feedback. Personally I would like to thank them, and the other regular contributors to *Preview,* for their good humoured response to my regular poking and prodding!

We will be back in 2016 and I am very much hoping that Don Emerson will be back with another Christmas treat. He tells me that it takes most of the year (in between getting on with life) for him to do the research and complete the article – a big commitment that he may not be prepared to make for many more years. So, let's make the most of the year to come. If you can think of a rock or mineral that has held a grip on human imagination through time and could do with the Don Emerson treatment then email him – or me.

A safe and happy festive season to you all!!

Lisa Worrall
Preview *Editor*
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ASEG News

SEG New Orleans, geophysical instruments, magnetic and gravity fields

Last month, as ASEG President, I attended the SEG meeting in New Orleans. Heading to New Orleans I thought of Howard Golden's article in *Preview* (December 2006), written after Hurricane Katrina (August 2005) had struck the Gulf Coast and burst the New Orleans levee bank causing widespread destruction. On arrival I wandered the downtown streets, vaguely heading for the museum district to kill time (and jetlag) until I could grab some decent sleep, but I came across Lafayette Square and the 10th Anniversary of the Katrina Blues & BBQ festival.

I never made it to the museums but having had a Cajun BBQ and a good night's sleep I was ready to set up the ASEG booth with Koya Suto the following morning, before attending the SEG Council Meeting and the Conference Centre. Just an aside on our booth props, Skippy and Hoppy, I have to admit that when I first heard of them I was quietly dismissive but, having been at the booth when passers-by instantly recognise where you must be from, I now realise that they are an instant ice-breaker and often led to more meaningful discussions. Curtin University even said they almost nicked Skippy because no-one knew where Curtin Uni was. So, I take back my silent indifference Greg!

This issue of *Preview* includes an article by Roger Henderson on a gravity meter built in the Department of Physics at Sydney University in the late 1800s. This gravity meter operated on the same principle that many modern gravity meters operate. I will not steal Roger's thunder here, but it is a fascinating piece of geophysics history that we should all know about. It reminded me of Doug Morrison's series on Neumayer in the 1850s, and the Flagstaff laboratory in

The ASEG booth at New Orleans with two characters well known to the membership, plus Koya and me.

Melbourne which was a first in the Southern Hemisphere. Doug's article from *Preview* 121 (April 2006) is entitled 'Neumayer: pioneer exploration geophysicist' and quotes Neumayer '…all my instruments are constructed on new principles ... by a Magnetic Map of a country we can draw a conclusion as to its probable value for agricultural and mining purposes. It is more than probable that there exists a relation of terrestrial Magnetism and the great tracts of auriferous land in Australia, and such a map would enable us to point out new spots of the above mentioned interest without making trials on an expensive scale.' Remarkably prescient given the time. So, Australia has been at the forefront of geophysics since the 1850s.

According to NASA, Mars' lack of a magnetic field is now thought to be responsible for its lack of a significant atmosphere. This came as a surprise to me because I attended lectures given by Ted Ringwood at RSES ANU in the 1960s where he would attribute the lack of the Martian atmosphere on the Sun's T-Tauri phase during accretion of the planets. In fact all inner planets were supposed to have lost their atmospheres during this stage and only those planets with residual volatiles in their mantles were able to redevelop atmospheres. Plate tectonics has certainly helped Earth to regain an atmosphere. But NASA now say that the solar wind, comprised of charged particles that on approach to Earth become deflected north or south depending upon polarity (and spiral relatively harmlessly into the magnetic poles), has stripped Mars of its atmosphere after its magnetic field ran out of ergs and the whole planet became directly exposed to the solar wind. Mars probably had a molten core for its first billion years but it is thought to have since solidified. NASA has made much of evidence for large quantities of water on Mars sometime in its past, so what has caused the loss of the Martian atmosphere becomes extremely important in whether it may be possible for mankind to establish a base there. You would want to be very careful recycling water at such a base.

Meanwhile, economist Saul Eslake has suggested that the final commodities boom in 'human history' may have just finished (from the International Mining and Resources Conference in Melbourne last Tuesday). This is hard to believe given the global population is growing more or less exponentially. I prefer to listen to Ross Gittins, (economics editor for Fairfax) who says economists make the worst soothsayers. I'm sticking to my belief that the next boom is around the corner, hopefully soon enough that universities do not start cutting geophysics courses.

Phil Schmidt
ASEG President
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Left: New Orleans 2006 (immediately post-Katrina). Right: New Orleans 2015 (10th Anniversary of the Katrina Blues & BBQ Festival).

Welcome to new Members

The ASEG extends a warm welcome to 23 new Members approved by the Federal Executive at its October and November meetings (see table).

First name	Last name	Organisation	State	Country	Membership type
Antonia	Bigault	University of QLD	QLD	Australia	Student
Sarah	Buckerfield	Geoscience Australia	ACT	Australia	Active
Adrian	Callum	University of the Sunshine Coast	QLD	Australia	Active
Wenchao	Cao	The University of Sydney	NSW	Australia	Student
Vince	Gerrie	DGI Geoscience	Ontario	Canada	Active O/S
Issac	Graves	University of Melbourne	VIC	Australia	Student
Bradley	Grosser	Chevron	WA	Australia	Active
Mahmood Ul	Hassan	Royal Institute of Technology		Sweden	Student
Paul	Hyde	Velseis Pty Ltd	QLD	Australia	Active
Nick	Jervis-Bardy	Zonge Engineering and Research Organisation Australia	SA	Australia	Active
Mehdi	Khaki	Curtin University	WA	Australia	Student
Alexandra	Lemenager	Macquarie University	NSW	Australia	Student
Yaoguo	Li	Colorado School of Mines	CO	USA	Active O/S
Louise	L'oste-Brown	Minotaur Exploration Ltd	SA	Australia	Associate
Luke	Mahony	University of Melbourne	VIC	Australia	Student
Mardi	McNeil	Queensland University of Technology	QLD	Australia	Student
Michel	Nzikou	Curtin University Of Technology	WA	Australia	Student
Joaquin	Pablo		WA	Australia	Student
Denny	Rompotes	Hiseis Pty Ltd	WA	Australia	Active
Beti	Slakeska	Geosoft	WA	Australia	Associate
Katri	Vaittinen	Boliden	Västerbotten	Sweden	Active O/S
Christopher	Yeomans	University of Exeter , Camborne School of Mines	UK	UK	Student O/S
Dailei	Zhang	Griffith University/Jillin University, China	QLD	Australia	Student

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Notice of Annual General Meeting (AGM)

The 2016 AGM of the Australian Society of Exploration Geophysicists (ASEG) will be held in Perth on 13 April 2016. The meeting will be hosted by the WA Branch. Details of the meeting time and address of the venue will be advised closer to the meeting.

The business of the Annual General Meeting will include:

- To confirm the minutes of the 2015 Annual General Meeting;
- To receive from the Federal Executive reports on the activities of the Society during the last preceding financial year;
- To receive and consider the financial accounts and audit reports that are required to be submitted to members pursuant to the Society's Constitution and to law;
- To consider and if agreed approve any amendments to the Constitution of the Society that the Federal Executive may bring to the meeting;
- To report the ballot results for the election of the new office holders for the Federal Executive;
- To confirm the appointment of auditors for the 2016 financial year.

The AGM will be followed by a scientific presentation. The speaker and title will be advised closer to the event.

Invitation for candidates for the Federal Executive

Members of the Federal Executive serve in an honorary capacity. They are all volunteers and Members are encouraged to consider volunteering for a position on the Executive or on one of its committees. Current members are listed in *Preview*; please contact one of them if you wish to know more about volunteering for your society.

The Federal Executive comprises up to 12 members, and includes the following four elected members:

(i) President,
(ii) President Elect,
(iii) Secretary, and
(iv) Treasurer.

These officers are elected annually by a general ballot of Members. Katherine McKenna was elected as President-Elect in 2015 and as such will stand for the position of President in 2016. Members wishing to nominate for one of these positions should note that in accordance with Article 8.2 of the ASEG Constitution '…The elected members of the Federal Executive are designated as Directors of the Society for the purposes of the [Corporations] Act'.

The following officers are also recognised in the Society's Constitution and serve on the Federal Executive:

(i) Vice President,
(ii) the Immediate Past President (unless otherwise a member of the Federal Executive),
(iii) the Chairman of the Publications Committee,
(iv) the Chairman of the Membership Committee,
(v) the Chairman of the State Branch Committees, and
(vi) up to three others to be determined by the Federal Executive.

These officers are appointed by the Federal Executive from the volunteers wishing to serve the Society.

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 Secretary:

Barry Drummond
ASEG Secretary
Care of the ASEG Secretariat
PO Box 576
Crows Nest
NSW, 1585
Tel: (02) 9431 8622
Fax: (02) 9431 8677
Email: fedsec@aseg.org.au

Nominations for the elected positions must be received via post, fax or email **no later than COB Wednesday 16 March 2016**. Positions for which there are multiple nominations will then be determined by ballot of Members and results declared at the Annual General Meeting.

Proxy forms and further details of the meeting will be sent to Members prior to the meeting by email and made available to Members on the Society's website.

Executive Brief

The Federal Executive of the ASEG (FedEx) is the overall governing body of the Society. It meets once a month to see to the administration of the Society. It also meets twice a year to consider and make more strategic plans. A report on the last planning meeting, which was held in September, is included in this brief.

In addition to reporting on planning meetings, the Honorary Editor of *Preview* has been asking for some time for FedEx to report to Members, via *Preview*, on the business conducted at its regular (monthly) meetings. Much of what we do at these meetings is routine and would make pretty boring reading if repeated verbatim. In the spirit of openness, however, it is our intention that the minutes of our meetings will eventually appear on the Members-Only part of our website. But, we need a re-design and re-engineer of the website before that can happen. In the interim FedEx will use this column to brief Members on its regular business. Anyone who would like to see the Minutes should add their name to a mailing list maintained by the Secretariat.

October meeting

At its October meeting FedEx reviewed the minutes of the September meeting. Unresolved action items, including unresolved action items from all other previous meetings, were considered and progress or otherwise noted. The meeting approved the Treasurer's report and endorsed individual expenditure items for the previous month. The Society's financial position at the end of September was:

Year to date income $333 638.26
Year to date expenditure $397 547.19
Net assets $1 050 785.34

Other issues discussed are itemised below.

2016 Membership fees

At the end of September, the Society had 1146 Members. Current membership fees were reviewed and it was agreed that the fees would increase by a 2.2% inflator in 2016. Fees for (non-corporate) Members who pay before 31 December 2015 will be:

Australian Active and Associate Members $127 including GST
Retired Australian Members $63 including GST
Australian Student Members free
Australian Life Members $633 including GST

Overseas members will now be charged at rates commensurate with their ability to pay based on the development status of their country.

2016 AGM

The meeting resolved to ask the WA Branch if it would host the 2016 Annual General Meeting in April.

Member survey

A report on the recent Member survey was tabled (see the article in *Preview* 178) and discussed in light of the outcomes of the recent planning meeting (see report below). The results of these discussions include an agreement to develop a business model for an OzLEAP programme of courses and an agreement to develop a proposal for a Promotions Committee and/or Promotions Officer for the Society.

Conferences

The accounts for the 2015 ASEG-PESA Perth Conference and Exhibition have been audited and the Society looks forward to the receipt of surplus funds in the near future. Planning for the 2016 Adelaide ASEG-PESA-AIG Conference is progressing well with a steady take up of sponsorship opportunities and exhibition space. Call for papers has gone out and expressions of interest in holding workshops closes in December.

There was discussion about a review, with PESA, of the recent ICE conference in Melbourne and agreement on a process to negotiate with SEG and AAPG about who hosts future meetings in Australia.

ASEG is a member of the Australian Geoscience Council (AGC). AGC has proposed holding an Australian Geoscience Conference in 2018-19 involving all the Societies in the AGC (except PESA). The intention is that this conference will focus on issues important to geoscience in Australia. It would be an opportunity to showcase geophysics to the whole geoscience community. We would like to know what Members think about this proposal – **would Members prefer to be part of a major conference or maintain the schedule of their own conferences?**

Committees

FedEx would like to appoint a new Chair for the Publications Committee; the Chair of this Committee will be a Member of the Federal Executive. **A call will be made for volunteers.**

Courses for 2015

FedEx reviewed progress with courses and lectures. A report on courses and lectures is provided elsewhere in this issue of *Preview (*see Education Matters*)*.

Outcomes of the September planning meeting

If fledgling plans initiated at a recent Federal Executive (FedEx) planning day come to fruition, the ASEG will have a broader education programme, an expanded publications programme with a greater international reach, more overseas Members in countries where many of our Members already operate, an improved website, and stronger and closer ties with other international societies that are increasingly working in our region, all delivered to Members who are more aware of what the Society has to offer them.

The ASEG FedEx meets monthly via telephone hook-up. These meetings are focussed mostly on the day to day running of the Society. Since 2013 FedEx has also met twice a year face to face to plan future directions and strategies for the Society. Representatives of the local Branch where these meetings are held and the Honorary Editors are also invited to attend.

FedEx held its second meeting this year in Adelaide in September. FedEx thanks Beach Energy for providing the venue. The meeting began with a look at whether our programme of work was aligned with Members' views as shown by the recent Member survey (reported in the October issue of *Preview*). We found that there is fairly good alignment between what FedEx believes it needs to do when managing the Society and Member responses. **FedEx is now awaiting feedback from the report on the Member survey in the October issue of *Preview*.** The survey will probably be repeated in whole or in part in 2016 to measure the effectiveness of the FedEx's response to Members' issues.

One thing that was noted clearly in the free form responses to the question 'List the benefits that you would like to see the ASEG introduce' is that many Members are unaware of a number of the services provided by the Society. Some time was spent discussing whether we need a more proactive promotional strategy; a proposal will be developed for FedEx to consider over the next few months.

The main body of the meeting was directed towards the aspirational goals set out in our strategic plan developed in 2013 and published in *Preview* that year. At this meeting we focussed on enhancing our education programme, broadening the reach of our publications, and further strengthening our membership base. We also discussed our relationships with overseas societies, several of which are becoming more active in our region. Many Members are aware of the programmes of visiting overseas lecturers and courses provided principally by the SEG and EAGE. One of the surprises that we found in the Member survey was the number of Members who do not know about our own OzSTEP programme of courses, despite their promotion and popularity.

OzSTEP courses are intended to fill the gaps between theory and application, university studies and industry practice, and between geophysicists and geologists. Each course typically takes a day. Expected audiences are graduate geophysicists with up to 10 years of experience and geologists and technical staff who are interested in geophysics. More effective promotion is clearly needed despite the courses being advertised through *Preview*, mail outs, and through Branch activities. The meeting resolved to investigate a second form of course proposed by the senior industry geophysicists on the FedEx. Called OzLEAP, it would make an attendee proficient and work-ready in a specialised area of geophysics. Courses could take up to 5 days of intensive classes and practical hands on experience. Typical attendees of an OzLEAP course would be practicing geophysicists who need to apply new skills in their work. FedEx resolved to ask the senior management of exploration companies about what subjects they would like to see covered.

All Members receive our journal *Exploration Geophysics* (EG) and our magazine *Preview* (PV). EG is also the Journal of the Japanese and Korean geophysical societies. We have had feelers from several other overseas societies interested in linking into EG. Should FedEx agree to further expand the base of EG its international reach and status will be significant.

FedEx is also keen to use our web site to provide a wider range of text and video services for Members. A session at the last ASEG conference was recorded and the lectures and question and answer session at the end were made available via YouTube. This has proven to be a successful experiment. FedEx is keen to extend this kind of service to the delivery of technical meetings, especially to regionally based Members. A major redesign of the website is underway with some of this added capability in mind.

FedEx noted that we have existing Honorary Editors for EG and PV. If some of our thinking turns into reality we may also need to consider editors for our web content and our special publications. Any Member interested in taking on either of these roles should contact Greg Street, who is currently the FedEx member on the Publications Committee (Greg's contact details are in the ASEG Officeholders page of this issue of *Preview*).

Sixteen percent of our Members are based overseas; our overseas cadre is second only to the WA Branch as a group. FedEx Members who travel and work overseas as well as in Australia reported that there is potential to attract many more Members, particularly from China, Southeast Asia and Africa. This is reflected in an increased number of applications for overseas student membership in the last few years. As we move more to on-line service delivery, particularly of our publications, the marginal cost to service additional Members will decrease. FedEx resolved to consider a fee structure similar to that operated by overseas societies in which international members are charged fees in accordance with their ability to pay; Members in developed countries pay more than those in developing countries. This would also reflect the reality that overseas Members do not receive the same level of services as Australian-based Members such as Branch technical meetings and hard copies of PV.

FedEx believes that collaboration, rather than competition and overlap, with other Australian societies continues to be in the interest of our Members. Our Conference and Exhibition in Adelaide next year will be held jointly not only with PESA, which has been the case for a number of previous meetings, but also with the Australian Institute of Geoscientists (AIG). Many of the technical and social functions organised by our Branches involve cooperation with PESA. But a number of international geophysical societies are now operating in our region and are seeking closer ties with the ASEG. The meeting agreed that members of our executive would meet with PESA to organise parallel approaches with a consistent message to our international sister organisations to ensure that the needs of our Members are not subsumed by the capacity of the much larger international organisations to dominate the planning and conduct of local events. The first meetings with the overseas societies have now been held.

Barry Drummond
Honorary Secretary
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ASEG Branch News

Queensland

The Queensland branch has had a very busy end to the year. In October we hosted **Bob Musgraves**' OzSTEP course; 'Potential fields: a (re)introduction for geophysicists and geologists'. The course was a great refresher for geologists and seismic geophysicists alike.

Bob also presented his talk 'What can geophysics tell us about the mobile phase of the Lachlan and Thomson orogens?' while he was in town.

In November we hosted **Brian Russell**'s OzSTEP course; 'AVO and inversion methods. Brian's course was well received by all who attended. We were also lucky enough to have Brian present to the local Branch while he was in town; his talk was titled; 'Integrating rock physics models and seismic pre-stack inversion'.

This November the Queensland Branch will also host SEG HL **Hansruedi Maurer** presenting his talk 'The curse of dimensionality in exploring the subsurface'.

This will be our last meeting for 2015. We would like to wish everyone Merry Christmas and look forward to seeing all our Members, and hopefully some new ones, in the New Year.

Megan Nightingale
(QLD Branch Secretary)

New South Wales

In September, **Keith Leslie** and **Clive Foss** from the CSIRO spoke about the work they have doing in regards to the application of magnetics. Their scope ranged from looking at 3D mapping of magnetite and hematite concentrations to logging magnetic phases using a travelling 3-component vector magnetometer to a downhole magnetic tensor gradiometer. Many questions and much discussion followed their presentation.

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

Luke Hardiman; 'Impact of climate on the development of pull-apart basins' (University of Sydney).

Alexandre Lemenager: 'Numerical modelling of the Sydney Basin using temperature dependent thermal conductivity measurements' (Macquarie University).

Nikita Golkin; 'Numerical modelling of microcontinent formation in the context of a passive margin' (University of Sydney).

Also in October, we hosted the OzSTEP workshop on potential fields given by **Bob Musgrave**. The workshop was attended by nine students.

Luke, Alexandre and Nikita after presenting to the NSW Branch.

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

Mark Lackie
(NSW Branch President)

South Australia & Northern Territory

Since the last edition of *Preview*, the SA/NT Branch has enjoyed several events including our annual Industry Night, an OzSTEP Course and the ever popular Melbourne Cup Luncheon.

The annual Industry Night, held at the Coopers Alehouse in September, was a fantastic opportunity for some of our sponsors to showcase the diverse range of projects they are currently involved with. Many thanks go to **Darren Evans** from Beach Energy, **Miles Davies** from the Department of State Development, **Andrew Thompson** from Minotaur and **Alan Waldron** from Santos for taking the time to present to our membership.

Following up in October, we were joined by **Bob Musgrave** who ran the one day OzSTEP course; 'Potential fields: a (re) introduction for geologists and geophysicists', held at the Richmond Hotel in the Adelaide CBD. This was a highly anticipated course, which did not disappoint, with an excellent turnout from industry, government and academia alike.

Finally, the annual Melbourne Cup Luncheon was a roaring success. With the Calcutta Sweep producing some unlikely winners, prizes for the best dressed colt and filly and a great atmosphere in the packed venue, much fun was had throughout the day and into the evening. We would like to thank our exclusive sponsor Beach Energy, the Ambassadors Hotel for holding this year's event, **Neil Gibbins** for giving up his time to MC,

Bob Musgrave presenting to the SA/NT Branch.

and **Jenni Clifford**, without whom the day would not have come together so successfully.

Without the support of all of our sponsors our monthly technical meetings would not be possible. As such, we would like to thank all of our sponsors for 2015, including Beach Energy, the Department of State Development, Geokinetics, Minotaur Exploration, Petrosys, Santos, Schlumberger, Borehole Wireline and Zonge. Of course, if you or your company are not in that list and would like to give your support, please get in touch at the email below.

As usual, further technical meetings will be held monthly, at the Coopers Alehouse on Hurtle Square, in the early evening. We invite all Members, both SA/NT and interstate to attend, and, of course, any new Members or interested persons are also very welcome to join us. For any further information or event details, please check the ASEG website under SA/NT Branch events and please do not hesitate to get in touch at joshua.matthew.sage@gmail.com or on 8338 2833.

Josh Sage
(SA/NT Branch President)

Tasmania

A recent highlight for the geophysical community in Tasmania was the presentation to Dr **David Leaman** of the Twelvetrees Medal, struck by the Geological Society of Australia's Tasmania Division to recognise important contributions to the Earth Sciences within Tasmania, or outstanding contributions to Earth Sciences while resident in Tasmania. In the spirit of eminent Tasmanian government geologist, **William Harper Twelvetrees** (1848–1919), contributions are considered to include meritorious feats of geological exploration in Tasmania or elsewhere, significant published works, or meritorious service to the Earth Sciences.

The Medal was presented to Dr Leaman at a joint meeting of the Tasmanian Branches of the GSA and ASEG at the University of Tasmania on 15 October. The citation highlighted David Leaman's astonishingly productive contribution over a career applying geophysical techniques to a wide range of geological issues. No one present was left in any doubt that Dr Leaman richly deserves this prestigious award, and nor will be anyone else who reads the citation (which is published in full elsewhere in this issue of *Preview*).

Mark Duffett, Keith Corbett, David Leaman and Bob Richardson after David Leaman was presented the Twelvetrees Medal.

Geophysics in Tasmania also greatly appreciates the efforts of **Bob Musgrave**, who carried off the epic effort of a full day's OzSTEP course delivery followed by an address to the joint GSA/ASEG meeting that same evening, with aplomb. Bob's passion for potential field geophysics, especially palaeomagnetics and the big picture was evident right to the end of his presentation; 'What can geophysics tell us about the mobile phase of the Lachlan and Thomson orogens?', which held an audience composed mostly of geologists enthralled.

The ASEG in Tasmania is now looking forward to the visit of SEG Near Surface Honorary Lecturer **Hansruedi Maurer** of ETH Zurich. He will present on 'The curse of dimensionality in exploring the subsurface' in the CODES Conference Room, University of Tasmania at noon on Monday 30 November.

Interested members and other parties should also keep an eye on the seminar program of the University of Tasmania's School of Earth Sciences, which regularly delivers presentations of geophysical as well as general earth science interest. Contact Mark Duffett taspresident@aseg.org.au for further details.

Mark Duffett
(Tasmanian Branch President)

Victoria

On Wednesday 7 October the ASEG Victoria Branch hosted a technical evening meeting at the Kelvin Club with **Bill Lodwick**, Fletchwick International, recently returned from Malaysia. The title of Bill's talk was 'Geophysicists, petrophysicists, seismic data and well logs'. Bill's talk was very well received and sparked a lengthy discussion.

On Tuesday 13 October we hosted the all-day OzSTEP course on 'Potential fields: a (re)introduction for geophysicists and geologists' presented by Bob Musgrave from the Geological Survey of New South Wales. We only had two attendees, but we decided to run the class anyway, which lead to some excellent audience-tailored teaching by Bob.

The Victorian Branch held our 'Annual Student Night' on October 29 with a great turnout of around 25 people to see four students from Melbourne and Monash universities presenting research from their Honours or Masters projects. The presenters and presentations were:

- **Matt Sisson**, Monash University, 'Using remanent magnetisation to differentiate rock packages: insights from the Birksgate Prospect, Curnamona Province, SA'.
- **Isaac Graves**, Melbourne University, 'Rheological and stratigraphic controls on fault linkages in the Timor Sea'.
- **Taylor Ogden**, Melbourne University, 'A redefined crustal structure of the Buchan Rift, Northeast Victoria: evidence from potential field modelling of newly acquired land-based gravity data'.
- **Gemma Cochrane**, Monash University, 'Integrated geological and potential field analysis for the exploration of IOCG deposits within the Battle Axe prospect, Cloncurry'.

Bill Lodwick presenting to the ASEG Victoria Branch.

ASEG News

A few drinks and nibbles beforehand helped to calm any nerves, as for some this was their first truly public scientific presentation. The audience wouldn't have known it, as we witnessed four very clear and confident presentations. Matt and Isaac had to contend with an uncooperative laptop and even managed to carry on their presentation by ad-libbing or taking questions, while the laptop rebooted. The judges were impressed with the quality of all the presentations and with the scientific content too. Picking a winner would prove tough, but the deciding factor in the end was probably the ability of Taylor Ogden to communicate his work with great clarity to the diverse audience assembled.

The prize pool was extended to reward each presenter, with Taylor Ogden receiving the first prize of $250. Celebrations continued afterwards at an adjacent pub as many students had also submitted their theses that day.

On 4 November the 'PESA VIC/TAS Geoscience R&D Forum' was held at Melbourne University in combination with VUEESC 2015 (the Victorian Universities Earth and Environmental Sciences Convention). ASEG was a Gold sponsor of the event and several local ASEG members were in attendance. The event was again well attended (about 80 in total) and the crossover between the industry-focussed R&D topics and the postgraduate student presentations gave the event a great energy boost. The interaction in between the sessions and subsequent follow-up observed suggests that much stronger ties between industry, private and academic research are already being forged in Victoria. A more detailed wrap-up is being prepared for the next PESA news, but keep an eye on the ASEG and PESA websites too, or contact **Jarrod Dunne** (JDunne@karoongas.com.au) for more information.

Now for the upcoming events:

Make a big tick in your calendars for the Annual Joint PESA-ASEG-SPE Christmas Luncheon on Wednesday 9 December from 12:00 pm to 16:00 pm at the Victoria Hotel, 215 Little Collins Street, Melbourne. This year **John Hughes** and **Bruce Holland** of The Norwood Resource will present 'The Norwood Resource: dismantling myths!', along with games, quizzes, excellent food and drink and even better company!

On Thursday 10 December the ASEG Victoria Branch will host a technical meeting with Dr **Hansruedi Maurer**, ETH Zürich and SEG Honorary Lecturer, presenting 'The curse of dimensionality in exploring the subsurface'. The meeting will be held at the Kelvin Club, starting at 6 pm (drinks and nibbles) for a 6:30 pm presentation.

Following the summer break, please look out for an invitation to the 'Joint ASEG/PESA/SPE Mid-Summer Social' for some serious networking to get 2016 going. The date and venue is yet to be announced.

On Thursday February 18 the ASEG Victoria Branch will hold its Annual General Meeting (AGM), along with a technical meeting with **Phil Schmidt**, owner of Magnetic Earth and ASEG President, presenting on 'Magnetic exploration projects in CSIRO from 1978 to now'. The meeting will be held at the Kelvin Club, starting at 6 pm (drinks and nibbles) for a 6:30 pm presentation.

Pre-meeting registration for any of the upcoming events is mandatory, and can be made via the ASEG Events web-page. We look forward to seeing many ASEG Victoria Branch members at the meetings in the coming months. All the best for the holidays, enjoy a well-deserved summer break, and may 2016 bring you joy, wisdom and prosperity!

Asbjorn Norlund Christensen (Victorian Branch President), with significant contributions from Jarrod Dunne

Bob Musgrave with an attentive Victorian OzSTEP audience.

Western Australia

The WA Branch held three technical sessions over the past two months including:

• 9 September 'Nuclear magnetic resonance and its application in hard rock mining and hydrogeology' presented by **Tim Hopper**, NMR Services.

• 14 October 'Application of high resolution Q-tomography – a case study' presented by **Kia Zhao** of CGG.

• 10 November 'Resurrection of ocean bottom seismography in Australia' presented by Dr **Alexey Goncharov** of Geoscience Australia.

The remaining technical session for November will be on Wednesday 18 November at the City West Function Centre. **Hansreudi Maurer** is part of the SEG Honorary Lecturer Tour and will present 'The curse of dimensionality in exploring the subsurface'.

The student presentation night will be the final technical session for 2015 and is scheduled for 2 December. A total of 11 submissions were received from geophysics students from UWA and Curtin University for the annual ASEG Student Awards. The awards will be announced the same evening.

Three OzSTEP courses run by **David Lumley**, **Bob Musgrave** and **Brian Russell** during October proceeded well but attendance was down compared to previous years. The final course for 2015 is being offered by the EAGE EET9 'Satellite InSAR data: reservoir monitoring from space' on Friday 20 November at the Auditorium, Australian Resources Research Centre, 26 Dick Perry Ave, Kensington. Check the WA Branch website for details.

David Lumley presenting at Geoscience Australia.

Bob Musgraves OzSTEP students, new and old, at Geoscience Australia.

Social events include the 28th annual ASEG/PESA Golf Classic at the Joondalup Gold Resort on 11 November, which remains ever popular amongst Members. The Christmas wind-up will be held, combined with the AGM, on 24 November at Willong Pavilion, Kings Park, accompanied by a Greek BBQ and refreshments. Parking is available nearby. The venue is near Hale Oval and otherwise close to public transport along Kings Park road or to West Perth.

Prue Leeming
(WA Branch Preview *correspondent)*

Australian Capital Territory

The ACT branch has had a busy few months with two OzStep courses being run at Geoscience Australia, both well attended and excellently presented. The OzSTEP ACT '4D seismic reservoir monitoring' by **David Lumley** and OzSTEP ACT 'Potential fields AND a (re)introduction for geophysicists and geologists' by **Bob Musgrave** were both outstanding educational and networking opportunities for our branch.

Ashby Cooper commented on David Lumley course; 'The highlight for me was gaining insight into the technological advancements in 4D reservoir monitoring. I am especially interested in the development of ocean bottom permanent arrays for 4D monitoring and the capability to measure ambient noise and earthquake events using these systems. I think it's an exciting time for seismology.'

Ian Roach commented on Bob Musgrave's course; 'Bob's course was a great refresher for me because I had first learned about potential fields over 30(!) years ago… Bob reminded me of all things that I had learned long ago, that were still correct, but also reminded me that the underlying principles of potential fields affect our daily work as geophysicists and geologists (and geophysical geologists like me). Bob also, and maybe this was because we were in the GA building, spoke highly of the fundamental work done by GA in potential fields, from the data collection, databases and breakthroughs in understanding the Australian potential fields by geophysicists at GA. Bob also spoke highly about the new isostatically corrected gravity model for Australia by our own Aki Nakamura. It was also a great catch-up for the latest developments in hardware and software and image processing. I greatly enjoyed the day, and was pleasantly surprised to discover that I hadn't forgotten so much in the intervening + 30 years.'

After Bob's talk there was a short tour given by **Phillip Wynne** to Geoscience Australia's A10 in the Gravity Laboratory that everyone enjoyed.

In November we run the EAGE EET9 'Satellite InSAR data reservoir monitoring from space' to be presented by world leader **Alessandro Ferretti** and December sees us host **Hansruedi Maurer** who presents 'The curse of dimensionality in exploring the subsurface'. He is the SEG 2015 Honorary Lecturer.

In November **Chris Pigram**, CEO of Geoscience Australia, released a Value to the Nation package, it presents Geoscience Australia's long history of achievement: contributions to industry, communities and the environment, advice to all levels of government, and collaborations with partners. Please visit http://www.ga.gov.au/value-to-the-nation to see some of the geophysical impacts we make to the nation.

The joint ASEG-PESA Christmas event will be held November 20 with our own **Ted Lilley** as guest speaker; 'Some memories of geophysics 50 years ago'.

Our Branch as always is grateful to the South Australian Branch for organising the Wine Offer – thank you. The ACT members are also preparing submissions for the ASEG-PESA Conference – get those abstracts in. Remember to join us on social media – Facebook, Twitter and Linked In – just search for Australian Society of Exploration Geophysics and join in.

Marina Costelloe
(ACT Branch President)

ASEG News

ASEG calendar: technical meetings, courses and events

Date	Branch	Event	Presenter	Time	Venue
2015					
2 Dec	WA	Student presentation night	Various	TBA	TBA
9 Dec	VIC	Annual joint PESA-ASEG-SPE Christmas luncheon and technical presentation entitled: 'The Norwood resource: dismantling myths!'.	John Hughes and Bruce Holland	1200–1600	TBA
9 Dec	ACT	SEG HL Near Surface: The curse of dimensionality in exploring the subsurface	Hansreudi Mauerer	TBA	Geoscience Australia, Symonston
10 Dec	VIC	SEG HL Near Surface: The curse of dimensionality in exploring the subsurface	Hansreudi Mauerer	1800–2000	The Kelvin Club, 14–30 Melbourne Place (off Russell Street), Melbourne
11 Dec	SA	SA Exploration and Mining Conference	Various	0830–1700	Adelaide Convention Centre, North Terrace, Adelaide
2016					
Early Feb	VIC	Annual Joint PESA-ASEG-SPE Mid-Summer Social	TBA	1700–2000	TBA
18 Feb	VIC	AGM & Technical Night: Magnetic exploration projects in CSIRO from 1978 to now	Phil Schmidt	1800–2000	The Kelvin Club, 14–30 Melbourne Place (off Russell Street), Melbourne
14–18 Mar	TBA	Rock physics and geomechanics of fluid-induced seismicity: hydraulic fracturing, stimulation of geothermal systems and hazard assessment	Serge A. Shapiro	TBA	TBA
13 Apr	WA	2016 ASEG AGM	TBA	TBA	TBA

TBA, to be advised (please contact your state branch secretary for more information).

Twelvetrees Medal for David Leaman

David Leaman

David Leaman was awarded the 2015 Twelvetrees Medal by the Tasmanian Division of the GSA because of his exceptional contributions in the use of geophysics, with geological constraints, to elucidate the three-dimensional structure of the Tasmanian crust and also for his ongoing commitment to geoscience education.

In February 1966, after graduating with Honours from the University of Tasmania, David was appointed as Groundwater and Engineering Geologist with the Geological Survey of Tasmania. His Honours thesis, titled 'Geophysics – Cygnet area including geological implications of the geophysical interpretation', marked the beginning of David's dedication to using geophysics to further geological knowledge. At the Geological Survey the projects he worked on included hydrogeology, basin studies, structural geology, engineering geology and geological mapping, with David applying geophysics in all these fields. During this period David also undertook and interpreted some of the first large area gravity surveys in the State to provide three-dimensional structural information for solving specific geological problems.

At this time David developed his life-long research interests in Jurassic dolerite, the relationship of water resources and land use, and the application of gravity and magnetic methods to solve geological problems. These interests were combined when David completed a PhD thesis on the mechanism of dolerite intrusions, titled 'Dolerite intrusion, Hobart district, Tasmania', under the supervision of Professor S Warren Carey AO. The thesis was undertaken whilst mapping for the Hobart 1:50 000 geology sheet and the interpretation was used to produce a perspex three-dimensional geological model of the greater Hobart area. David also started an educational role which still continues and has included groups as diverse as university students, exploration companies and adult groups, as well as writing and publishing five books. He held a part-time teaching and research role at the University of Tasmania from 1972 until 2001, supervising multiple generations of Honours and postgraduate students who have gone on to apply his methods and philosophy throughout the geoscientific world.

David was appointed to the newly created position of Principal Geophysicist with the Tasmanian Geological Survey in 1973. In addition to a wide variety of geophysical surveys for solving specific geological and technical problems, David started a programme of gravity data acquisition in key areas of the State to add detail to the 7 km-spaced 1973 Bureau of Mineral Resources state-wide gravity survey. Areas covered included the Tamar region, Rossarden-Storys Creek, northeast Tasmania and the area of the East Coast Coal Project. Detailed three-dimensional interpretation of many of these surveys provided guidance for future Department of Mines drilling but remained isolated interpretations. In 1980 this work culminated in production of the first state-wide residual gravity anomaly maps, maps where the anomalies from large bodies, such as many of the granitoids, were clearly visible rather than obscured in the Bouguer Anomaly map by combination with anomalies from other sources. This regional-residual separation was progressively refined until the 1988 release of the Mantle88 Moho and water model that allowed quantitative interpretation of gravity data after removing a regional gravity field that was not data dependent. David recognised the crucial importance of the terrain correction for gravity observations in Tasmania, and undertook the mammoth task of calculating this for most of the stations in the State database.

The exploration consultancy Leaman Geophysics was founded by David in 1981, when he left the Survey, and in this new environment he has focussed on undertaking challenging evaluations of geological structures using gravity and magnetic methods within Australia and beyond. During the Department of Mines Mount Read Volcanics Project (1985–1988), David's modelling showed that there were Cambrian granite bodies embedded in the Mt Read Volcanics and concluded that these may well be associated with mineralisation. Other innovative Tasmanian crustal interpretations since 1981 have included a model of the major Tasmanian granitoids, recognition of major structures and pre-Carboniferous geology throughout Tasmania, interpretation of the magnetic and gravity data from the Western Tasmanian Regional Minerals Program (2001–2003), interpretation of the form of the King Island and eastern Tasmania granitoids, and assessment of features from the 2007 aeromagnetic surveys of northeast Tasmania.

David's achievements have resulted in major advances in the understanding of the three-dimensional structure of the Tasmanian crust. He is also senior or sole author of 10 geological maps and explanatory reports, sole author of 192 Geological Survey publications and records, and co-author of 38 other Survey publications and records. David is also sole author of 102 reports lodged with Mineral Resources Tasmania by exploration companies that are now open-file, and is author or co-author of 70 refereed papers. Among these are significant contributions to understanding the three dimensional architecture of the metallogenically prolific Mount Isa-McArthur Basin terranes of northern Australia. He is also the author and publisher of five books (one in its third edition) discussing Tasmanian geology or hydrology and interpreting Tasmanian geology for bushwalkers. In recent years David has applied geophysical and physical techniques to assessment and management of Tasmania's water resources.

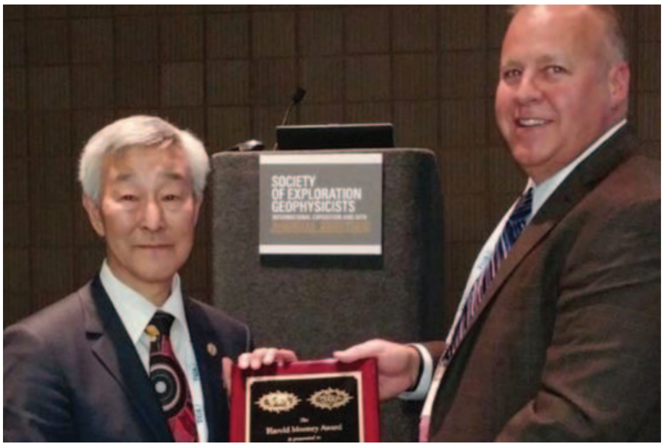
In summary, David Leaman has been an enormously productive contributor to Tasmanian geology and geophysics over 50 years, with major contributions in modelling geological domains using gravity and magnetic surveys, determining the three-dimensional form of Tasmanian granitoids, clarifying Jurassic dolerite structure and deep crustal structures across Tasmania, the nature of groundwater aquifers, the management of our water resources, and many more. His approach has been fearless and sometimes controversial, but he has stimulated geological discussion and challenged accepted dogmas to the betterment of our understanding. He has also made a major contribution to educating and informing students and the general public in the fields of geology, geophysics and the rocks of Tasmania. The ASEG congratulates David on his award. He is a most worthy recipient.

Bob Richardson, Keith Corbett and Mark Duffett

SEG award for Koya Suto

The 2015 Harold Mooney Award was presented to Koya Suto by the SEG Near Surface Geophysics (NSG) section during its reception and dinner at the SEG annual meeting in New Orleans. The awardee is chosen by peers through nominations from the membership and recommendation to the SEG Near Surface Executive Committee. The SEG Near Surface Harold Mooney Award is presented to an individual in recognition of long-term, tireless, and enthusiastic support of the near-surface geophysics community through education, outreach efforts, professional service, or development of opportunities with other professional disciplines that employ geophysics. Well done Koya!

Phil Schmidt



Koya Suto receives the 2015 Harold Mooney Award from John Lane, Chair of SEG Near-Surface Group.

Hole in one for Bob Smith

ASEG stalwart, Honorary Member and Past President (1986–1987) Bob Smith notched another string to his formidable bow when he scored a hole in one during a recent round of golf at the picturesque Leongatha Golf Course in South Gippsland. The feat is even more remarkable as Bob only took up golf seriously in the last few years, after retiring to the scenic seaside retreat of Inverloch following a successful professional career with CRA/Rio Tinto Exploration and as an independent consultant.

Bob enjoys getting out on the course on a regular basis, playing in the club competition rounds most weeks, in invitation tournaments at nearby courses, and social games with other retired geophysicists or anyone visiting the area who may be up for a game.

Andrew Mutton

Bob Smith retrieving his hole-in-one ball at the Leongatha Golf Course 14th hole.

Nominate a colleague for an ASEG Honour or Award in 2016

An important role of the ASEG is to acknowledge the outstanding contributions of its individual members both to the profession of geophysics and to the ASEG. The Society has a number of different Honours and Awards across a range of categories. The next Awards are scheduled to be presented at ASEG-PESA 2016: 25th Geophysical Conference & Exhibition, 21–24 August 2016 – Adelaide, South Australia.

All ASEG members as well as State and Federal executives are invited to nominate those they consider deserving of these awards. A list of the various available awards is set out below. These awards carry considerable prestige within the Society and geophysical community and therefore some detailed documentation to support the nomination is required. Please contact the Committee Chairman, Andrew Mutton, if you require further guidelines on what is required.

ASEG Gold Medal

For exceptional and highly significant distinguished contributions to the science and practice of geophysics, resulting in wide recognition within the geoscientific community. The nominee must be a Member of the ASEG.

Honorary Membership

For distinguished contributions by a member to the profession of exploration geophysics and to the ASEG over many years. Requires at least 20 years as a Member of the ASEG.

Grahame Sands Award

For innovation in applied geophysics through a significant practical development of benefit to Australian exploration geophysics in the field of instrumentation, data acquisition, interpretation or theory. The nominee does not need to be a Member of the ASEG.

Lindsay Ingall Memorial Award

For the promotion of geophysics to the wider community. This award is intended for an Australian resident or former resident for the promotion of geophysics (including but not necessarily limited to applications, technologies or education), within the non-geophysical community, including geologists, geochemists, engineers, managers, politicians, the media or the general public. The nominee does not need to be a geophysicist or a Member of the ASEG.

Early Achievement Award

For significant contributions to the profession by a Member under 36 years of age, by way of publications in *Exploration Geophysics* or similar reputable journals, or by overall contributions to geophysics, ASEG Branch activities, committees, or events. The nominee must be a Member of the ASEG and have graduated for at least 3 years.

ASEG Service Awards

For distinguished service by a Member to the ASEG, through involvement in and contribution to State Branch Committees, Federal Committees, Publications, or Conferences over many years. The nominee will have been a Member of the ASEG for a sustained period of time. All nominations will be considered for the award of an ASEG Service Certificate. Where the nomination details outstanding contributions to the shaping and the sustaining of the Society and the conduct of its affairs over many years, consideration will be given to the award of the ASEG Service Medal to the nominee. Honorary Members are not eligible for nomination.

Nomination procedure

Any member of the Society may nominate applicants. These nominations are to be supported by a seconder, and in the case of the Lindsay Ingall Memorial Award by at least four geoscientists who are members of an Australian geoscience body (e.g. GSA, AusIMM, AIG, IAH, ASEG or similar).

Nominations must be specific to a particular award and all aspects of the defined criteria should be addressed. To gain some idea of the standard of nomination expected, nominees are advised to read past citations for awards published in the *Preview* edition immediately following each conference.

Lists of previous awardees, award criteria and nomination guidelines can be found on the ASEG website at: https://aseg.org.au/honours-and-awards. Proforma nomination forms are available from the website or by contacting the Chair of the Committee. Nominations including digital copies of all relevant supporting documentation are to be sent electronically to:

Andrew Mutton
ASEG Honours and Awards Committee Chair
awards@aseg.org.au

ASEG-PESA-AIG 2016: News from the Conference Organising Committee

ASEG-PESA-AIG 2016
25TH GEOPHYSICAL
CONFERENCE & EXHIBITION
Interpreting the Past, Discovering the Future

It has been a busy couple of months for the conference organising committee. We're pleased to announce the addition of Velseis and Wireline Services Group to our group of sponsors. We're also very grateful to those companies who have committed to booths as part of the trade exhibition (allocation will take place early in the new year, so get in quickly). You can find the prospectus on the conference website: http://www.conference.aseg.org.au/

The programme subcommittee has been hard at work contacting potential keynote speakers. Some confirmed speakers include:

Seismic Processing – Andrew Long
Seismic Interpretation – Peter Boult
Inversion – Dave Lumley
Unconventionals – Creties Jenkins
Stratigraphy and Facies – Rob Kirk
Passive seismic – Mark Dransfield
AVO inversion techniques – Dennis Cook

The workshop committee is also finalising an exciting workshop programme. Some highlights will include the Airborne Gravity 2016 Forum, a near-surface passive seismic surveying workshop, and many more. Conference Delegates will be able to register for the workshops via the online registration tool when it opens.

Registration for the conference will be available from January 2016. The table below outlines the fees. Earlybird registration closes 31 March 2016; Standard registration closes 31 July 2016; Late registration after 1 August 2016. (The prices for conference registration are in $AUD and include GST.)

As always you can get up-do-date news regarding conference developments on our LinkedIn, Facebook and Twitter accounts, as well as on the conference website.

Finally, the call for abstracts is open. You can find the template and submission tools on the conference website: http://www.conference.aseg.org.au/

Philip Heath
Co-chair Minerals
philip.heath@sa.gov.au

Luke Gardiner
Co-chair Petroleum
luke.gardiner@beachenergy.com.au

Category	Earlybird	Standard	Late
Member* Full	$850	$1050	$1250
Non Member Full	$1100	$1300	$1500
Member** Retired	$500	$700	$900
Student	$150	$150	$150
Member* Day	N/A	$450	$650
Non Member Day	N/A	$600	$800
Booth Staff Per Day	$110	$110	$110
Welcome Reception (guests)	$75	$75	$75
Dinner (all delegates and guests)	$130	$130	$130

**Members of the The Australian Society of Exploration Geophysicists (ASEG), The Petroleum Exploration Society of Australia (PESA) and the Australian Institute of Geoscientists (AIG).*
***Retired Members must provide confirmation from the associated society.*

Update on geophysical survey progress from the Geological Surveys of Western Australia, South Australia, Northern Territory, Queensland and Victoria (information current on 16 November 2015)

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

Table 1. Airborne magnetic and radiometric surveys

Survey name	Client	Project management	Contractor	Start flying	Line km	Spacing AGL Dir	Area (km^2)	End flying	Final data to GA	Locality diagram (*Preview*)	GADDS release
Coompana	GSSA	GA	GPX Surveys	7 Feb 2015	255 265	400 m 80 m E–W	85 910	8 Nov 2015	TBA	173: Dec 2014 p. 24	TBA
Delamere/ Spirit Hills	NTGS	GA	Thomson Aviation	20 Jul 2015	96 500 est.	400 m 80 m N–S	33 690	7 Nov 2015	TBA	176: Jun 2015 p. 22	TBA
Yalgoo	GSWA	GA	MAGSPEC Surveys	30 May 2015	110 516 est.	100/200 m 50 m E–W	11 200	27 Sep 2015	TBA	176: Jun 2015 p. 23	10 Dec 2015

TBA, to be advised.

Table 2. Gravity surveys

Survey name	Client	Project management	Contractor	Start survey	No. of stations	Station spacing (km)	Area (km^2)	End survey	Final data to GA	Locality diagram (*Preview*)	GADDS release
Gippsland	GSV	GA	Atlas	30 Jun 2014	1440	12 traverses at 500 m station spacing	8358	21 Jul 2015	Final data expected to be released via GADDS when permission to do so is received from GSV	170: Jun 2014 p. 25	To be released with the North Wiso data
Northern Wiso Basin	NTGS	GA	Atlas	18 Jun 2015	5020	4 km regular grid with areas of 2 km and 1 km infill	83 240	9 Aug 2015	Preliminary final data supplied to GA in Sep 2015	176: Jun 2015 p. 24	Released on 14 Oct 2015
SW Yilgarn WA	GSWA	GA	Atlas	12 Jun 2015	28 678	2 km along public roads and tracks	175 000	73.4% complete at 8 Nov 2015	TBA	176: Jun 2015 p. 24	TBA
Victoria Basin	NTGS	GA	Atlas	14 Aug 2015	6300	4 km regular grid	99 170	17 Sep 2015	Preliminary final data supplied to GA on 13 Nov 2015	177: Aug 2015 p. 17	10 Dec 2015
Stavely	GSV	GA	TBA	Survey Quotation Request in preparation	Approx. 8000 in 9 separate areas	500 m regular grid in 8 areas and 500 m station interval along one traverse	TBA	TBA	TBA	177: Aug 2015 p. 18	TBA

TBA, to be advised.

Table 3. AEM 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
Musgrave Region	GSSA	GA	TBA	TBA	16 000 est.	2 km; E-W lines	30 691	TBA	TBA	See Figure 1	The Quotation Request was released on 12 Oct 2015 and closed on 30 Oct 2015. The proposed survey covers parts of the Mann, Woodroffe, Alberga, Birksgate, Lindsay and Everard Standard 1:250k map sheets
West Kimberley and Ord-Bonaparte	WA Government: Departments of Water, Agriculture and Food	GA	SkyTEM Australia	26 Sep 2015	7837	Various +/– traverses	TBA	3 Nov 2015	TBA	177: Oct 2015 pp. 30–31	TBA
Isa Region	GSQ	GA	TBA	Winter 2016. Centered on Cloncurry	TBA	TBA	TBA	TBA	TBA	The Technical Specifications of the survey are being planned between GSQ and GA	The National Collaboration Framework Agreement was expected to be executed between GA and GSQ by Dec 2015

TBA, to be advised.

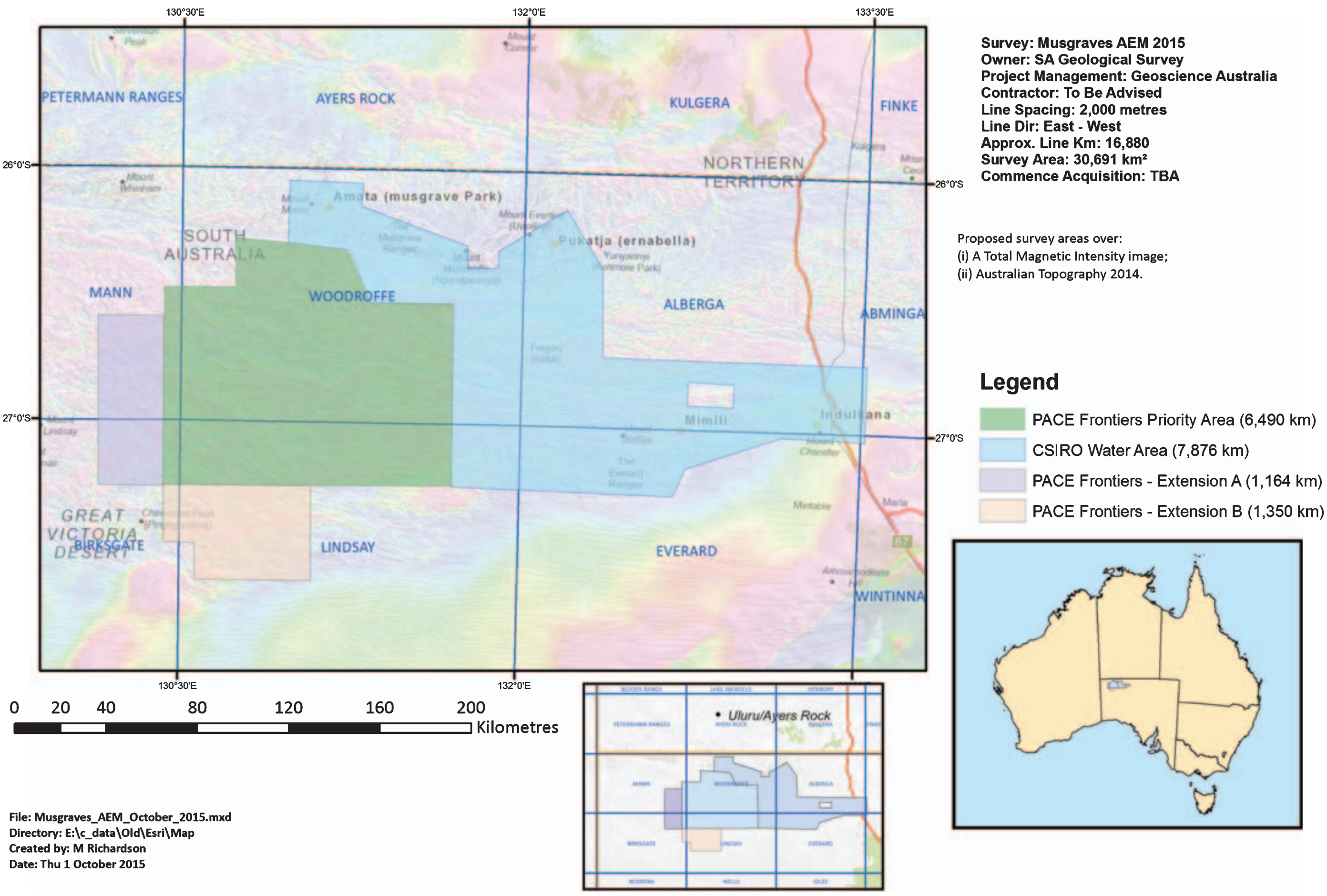


Figure 1. *Proposed Musgrave Region AEM survey.*

New public domain geophysical data from South Australia

Geophysical data held by the South Australian Government is routinely made available for free download via SARIG. In December 2015 – coinciding with the annual South Australian Exploration and Mining Conference (SAEMC) – another batch of data will be uploaded to SARIG.

As well as the latest state grid merges, 14 airborne surveys have been uploaded to the system and are available for download now. Table 1 lists the most recent surveys added to SARIG.

The surveys can be downloaded by navigating to SARIG (sarig.pir.sa.gov.au), selecting Geophysical Data from the Databases menu, and drawing a box in your area of interest. Enter your search parameters (e.g. magnetics, radiometrics and so on) and click Perform Search. All available surveys in your area of interest will be listed. Simply choose the surveys you're after, enter your email address and click on Download Results. Once the data has been clipped to your area of interest, an email will be sent to you with a link to download the data.

Relevant reports for each survey will be included with the download package. Further information can be found in the Open file envelopes, listed in the table below. To find an envelope using SARIG, select Publications and Reports from the Databases menu, and type in Env 11098 (or the envelope number you are searching for) and click Search. The document will be found next to the Mineral Exploration Reports option.

The next upload of data is scheduled for May 2016, to coincide with the South Australian Resources & Energy, Investment Conference (SAREIC).

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Table 1. Survey data added to SARIG in December 2015

Survey code	Survey name	Survey type	Flown by	Flown for	Line spacing	Line (km)	SA Government Open file envelope
2004SA003	Curnamona	AEM (Tempest)	Fugro Airborne Surveys Pty Ltd	Afmeco Pty Ltd	1000 m	4508.05	11098
2005SA002	Sandyoota	AEM (Tempest)	Fugro Airborne Surveys Pty Ltd	Afmeco Pty Ltd	1000 m	997	11098
2005SA012	Cuorunna	Mag/Rad	Fugro Airborne Surveys Pty Ltd	Cameco Australia Pty Ltd	200 m	12 008	11125, 11178
2005SA015	Sandyoota	AEM (HoisTEM)	GPX Airborne Pty Ltd	Afmeco Pty Ltd and Areva Resources Australia Pty Ltd	500 m	72.7	11098
2006SA013	Gawler	AEM (Tempest)	Fugro Airborne Surveys Pty Ltd	Tasman Resources NL	1000 m	1442.91	11241
2006SA019	Elliston	Mag/Rad	Geotech Airborne Ltd	Afmeco Pty Ltd and Areva Resources Australia Pty Ltd	400 m	2250	11338
2006SA177	Ambrosia, Wynbring and Dingo Hill	Mag/Rad	UTS Geophysics Pty Ltd	Monax Mining Ltd	100 m	16 949	11300, 11698, 11887
2006SA180	Mt Hope – Moorland	Mag/Rad	UTS Geophysics Pty Ltd	Monax Mining Ltd	100 m	10 073	11200, 11568
2006SA219	Corunna South	AEM (Tempest)	Fugro Airborne Surveys Pty Ltd	Cameco Australia Pty Ltd	100 m	3584.9	11178
2007SA043	Algebuckina	AEM (RepTEM)	Geosolutions Pty Ltd	Red Metal Ltd	500 m and 1000 m	1642	10849, 11256, 11257, 11706
2008SA052	Blinman	Mag/Rad	Fugro Airborne Surveys Pty Ltd	Helix Resources Ltd	100 m	7540	11659
2008SA093	Coulta	AEM (RepTEM)	Geosolutions Pty Ltd	Intermet Resources Ltd	400 m	1090.8	11231
2009SA045	Hillside	AEM (RepTEM)	Geosolutions Pty Ltd	Rex Minerals (SA) Pty Ltd	25 m	420.5	9937
2010SA026	Mount Martin	Mag/Rad	GPX Airborne Pty Ltd	Aldershot Resources	50 m	537	11344

Education Matters

Michael Asten
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It is the end of year, and our students (and academic staff and teachers) will be breathing a sigh of relief. But, it is our opportunity to review a year of great progress.

This column has three highlights:

Teacher Earth Science Education Programme (TESEP): ASEG has been a supporter of the TESEP programs for five years, believing that its approach of educating high-school science teachers about geosciences is the most efficient way of making geosciences concepts available to high-school students. Jill Stevens' article below is a great account of a successful field tour organised by TESEP for teachers.

OzSTEP courses: These professional development courses, organised by the ASEG using guest lecturers from within our own ranks, have completed their third year of operation. Coordinator Wendy Watkins gives an upbeat assessment for the future.

Geophysics projects completed this year: We have a report from Jarrod Dunne of the ASEG Victorian Branch giving the results of the ASEG Student Night presentations. Congratulations to Taylor Ogden of the University of Melbourne for winning the State Prize (and for gaining fame on the front cover of this issue *Preview*). Other State Branches will no doubt file reports after the student nights that are scheduled after the closing dates for this issue of *Preview*. Following the Branch Report, we have published the abstracts for 12 PhD/Masters projects, and 19 honours projects. Seven of the students involved have received ASEG or PESA awards, and two have received meritorious university prizes. I think that our profession has a bright future – talented people will outlast the current downturn in exploration activity.

Science teachers in the field

TESEP Cape Liptrap, Victorian Fieldtrip and International Conference, Melbourne (11–14 September 2015)

In September, the Teacher Earth Science Education Programme (TESEP), supported by many geological societies and some government, university and corporate partner funds, including the ASEG was able to give 30 Science Teachers of Excellence, from across Australia, the chance to learn from experienced industry geologists at some world-class field exposures in Gippsland, Victoria. Three days in the field were followed by Teachers' Day at an international conference in Melbourne (AAPG SEG 2015 ICE).

At Teachers' Day, eight industry professionals ranging from a geotechnician; oil/gas, mining and environmental geologists; geophysicist; palaeontologist and board director spent several hours sharing their stories of work and career choices, which had begun with a secondary school Science and Mathematics background.

Seismic for the Classroom was demonstrated using government and industry-donated geophones. Teachers took geophones, career booklets (AusIMM) and TESEP Plate Tectonics posters back to their schools. Teachers enjoyed plenary sessions, Exhibition Hall, technical sessions and meeting industry and university geologists.

The teacher group was dominated by young female Science teachers and a few senior male and female teachers. This demographic reflected the athleticism needed to get down steep slopes and rock-scramble at Cape Liptrap field exposures. The three days of fieldtrip went smoothly and to plan, with no incidents or injuries and the satellite phone taken for emergencies was not used.

The 30 teachers from Qld, NSW, ACT, Tas, Vic, SA (including six TESEP state coordinators) were guided on the three-day Gippsland fieldtrip by presenters structural geologist Dr Kevin Hill (OilSearch) and sedimentologist Dr Richard Lovell (ex-ExxonMobil) and assisted by TESEP Coordinator presenters. The team made an earlier reconnaissance trip to the field sites and scoped out the fieldtrip specifically for teachers. Using high-quality industry workbook material, generously supplied by Dr Kevin Hill, TESEP Executive Officer, Greg McNamara, compiled a hands-on field workbook including many questions for teachers to take back to their classrooms. Sites visited were:

Walkerville: Waratah Fault, historic lime kilns, Devonian-Ordovician marl and limestone and Cambrian volcanics and metamorphics.

Wonthaggi State Coal Mine: underground mine tour of this historic mine with a veteran coal miner.

Cape Liptrap: turbidites and deepwater sedimentary facies with colonial coral fossils, folded and faulted by Tasman Fold Belt orogenic movements.

Inverloch: Cretaceous dinosaur dig site; palaeoenvironment/ sedimentology of coastal outcrops and visit to the Dinosaur Museum at Inverloch – tour of the site and museum was led by Mike Cleeland from Dinosaur Dreaming.

Teacher feedback

A TESEP state coordinator wrote 'Thanks again for a wonderful experience. I spoke to the Head Teacher from East Hills Girls High School this morning. She commented that the teachers had returned to school extremely motivated about earth and environmental science and raving about their weekend'.

A teacher wrote 'I would like to commend all those involved in organising the recent TESEP Field Trip in Victoria. It was obviously a well thought and well planned event, and was of great benefit to all those involved. Apart from the opportunity to see some unique geology, even more importance was the chance to spend time with teachers that share a passion for earth science'.

A TESEP state coordinator wrote 'This trip was an excellent example of how TESEP can engage with a broad range of interested teachers to deliver an informative and memorable experience. I am confident that everyone completed the trip feeling much more confident with their understanding of a wide variety of geological concepts. The location was spectacular, the geology varied and able to keep the teachers engaged, and of course the weather was absolutely fantastic!

The opportunity to attend the AAPG-SEG ICE was an event that none of them would have experienced… to hear from industry personnel their individual stories added a real human dimension to the whole four days of 'rocky stories'.

Those that attended my demonstration of remote sensing through a classroom seismograph saw the benefit of how hugely expensive technologies could be shown in an easily understood method that can be done with basic equipment in the classroom'.

TESEP Chairperson, Jill Stevens, said 'It was great to speak to an excited year-12 Science teacher, who said that this was the best PD she had ever done – so well organized'.

A teacher said 'Best geology weekend ever. I will have more enthusiasm in teaching Geology (after doing this PD). I could influence about 600 students (yr 7–12)'.

Another reported 'I could pass this experience and knowledge on to 10s of teachers and 100s of students'.

One 7–10 Science/Maths teacher said 'The fieldtrip was amazing … so much of my Tertiary studies was made real here, (albeit 20 years later). Kevin and Richard's knowledge was presented at a very appropriate level'.

'I welcomed the opportunity to discuss applications with teachers from other states'.

'The field exposures were fantastic'.

Science teachers in the TESEP Education Workshop visit Cape Liptrap, Vic., for some hands-on geology.

This type of extraordinary learning experience for teachers, outside of the national, one-day professional development PD workshops that TESEP generally runs, was only possible through the financial support of TESEP partner societies PESA, ASEG, MCA (Vic), AIG, AusIMM, AGC and GSA. Thanks to ExxonMobil for staff time in field workbook preparation. Thanks also to Velseis and Geoscience Australia for geophones.

While the state coordinators were in Victoria, a TESEP Coordinators' Forum was held on 13 September 2015, Melbourne.

Key special projects on the TESEP coordinators wish list are:

1. **Rock Doctor rock kit checks** and compilation of 35-piece **new Rock & Mineral Kits** for schools without any kit – Schools either have no rock and mineral kit or ones that are incomplete and inadequate, Tasmania has a Rock Doctor program that has assisted in improving their kits. TESEP needs a collective of AusIMM, MCA, GSA, PESA geologists to run this and expenses funded via TESEP general partner funding – a TESEP special project through 2015–1017.
2. **Teacher mentoring** (a day at the classroom or with students at field sites), cost $440/day/TESEP presenter, (WA & SA already doing this) – a TESEP aim during 2015–2017 national curriculum roll-out

(member society geologists could assist)

3. **Hands-on Exercises** – develop more EES integrated science exercises e.g. remote sensing, basic mapping & map-reading – a TESEP special project
4. **Case Studies** – on geological locations across Australia (with student worksheet questions – to supplement each of the chapters in the Year 11–12 EES Textbook (each 4 to 6 x A4 pages in length, including short text descriptions of photos, maps, cross sections, core images, seismic, remote sensing, fossils, rock exposures, thin sections etc.) – a TESEP special project (see website for some uploaded examples)

See www.tesep.org.au if you would like to discuss how you could assist TESEP, please contact Jill Stevens cp@tesep.org.au or Greg McNamara eo@tesep.org.au

OzSTEP courses complete for 2015!

The final OzSTEP course for 2015 was completed on 4 November. A total of 11 one-day courses were held throughout Australia during October and November 2015. Two courses were presented by David Lumley on '4D Seismic Reservoir Monitoring', two courses by Brian Russell on 'AVO and Inversion Methods in Exploration Seismology' and seven courses by Bob Musgrave on 'Potential Fields: a (re) introduction for Geophysicists and Geologists'.

OzSTEP course in Adelaide, led by Dr Bob Musgrave.

Due to poor numbers, several courses were cancelled and numbers for the courses were generally low this year. We had a total of 123 registrations across all the courses.

Feedback from the courses was excellent, with both presenters and participants interested and keen to learn more about the topics presented. Any feedback from the courses is appreciated, we try to improve the courses each year and appreciate your comments on how to do this.

Thanks to Brian, David and Bob for presenting our courses for this year, with a note of thanks to Brian for travelling from Calgary to present the courses for us, with most expenses covered by his company.

Planning for next years courses will start soon, suggestions for topics or presenters are always welcome.

The Education committee is also planning for more courses in future, with a one day course presented by Dr Serge Shapiro planned to be held in 2–3 venues in March 2016. Further details are in this issue of *Preview*.

We are also planning for longer, more advanced courses to be held in future. We need your support to continue holding courses, so let us know what you want to see and please come along and support the courses when they are on!

Wendy Watkins
ASEG Education Committee
continuingeducation@aseg.org.au

Melbourne and Monash Universities compete for the ASEG Vic/Tas Student Prize

ASEG Vic/Tas held their 'Annual Student Night' on October 29th with a great turnout of around 25 people to see 4 students from Melbourne and Monash universities presenting research from their Honours or Masters projects. The presentations and presenters were:

Matt Sisson, Monash University, 'Using remanent magnetisation to differentiate rock packages: insights from the Birksgate Prospect, Curnamona Province, SA'.

Isaac Graves, Melbourne University, 'Rheological and stratigraphic controls on fault linkages in the Timor Sea'.

Taylor Ogden, Melbourne University, 'A redefined crustal structure of the Buchan Rift, Northeast Victoria: evidence from potential field modelling of newly acquired land-based gravity data'.

Gemma Cochrane, Monash University, 'Integrated geological and potential field analysis for the exploration of IOCG deposits within the Battle Axe prospect, Cloncurry'.

A few drinks and nibbles beforehand helped to calm any nerves as for some this was their first truly public scientific presentation. The audience wouldn't have known it as we witnessed four very clear and confident presentations. Matt and Isaac had to contend with an uncooperative laptop and even managed to carry on their presentation by ad-libbing or taking questions while it rebooted. The judges were impressed with the quality of all the presentations as well as the scientific content. Picking a winner would prove tough but the deciding factor in the end was probably the ability of Taylor Ogden to communicate his work with great clarity to the diverse audience assembled.

The prize pool was extended to reward each presenter, with Taylor Ogden of the University of Melbourne receiving the first prize of $250. Celebrations continued afterwards at an adjacent pub as many students had also submitted their theses that day.

Jarrod Dunne
ASEG Vic Committee
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ASEG one-day short course for 2016


Dr Serge A. Shapiro

Rock physics and geomechanics of fluid-induced seismicity: hydraulic fracturing, stimulation of geothermal systems and hazard assessment

Presented by: **Dr Serge A. Shapiro,** Professor of Geophysics, Freie Universität Berlin, Germany.

Anticipated dates: week of 14–18 March 2016.

Venues: To be advised – check website for more details closer to event!

Course description:

Stimulations of rocks by fluid injections belong to a standard reservoir-development practice. Production of shale oil, shale gas, heavy oil and geothermal energy require broad applications of this technology. The fact that fluid injection causes seismicity has been well-established for several decades. Understanding and monitoring of fluid-induced seismicity is necessary for hydraulic characterisation of reservoirs, assessments of reservoir stimulations and for controlling the seismic risk. The course provides systematic quantitative rock-physics and geomechanical fundamentals of these aspects.

Course objectives:

- To demonstrate the potential of microseismic monitoring for characterisation of hydrocarbon and geothermal reservoirs.
- To provide a systematic introduction into quantitative interpretation of microseismic monitoring and into assessment of the hazard of induced seismicity.

Approximate course outline:

Rock physics and geomechanics of induced seismicity
- Poroelastic phenomena and seismic waves
- Stress, pore pressure and rock failure
- Geomechanics of earthquakes

The method of microseismic monitoring:
- Observation systems, detection and location of events
- Microseismic wavefields and imaging

Seismicity, pressure diffusion and hydraulic fracturing
- Modelling of fluid–induced seismicity
- Seismicity during a fluid injection
- Seismicity after a termination of a fluid injection
- Hydraulic properties of reservoirs and induced seismicity
- Hydraulic fracturing of hydrocarbon reservoirs
- Seismicity induced by hydraulic fracturing
- Non–linear diffusion and seismicity in unconventional reservoirs

Hazards of induced seismicity
- Rates and magnitudes of fluid–induced earthquakes
- Seismogenic index
- Statistics of large magnitudes

About the lecturer:

Serge A. Shapiro is Professor of Geophysics at the Freie Universität Berlin, Germany and since 2004, Director of the PHASE (PHysics and Application of Seismic Emission) university consortium project. From 2001 till 2008 he was a Coordinator of the German Continental Deep Drilling Program. His research interests include seismogenic processes, wave phenomena, exploration seismology, and rock physics. He received the SEG Virgil Kauffman Gold Medal in 2013 for his work on fluid-induced seismicity and rock physics and in 2004 was elected a Fellow of The Institute of Physics.

Who should attend?

Geophysicists, Geologists, Petrophysicists, Reservoir Engineers, Graduate Students, Researchers.

The book for the course:

S.A. Shapiro, 2015, *Fluid-Induced Seismicity,* Cambridge (UK): Cambridge University Press, pp. 289. ISBN: 9780521884570.
http://www.cambridge.org/9780521884570

AUSTRALIAN SOCIETY OF EXPLORATION GEOPHYSICISTS

RESEARCH FOUNDATION

All geophysics students at honours level and above

- **You are invited to apply for ASEGRF grants for 2016.**
- Closing date **27 February 2016.**
- Awards are made for:
  - BSc (Hons) Max. $5,000 (1 Year)
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  - PhD Max. $10,000 per annum (3 Years)
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- Awards are made to project specific applications and reporting and reconciliation is the responsibility of the supervisor.
- Any field related to exploration geophysics considered, e.g. Petroleum, Mining, Environmental, Engineering.
- Applications must be electronic and on the application form.

EMAIL: dcrgeo@tpg.com.au
Doug Roberts (Secretary ASEGRF)

ASEG Research Foundation

Goal

To attract high-calibre students into exploration geophysics, and thus to ensure a future supply of talented, highly skilled geophysicists for industry.

Strategy

To promote research in Applied Geophysics, by providing research grants at the BSc (Honours), MSc, and PhD level (or equivalent).

Management

The ASEG RF Committee comprises ASEG Members from mining, petroleum and academic backgrounds, who serve on an honorary basis, and who share the administrative costs to spare Research Foundation funds from operating charges. The funds are used in support of the project, for example, for travel costs, rental of equipment, and similar purposes. Funds must be accounted for and, if not used, are returned to the ASEG Research Foundation.

Donations to the ASEG Research Foundation are always very welcome and are Tax Deductible. Contact the ASEG if you wish to make a donation.

2015 student projects in geophysics

Honours Projects, Victoria

Taylor Ogden

Taylor Ogden, Melbourne University: 'A redefined crustal structure of the Buchan Rift, Northeast Victoria: evidence from potential field modelling of newly acquired land-based gravity data'.

The Buchan Rift in north eastern Victoria is a north-south trending basin which formed due to east-west crustal extension in the Early Devonian. The rift is filled mostly with an Early Devonian sequence of volcanic and volcaniclastic rocks named the Snowy River Volcanics. The structure and geometry of the Buchan Rift and its major bounding faults are mapped at the surface, however a significant discrepancy exists between the surface distribution of the rift fill, and its expected potential field response. Two new detailed land-based gravity traverses that span the rift and surrounding basement rocks in an E-W orientation have been acquired and integrated with pre-existing government data.

Qualitative interpretation of the observed gravity data suggests the lower density rocks of the Snowy River Volcanics have a wider distribution than mapped extent of the rift. Forward modelling of both land-based gravity data and aeromagnetic data supports this interpretation, and resolved geometries show that the boundaries of the Buchan Rift are wider at depth. These geometries can be explained by the inversion and rotation of previous extensional faults and initiation of reverse faults causing over thrusting of older sediments and granite intrusions, most likely during the E-W crustal shortening in the Tabberabberan Orogeny. Moreover, new tectonic models proposed by Cayley et al. (2012) have suggested that the Macquarie Arc extends further southward and underlies the rift. This is supported by forward modelling in the northern and central part of the Buchan Rift, however it cannot be resolved in the south.

Taylor Ogden received the ASEG Vic/Tas prize for Best Student Presentation.

Gemma Cochrane, Monash University: 'Integrated geological and potential field analysis for the exploration of IOCG deposits within the Battle Axe prospect, Cloncurry'.

The Eastern Succession of the Mount Isa Inlier, NW Queensland, preserves a complex history of poly-phase deformation, protracted metasomatism, episodic magmatic intrusion, and IOCG mineralization. The diverse mineral systems of the Eastern Successions require an integrated approach to identify and resolve the structural frameworks which control IOCG mineralization and their alteration system, particularly in regions dominated by cover. This project aimed to identify the structural controls associated with IOCG mineralisation and its associated alteration systems within the Battle Axe prospect, and to provide a regional context for these systems within the Eastern Succession.

Integrated analysis using structural geology, drillhole data, geophysical datasets, and forward modelling revealed a complex structural framework involving early (D1) NW-directed thrust faulting, followed by regional N-S-trending meso to macroscale folding (F2) and steeply dipping reverse faulting (D2). A switch in shortening direction to a N-S trend produced overprinting upright E-W-trending folds (F3). E-W to NW-SE oriented crustal shortening produced a large-scale shear zone and extensive D4 reverse fault, re-activating D2 reverse faults. Early magnetite-enrichment was concentrated in the hinges of mesoscale F2 folds, with a second magnetite enrichment cross-cutting along a NW-trend. Magnetite-depletion was observed to correlate with D4 shear-zones. Potassic-enrichment cross-cut D2 reverse faults, and was concentrated in the hinges of macro-scale F2 folds.

The intersections of magnetite-depletion, late magnetite-enrichment and potassicenrichment coincided with NW-trend of copper and gold mineralisation on the Battle Axe prospect.

Gemma Cochrane shared the ASEG Vic/Tas runner-up prize for Best Student Presentation.

Isaac Graves, Melbourne University: 'Rheological and stratigraphic controls on fault linkages in the Timor Sea'.

In the Timor Sea region, Neogene continental collision has caused basement reactivation and normal faulting in the overlying sediments, with basement structure known to influence the location of cover sequence deformation. The characteristics of a ductile, shale layer located between basement Jurassic rift structures and the brittle Cenozoic carbonate cover sequence are thought to control the degree of fault linkage, but a more exact understanding of the individual influential factors is yet to be realised. Previous physical models of a mechanically anisotropic stratigraphic column in an extensional setting suggest that the rheology and thickness of both the central ductile layer and overlying cover sequence influence the coupling between deep and shallow deformation, but more modelling data is needed to provide additional evidence.

This study presents time-dependent numerical models that replicate and expand upon previous physical models in order to further evaluate the controlling factors and enable quantitative analysis. Experiments involved systematically varying the thickness of both the ductile layer and cover sequence, the viscosity of the ductile layer and the strength of the cover sequence as the domain was extended 2%, with the number and magnitude of the shear bands that formed in the cover sequence analysed. Modelling results suggest that the strength of the cover sequence and the thickness and viscosity of the ductile layer strongly contribute to varying the influence of the basement fault on cover sequence deformation.

Isaac Graves shared the ASEG Vic/Tas runner-up prize for Best Student Presentation.

Matt Sisson, Monash University: 'Using remanent magnetisation to differentiate rock packages: insights from the Birksgate Prospect, Curnamona Province, SA'.

Geophysical surveys are commonly incorporated into the exploration

Matt Sisson

workflow in order to target and model potential ore deposits. The magnetic response of these anomalies is often assumed to be predominantly related to the induced magnetism of the targeted body. This approach overlooks the remanent magnetisation component of the rock package, and the impacts of this remanent component of the magnetic response. This project is based in the Birksgate Prospect, Curnamona Province, where a magnetic gabbro and a magnetic metasediment cannot be differentiated through conventional geophysical techniques. The prospect is covered in approximately 200 m of younger cover sequences, and was only differentiated in the drilling program.

Using the Magnetic Vector Inversion (MVI) method, developed by Ellis et al. (2012), the magnetisation vector and the intensity of remanent magnetisation of each of these rock packages can be measured from the TMI data. Using samples of the rock packages from the drilling program, the intensity and orientation of the remanent magnetisation component was measured in the laboratory. The results found that across both rock types there was an average soft magnetisation component of 69%, with a third of samples showing overprinting from isothermal remanent magnetisation from drilling or overprinting from the Earth's field. Six samples (five from the skarn, one from the gabbro) showed a coherent magnetisation vector with an average inclination of –34.2° and an average declination of 132.5°. The MVI results found contrasting vector directions for the meta-sedimentary rocks, with an inclination/declination of –66.5°/286.3° and –74.6°/148.4 for the two bodies modelled. This study concluded that the MVI results delineated the targets; however the results did not correspond to the remanent magnetisation orientations measured in the lab. This difference has been attributed to the petrophysics of the rock packages and limitations with the MVI method.

Matt Sisson shared the ASEG Vic/Tas runner-up prize for Best Student Presentation.

Julian Geldard, Monash University: 'The Eclipse Cu-Au deposit'.

The Eclipse Cu-Au deposit in the Mount Stavely Volcanic Complex, Western Victoria, possesses characteristics of both a porphyry and VHMS system. Geophysical techniques are used to identify controls on mineralisation to aid interpretation and constrain its nature and origin. High resolution gravity data was acquired and petrophysical properties from limited drill core are used to constrain potential field (gravity and magnetic) data and forward models. A demagnetised zone of strong to intense phyllic alteration corresponds with a gravity low and is attributed to an andesitic intrusion with base metals and quartz veins. The gravity survey also reveals an offset of the north-northwest trending volcanic belt. An interpreted submarine porphyry-style intrusion at depth (~800m) fits the potential field data and alteration styles.

Duncan McIntire, Monash University: 'Geometry and distribution of subsurface basalt domes at Tatyoon, Victoria: implications for geophysical modelling and exploration in the Stawell Zone'.

Cambrian basalt domes in the Stawell Zone provide the focus for localising deformation and gold mineralisation on their margins. At Tatyoon, 60 km south of Stawell, three interpreted basalt domes have previously been identified as gold prospects through gravity and magnetic mapping, and diamond drilling. However the resolution of pre-existing geophysical surveys has not been sufficient to identify structures likely to host gold mineralisation.

This thesis investigates the application of a high resolution gravity survey (100 m station and line spacing) at Tatyoon. Accompanying gravity forward modelling, constrained by drill hole and induced polarisation (IP) data, has been integrated with petrophysics to better define the geometry and architecture of the Grange Cambrian basalt dome, and its evolution in the context of the Delamerian and Lachlan orogenies. In addition, this thesis will examine the likelihood of mineralisation at the high gravity, low magnetic response at the dome inferred at the Shiraz prospect.

This thesis concludes that Cambrian basalt domes at Tatyoon were originally deposited as a cohesive series of overlapping lava flows, which have been reoriented by regional deformation and intrusion of localised apotheosis of the Ararat granodiorite. The Grange and Hermitage domes are most likely to be mineralised. The Tatyoon Fault likely served as a conduit for magnetite-destroying fluid flow that permeates the Shiraz dome.

PhD Projects, Victoria

David Moore

David Moore, PhD, Monash University: 'The pre-Carboniferous geology of Bass Strait and surrounds'.

This thesis examines the Proterozoic and early Paleozoic connections between Victoria and Tasmania. Many different models have been suggested, and I conclude here that the Selwyn Block model is the most appropriate as it satisfies both the geological and geophysical data. The model proposed that the Proterozoic cratonic crust of western Tasmania continues north under Bass Strait and lies unconformably below the Melbourne Zone in central Victoria. The Selwyn Block is the northern end of the Proterozoic micro-continent, VanDieland, which also includes western Tasmania, the west South Tasman Rise and the East Tasman Plateau.

In order to be able to extrapolate the major rock packages in Tasmania across Bass Strait, they first had to be determined in Tasmania. Seven

Proterozoic zones were outlined—King Island, Rocky Cape, Burnie, Pedder, Tyennan, Sorell-Badger Head, and Glomar, with an eighth, the Eastern Tasmanian Zone equivalent to the Paleozoic Tabberabbera Zone in eastern Victoria. Only the first three Proterozoic zones continue across Bass Strait, with the other four truncated either in Bass Strait or lying further south. Outcrops of rocks from the King Island and Burnie Zones are present in windows in Victoria but the Rocky Cape Zone is completely concealed. However, the presence in the mid-crust of the Rocky Cape and King Island zones can be seen in the enclaves and in the geochemical signatures of the Upper Devonian granites of central Victoria and in rare conglomerate clasts.

VanDieland was initiated inside Nuna, between Laurentia and East Antarctica, at about 1.8 Ga. Much of the sedimentation seen in the Rocky Cape Zone is the erosional products of the Grenville Orogeny. As Rodinia broke up, VanDieland began to be extended at about 760 Ma, and this continued until final separation from Antarctica at about 570 Ma. After this, it drifted 'north' as micro-continental slivers along the Terra Australia margin until about 530 Ma. It then re-amalgamated in a closing back arc system within the greater Ross-Delamerian Orogeny, although it did not accrete onto Gondwana, remaining perhaps 200 to 300 km outboard. In the Early Devonian, as VanDieland got closer to Gondwana, a Banda Sea-style subduction system retreated southwards outboard of its eastern margin. This accreted VanDieland into Gondwana and gave rise to a crude, clockwise age distribution of the granites in Tasmania, from approximately 400 Ma on Flinders Island to 350 Ma on King Island.

David has worked for over 40 years in both the public and private sectors, most often on gold-related projects. While at BHP, he learned to interpret potential field data and specialised in regional interpretations. Subsequently, he joined the Geological Survey of Victoria, working initially on the basement geology of the covered and poorly outcropping areas of western Victoria. He also completed basement interpretations of the Gippsland and Otway basins, projects that inevitably got him looking south towards Tasmania and thinking about the topic of his thesis.

Stefan Vollgger

Stefan Vollgger, PhD, Monash University: 'Implicit 3D geological modelling in structurally complex environments'.

Geological structures are closely related to the genesis of ore deposits due to their ability to transport and trap hydrothermal fluids. Structurally-controlled mineralisation commonly shows distinctive geometries, orientations and spatial distributions that derive from associated structures. Moreover, structures such as faults and shear zones can offset, truncate and redistribute earlier mineralisation. Consequently, the analysis of these structures provides fundamental insights on the genesis of ore deposits and their evolution in a regional context. Accurate three-dimensional (3D) geological models are therefore required to visualise and analyse ore bodies and their host rock geometries in order to understand the underlying controls on mineralisation or remobilisation processes.

The aim of this thesis is to understand the relationship between ductile structures (i.e. folds), brittle structures (i.e. fractures) and mineralisation. 3D implicit modelling of dense lithogeochemical drillhole datasets is employed to assess mineralisation in structurally complex environments. Such models are used to determine the geometry, size and orientation of ore bodies and first-order structures, and to understand their spatial relationships to host rocks. Working hypotheses based on such geometrical analyses can then be tested and compared to field measurements and to other independent datasets (e.g. geophysical maps). This approach is applied here to both the Navachab lode gold (Namibia) and the Currawong base metal (Victoria, Australia) deposits. In both cases, links are established between modelled ore bodies and local to regional structural patterns. The modelling also constrains the structural frameworks of the deposits and explains their temporal evolution. First order (regional) structural controls are also identified for future exploration in these areas and similar geological environments worldwide.

In a third case study at Cape Liptrap and Cape Paterson (Victoria, Australia), the complex structural framework of basement folds and faults and their influence on brittle deformation in younger cover sediments are assessed by a combination of 3D implicit modelling and unmanned aerial vehicle (UAV) photogrammetry. The latter results in the computation of dense 3D point clouds and corresponding orthorectified photographs at sub-centimetre resolution. Bedding orientation measurements from Cape Liptrap are extracted from the point cloud and used to generate a 3D implicit model, which facilitates the analysis of fold geometries and the estimation of bulk shortening strain. Orthorectified photographs are used to measure and analyse fracture orientations in order to understand their relationship to the development of folds and fractures in the overlying cover rocks. This approach is applied to constrain the structural history of the southern part of the Lachlan Orogen and to elucidate the role of basement structure inheritance on subsequent basin development and deformation.

The understanding of deformation-related structures and their influence on the emplacement and redistribution of mineralisation can be significantly enhanced by combining of modern modelling and mapping techniques with well-established geological methods and principles.

Stefan A. Vollgger finished his BSc in Applied Geosciences / Economic Geology at the Montanuniversitaet Leoben (Austria) in 2007. After starting his MSc in Economic Geology with an exchange semester at the Colorado School of Mines (USA), he graduated from the Montanuniversitaet Leoben (Austria) in 2010. Both, his bachelor thesis and master thesis had a strong focus on economic geology and 3D modelling. He was also working part-time for an Austrian mining consultancy (mineIT) throughout his study time. During that time, Stefan was able to gain experience and insights into the mining industries and was working on several mineral and ore deposits of *various commodities (lithium, halite, iron). In 2011 he commenced his PhD at Monash University, focusing on the relationship between deformation and mineralisation. He is applying state-of-the-art technologies and workflows such as 3D implicit geological modelling and UAV photogrammetry to gain a better understanding of structural control on mineralisation.*

Robin Armit

Robin Armit, PhD, Monash University: 'Unearthing the marginal terranes of the South Australian Craton'.

The marginal terranes of the South Australian Craton consist of predominantly buried Neoarchean to Early Mesoproterozoic meta-sedimentary and magmatic rocks that cover an area in excess of 150 000 km^2. The terranes include the buried northern Gawler Craton and the outcropping Mount Painter Province on the north-west margin of the Curnamona Province.

The position of these terranes at the margins of the Archaean to Palaeoproterozoic Gawler Craton and the Palaeoproterozoic Curnamona Province makes them the ideal location to test links between these Precambrian terranes and to understand the relationship between the south and north Australian cratons.

U-Pb dating of zircon reveals maximum depositional ages for the siliciclastic Radium Creek Group of ca. 1595 Ma. Relatively diverse and evolved Hf isotopic signatures are correlated with zircon signatures from the Olympic and Spencer domains of the Gawler Craton and suggest that the Radium Creek Group is sourced from the Gawler Craton at ca. 1595 Ma. This indicates that the Curnamona Province and the Gawler Craton were co-located at this time.

Rapid burial accompanied by ductile deformation followed by exhumation within 6 Myrs of deposition supports tectonic mode switches and suggests that the Mount Painter Province occupied a complex plate tectonic setting in the overriding plate of two convergent margins in the Early Mesoproterozoic and appears to have similar tectonic evolution to the northern Gawler craton and north Australian Craton.

A validation of the 3D architecture of the Mount Painter Province using a constrained potential-field inversion modelling process argued for the addition of a larger volume of felsic material in the sub-surface and suggests that there was an increased heat budget in the early Palaeozoic and may have be a driver for the pervasive hydrothermal alteration in the region.

SHRIMP and LA-ICPMS U-Pb dating from a series of meta-sedimentary horizons intersected in the drill holes into the buried northern Gawler Craton yielded maximum depositional ages of ca. 1736 Ma and minimum depositional ages from cross-cutting leucocratic veins of ca. 1731 Ma. Similar ages, isotopic and REE characteristics are interpreted from meta-sedimentary rocks in the Mabel Creek Ridge, Yoolperlunna and Welbourn Hill regions. Collectively these meta-sedimentary rocks (Manguri Group) are likely derived from the Arunta Province in North Australian Craton. Wider correlations of the ca. 1740 Ma meta-sedimentary rocks suggest that these sequences form part of an extensive and contiguous basin system in the mid-Proterozoic across the Australian continent. Inversion and tectonic mode switches during the ca. 1730–1690 Ma Kimban-Strangways Orogeny and ca. 1590–1560 Ma Kararan-Chewings Orogeny support a far-field back-arc basin setting for the basin system. Systematic similarities in the ages, isotopic and geochemical signatures of Neoarchaean to late Palaeoproterozoic magmatic and meta-sedimentary rocks across crustal-scale faults in the northern Gawler Craton suggest these faults do not represent sutures between allocthonous crustal blocks.

In the palaeogeographical reconstruction models the marginal terranes of the South Australian Craton are positioned in the overriding plate of a long-lived north dipping subduction zone along the southern margin of Palaeo-Mesoproterozoic Australia.

Robin is an assistant lecturer at Monash University in the School of Earth, Atmosphere and Environment. His research interests include tectonics, strucutral geophysics and high-temperature geochemistry.

Honours Projects – Tasmania

Will McAdam, University of Tasmania: 'A Geophysical Interpretation of the Mole Creek area, central Tasmania'.

The Mole Creek area hosts a diverse array of geology including Proterozoic 'basement', overlying Palaeozoic volcanic and sedimentary rocks together with Mesozoic and Cenosoic cover sequences. The subsurface distribution of Proterozoic and Palaeozoic rocks is poorly constrained in part due to a lack of high resolution geophysical data. This study presents new semi-regional gravity data which together with recently acquired aeromagnetic data and petrophysical measurements provides the basis for new geophysical interpretations of this area.

Petrophysical sampling including 2829 magnetic susceptibility and 167 dry bulk density measurements from 12 drill cores from the Mole Creek area to constrain physical property values of major geological units. 695 new gravity stations were acquired to infill pre-existing stations to a spacing of ~500m. Forward modelling of gravity and magnetic data was used to evaluate the geological interpretations of Vicary (2015) and to interpret specific geophysical anomalies in the Mole Creek area including the unexplained Stockers magnetic anomaly.

Tertiary basalt and some Tyndall Group rocks display higher magnetic susceptibility than all other sampled units while Permian sediments have lower density than all other sampled units. There is significant overlap in the properties of many Palaeozoic units that fundamentally limits the ability of geophysical interpretation to distinguish these units. The new gravity data delineates a 'new' zone of Owen Group rocks in the north of the study area. Cambrian and Proterozoic rocks are characterised by positive gravity anomalies in the study area and there is no residual gravity anomaly associated with the Stockers magnetic anomaly. TMI data can broadly be correlated with some of the mapped geologic units within the study area. Several isolated magnetic zones are interpreted to be due to faulted slices of Cambrian andesite and basalt. Some previously unexplained magnetic anomalies are best modelled by slices of Cambrian basalt. The source of the Stockers magnetic anomaly cannot be confidently identified due to limited geological and geophysical constraints that can be imposed on a solution. Three possible solutions (basalt, serpentinite and Tyndall Group rocks) for the Stockers magnetic anomaly were investigated. A 3km × 4.5km × 1km package of Cambrian basaltic/andesitic rocks that extend upwards to a depth of approximately 1000m and dips/plunges gently to the NW is the preferred interpretation for this feature.

Reuben McCormack, University of Tasmania: 'Geophysical Assessment of Potential Magnetite Skarn Mineralisation at the L13 Prospect, Highclaire, Northwest Tasmania'.

(Abstract under confidentiality for 12 months)

Mark Smith, University of Tasmania: 'Distribution, Nature of Sediments and Depth to Bedrock in Bass Strait, in the Region of Burnie Port'.

(Abstract under confidentiality for 12 months)

Honours Projects – NSW

Nikita Golkin, University of Sydney: 'Numerical modelling of microcontinent formation in the context of a passive margin'.

Microcontinents are a collective term, which refers to small, isolated fragments of continental crust surrounded by oceanic lithosphere. The formation of such features has been attributed to rifting and continental breakup in the vicinity of continental margins. Using 2D coupled thermo-mechanical models, where extensional force is applied to a lithospheric plate made of an oceanic segment adjacent to a non-cratonic continent, this study shows that breakup occurs in the weakest zone located within the continent, a few hundred kilometres away from the continent-ocean boundary. This breakup leads to detachment of a microcontinent, which consists of the continental margin and a segment of the adjacent continent.

The results of this study provide support for previous conceptual analysis of lithospheric strength variation in passive margin regions, which suggested that the strength minimum along a rifted margin is located landward of its hinge zone. The results also suggest that microcontinent detachment can only occur when the oceanic lithosphere adjacent to the margin is older than 10 Myr. Simultaneous detachment of 2 microcontinents occurs in our models, where the oceanic segment is between 20 and 40 Myr of age and high extension velocity is prescribed. The results of our numerical experiments indicate that extensional velocity, lithospheric thickness, and mechanical heterogeneity can have significant influence on the size, morphology, and internal structure of microcontinents. In particular, microcontinents produced via fast extension tend to be larger in size, have more extended margins and may contain a failed rift structure produced due to formation of multiple necking zones.

Nikita is recipient of a 2015 PESA scholarship.

Carmen Braz, University of Sydney: 'Cretaceous kinematic and geodynamic evolution of the Caribbean and Northern Andes'.

A complex history of subduction, back-arc basin formation, terrane accretion and transpressional shearing characterise the Cretaceous to present day evolution of the Caribbean and northern South American margin. However, current models of Caribbean evolution leave a significant body of geological and geophysical observations unexplained, which relate to the formation of a back-arc basin offshore north-western South America in the Cretaceous.

To constrain the Jurassic-Cretaceous subduction history of eastern Panthalassa we develop a revised plate tectonic model, which is tested against two previously published models. These alternative kinematic scenarios were coupled with global numerical mantle convection simulations using CitcomS. Comparisons of mantle tomography with the predicted present-day temperature profile are used to determine the kinematic scenario that best reproduces present-day mantle structure. Based on geological observations and seismic tomography, we create a new tectonic model that includes the extension of a Northern Andean back-arc basin, called the Quebradagrande back-arc, opening at 145 Ma westwards into the Panthalassa domain. At its maximum extent, subduction associated with the back-arc is located ~15° west of the continental margin. Closure of the basin is modelled to start at 120 Ma, followed by terrane accretion and northward translation along the South American margin starting at 100 Ma. Our geodynamic modelling results show that subduction outboard of the South American margin is required to reproduce mid-mantle positive seismic anomalies imaged in P- and S-wave seismic tomography beneath South America, 500–2000 km in depth. Furthermore, we show this subduction zone is likely produced by a back-arc basin that developed along the northern Andes during the Cretaceous via trench roll-back. Our preferred kinematic scenario results in seafloor-spreading isochrons that provide a much improved match with the previously interpreted age of the oceanic basement in the Venezuela Basin.

Luke Hardiman, University of Sydney: 'Numerical modelling of landscape development during pull-apart basin formation'.

Pull-apart basins represent a complex process of tectonic interaction between two separate strike-slip faults. While previous work has identified the importance of the tectonic regime on the form of the basin, however little work has so far been undertaken to investigate how climate and surface processes may alter the basin's form. Therefore a series of models were developed to investigate how these processes alter the basin's form. The models were produced through a one-way coupling of the geodynamic modelling code Underworld and the landscape evolution modeller Badlands. In addition a series of python scripts were developed which enabled the extraction of features including the longitudinal river profile, Peclet number and Chi factor directly from the model outputs.

Analysis of the models suggests that the tectonic regime has a strong influence of the development of the drainage systems across the basin predominantly through subsidence producing sinks that the drainage systems outlet into. Additionally the lateral motion of the model results in a lack of stability within the drainage systems, resulting in large scale drainage reorganisation throughout the models. The climate and surface processes still influence the form of the developing pull-apart basin, however, with the minimum width basin defined by the tectonic regime and the maximum width by the efficiency of the surface processes.

While several of the climatic regimes imposed resulted in a purely erosive landscape the addition of standing water within the pull-apart basin resulted in large scale deposition across the basin and an increase in the erosion of the basin walls. Overall the results suggest that the surface processes influence the dimensions and internal features of the basin, however much of the basic form of the pull-apart basin can be attributed to the tectonic regime.

Amanda Thran, University of Sydney: 'Tsunamigenic potential of submarine landslides on the central Queensland continental slope: insights from numerical modeling'.

Submarine landslides are capable of generating tsunamis that can incur highly localized and potentially catastrophic damage on neighbouring coastlines with relatively little warning. The recent discovery of numerous slides on the north-eastern Australian continental slope warrants an urgent need to quantitatively assess their hazard potential. This thesis presents a multi-scenario numerical evaluation of the tsunamigenic capacity of three notable past slides and one potential future slide in the Great Barrier Reef region. Special attention is given to near-field tsunami interactions with reef platforms.

Failure scenarios are presented for the Viper Slide, the Gloria Knolls Slide, the potential Noggin Block failure, and the newly-described Bowl Canyon Slide. Tsunami propagation is computed using a nonlinear shallow water code that employs the wave-generation formulations presented by Watts et al. (2005) and Løvholt et al. (2005). Here, the code was further modified to account for variations in the spatial distribution of bottom roughness, where roughness introduced by reef cover is accounted for using previously determined field-derived parameters to ensure an accurate construction of the reef's structural complexity. Additional setups incorporate anthropogenic climate change-induced sea level rise scenarios for the Noggin Block and a reconstructed paleo- shoreline scenario for the Viper Slide.

In light of the current lack of consensus on the effects of reefs on tsunami propagation, the impact of the Great Barrier Reef on run-up is assessed for each principal scenario by successively sequestering the region's small-scale and large-scale bathymetric complexity. The small-scale influence of reef growth is examined by way of a sensitivity analysis for bottom roughness, whereas the larger-scale influence of the reef platforms is isolated by excising the platforms and imposing a smooth interpolation upon the continental shelf incline. Run-up estimates under these conditions are then compared to those of the reference scenarios.

Numerical simulations indicate that the Gloria Knolls Slide and the Bowl Canyon Slide are capable of producing significant run-up (>3m). The smaller Viper Slide would pose a minimal threat to the present-day coastline, though run-up would have been substantially larger in its proper spatio-temporal context, as sea level was at least 85m lower at the time of its failure. The Noggin Block is currently capable of producing an estimated 4.5-7.1m run-up onshore, though sizable increases can be expected under the current 50-year (+0.3m), 100-year (+0.8m), and 'Greenland Ice Sheet collapse' (+7m) sea level rise benchmark projections.

The landslide-generated tsunamis exhibit a multitude of complex interactions with reef platforms, where platforms and upper slope features induce shoaling, reflection, refraction, and focussing of propagating wave trains. Overall, the reef demonstrates a remarkable capacity to attenuate and reflect wave energy. For the principal scenarios, run-ups increase up to 69% when reef cover is removed and up to 545% when platform structures are removed. The ability for small-scale reef growth to reduce tsunami energy additionally carries significant implications with regard climate change, as the compounding effects of both sea level rise and coral cover decline will likely render the Queensland coastline more vulnerable to coastal inundation.

Jonathon Leonard, University of Sydney: 'Influence of Mantle Convection on the Topographic Evolution of Tethyan Orogens'.

Continental collisions produce orogenic belts that represent the highest elevations on Earth. This is due to thickened crust caused by collision producing isostatically compensated topography. Isostatic topography is a function of lithospheric thickness where the weight of lithosphere comes into buoyant equilibrium with the astheno- sphere. Because of high isostatic topography, many studies of mountain belts ignore the possible role of dynamic processes in their evolution. Significant uplift and growth of the Tibetan plateau during the Miocene period is unlikely to be wholly caused by crustal thickening. This has lead to the suggestion by some that vertical stresses from mantle convection (known as dynamic topography) have contributed to the anomalous recent uplift of the plateau and mountain belt as well subsidence of the Himalayan foreland basin (Husson et al. 2014). Similar recent growth of the cen- tral Iran plateau have also lead to suggestions that dynamic topography has played a role in the evolution of the Zagros-Iran orogen (Francois, Burov, et al. 2014).

We produce time-dependent, global mantle convection numerical models using deform- ing plate reconstructions that track the evolution of dynamic topography as well as total model topography since 40 Ma, when continental collision between India and Eurasia began. We find that orogenic belts have negative present-day dynamic to- pography that ranges from –500 m to –1000 m. We investigate a number of different subduction histories for the convergence of India into Eurasia. Our findings show evidence for recent dynamic subsidence beneath the Himalayan foreland basin of the order of –200 m to –300 m whilst showing little change in dynamic topography under the Himalayan belt and Tibetan plateau. Considering foreland basins have topography close to sea level, there is evidence this recent subsidence has had a significant contribution to the evolution of the foreland basin. On the other hand, we find little evidence that dynamic topography has significantly contributed to the uplift of the Tibetan and Iranian plateaux.

MSc Projects – NSW

Alexandre Lemenager

Alexandre Lemenager MSc, Macquarie University: 'Numerical modelling of the Sydney Basin using temperature dependent thermal conductivity measurements'.

The thermal structure of continental crust is a critical factor for geothermal exploration, hydrocarbon maturation and crustal strength, and yet out knowledge of it is limited by our incomplete knowledge of its geological structure and thermal properties. One of the most critical parameters in modelling upper crustal temperature is thermal conductivity, which itself exhibits strong temperature dependence.

In this study, finite-element geothermal models of the Sydney Basin are generated through the use of deal.II finite element libraries. Basin geometry and structure is adapted from Danis, et al. (2011), which quantified the extent of Triassic sediment, Permian coal measures, Carboniferous volcanics and Basement thickness. We find that temperature-dependent thermal conductivity result in lower lateral variation in temperature, compared to constant thermal conductivity models. However, the average temperatures at depth are significantly higher when temperature-dependent thermal conductivity effects are included.
A number of regions within the Sydney Basin demonstrate temperatures above 150°C at depths of less than 2000 m in these models, including the NW Singleton geothermal anomaly, demonstrating the potential geothermal prospectivity of the region for experimentally-constrained thermal parameters.

Alexandre Lemenager was awarded an ASEG scholarship by the NSW branch in 2015. He started at Macquarie University as an undergraduate in 2011, studying geosciences, went on to a Masters of Science in 2014, and transferred into the new Masters of Research early in 2015. His focus is on a very new side of geology – geodynamic modelling.

Honours Projects – ANU

Manon Dalaison, ANU: 'Investigation of the nature of a major resistive boundary at Majors Creek, New South Wales, Australia using inversion techniques and mineralogy of surface samples'.

The electrical resistivity of the subsurface was measured along a 400 m line up to 60 m deep in the Majors Creek area, southeastern New South Wales. Manual auger samples, collected up to 250 cm depth, were analysed using X-Ray powder diffractometry, to characterise the resistivity anomalies. Particular attention was paid to the geophysical inversion method and to the identification and quantification of minerals in auger samples.

The smoothness-constrained least-squares optimisation method produced a modelled resistivity bounded between 20 and 600 m, with a vertical discontinuity at depth (~15 m and downwards) near the middle of the pseudosection, and a clear delimitation of groundwater in the first 15 m below the surface. The regularly sampled subsurface was made up of in-situ weathering products, comprising mottled clays and moderately weathered saprolite of felsic igneous rock with preserved granitic texture. The effect of weathering was found to override all the other trends in the mineral quantification, correlating zones of water storage and mottling with high clays and amorphous content and low plagioclase, micas, magnetite and, in a lesser extent, low K-feldspar and inversely in dryer area, for relatively constant quartz. The nature of the deep resistive discontinuity could be the result of a conductive/resistive dyke or a local fault, interpretations that are supported by previously published geological map and aeromagnetic data, but for which the auger samples are of little use.

Honours Projects – SA

Matthew Musolino, University of Adelaide: 'First Steps Into The Unknown: Potential Field Surveying as an Effective First Step in Exploration – Uno Fault Example South Australia, Australia'.

The Uno Province in South Australia is a current focus of mineral exploration. The province, is bounded to the north by the Gawler Range Volcanics, a large felsic igneous province of mesoproterozoic age that overlies the palaeproerozoic basement. The nature of the boundary is postulated to be structurally controlled by the east-west trending Uno fault. However, little is known of the morphology of the fault. The fault, over time, has been continually extrapolated eastward with minimal geological rational. Information and knowledge adhering to the nature of the fault, its possible extent and the exact boundaries between geological units adjacent to it, does not yet exist.

To provide new constraints on the Fault, two lines of gravity data were procured in June 2015. The lines were approximate 52 km and 27 km long, and comprised 156 stations spaced approximately 250 m to 1 km apart. It's hoped that description of the planning phases and the two transect lines of variable gravity station spacing produced a valuable replicable method for this line of work. Regional elevations changes are small (less than 150 m) so that only simple gravity reductions methods were applied and the data were tied into a reference South Australian gravity framework. The lines were designed to cross the boundary of the GRV approximately at right angles, although stations had to be collected along roads for logistical reasons.

Two-dimensional modelling of the fault using representative densities for the major lithological units shows that the Uno Fault represented a clear boundary in physical properties, but the data could not determine fault from unconformity. The continuation of the fault was not detected to the east in the Siam line. Anomalous areas other than the fault were investigated and discussed including parts of the Hutchinson's group and the geometry of the Hiltaba suite. Conclusions were bounded by the uncertainties inherent in non-unique solutions. However possible explanations to gravitational trends along both lines have been stated and may aid in the continued exploration of this area for minerals.

Brad Cox, University of Adelaide: 'Uncover: MT and Seismic transect across the Western Gawler Craton and Eucla Basin'.

The Eucla Basin in Southern Australia is a Tertiary Basin, which covers Proterozoic crust between the Yilgarn Craton in Western Australia and the Gawler Craton in South Australia. However, very little is known of the crustal framework of this major orogenic belt, and as a result, the geological evolution of the area is poorly understood. In 2014, a deep reflection seismic and magnetotelluric (MT) transect was undertaken to provide new constraints on the survey area.

The MT profile was 830 km long, with 167 stations separated 5 km apart. Broadband MT responses were obtained at all sites in the bandwidth of 200 – 0.0005 Hz (0.005–2,000 s) which records data from the top 100 m, up to 100 km in depth. The MT responses showed different characteristcs along the line. In the western 500 km of the profile, the responses were approximately 1D and were more sensitive to the presence of thick sedimentary sequences with high porosity. For much of the Eucla Basin, the sedimentary thickness was about 500 m, but in places reached depths of around 2 km. Two dimensional inversion revealed a generally very electrically resistive upper crust of > 1,000 Ohm.m, but more conductive lower crust of < 100 Ohm.m. However, the lower crustal conductive regions were not continuous, indicating that there are significant crustal domains with different thermal and fluid evolutions. In the eastern 300 km of the survey, the Eucla basin sediments thin and the profile crosses major shear zones and the western extent of the Gawler Craton. The MT responses here are much more three dimensional and the crust appears to be much more electrically heterogeneous.

Matthew Gard, University of Adelaide: 'Monitoring Groundwater Flow in Fractured Rock Environments Using Self-Potential Methods'.

Self-potential (SP) data has been successfully utilised in porous media environments for mapping groundwater flow, through measurement of surface voltages. Little research has occurred into utilising this method in fractured rock aquifer systems. Such systems are highly heterogeneous in comparison, with groundwater flow focussed along discrete faults, fractures and bedding planes rather than through the bulk matrix as in porous systems. An SP field survey was conducted at Watervale, South Australia in association with a pumping test, with the aim to analyse the viability of this method in this hydrogeological environment. This data was then processed using both a 2D and 3D tomography algorithm, based on the assumption of uniform resistivity due to a lack of a resistivity profile.

SP tomography delineated preferential flow directions centred on Line 2, in a NNE-SSW orientation, which was supported through physical drawdown measurements at the associated well. As the dominant fracture and bedding orientations in the region are similarly aligned, it can be assumed the SP response has resolved these discrete fluid pathways. These SP results are encouraging, correlating well with physical observed data and geological information, and support the hypothesis that the SP method has viability for use in fractured rock aquifers.

PhD Projects – SA

Sebastian Schnaidt

Sebastian Schnaidt PhD, University of Adelaide: 'Improving Uncertainty Estimation in Geophysical Inversion Modelling'.

Numerical inversion modelling is an integral part of geophysical data interpretation. Growing computational resources are used to invert ever-growing data sets and higher dimensional data.

However, models without meaningful uncertainty estimates are difficult to interpret reliably and limited attention has been paid to the advancement of model quality estimation techniques to keep up with the more sophisticated inversion schemes.

The employment of meaningful uncertainty estimation methods is often hindered by the complicated implementation of those methods, and inadequate model quality estimators are frequently used.

This project was aimed at the advancement of model uncertainty estimation, to enable a more common use. Two different approaches were developed, approaching the problem from different directions:

Firstly, a bootstrap resampling approach for the qualitative estimation of model uncertainties is presented. The algorithm is characterised by an easy implementation and the fact that it can provide model quality estimation capabilities to existing inversion algorithms without requiring access to the inversion algorithm's source code. A given data set is repeatedly resampled to create multiple realisations of the data set. Each realisation is individually inverted and the variations between the generated models are analysed and visualised to generate interpretable uncertainty maps.

The capabilities of the approach are demonstrated using the example of synthetic and real 2-D magnetotellurics data.

Secondly, the multi-objective joint optimisation algorithm MOJO is presented, which aims to remedy the common shortcomings of classical joint inversion approaches. Joint inversion modelling is a powerful tool to improve model results and reduce the effects of data noise and solution non-uniqueness. Nevertheless, the classic joint inversion approaches have a variety of shortcomings, such as a dependency on the choice of data weights, optimising only a single solution resulting in inadequate uncertainty estimates, and the risk of model artefacts being introduced by the accidental joint inversion of incompatible data. MOJO is based on the concept of Pareto-optimality and treats each data set as a separate objective, avoiding data-weighting. The algorithm generates solution ensembles, which are statistically analysed to provide model uncertainty estimates.

The shapes and evolutions of the solutions ensemble's distribution in objective space is dependent on the level of compatibility between the data set. The solution distributions are compared against a theoretical solution distribution corresponding to perfectly compatible data to estimate the compatibility state of any given objective-pair, allowing to distinguish between compatible and incompatible data, as well as identify data sets that are neither mutually exclusive nor sensitive to common features.

MOJO's effectiveness was demonstrated in extensive feasibility studies on synthetic data as well as real data. The algorithm is adaptive and can be expanded to incorporate a variety of different data types.Additionally, ways were explored to make the communication of the modelling results and the model quality estimates as clear and concise as possible, to allow the user to make an informed decision and avoid misinterpretations.

Sebastian Schnaidt studied Physics at the University of Göttingen, specialising in astro- and geophysics and was awarded a B.Sc. in Physics in 2009 and a M.Sc. in Physics in 2011.

From February 2012 to July 2015 he studied for a PhD at the University of Adelaide in collaboration with the Deep Exploration Technologies CRC. He now works as a geophysicist at DownUnder GeoSolutions in Perth.

Honours Projects – WA

Simon Shook, University of WA: 'Advanced Imaging Techniques for Azimuthally Anisotropic Velocity'.

Many seismic imaging algorithms do not account for anisotropy, which can result in physically inaccurate results and introduce increased exploration risk. Azimuthal anisotropy, in particular, has been observed in a number of seismic data sets from WA's North West Shelf (NWS), as is likely to be increasingly recognised in seismic datasets as more wide-azimuth (WAZ) and multi-azimuth (MAZ) surveys are acquired. This project aims to develop a set of imaging codes to quantitatively examine the benefits of – and the detriments of not – taking this form of anisotropy into account. We develop a 3D finite–difference time domain approach to a modified form of the Tilted Transverse Isotropy (TTI) wave equations that allow us to accurately model wave propagation through a Horizontal Transverse Isotropy (HTI) medium. After validating the modelling codes through standard impulse response tests for both the isotropic and HTI scenarios, we develop and apply isotropic and HTI migration algorithms to two large synthetic seismic dataset simulated through a 3D elastic model with and without HTI anisotropy. We examine the resulting matrix of images using various statistical and analytical methods to develop a quantitative understanding of the artefacts introduced by applying isotropic migration on anisotropic data. Key project outcomes are the identification of qualitative differences in the overall image and point diffractor resolution and a quantitative assessment of the introduced errors in migration dip angle.

Simon will commence with a Graduate Geophysicist position at Woodside Energy Ltd in early 2016.

PhD/MSc Projects – WA

Yathunanthan Sivarajah

Yathunanthan Sivarajah, PhD, University of WA: 'Monitoring of Human-Data Interactions Towards Understanding the Interpretation Process of Geoscientific Data'.

Qualitative data interpretation forms the basis of important decisions with significant social, financial, and environmental implications across diverse sectors of our society including the medical, legal, astronomy, and resource sectors. These interpretations typically involve the recognition of anomalies or specific features of interest within data. In this process, interpreters' intuition and biases play an important role, resulting in outcomes that are highly subjective and uncertain. This thesis presents a study that aims to understand and address uncertainties in geoscientific data interpretation, specifically focusing on geological target spotting within magnetic geophysical data.

Previous studies on geological interpretation uncertainties have mainly focused on analysing the interpretation outcomes and identifying factors that influenced these outcomes. This thesis on the other hand aims to understand and address uncertainties in human-data interactions, that is, the process by which the interpretation outcomes are reached. This is achieved by monitoring and quantifying physiological and neurological responses of interpreters during target spotting exercises through an eye tracker system (ETS) and electroencephalography (EEG) techniques. These technologies are widely used in various fields, such as human computer interaction (HCI), brain-computer interface (BCI), clinical studies, and web marketing, but their use in geoscience is in its infancy. Various experiments were carried out to capture ETS and EEG data during target spotting exercises involving the identification of prescribed geological 'targets', specifically porphyry style intrusive systems within magnetic data. Interpreters with varying levels of expertise and experience participated in the experiments, and their data observation patterns were profiled using an ETS and their brain responses were monitored using EEG techniques.

This thesis reports three applications of the ETS and EEG techniques, and their potential to be used to understand biases in geological target spotting. The first application used eye gaze movements, captured through ETS to identify effective data observation practices. Variability in data observation patterns of different interpreters and their target spotting outcomes were analysed. The results show that target spotting performances can be improved by observing the data more systematically and by observing it from multiple orientations. These findings may be useful in devising a roadmap for the training of magnetic data interpreters.

The second application used ETS data to identify image locations of potential visual attention biases of interpreters. The eye gaze fixation patterns derived from the ETS data were compared with saliency maps. These maps, which represent visual saliency of an image, were generated using various algorithms. The results showed a close correlation of the eye gaze fixation maps with the image saliency maps of a well-known algorithm, the Itti's saliency model (ITTI) algorithm. This study then proposed the use of this image saliency algorithm to predict and compensate for potential visual attention biases when choosing a set of magnetic data enhancement methods for interpretation. A set of experiments using three different magnetic datasets demonstrated the feasibility of using saliency maps as a tool to select a set of enhanced images for interpretation. This was achieved by analysing the similarities and differences in visual saliency regions between different enhanced images and to ensure the wide coverage of saliency regions across different enhanced images.

Finally, the third application investigated the feasibility of using brain responses to automatically identify geological target selection epiphany, without the need for behavioural responses. Experiments were conducted using target and non-target images and a P300 response associated with target detection was identified from the EEG data using a pattern classification technique, namely support vector machine (SVM). A single trial average classification accuracy of 83% was obtained, which demonstrates the effectiveness of using the P300 response to detect geoscientific target selections.

Yathunanthan Sivarajah won The Nick Rock Memorial Prize at UWA in 2014, which is awarded to a student completing the degree of Doctor of Philosophy in geophysics, for completing the most outstanding piece of research in the fields of numerical geology or computer modelling in geoscience. He received a B.Sc. Eng. (Hons) (2008) from the University of Moratuwa, Sri Lanka and a Ph.D. (2015) from the University of

Western Australia. He is a visualisation specialist at the Pawsey Supercomputing Centre. His research interests include large-scale data visualisation, human-data interaction and human-computer interaction.

Wendy Young, MSc, University of WA: 'Feasibility of time-lapse gravity monitoring of gas production and CO2 sequestration, Northern Carnarvon Basin, Australia'.

Time-lapse (4D) seismic data, often used to monitor hydrocarbon production and CO2 injection in subsurface reservoirs, cannot readily detect gas saturation changes under certain conditions. Seismic data respond primarily to variations in the compressibility of a rock, but for gas-fluid mixtures greater than ~20%, a change in gas saturation may cause only a minimal change in the compressibility of the reservoir rock. Therefore, it can be difficult to discriminate reservoirs with high and medium gas saturations using the seismic technique.

To better monitor changes in reservoir gas saturation, a non-seismic technique may be more favourable. Complementary geophysical techniques, such as gravity and electromagnetic (EM) methods, respond to subsurface variations in density and resistivity respectively, and these physical properties are highly dependent on the saturation values of the rock's pore fluids. Compared to 4D seismic surveys, time-lapse gravity and EM acquisition costs have the potential to be less expensive; however, they also contain less spatial resolution. Gravity data has an additional benefit of being linearly proportional to changes in mass/density, and thus may be easier to interpret than alternate geophysical data types.

To detect small mass changes in offshore subsurface reservoirs requires high precision gravity data, which can be achieved by accurate repositioning of the gravimeters on the seafloor. After applying a variety of data corrections, the change in the gravity signal over time can be related to variations in the fluid saturations or pore pressures in the subsurface reservoir. The time-lapse gravity signal may be particularly useful because the amounts of aquifer influx and/or pressure depletion in an offshore reservoir are key uncertainties impacting ultimate gas recovery.

The objective of my thesis research is to develop and perform a feasibility analysis for time-lapse gravity monitoring of gas production and CO2 injection in Northern Carnarvon Basin reservoirs. To do this, I have developed a method to quickly assess the sensitivity of time-lapse gravity measurements to reservoir production or injection related changes. I show that gravity monitoring of Carnarvon gas reservoirs appears to be technically feasible and encourages further detailed assessment on a field-by-field basis. For example, in a strong water-drive scenario, a field-wide height change in the gas-water contact greater than 5 m can produce a detectable gravity response greater than 10 μGal for a reservoir at a depth of 2 km, with a porosity of 0.25 and a net-to-gross sand ratio of 0.70. Alternately, for the same reservoir in a depletion-drive scenario, a 6 MPa (~900 psi) decrease in pressure throughout the field can also produce a detectable gravity response. To monitor CO2 sequestration using the time-lapse gravity technique, I find that it is easier to detect a CO2 plume (or potential leaks) in shallower formations (at or less than 1 km below mudline) compared to deeper storage formations at depths greater than 2 km. In order to produce a detectable gravity anomaly, significant amounts of CO2 in excess of 4-8 MT must be injected for reservoirs at 2 km depth, compared to only 1 MT of CO2 injection for formations at 1 km depth.

The methods I have developed to assess the feasibility of gravity monitoring are both flexible and practical. They can be used in a wide range of applications, and provide a quick first-order assessment of the feasibility of time-lapse gravity monitoring of subsurface density/mass changes caused by changes in fluid content or pressure in porous reservoir rock.

Wendy Strong (nee Young) received Best Student Paper award, ASEG Conference, Brisbane, 2012.

Matthew Saul, PhD, University of WA: 'Pressure-dependent elastic properties of sandstones, with applications to seismic reservoir characterisation and monitoring'.

Knowledge of the pressure dependence of rock properties is essential for a diverse range of earth science problems, including seismic characterisation and monitoring of subsurface fluid flow processes, as are common in hydrocarbon, groundwater, and CO2 sequestration reservoirs. This thesis focuses on developing a better understanding of the pressure dependent elastic properties of unconsolidated and partially consolidated sandstones. The key contribution of this thesis is to improve the prediction and interpretation of pressure dependent rock properties and their effects in seismic data.

A long-standing research problem is that theoretical models of velocity-pressure response often do not match laboratory measurements, and alternately, empirical regressions fit to such data do not extrapolate accurately to wider pressure ranges since they have little or no underlying physical basis. In this thesis we develop a new model to describe the pressure sensitivity of the bulk and shear moduli for uncemented sedimentary rocks. The model incorporates effects of sedimentary compaction and the concept of critical porosity, including a relationship to account for porosity and density change with pressure. We demonstrate a method to estimate the critical porosity constraint at zero effective pressure using grain-size distribution data. The strong physical basis of this model, along with a unique two-stage model parameter fitting process, enables us to predict the elastic properties of unconsolidated sediments at a wide range of pressures, including low effective pressure when only data at higher pressures is available. The model is tested on laboratory measurements for various rock samples and fits well over a wide range of pressures. The new model should have implications for the improved prediction and interpretation of 3D and 4D seismic data, including for pressure prediction, quantitative AVO analysis, seismic reservoir characterisation, and time-lapse fluid-flow monitoring.

Additionally, we investigate further the reasons for observed discrepancies between theoretical predictions of unconsolidated sediment elastic properties and laboratory measurements. We show that grain contact heterogeneity and porosity variation (sorting and compaction) can explain the observed discrepancies, and develop a new modified grain contact theory model that incorporates these effects. We also show how porosity variations associated with sorting and compaction can explain observed Poisson's ratios > 0:25, thereby overcoming weakness in previously published grain contact theory models. The calibration parameters of the new model agree with the observations of published granular dynamics simulations and provide an improved fit to laboratory data compared to existing models, including the ability to describe the correct variation in Poisson's ratio with effective pressure, and values of Poisson's ratio > 0:25.

Finally, we present a reservoir characterisation and monitoring case study, in which we analyse time-lapse seismic data acquired over a high-pressure water injector in the Carnarvon basin, offshore Australia. We show how rock physics diagnostics and seismic reservoir characterisation can be used to enhance the interpretation of 4D seismic data in terms of pressure and grain cementation effects. It is commonly assumed that certain rock properties remain constant during fluid production and injection, including porosity and grain contact cementation. However, in this thesis we show evidence from the Carnarvon basin case study that water injection at high pressure can damage or weaken grain contact cement in poorly consolidated sands, resulting in significantly larger time-lapse seismic anomalies than expected from initial feasibility work. These observations are important for assessing 4D seismic feasibility and interpretation in sedimentary rock in general, particularly in Macedon reservoir sands and other geologically analogous systems.

In summary, the work presented in this thesis allows for the improved analysis, prediction, and interpretation of pressure-dependent rock properties and their effects in seismic data, as a result of our development and analysis of new, more accurate relationships between stress-dependent elastic properties and seismic data.

Matthew Saul received the UWA Hesperian Press Award (top PhD Thesis in Geosciences), and the Best Student Paper award, SEG Conference, Las Vegas, 2012.

Mohammad Emami Niri

Mohammad Emami Niri, PhD, University of WA: 'Seismic data integration and multi-objective optimization for 3D reservoir'.

Reservoir modeling is the practice of generating numerical representations of reservoir conditions and properties on the basis of geological, geophysical and engineering data measured on the Earth's surface or in depth at a limited number of borehole locations. Building an accurate reservoir model is a fundamental step of reservoir characterization and fluid flow performance forecasting, and has direct impact on reservoir management strategies, risk/uncertainty analyses and key business decisions. Seismic data, due to its high spatial resolution, plays a key role not only in defining the reservoir structure and geometry, but also in constraining the reservoir property variations. However, integration of 3D and time-lapse 4D seismic data into reservoir modeling and history matching processes poses a significant challenge due to the frequent mismatch between the initial reservoir model, the reservoir geology, and the pre-production seismic data. The key objective of this thesis is to investigate, develop and apply innovative solutions and methods to incorporate seismic data in the reservoir characterization and model building processes, and ultimately improve the consistency of the reservoir models with both geological and geophysical measurements. In this thesis we first analyze the issues that have a significant impact on the (mis)match of the initial reservoir model with well logs and 3D seismic data. These issues include the incorporation of various seismic constraints in reservoir property modeling, the sensitivity of the results to realistic noise in seismic data, and to geostatistical modeling parameters, and the uncertainties associated with quantitative integration of seismic data in reservoir property modelling.

Inherent uncertainties and noise in real data measurements may result in conflicting geological and geophysical information for a given area; a realistic subsurface model can then only be produced by combining the datasets in some optimal manner. One approach to solving this problem is by joint inversion of the various geological and/or geophysical datasets. In this thesis we develop a new multi-objective optimization method to estimate subsurface geomodels using a stochastic search technique that allows a variety of direct and indirect measurements to simultaneously constrain the model. The main advantage of our method is its ability to define multiple objective functions for a variety of data types and constraints, and simultaneously minimize the data misfits. Using our optimization approach, the resulting models converge towards Pareto fronts (a set of best compromise model solutions). This approach is applicable in many Earth science disciplines: hydrology and ground water analyses, geothermal studies, exploration and recovery of fossil fuel energy resources, and CO2 geosequestration, among others.

We adapt this new approach for creating reservoir models by combining geostatistical simulation and multi-objective optimization to improve static reservoir model estimation by simultaneously integrating multiple datasets including well logs, geologic information and various seismic attributes. We test our new approach on a 3D object-oriented reservoir model, where variogram-based simulation techniques typically fail to reproduce realistic models. We also demonstrate an application of our new method on a real case study from offshore Western Australia. Our results indicate that improved reservoir property models and flow-unit connectivity can be obtained with our new multi-objective optimization approach.

Finally, we develop a new method for seismic reservoir property modeling based on an integrated analysis of 3D seismic data and hydraulic flow units, and apply it to an example of a producing reservoir offshore Western Australia. Our method combines hydraulic unit analysis with a set of techniques for seismic reservoir characterization including: rock physics analysis, Bayesian inference, pre-stack seismic inversion and geostatistical simulation of reservoir properties. We develop a probabilistic relationship between certain 3D seismic data attributes and the hydraulic units we determine at well locations. Since porosity and permeability distributions are estimated for each hydraulic flow unit as part of the process, we can use the 3D seismic probabilistic relationships to constrain geostatistical realizations of porosity and permeability in the reservoir, to be consistent with the flow unit analysis. Reservoir models jointly constrained by both 3D seismic data and hydraulic flow unit analysis can therefore help to improve the accuracy of dynamic reservoir flow predictions and production history matching.

In summary, the research presented in this thesis develops and tests new methods to generate reservoir models that optimally match geological and geophysical data, to improve the processes of reservoir characterization, fluid flow performance forecasting and production data or 4D seismic history matching.

Mohammad completed a PhD degree in geophysics at the centre for Energy Geoscience (CEG), University of Western Australia. He worked for oil and gas companies as a geophysicist for more than 6 years after completing my B.Sc. and M.Sc. degrees in petroleum exploration engineering. He recently joined Institute of Petroleum Engineering of Tehran University as an assistant professor. His current research and applied industry work interests include quantitative seismic interpretation, seismic reservoir characterization, reservoir static and dynamic modeling.

Olivia Collet

Olivia Collet, PhD, Curtin University: 'Study of stress-induced anisotropy and effect of crack infill in oil and gas reservoirs'.

For most of its history, seismic processing and inversion has been based on an isotropic earth model, despite the recognized fact that many geological formations are anisotropic. Seismic anisotropy is defined as the dependence of seismic velocities upon propagation direction. Analysis of seismic anisotropy is challenging as it requires a number of parameters that are difficult to constrain from measured field data. This thesis aims at deriving new rock physics models in order to gain a better insight on how external stresses and fluid affect seismic anisotropy.

First, we focus on modelling the stress-induced anisotropy of dry rocks. The anisotropy pattern resulting from the application of a small triaxial stress on an initially isotropic medium is expressed in terms of anisotropy parameters, which are a convenient notation to describe the effect of anisotropy on velocities. Interestingly, the medium is found to be ellipsoidal. This result provides a potential way of differentiating between stressinduced and fracture-induced anisotropy by estimating the degree of anellipticity. The model also expresses the ratio of P- to S-wave anisotropy parameters as a function of the compliance ratio of grain contacts and the Poisson's ratio of the unstressed isotropic rock. The model predictions are consistent with laboratory measurements made on a sample of Penrith sandstone, although crack opening in the direction of maximum stress should be taken into account for larger stresses.

Next, we analyse the effect of fluid on anisotropy based on Gassmann theory. In the limit of weak anisotropy, it is possible to derive analytical expressions relating anisotropy parameters in saturated transversely isotropic or orthorhombic media as a function of anisotropy parameters in the dry medium. This approach is only valid at low frequencies, for which pore pressure is equilibrated throughout the pore space.

At higher frequencies, fluid pressure gradients cause local flow between pores of different shapes and orientations. This squirt flow is responsible for velocity dispersion and attenuation. To tackle this issue, a simple model of squirt-flow relaxation in anisotropic media saturated with fluid is developed for two cases: the simple case for which cracks are parallel and the case for which anisotropy results from the application of uniaxial stress on an initially isotropic medium. For liquid-saturated rocks in the limit of weak anisotropy, simple analytical expressions of elastic moduli and anisotropy parameters are presented. The anisotropy and attenuation patterns are significantly different in the two investigated cases. In particular, we show that the stress-induced anisotropy remains elliptical for all frequency ranges in saturated media, contrary to the anisotropy resulting from the presence of aligned cracks.

Finally, we use some of the results described above to derive a new methodology for estimating stress-induced azimuthal P-wave anisotropy from S-wave anisotropy measured in logs or vertical seismic profiles (VSP). The azimuthal P-wave anisotropy of the dry medium is first calculated from the measured S-wave anisotropy using results of the stress-induced anisotropy model developed for dry rocks. Then, analytical expressions linking the anisotropy parameters in the saturated and dry media are utilized in order to infer the azimuthal P-wave anisotropy parameter in the saturated medium as a function of its counterpart in the dry medium. This workflow is tested using log data acquired in the North West Shelf of Australia, where substantial azimuthal P-wave anisotropy has been inferred from seismic data using orthorhombic tomography. This anisotropy is likely caused by large differences between minimum and maximum horizontal stresses in the area. In the clean sandstone layers, for which the stress-induced anisotropy model is expected to be applicable, the results show a fairly good agreement with the azimuthal P-wave anisotropy estimated by the tomographic analysis. The methodology could be used to provide prior information to constrain an initial velocity model for anisotropic migration or azimuthal amplitude variations with offset (AVO) inversion.

Olivia Collet is currently living and working in Canada for Hampson-Russell, Calgary.

Mamdoh Saad Alajmi

Mamdoh Saad Alajmi PhD, Curtin University: 'Feasibility of seismic monitoring methods for Australian CO2 storage projects'.

Global warming is the natural consequence of increasing greenhouse gas (GHG) levels in the atmosphere, which contributes to global climate change. The technique of Carbon Capture and Storage (CCS) is one of the solutions used to capture CO2 emissions and inject them into deep geological storage. Several projects have been established or proposed for different parts of Australia to evaluate and implement this technique in order to eliminate CO_2 from the atmosphere. CO_2 storage verification and monitoring is crucial both during and after CCS and geophysics plays important role in this process; first it is required to find the appropriate geological storage for injection and then it is involved in tracking and imaging CO_2 storage and movement. Among the geophysical methods, seismic methods play a crucial role in these tasks in most projects around the world.

Many factors influence the accuracy and sensitivity of CO_2 seismic monitoring; some of them relate to the survey design and quality, while others relate to processing and imaging issues. I study both of these factors by modelling synthetic seismic data based on different seismic survey types, including surface, marine and VSP. To study these, I design the surveys based on the expected needs for different proposed or existing storage projects across Australia. I model a variety of volumes of carbon dioxide plumes and inject them into realistic finite difference models in order to acquire several synthetic time-lapse data sets. The main purpose of this work is to establish the CO_2 detectability limits for Australian CCS projects. One of the main factors in detecting changes in time-lapse surveys is the level of noise in the data. I generate diverse realistic time-lapse noise models for all project areas in order to evaluate the use of seismic applications for accurate CO_2 monitoring. In this thesis, I study the feasibility of using the seismic exploration methods (surface, marine streamers, ocean-bottom cables and VSP) in order to assess CO_2 storage verification and monitoring for three Australian projects: Southwest Hub, CarbonNet and Otway.

In detection feasibility studies for the Southwest Hub and CarbonNet projects, I identify the noise levels from real data, and model several injection scenarios in finite difference models in order to assess the detectability of different CO_2 plumes. I simulate the rock physics properties of the CO_2-saturated reservoir from log data, expected brine salinity and CO_2 temperature and pressure using Gassmann's fluid substitution equations to create a realistic finite difference model for several volumes of CO_2 plumes. For these two storage projects, I construct numerical models using all these proprieties to evaluate effectiveness of surface, VSP, marine streamers and ocean-bottom cables time-lapse seismic monitoring methods.

For the Otway project, I present two feasibility analyses to investigate CO_2 detectability and model a realistic time-lapse noise. First, I verify the seismic monitoring imaging ability of CO_2 detectability using two seismic migration application techniques.
I compare the detectability of the CO_2 plume using pre- and post-stack Kirchhoff migration algorithms on synthetic time-lapse data sets. For this feasibility study I use real seismic noise from the baseline Sodas Road field data to model realistic band-limited random noise.

Second, I perform a seismic monitoring feasibility analysis for the Otway region by predicting the time-lapse seismic signal and noise and then model realistic 3D time-lapse noise using Otway 4D seismic field data. In general, the observed time-lapse noise is spatially-correlated, band-limited and exhibits lateral and temporal variations in its characteristics. If one wants to perform a statistical analysis of the detectability of the time-lapse signal, one would need to have multiple realisations of such noise. To obtain such realisations, I propose a method for the modification of a single measured time-lapse noise volume.

The research presents techniques and modelling concepts to evaluate the use of seismic methods in CO_2 storage verification and monitoring. The main new developments and workflows in this thesis are the modelling of the time-lapse noise and its use for evaluating time-lapse monitoring methods. I trust that the presented results can improve feasibility studies of seismic CO_2 detectability and contribute to future applications in Australian CCS projects.

Dr Mamdoh Saad Alajmi has now resumed his position of employment at King Abdulaziz City for Science and Technology (KACST), Saudi Arabia.

Mohammed Alkaff

Mohammed Alkaff, M.Phil, Curtin University: 'Integration of depositional process modelling, rock physics and seismic forward modelling to constrain depositional parameters'.

Sedsim, a numerical stratigraphic forward modelling package, which quantitatively and deterministically predicts variations in sediment distribution over time as the depositional environment changes, was used to generate a stratigraphic model over the Cornea field, Browse Basin, Australia. The target reservoir within the Cornea field is the Albian sandstones which form isolated sandstone bodies within siltstones and clay-rich sediments.

Although numerical stratigraphic forward modelling is powerful technique for predicting the subsurface, it comes with uncertainty. In this study, it took thirty one runs to generate the final Sedsim model. Before each run, initial Sedsim parameters had to be modified. Initially, during the earlier runs, uncertainty in the stratigraphic model was easily identified just by viewing the results. Initial Sedsim parameters were then modified accordingly. However, as the stratigraphic model became more reasonable, uncertainty became difficult to identify.

In order to identify and reduce the uncertainty in the stratigraphic model, this thesis proposed and applied the method of closing the loop, where the stratigraphic model over the Cornea field was integrated with the velocity-porosity-clay (VPC) rock physics model and the process of seismic forward modelling. The VPC rock physics model, which is suitable for clean sandstones as well as clay rich sandstones, was used to convert input from the stratigraphic model to elastic parameters. The elastic parameters were then used to calculate acoustic parameters. The acoustic parameters were used to generate synthetic seismic data via the process of seismic forward modelling. The simulated synthetic seismic data was then compared to its corresponding observed seismic data. The parameters of the generated Sedsim stratigraphic model were modified based on the results of the comparison.

The process of closing the loop was successfully applied twice in this study. Once where sediments were deposited abruptly resulting in the formation of one thick interval. It was hard to see this in the stratigraphic model but when the model was converted to seismic, uncertainty was identified by the absence of synthetic seismic reflections within that interval compared to observe seismic and initial Sedsim parameters were modified accordingly and the stratigraphic model was regenerated. During the second time, closing the loop revealed problems within a carbonate interval overlaying the target. It was concluded that once possible source for these problems was the application of the VPC rock physics model, designed for siliciclastics, within a carbonate interval. Other possible sources of error such as inaccurate initial Sedsim parameters are not to be excluded.

Ideally, another rock physics model, suitable for carbonate rocks, should be run within the carbonate interval. Then, the process of closing the loop should be applied to identify the source of the problem within the carbonate interval, whether it is from the VPC model or the initial Sedsim parameters, and reduce uncertainty to a satisfactory degree. However, due to the limited time given for this study, this was stated as a recommendation for future work.

Comparison between synthetic and observed seismic remained qualitative in this study. However, it was recommended to turn it into a quantitative process by inverting observed seismic data. Hence, one could perhaps in the future automate the process.

The process of closing the loop can be used to identify and reduce uncertainty in numerical stratigraphic modelling. The process of closing the loop is practical in terms of identifying uncertainty. However, finding the correct Sedsim parameters to modify in order to reduce the identified uncertainty in addition to re-running the Sedsim model can be time consuming. The run time problem can be overcome by reducing some Sedsim parameters such as grid size or by breaking the modelled area into smaller parts. In addition, the process of closing the loop came with by-products and applications that could be used utilized for other purposes.

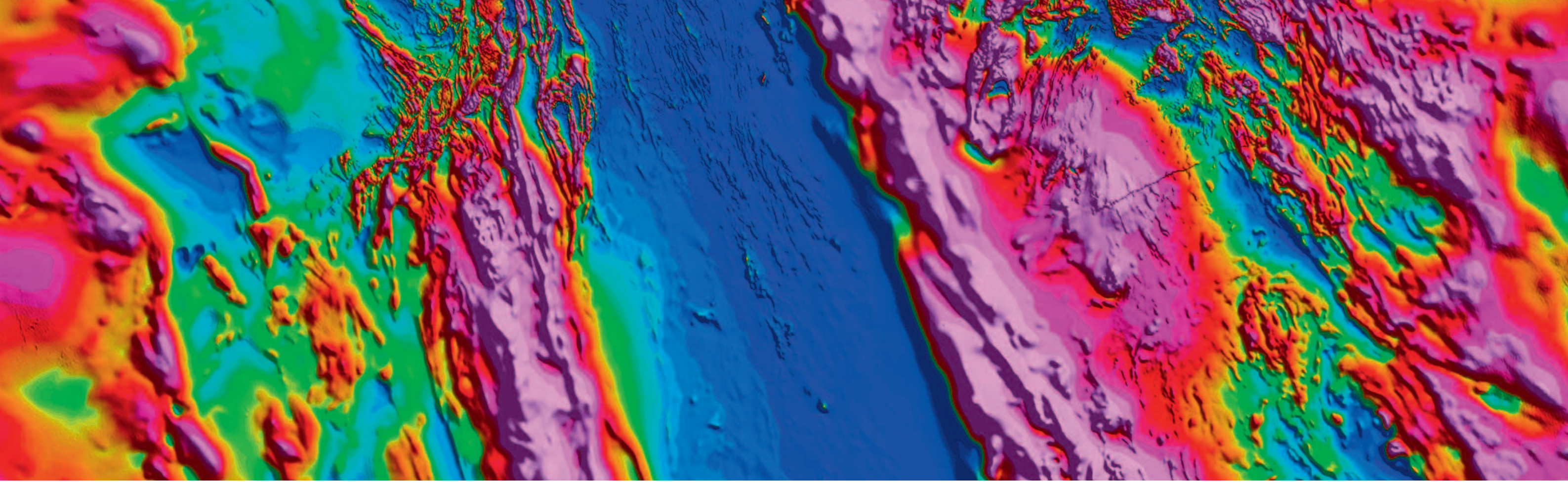
Mohammed Alkaff has now resumed his position of employment at Saudi Aramco, Saudi Arabia.

Toby Colson, MSc, University of WA: 'Fault Seal Analysis: Constraining fault seal risk using seismic velocities'.

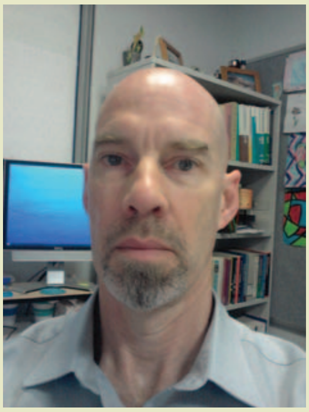
Fault seal capacity is an important component in the conventional petroleum system. Assessing the capacity for a fault to seal or leak can be difficult, particularly where well constraint is lacking. In the frontier basin, in a marine setting, seismic velocities may be the only data available. However, useful constraints on a faults sealing capacity can be extracted from this data alone. This study investigates the robustness of a number of empirical relations that can assist in extracting useful constraints from seismic velocities and amplitudes. Reliable estimates on maximum and minimum stress tensors and pore pressures can be calculated and combined with basic fault architecture analysis, to place practical constraints on fault risk.

In this study of an area on the Rankin Trend found good correlation between well-based and seismic velocity-based pore pressures and stress magnitudes allowing a coulomb failure function based only on stacking velocities to be calculated. Faults separating the Rankin 1 well block from the Dockrell/Keast Field, were shown to be within a stable stress regime. Calculated pore pressures match known RFT measurements and show that overpressure can be assessed using basic time-migrated velocity stacks. Furthermore, theoretical capillary pressure and hydrocarbon column calculations correlate with known values and highlight the capillary seal potential of sand-sand juxtaposition seals which can support 100 to 200 m column heights within the Triassic play. They suggest that many traps on the Rankin Trend within the Triassic play are limited by a combination of pore pressure and stress orientation. However, deeper intra-formational seals are likely to have increased seal capacity by virtue of overburden stress and reduced porosity exceeding any capacity for shear stress failure. Well data for this area confirms a Shmax orientation of approximately 110 +/– 10° and calculations show that faults striking within 20° of this direction may be at high risk of failure within the neotectonic setting, where pore pressures and dip predicate fault slip.

Toby has won a place on an IODP expedition to the Sumatra subduction zone for 2016.



Webwaves



Dave Annetts
david.annetts@csiro.au

How good is your access to the internet?

The last edition of Webwaves referred to the internet's ubiquity. This reference was made on the basis of my lab-based existence since the internet's inception. However, a recent field trip brought home the magnitude of my misapprehension.

Figure 1 (from opensignal.com) shows the degree of mobile coverage of the top three cellular network providers over Australia. Reds indicate strong signals while greens indicate weak signals. As one might expect, there is better coverage near major cities, and on the east coast of the country, than elsewhere. There is sparse coverage along highways (e.g. along the Barrier Highway from Sydney to Adelaide via Broken Hill, and along the Great Northern Highway from Perth to Port Headland via Newman). With the exception of Darwin, Cairns and Port Douglas, there is very poor coverage north of Broome (*Editor's note: Tell me about it, living in a dead spot (coverage wise) southwest of Cairns the compilation of bimonthly issues of* Preview *can be a struggle involving regular drives to the top of lonely hills – lonely that is apart from the odd interested cow!*).

There is better coverage some countries and worse in others. One could argue that cellular network coverage should be directly related to need and thus - why provide coverage if there is no one to cover?

Figure 1. *Degree of mobile coverage of the top three cellular network providers over Australia.*

One reason to improve coverage is to support exploration. Figure 1 shows that the Capricorn inlier (for example) is largely free of coverage, yet this is an active area of mineral exploration. Traditionally, inversion has been a compute-intensive operation, and inverting potential fields data is generally much less onerous than (e.g.) electromagnetic data. Inverting for simple earth models is also much less onerous than inverting data for multidimensional earth models. While inverting data acquired from regional airborne surveys may still require desktop and larger computing resources, inversion of smaller data sets, such as those around prospects, for reasonably complex models, is within the capability of typical field notebook computers and allows for a more agile approach to exploration.

A recent paper by Constable et al. (2015) suggests that evaluation of many different models may be required in order to properly interpret geophysical models, especially when data are gathered in difficult exploration terrains, such as those under conductive cover. Next-generation codes, codes that invert multiple data sets, and/or codes that employ stochastic methods, will likely require more substantial capabilities than field notebooks. However, without capabilities to send data for processing, or to receive updated models, data processing becomes an office-only task. A certain degree of agility regarding field operations is lost. One way to regain this agility would be to provide field camps with better computing power. While Google's newer data centres in Arizona are air-cooled, running transportable clusters in extreme temperatures and dusty environments, might prove... well, interesting…

Another way to regain lost exploration agility is to make use of cloud-based computing. However, this requires the ability to send and receive data using an internet connection. This might be one reason for explorationists to lobby telecommunications companies for better coverage, even though there may be few direct permanent beneficiaries.

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Environmental Geophysics

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Instream TEM: unresolved questions

Welcome to *Preview* readers this month. Just a few days ago (in November when I was writing this column) I got into an email conversation with Volmer Berens and Roger Cranswick from the South Australian Department of Environment, Water and Natural Resources (SA DEWNR) and Tim Munday from CSIRO (Minerals Resources / Land and Water) about the interpretation of instream TEM data collected on the Murray River; they were looking specifically at some data that had been collected earlier this year.

As many of you would know, instream TEM is a subject close to my heart, having been involved with this type of data acquisition and analysis since 2004. For those of you who don't know what I am talking about, I think of instream TEM as basically floating a small, low-power, time-domain EM system off the back of a boat. For most of this work the transmitter loop is only 7.5 m × 7.5 m, and the receiver 2.5 m × 2.5 m, with the transmitter and receiver (in this case a Zonge NanoTEM system) set up to collect data in ~2 s bursts.

These data have been presented in some beautiful atlases (e.g. Telfer et al., 2004), developed as a result of collaboration between Australian Water Environments (AWE), Zonge Engineering and various SA Government agencies. After some investigation, it was determined that while the TEM was providing some information about hydrogeology under the river, much of the information was about the interaction between the river and the often saline groundwater immediately under the base of the river (Berens, 2006, Tan et al., 2007). One of the original motivations for the original work was to investigate the area adjacent to a number Salt Interception Scheme bores (see for example Forward (2004) for a description of SIS in SA) to evaluate whether the bore schemes were operating efficiently. The main question was whether the SIS bores adjacent to the river were removing all of the saline groundwater before that water had a chance to enter the Murray; did they need to be pumped harder or could they be pumped less?

Back to our email conversation, Volmer kicked off the conversation with: 'A colleague of mine [that was Roger] is working with recently acquired instream NanoTEM data and has asked an interesting question – has anyone defined the resistivity threshold that could be used to discriminate between losing and gaining river stretches?'. And after a few emails we realised that the answer is probably 'no'. Understanding whether a given stretch of river is 'losing' or 'gaining' is very important for understanding salt accession to the river, and we had been making this interpretation by examining the depth sections and the GIS images without having determined any objective 'rules' (or even 'rules of thumb').

Roger took the bull by the horns and did some simple analyses using Archie's Law (Archie, 1942). He made the usual assumptions, setting porosity to 35% and assuming that the sample was 100% saturated (not a bad assumption directly under the river). He then set the empirical constants to the 'usual' settings, i.e. m=1.3, n=2 and a=1. I then took one of the older instream EM data sets, collected in 2005 near Bookpurnong (which is near Loxton, in SA), and plotted the data using a 'rainbow' colour stretch that shows the variability in the data nicely, but doesn't encourage 'targeted' interpretation, as is the goal here.

I then plotted the data based on Roger's Archie's Law results, first assuming that the resistivity of the river was 20 ohm-m (about right from memory) – which I then dropped to 15 ohm-m to give myself a little salinity leeway from the 20. I then arbitrarily set the resistivity of saline groundwater to ≤5 ohm-m. Using that 15 ohm-m river water assumption Archie tells us (via Roger and the other assumptions that he made) that the resistivity of that river water and sediment package would be about 60 ohm-m. Then, using that 5 ohm-m saline groundwater assumption, Archie again tells us that the resistivity of the saline groundwater-sediment package should <20 ohm-m. Based on these two rules we would then say that anything on the conductivity depth section close to the river base that is <60 ohm-meter is likely

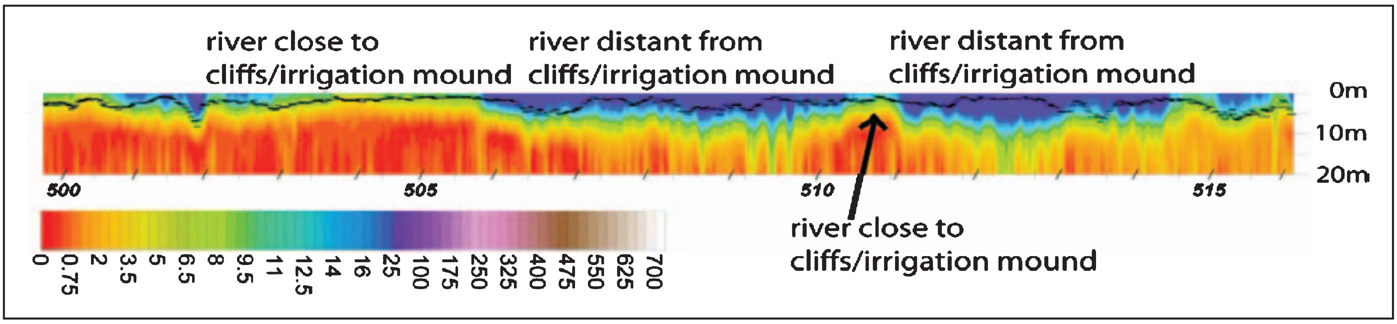

Figure 1. *Resistivity-depth section near Bookpurnong, on the Murray River, collected in 2005. Distance on the x-axis is in River Kilometres (and are used on Figure 2 as well). Depth of the river is indicated with the black dashed line. All of the orange has been interpreted as saline groundwater. In many places it is touching the base of the river (interpreted as gaining) and is never more than 5 m from the base of the river.*

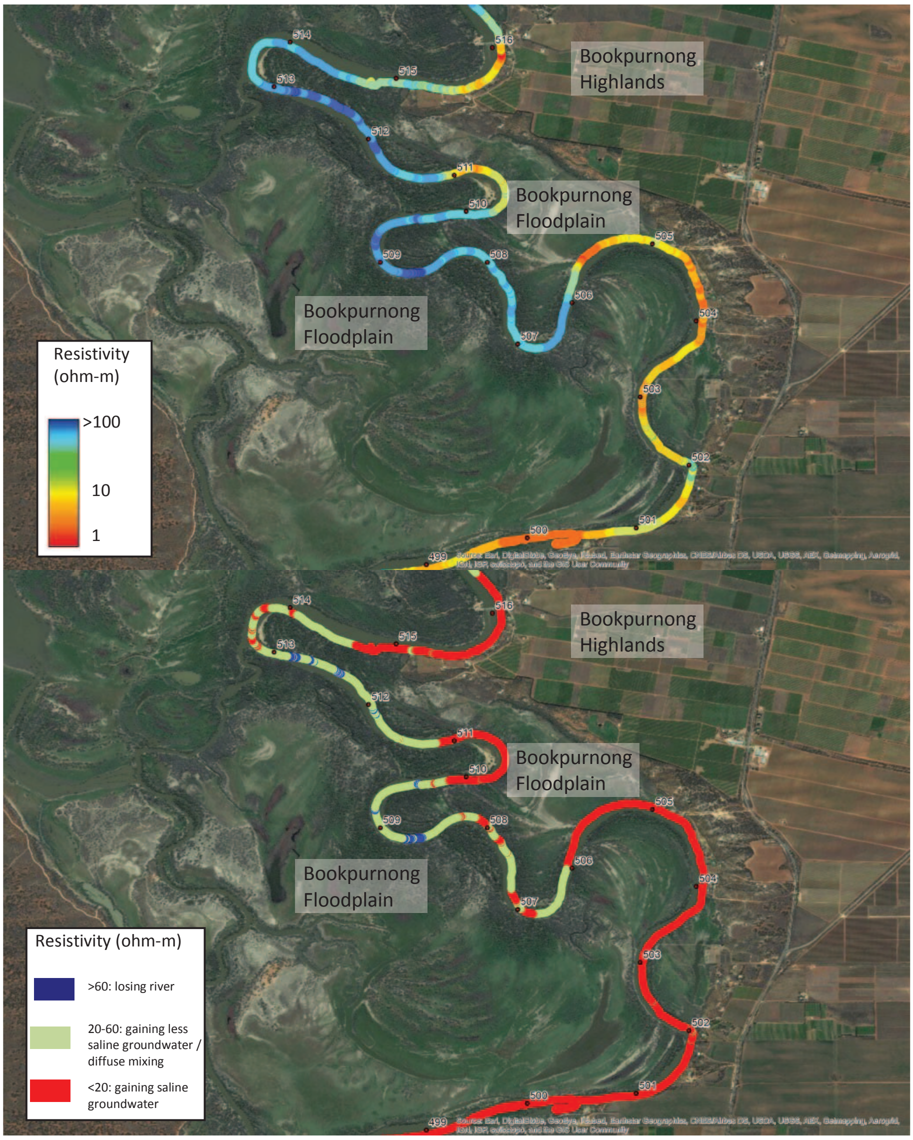

Figure 2. *Contoured river bottom resistivity data. In these GIS images, the trace of the river is shown using the resistivity value just below the bottom of the river from the conductivity sections in Figure 1. The top panel is how we usually show the data, while the bottom panel uses the colour scheme suggested by the collaborators*

to be influenced by saline groundwater and therefore the river is likely to be gaining groundwater.

Resistivities between 20 and 60 ohm-m are likely to be associated with zones of diffuse mixing (e.g. the saline groundwater is not in direct contact, but is still some distance from the river bottom). When resistivities are >60 ohm-m we would say that river is quite fresh and is likely to be losing to the underlying groundwater system. Figures 1 and 2 show and compare the results of this analysis. Personally, I think that the simplified three colour map is intriguing and may even be close to right. Looking at Figure 1, the conductivity-depth section for this part of the river, I would say that saline groundwater is not far from the river bottom along this entire stretch of river, and most of this stretch is gaining or will be soon (remember these data were collected in 2005). Interestingly SA Water agrees as they have built a major SIS through this stretch, based on this work, (and possibly more importantly) an extensive in-river salinity monitoring program, other hydrogeological studies and numerical modelling.

In the end, the question remains: have we come up with an improved classification scheme that makes interpretation simpler for this particular problem (and is it right)? Back to you Roger, Volmer and Tim…

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Seismic Window

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4D and the war on noise (and other geophysical warfare)

I'm led to believe that during the cold war there were some interesting ideas developed that enlisted geophysics to build weapons to attack the west. However, the real geophysical war conducted daily is the war on seismic noise. This is particularly important in 4D seismic where subtle changes are often difficult to see because the changes are of similar magnitude to the seismic noise.

4D seismic or time lapse 3D is used to monitor fluid movements in a producing hydrocarbon field. The process involves recording a base 3D survey before production starts (or shortly after) and also one or more monitor 3D surveys sometime later – time is the fourth dimension.

As hydrocarbons are produced the reservoir properties change. For instance, pressure may decrease near producing wells and increase around injector wells, or oil may replace gas or water saturation may change. These changes result in small changes to the seismic response that can be observed as time and amplitude differences between the base and monitor surveys. The example in Figure 1 is from the Enfield oil field in Western Australia's Exmouth sub-basin. There are many other examples of the successful application of 4D seismic providing valuable information that resulted in better reservoir management but I find there is still reluctance to try the method in some quarters. The problem is noise which may affect the repeatability of the seismic data.

Seismic processing has many tools and perhaps the most powerful weapon in the war on noise is stacking. The modelled example of Figure 2 illustrates how a small change in seismic amplitude is difficult to see in the presence of seismic noise of similar magnitude. But, after the application of a stacking process, the noise is reduced and the 3% difference between base and monitor surveys is now apparent (Figure 3). This illustration may over-simplify the problem but it does show that even in the presence of strong noise a relatively small change in the seismic response (3%) can be detected and there is no need for a pessimistic approach if appropriate processing is applied.

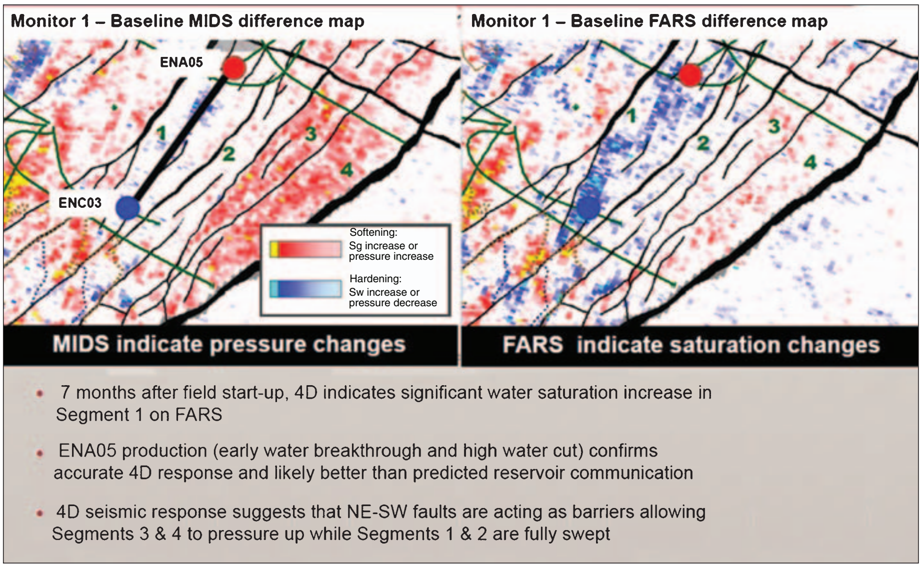

Figure 1. *Example of 4D seismic response caused by changes in the reservoir as a result of production. In the centre of the maps, blue area on FARS (far angle stack) indicates increase in water saturation while white area on MIDS (mid angle stack) suggests no change in pressure (from Hamson, 2012).*

Figure 2. *Modelled amplitude of base survey and monitor survey in the presence of different random noise for each. Vertical axis is amplitude, horizontal axis represents CDP location. Original amplitudes are 100 for base and 97 for monitor which represents a 3% change. There is significant overlap between the two lines.*

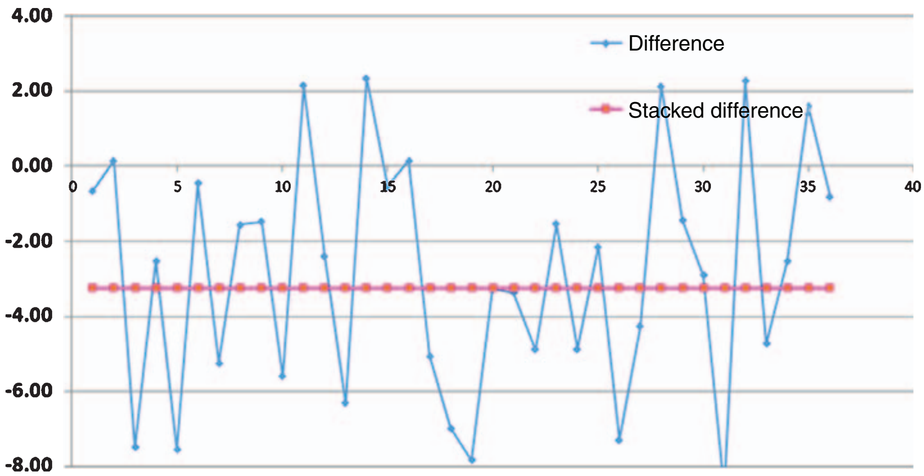

Figure 3. *The difference between monitor and base models of Figure 2 before and after stacking. The magnitude of the 4D response is difficult to discern on the raw data (blue) but after stacking (pink) it is similar to the actual value.*

Getting back to the cold war. I have never been to Eastern Europe but I know some people from the former eastern bloc who have described some more destructive applications of geophysics. The aim was to invoke a natural disaster in the targeted country without arousing suspicion or reprisals. They sound a bit Hollywood but I'm assured they were real avenues of research. Geophysical weapon A involved changing the course of small asteroids so that they landed in the targeted country and caused widespread damage. That sounds a bit hard to do, but geophysical weapon B is easier. The plan was to create an artificial earthquake in the Black Sea that would generate a tsunami which would travel west and flood Turkey. Why would anyone want to do that? At the time, Turkey had a large contingent of NATO forces which, it was hoped, would be rendered useless.

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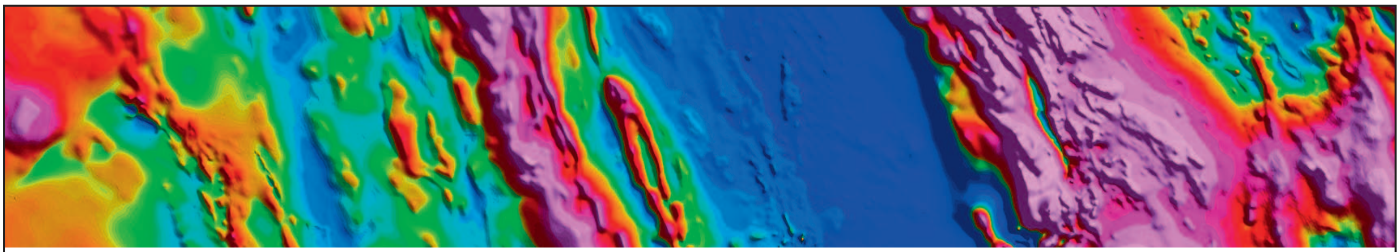

Letter to the Associate Editor Petroleum Geophysics

Associate Editors' Note: I'd like to thank Doug Morrison for this response to last month's article. As well as providing some solutions, Doug also highlights another problem faced by explorers – the lack of data. We always want to have just one more data point or line or well!

Dear Michael,

I liked your short article in *Preview* on visualisation and hand contouring – with hand contouring a lost art form and redundant nowadays. I couldn't resist having a go at your exercise. The classic 'insufficient information' – just one data point somewhere in the middle would be enough. Although I am now retired and don't need to be concerned you have hit on some points I was harping on for years. The data point locations or, in aeromagnetics for instance, the flight lines, should be the first overlay produced in any image processed gridded data.

Anyway, I couldn't resist having a go at your exercise with a series alternatives – the first hand contouring I have attempted for 25 years (Figure 1). I would have sent people back into the field to finish the survey. A nice test and a bit of fun.

My first attempt at hand contouring was on the Bass Strait aeromagnetic survey in 1961–62 for my then employer Aero Service Corp for BHP/Hematite Petroleum – interestingly it was a survey I recompiled (from original analog data) and image processed for Geoterrex and the Victorian Government in 1993. Nice memories.

For your interest - hand contouring as art does happen. See attached example (Figure 2). These aeromagnetic contours are of some radiating dykes in Queensland – probably about 500 km of acquired data in this image. The reproduction here is not all that good as it is from a hand-held photo. I drew and had this framed sometime in the early 1980s and it is in my shed somewhere if it hasn't faded away. There were gridded computer contours produced for this survey and they were in places a mess and I took on the task to fix it – the varying strike directions and narrowness of the dykes couldn't be handled all that well when gridded and contoured. I must admit the computer generated images didn't look too bad as greyscale (sun angled) and full spectrum colour images although some of the dykes were just a series of bulls eyes.

Regards

Doug Morrison
ASEG Member

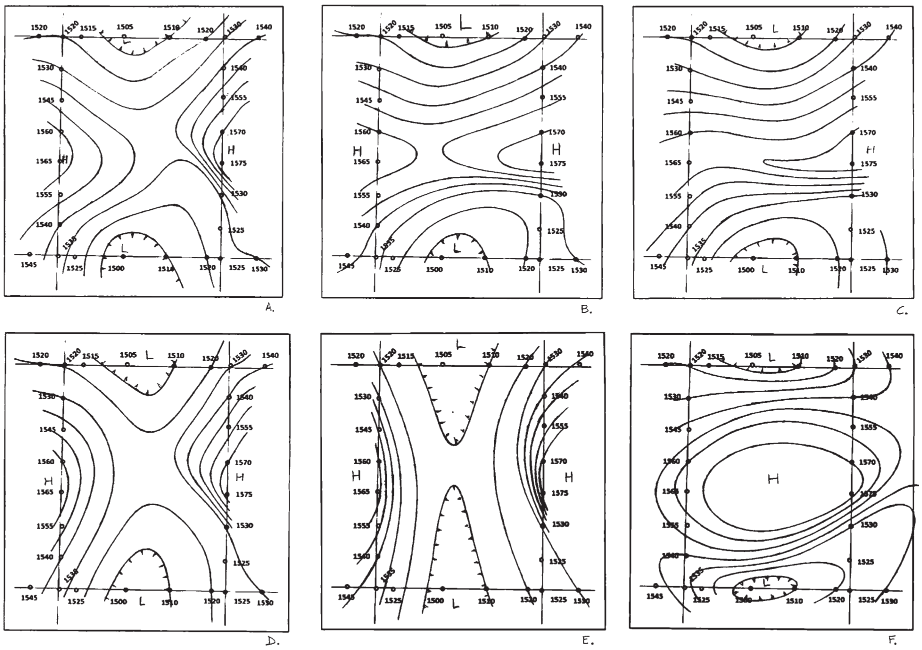

Figure 1. *A series of solutions to the hand contouring exercise published in the October 2015 issue of* Preview *(drawn by Doug Morrison).*

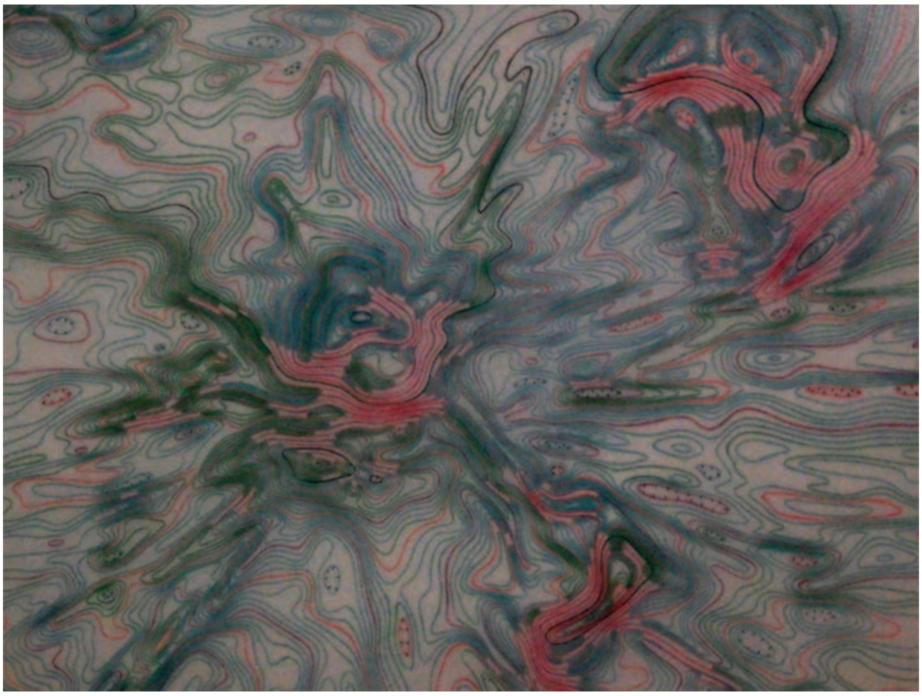

Figure 2. *Geophysics as art.*

Data Trends

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Quantum computing explained (not)

On 5 October 2015 Australian engineers at the University of New South Wales announced that they had built what they have termed a qubit logic gate in silicon (http://www.engineering.unsw.edu.au/news/quantum-computing-first-two-qubit-logic-gate-in-silicon). This gate makes calculations between two qubits of information possible for the very first time. Previously engineers had been unable to make two silicon quantum bits share information, or even talk to each other.

This news, of course, made less press than Bruce Jenner being named woman of the year, and got less clicks than the 'The Best of Cute Cats Vine Compilation 2015'. Truth be told, I did not see the news myself until the Editor of *Preview* passed on the link suggesting that maybe I could write something serious this month.

To be sure that this news on quantum computing was, in fact, worthy of my column, I did watch the cute cats videos (and maybe 10 or so more after that just to be sure) and I reviewed the in-depth article in my Facebook account about how Bruce (now Caitlyn) Jenner was named woman of the year – for comparative purposes only. As expected, the *Preview* Editor was right… always right…

To understand why the UNSW announcement represents such an amazing first in computing, one needs to first understand what quantum computing is and why it is so different to 'regular computing'. So, here goes a feeble attempt at doing just that. Please note that I turned to Michael Nielsen's blog entitled 'Quantum computing for everyone' to help me (http://michaelnielsen.org/blog/quantum-computing-for-everyone/). Michael has written 60 papers and co-authored the standard text on quantum computing and in his well-written article he explains how even describing quantum computing almost requires a quantum computer.

Okay, I have read Michael's article five times now, and I am still not able to explain what a quantum computer is. In fact Michael agrees that he can't adequately explain it either. The best he seems to be able to do is to explain how one might go about explaining it, if only there was a way to explain it (*Editor's note: Apologies to the author of The Hitchhikers Guide to the Galaxy would seem to be in order*). However, some of the salient points of the article are as follows:

- Quantum computer scientists believe that quantum computers can solve problems that conventional computers are not able to – hence their interest in quantum computing.
- A standard 20 bit computer can be described with 20 numbers, whereas a computer using qubits doubles the numbers required for description with every qubit added…. So, a 20 qubit computer would need over 1 million numbers to describe it.
- The perceived benefits of a quantum computer, when compared to a conventional computer, is that quantum computers can explore many possible solutions to a problem simultaneously – known as quantum parallelism.
- The downside is that quantum parallelism can produce so many possible solutions that it may take another quantum computer to try and figure out which of the possible solutions is the correct one.

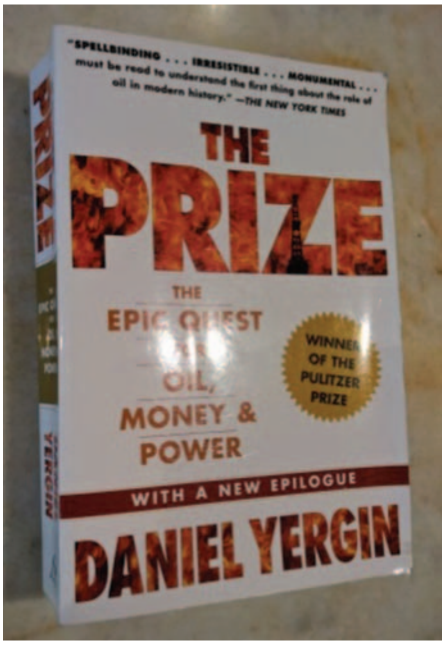
Put simply, there is a quantum gap between finding a simple way to describe quantum computers and the way that quantum computers actually work.

All that being said, rest assured that the engineers who created the quantum bit logic gate at the University of New South Wales have expanded the possibilities of computing in a major way. Quantum computers are likely to be the pivot point in computing in our lifetime. Like the calculator to the abacus, or the email to regular post. In the field of geophysics quantum computing will be a very welcome addition to our ability to simulate and test our theories.

The day that quantum computers can be explained to the masses, is the day that quantum computers become available to the masses. In the words attributed to Albert Einstein, 'if you can't explain it simply, you don't understand it well enough'.

The Prize: the epic quest for oil, money & power

By Daniel Yergin



Publisher: FreePress, 2009, 908 pp.
RRP: $22.99 (paperback)
ISBN: 978-1-4391-1012-6

The Prize is a monumental work documenting the discovery of oil and how it became a commodity that touches almost all aspects of our lives, from economics, recreation, technology and politics, to war and peace. The book is set out in five parts, each comprising about 10 chapters. The parts are; 'The Founders', 'The Global Struggle', 'War and Strategy', 'The Hydrocarbon Age' and 'The Battle for World Mastery'. There are nine maps to orient readers, like myself, who have never been to the exotic locations that the oil industry revolves around, and 97 photographs of the main players.

Part I begins with Oil Creek, where 'rock' oil, so-called to differentiate it from vegetable and animal oils, was known to bubble out of springs and into salt wells in northwestern Pennsylvania. In the 1850s rock oil was being used as a folk medicine, a remedy for ailments from headaches and toothaches to dropsy. A learned man, George Bissell, who was a genuine polymath, knew rock oil was flammable and saw that it could be used for illumination. That was the start of the Age of Petroleum.

The distillate of rock oil was called kerosene, from *keros* and *elaion* (Greek for 'wax' and 'oil'). Of course bitumen had long been used in the Middle East (3000 BC in Mesopotamia!) as a building mortar, and for caulking. The Roman naturalist, Pliny, wrote of the pharmaceutical benefits of bitumen. Homer wrote in the *Iliad* of the use of arrows tipped with flaming bitumen to set enemy craft on fire. The reason that rock oil eventually prevailed over coal oil for illumination was price. Bissell adapted salt boring techniques to discover oil at depth, to much ridicule at first but, in August 1859, Bissell's consortium struck oil.

John D. Rockefeller's activities from February 1865, and the Sherman anti-trust laws that led to the dissolution of Standard Oil consume Chapters 2 to 5. One thing Yergin does well is descriptions of characters. This is not simply a chronicle, it develops the individual strengths, and the peccadillos, of the people involved in the oil story, and Rockefeller senior is ripe for the plucking. Rockefeller was a seriously unusual person. His relentless negotiation style would wear his opponents down until they capitulated. As such, Rockefeller built Standard Oil into the largest monopoly in the world, refining 90% of American oil by 1880. One lasting impression the reader of *The Prize* will have is the number of strange personalities amongst main players in the petroleum industry in the early days. Today we would probably describe them as 'being on the spectrum'. J. Paul Getty was one such person. His idea of a relaxing evening was toting up his incomings and comparing the total to the total of his outgoings. His income was many thousands of dollars per day, while his expenses were typically amounts like a dime for a newspaper and 3 cents for a cup of tea. Getty famously rewarded the Canadian geologist who made him very rich with only $1000. While that was a lot of money in the early 20th Century, given the accurate expert opinion this geologist gave Getty, which made him the multi-millionaire that he became, it seems somewhat deficient. Rockefeller was a curmudgeon early on but redeemed himself in later life.

The invention of the internal combustion engine towards the end of the 19th Century was a game changer which is analysed in detail in Part II. By WWI oil was a strategic commodity and the world changed irrevocably. Navies converted from steam to oil allowing them to manoeuver and cruise faster, and, more importantly, to refuel at sea. The French and British, neither having oil fields of their own to exploit, divided the Middle East between themselves; or, at least the French Premier, Georges Clemenceau, and the British PM, Lloyd George did. Unfortunately they failed to inform their respective foreign ministers leading to strained relationships between France and Britain. And soon the Americans and Germans were making their move on the Middle East. What could go wrong?

Part III begins with the Japanese under threat from both Soviet communism and Chinese nationalism in the 1930s. The Japanese had their sights set on the Dutch East Indies, Malaya and Indochina and oil, in the 'spirit of co-prosperity and co-existence based upon the Imperial Way'. Japan was dependent on American oil and Tokyo instituted a policy to establish industrial self-sufficiency. Tokyo reasoned that the ABCD (American British Chinese Dutch) powers were engaged in a conspiracy to strangle Japan and the rest is history. Towards the end of WWII both Japan and Germany were starved of oil. Oil had become crucially important to the security of nations.

Following WWII the domestic consumption of oil in the US began to surge as affluence increased and every household acquired automobiles. Middle East oil became even more important. Part IV covers the post-war petroleum order, the Suez crisis and the rise of OPEC. Part V deals with the events that have directly affected many of us alive now. Chapter 28 is entitled 'The Hinge Years: Countries versus Campanies'. By the 1970s demand had increased beyond supply and the world depended on America and the Middle East for oil. Automobiles were getting larger, had automatic transmissions and were air conditioned. Environmental concerns also meant a shift away from coal. Then came the oil shock (Chapter 29 'The Oil Weapon') after the Arab-Israeli wars, with armaments courtesy of the Soviet Union and the US respectively. Foreign policies of many nations are now dictated by oil and national security. Anyone wondering about the driving forces in global politics today should read *The Prize*. I highly recommend it.

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The first gravity meter designed, built and used in Australia in the late 1890s – and very possibly the first in the world

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Introduction

In October 1893 a gravity meter constructed in the Physics Department of the University of Sydney, and based on the same (fused-quartz balance) principle as some gravity meters in use today, was taken on its first field trip to Armidale, in north-eastern NSW. This trip was the culmination of 5 years of painstaking experimentation and trials in Sydney and I believe that the instrument was not only the first gravimeter built and used in Australia, but the first in the world (evidence for this claim is given below).

The instrument used the same static principle employed in modern gravimeters, as distinct from dynamic measurements such as those made by pendulums. Construction took place in the Department of Physics to a design devised by Dr Richard Threlfall, Professor of Physics, and James Arthur Pollock, a demonstrator in the Department of Physics at the time. Put simply, it was based on measuring the very small movements, due to variations in gravity, of a weighted pointer attached to a stretched wire (if you can't wait to see how the instrument looked, take a peek Figure 5).

A second journey was made to Armidale in February 1894, and another in May 1897 to Bowenfels, near Lithgow. Between June 1897 and December 1898 a more reliable version of the instrument was read in Melbourne, Hobart and Launceston, Armidale (for a third time), Springwood in the Blue Mountains of NSW, Melbourne again, and six times in Hornsby Junction, 34 km by train from Sydney. All this activity took place in the late 19th century, before Australia was a federation and before the arrival in Sydney of motor cars and electricity.

Full details of the gravity meter, including the theory, design, construction, operation and results obtained, are described, in considerable detail, in a paper by Threlfall and Pollock submitted to the Royal Society of London in April 1899 and published in the Philosophical Transactions of the Society (Threlfall and Pollock, 1900)[1]. Because of the historical significance of the instrument this paper is worthy of close study, which I will now attempt to provide. In the following text references to the paper will be abbreviated to the 'T-P paper' and the authors as 'T-P'. All quotations are from this paper unless otherwise indicated. My comments on the form and presentation of the paper itself are given in 'Some observations on the published paper'. Brief biographies of the two physicists are given below (see 'About the authors').

T-P explain, in the introduction to the paper, their desire to have a 'static' measurement using the elastic properties of a spring balance. They knew that this would restrict them to measuring only relative variations but expected that there would be "a smaller expenditure of time and trouble than is incidental to the observations of pendulums". At this time the pendulums that were mostly used to measure absolute gravity in observatories were also being developed to measure relative gravity (see http://en.wikipedia.org/wiki/Pendulum#Later_pendulum_gravimeters. They were intended for geodetic use[2]. However, T-P now planned to build a relative reading instrument better suited to field surveys; a gravimeter[3].

The meter was not given a name in the T-P paper so, in the tradition of gravimeters being named after their inventors (for example, Worden, La Coste and Romberg) I will call it the "Threlfall-Pollock" gravimeter or "T-P meter".

At first T-P considered making accurate measurements in one place where "observations should be of a higher order of accuracy than is necessary during a gravity survey", but after two years they realized they were not going to obtain "sufficient sensitiveness"[*sic*] and turned their attention to a portable instrument. Construction of what was to become the field instrument commenced in August 1892 and by September 1893 it was ready to begin "systematic observing". T-P then understood the consequent need "of such construction that it is not possible to disturb it's mechanism by the shaking inseparable from transport", which required them "to face a mechanical and physical problem of considerable difficulty".

The case for the T-P meter being the 'first'

T-P acknowledge that until the discovery of the unique properties of fused quartz by "Mr Boys" in 1887 (Boys, 1887) no other material had the requisite elastic properties and "….all attempts [*i.e.*, before 1887] at constructing a statical [*sic*] instrument of reasonable accuracy must necessarily have failed – as they all did". The 'all' here must refer to attempts by instrument makers other than T-P, as they declare "Our own attempts to construct a gravity balance began in September, 1889".

This proposition is also strengthened by the disclosure by T-P that "a committee of the British Association, which in 1886 had

[1]The paper, no. A245 in the Philosophical Transactions, was also published as a separate booklet for the Royal Society. A copy is available in the Rare Books section of Fisher Library, University of Sydney.

[2]Specifically, T-P may have been aware of one of the relative reading pendulums developed in 1887 by Von Sterneck who is listed in T-P paper's "Bibliography" with references to him, dated 1885 and 1895.

[3]Gravimeters fall into two classes, 'static' or stable, and 'astatic' or unstable. Both types are still in use today.

invited designs for a gravity meter, reported in 1889 that work had been suspended pending a trial of the fused quartz"[4]. So until then, no other construction was successful, at least via the British Association[5]. This is my basis for supposing that the T-P development is the first successful one of its kind, not only in Australia but in all the world.

I may be not alone in my assertion as Dooley and Barlow (1976) in their review paper of 'Gravimetry in Australia, 1819 –1976', state; "One of the earliest, if not the first, gravity meter in the world was constructed at Sydney University (Threlfall & Pollock, 1900)".

Heiland (1940) is the only textbook I know (that is old enough?) to refer to the T-P meter, where in his discussion on types of static gravimeters, he begins with, "The Threlfall and Pollock gravimeter is one of the earliest examples…" and then gives a brief description with the 1900 reference. As further substantiation of how early this meter is in the development of gravimeters, all the following six meters described by Heiland have references dated 1932 or 1938 including the next one listed, the 'Wright gravimeter' which he claims "closely resembles the Threlfall-Pollock instrument…", but 38 years later![6]

Description of the T-P meter.

Briefly, the principle of operation was one of observing the microscopically small twists of a fused-quartz 'thread' under tension when subjected to changes of gravitational attraction, g, as illustrated by the movement of a pointer or 'lever' attached to the thread. The amount of twist on the thread needed to return the lever to its original position, as determined by a fixed microscope, was read as seconds of arc on a sextant. This angle can be directly related to the value of g (see 'About the theory', following).

Figure 1 as "Fig. 1" from the T-P paper, is a very much a simplified schematic of the assembly where 'H' - 'I' is the fused-quartz thread, 'D' is the wire lever soldered to the thread to reveal the twist due to gravity, 'C' is the sextant arm and 'E' is the microscope to observe the movement of D. This has some similarity to the simplified schematic of modern gravimeters and the T-P meter was clearly the precursor of these. See, for example, Figure 2, which is from Figure G-5 (b) of Sheriff (1991) illustrating the schematic of a Worden gravimeter (in use from 1960) where the 'Hinge beam of fine quartz' is equivalent to the thread H-I and the 'Pointer' is equivalent to the lever at D. The Worden also uses a microscope. For a further comparison of the T-P meter with current meters see 'Comparison with modern gravity meters', below.

A much more detailed scale drawing of the whole assembly is shown as Figure 3 (from 'Plate 1' in the T-P paper) with an index to the lettering given as the last page in the paper. For an idea of scale, the thread, 'OOO', is 30.5 cm long. Additional

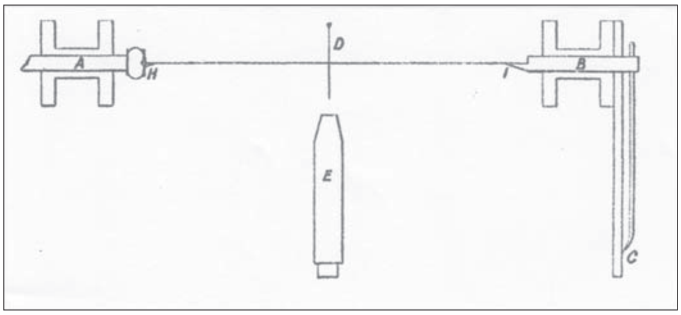

Figure 1. *A simplified drawing of the T-P meter mechanism from "Fig. 1" of the T-P paper showing the 'thread', H to I, the 'lever', D, the microscope, E and on the right side at 'C', the 'sextant' arm.*

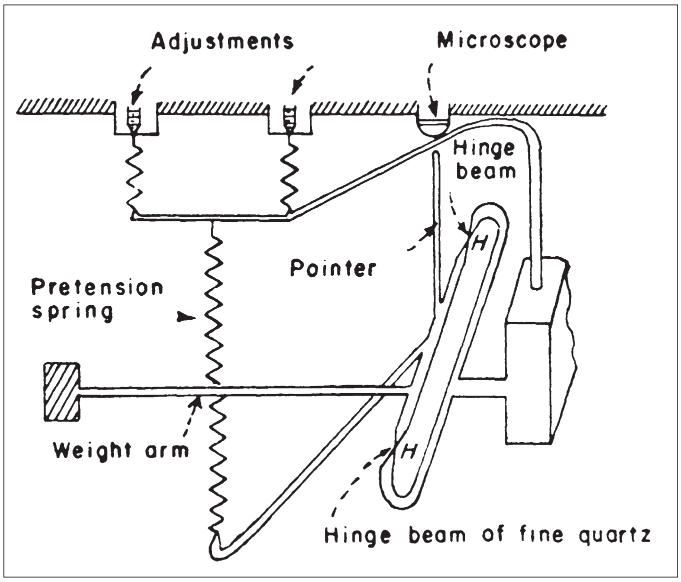

Figure 2. *A schematic of a Worden gravimeter from Figure G-5 (b) of Sheriff (1991) where the "Hinge beam of fine quartz" is equivalent to the thread H-I and the "Pointer" is equivalent to the wire at D. It also uses a microscope.*

elements to those in Figure 1 include the platinum wire thermometer finally chosen to measure the internal temperature and the assembly block attached to the thread, which is the 'arrester', or 'clamp' to the lever.

The whole assembly was contained in a tube of copper, which was thermally insulated to some extent (using paper!) and as air-tight as possible, given the seals employed, to ensure a constant density and humidity of air. Indeed, typical of the detail of T-P's descriptions (of which more later), "The air is passed over potash and through a filter of cotton wool, the object being to have dry dust-free air in the balance case". Constant density ensured no variation resulting from the "flotation of the lever by the air surrounding it", which would affect the moment of the gravitational force. T-P never used a vacuum chamber to solve this problem.

Of the 12 sections in the T-P paper describing individual components of the Instrument in some detail (see "Some observations on the published paper"), the section on the (fused) Quartz Thread acknowledges that it is the most essential part of the instrument and it required "an immense amount of experimenting" to get the right diameter and "the greatest possible uniformity". The T-P paper mentions two main methods of drawing out the quartz thread, as devised by Mr. Boys: the

[4]The British Association was founded in 1831 by persons who, at the time, regarded the Royal Society as elitist and conservative. In 2009 the name was changed to the British Science Association (BSA).

[5]Lorand Eötvös, better known for his development of the pendulum based torsion balance to measure gravity gradient, is reported by Szabo (1998) to have built a "gravimeter" in 1901 but it failed to meet expectations and nothing was published on it.

[6]Heiland includes the T-P meter in the 'static' sub-class but T-P explain that their readings were deliberately made at a point of the lever "upsetting" to be more sensitive, which by Heiland's own definition puts it in the 'astatic' class as he does for the Wright meter.

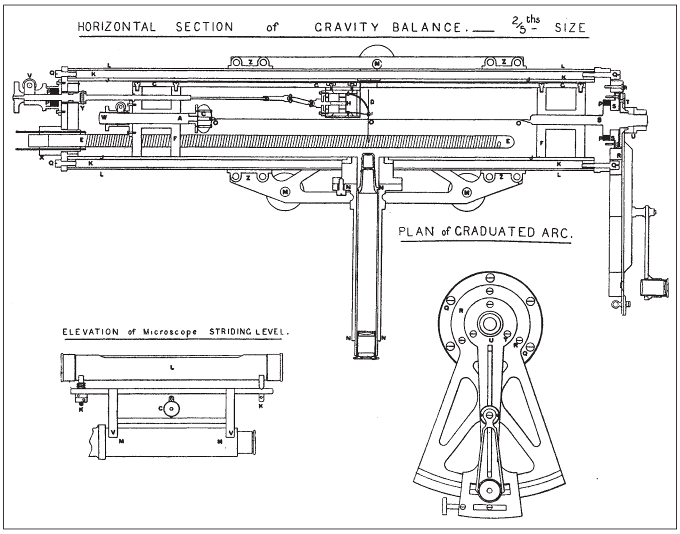

Figure 3. *Scale-drawings of sections of the T-P meter from "Plate 1" of the T-P paper also showing the 'thermometer', E-E, the 'arrester' block on the 'thread', OOO and connected to the 'lever', D. For scale, the thread is 30.5 cm long.*

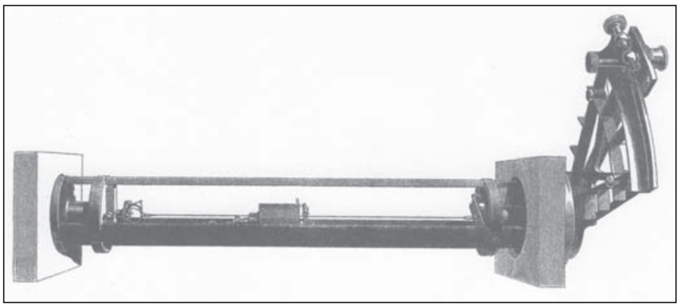

Figure 4. *A "photograph" of the internal assembly of the T-P meter from "Plate 2" of the T-P paper showing the 'thread', the 'arrester' block attached to it and on the right, the 'sextant'.*

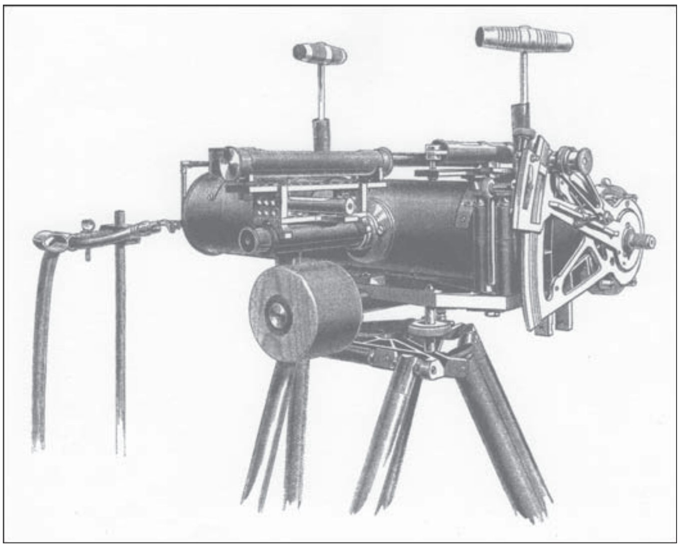

Figure 5. *A "photograph" of the exterior of the T-P meter mounted on a tripod, from "Plate 2" of the T-P paper, showing the 'vernier arm' of the 'sextant', the microscope as the horizontal tube at right angles to the main circular body, and levelling screws.*

"catapult method" and the "shot" or "bow and arrow" method, the latter giving "better threads for our purpose"[7]. However, "the process is so uncertain that we have on occasion got a thread within a few days, and on others we have spent a fortnight over it" (we see in 'Instrumental development' that for the initial threads T-P used, it can actually take months to get a satisfactory thread). Such a 'hit and miss' process of drawing the thread is much as it still is for modern instruments[8]. The thickness of thread they finally found to be reliable was 0.0038 cm in diameter, still very thin and equal to the thickness of a very thin type of human hair.

The next section on the Lever, used to illustrate the twists of the thread, describes the lever finally used, after trying other metals, as "of gilded brass wire of the smallest diameter we could get"; namely 0.013 cm, and with a length of 5.3 cm and weight of 0.018 gm. The center of gravity of the lever is adjusted by applying to it "a small drop of fusible metal, rather larger than a pin's head" (T-P suggested that if making a new instrument they would try using fused quartz for the lever).

Figure 4 (the upper section of 'Plate 2' from the T-P paper) shows the interior assembly with the thin thread just visible and the block attached to it the "arrester" assembly. At the right-hand end is the 'sextant' for measuring the angle of twist of the lever. Figure 5 (the lower section of 'Plate 2' from the T-P paper) shows the exterior view of the full assembly. The arcuate graduated scale on the right-hand end is the "vernier arm" of the sextant. The microscope for aligning the position of the lever is apparent as the horizontal tube at right angles to, and in the centre of, the main body. Various levelling screws are also seen.

The overall dimensions of the instrument alone are not given by T-P, only the outside dimensions of the three transit boxes containing the instrument and accessories. However, from knowing the length of the thread shown in Figure 3 as 30.5 cm, one can scale the overall length to be 65 cm with a width of 30 cm, including the microscope barrel which extends about 18 cm from the main enclosure. The enclosure appears from the "photograph" of the balance (see Figure 5) to be of circular section, about 10 cm in diameter. The overall height of the balance is estimated from the photograph as about 25 cm. These dimensions comply with the outside dimensions of the transit box for the balance, given in the paper as 85 × 48 × 39 cm.

The weight of the 'balance' alone was not given in the T-P paper either, only the combined weight of the balance and it's transit box, a total of 48 kg. The weight of the balance could therefore be as much as 20 kg. Modern meters weigh 8 kg or less. However, "the great weight of the instrument" was found to be a "drawback" and modifications were made to make it lighter. The 48 kg weight of the transit box containing the balance can be appreciated from its description as a "pine box" into which the balance is secured tightly. The box was supported by "a set of sofa springs, which were attached to a false bottom" and then encased in an "iron framework" (!) with "rubber buffers" to prevent sideways movement. Two handles were provided for it to be carried. Whilst elaborate care was taken to prevent any damage during transit, the resulting weight (equal to two heavy suitcases) did render it susceptible to damage in transit (see examples in 'Testing in the field').

[7]The reference given to these methods, namely, 'Laboratory Arts, Threlfall, Macmillan, 1898' has not been investigated by me but one can only imagine how such names can be appropriate!

[8]I am aware that the manufacture of LaCoste & Romberg gravimeters used to rely on one particularly skilled person who had the most success in drawing their quartz springs.

The two other boxes of accessories and the tripod made the total weight of the whole assembly 103 kg, which T-P acknowledge could have been halved with some obvious modifications.

About the theory

The development of theory in the paper begins with an "equation of equilibrium" (Equation (1) in the paper) linking the angle of twist, θ (the measurement) to acceleration of gravity, g. This equation is then rewritten taking into account the effect of temperature (t) on the reading by introducing a temperature coefficient (α) to incorporate all the effects of a change of temperature (Equation (2) in the paper). By recognizing that all factors in the equation except θ, g and t are constants (such as the mass of the lever, etc.), T-P produce an equation involving all three variables,

$$\theta = Kg\,(1 - \alpha t) - C,$$

where K and C are constants. (The T-P paper has "(1 + αt)", incorrectly). In this case, g can only be a relative value as the constants "can only be approximately determined". By applying this equation to three specific locations (labelled 1, 2 & 3) for one value of 'αt', another relationship is developed linking only the three angles of twist and the three values of 'g', namely,

$$(g1 - g3) = [(g1 - g2) / (\theta1 - \theta2)] \times (\theta1 - \theta3)$$

If two of the places are chosen where the values of 'g' are known and the meter is read there, say places 1 & 2, then their differences of g and θ are a constant in the above equation, which is a form of sensitivity of the meter giving a value of 'g' equivalent to a value of θ (we learn a specific value of this in 'Results', below). Then the unknown value of 'g' at a third place (g3) can be obtained relative to one of the known values when the meter is read there. This is valid providing 'α' does not change in the meantime. However, there are instances reported in the paper where 'α' has changed, particularly after alterations are made to the meter. Establishment of a new value of the temperature coefficient was "sometimes a lengthy process". Also, as we see below in 'About the results', a different reading can occur at the one place due to a 'daily drift' in the meter, which must also be taken into account.

T-P were given "the most probable" values of 'g' for Sydney and Melbourne observatories as derived by pendulum measurements by "Mr Love" (later expanded in a footnote to "Mr E. F. J. Love") so, to put this theory into practice, T-P needed to make a trip to Melbourne a priority, which they did (see 'About the results')[9]. As these two values are the only absolute values of 'g' mentioned by T-P, apart from published values at the pole and the equator, they may have been the only known values of 'g' in Australia at this time.

Testing in the field

After mounting the first thread in September 1893, the instrument was taken first to Armidale, in north-eastern NSW, in October, 1893. Possibly this was to make use of the biggest elevation-induced gravity difference from Sydney as Armidale is, in fact, the highest city in Australia at 980 m a.s.l. Although the distance from Sydney was 570 km, one can surmise that they thought at this early stage that they needed all the difference in gravity they could get. Presumably T-P knew that the sensitivity of the meter was not nearly enough to make use of the elevation increase in buildings or towers that were no higher than a few storeys in Sydney at the time. As we later learn, the level of sensitivity of the meter would have required a structure at least 30 m high.

While not revealed specifically on this occasion, it is likely that T-P used the train to get to Armidale as the line from Sydney to Armidale opened in 1883. The only other possible land transport at this time was horse and cart (cars not being readily available until the early 1900s), but transport by horse and cart would have been very slow.

Rail transport was not only more suitable for the heavy transit boxes but for T-P it was free. In their acknowledgements, they thank no less than the "Commissioners of the Railways of New South Wales" who through their "enlightened liberality [sic]" provided them with "free passes over the government railways". Furthermore, T- P also gave thanks to the "Secretary for Railways….for the unfailing kindness and courtesy which they showered upon us".

Unfortunately, on this first outing, "the balance was knocked off its stand and practically destroyed". This must have been a huge set-back as 18 months had been spent on its construction. After its restoration, the balance was again taken to Armidale in February 1894 and, unlike the first time when no outcome was mentioned, this time "the results were quite disappointing" and adjustments were needed to be made to the "method of observing". Just as before, however, no actual readings were revealed.

No further field trips were mentioned until May 1897 (three years later) when "the instrument was considered fit to travel" after many experiments with threads (see 'Instrumental development' below) and was taken to Bowenfels (near Lithgow) at an elevation of 900 m a.s.l. and a distance from Sydney by rail of 160 km "… and here we made some promising observations" (but still no details were disclosed). It is puzzling that this site was not chosen for tests before Armidale, being much closer to Sydney and with almost as much elevation difference. One assumption could be that T-P were now, after two unsatisfactory trips to Armidale, no longer as confident that they would get satisfactory results there and chose a location closer to Sydney for better use of their time.

With a new thread, mounted in September 1896, that was thought to be reliable (it lasted for all subsequent readings described in the paper, a period of over two years) a field tour was made in June 1897 from Sydney to Melbourne "by train" and then to Hobart "by steamer", to Launceston by train and then back to Hobart by train, Melbourne by steamer and Sydney by train. It is of interest to know the actual reading sites and in Melbourne the meter was "set up in a cellar of the Physical Laboratory of the University", in Hobart "in a cellar of the Museum and in the University Physical Laboratory" and in Launceston "in the strong room of the Custom House". Such places with solid floors were used, as "Boards…do not form a sufficient inelastic support". Cellars were also favoured, presumably because the temperature was less variable in them during the somewhat lengthy time for a measurement.

[9]According to Home (1986), Mr. E. F. J. Love was, from February 1888, an assistant lecturer in the University of Melbourne and during the 1890s, "undertook precision determinations of the gravitational acceleration at Melbourne and Sydney" (observatories by using pendulums).

In September 1897 yet another (third) sortie was made from Sydney to Armidale. The reason given for choosing Armidale at this time was that "A gravitational survey connecting the towns of the eastern Queensland seaboard with Sydney, was now projected" and Armidale was chosen to be the first station in this survey[10]. In November 1897 the instrument was taken to Springwood in the Blue Mountains (much closer than Bowenfels, at 70 km from Sydney) on three occasions and again to Melbourne in October 1898. From October to December 1898 tests to determine the cause of effects due to travel were made between Sydney and nearby Hornsby Junction on six separate occasions. In all, by now, the meter had travelled over 10,000 km, by horse and cart, train and steamer.

In Springwood, readings were made in the cellar of the Oriental Hotel. In Bowenfels they were made in the house of a Mr Flint (who was thanked for "allowing us to use his house as an observing station") and at Hornsby Junction it was read "at night in the lamp room of the station"[11]. The location in Armidale was never mentioned but quite possibly that was also in some similar place at the station.

Many of these trips resulted in damage to the instrument (let alone being "practically destroyed" as reported in 1893) that then necessitated changes and repairs to many of the components. On return from Springwood for the third time, in November 1897, one of the handles of the (transit) box broke allowing the box to fall 60 cm to the road. The thread was not broken but it resulted in a shift in readings of 60 sextant minutes (as we learn later, equivalent to the difference in gravity between Sydney and Melbourne).

Manner and duration of reading

The method of reading is described in detail in the T-P paper. The variables to be observed were the temperature of the interior of the meter and the amount of twist of the thread to bring the image of the lever "coincident with a cross wire in the eyepiece of the microscope" which was then read on the sextant arm. Readings over periods of temperature change (in one case a rapid change due to the infamous Sydney "southerly buster") show in T-P's "Plot 1" that the platinum wire thermometer reacted more quickly to changes in temperature than did the lever. Also, the sextant reading varied greatly depending on whether the temperature was rising or falling as well as the rate of change. This gave different readings for the same temperature and led to the procedure of making readings just when the temperature reversed, such as in the early afternoon when a maximum temperature is reached. A reading could also be made at minimum temperature, especially if they chose to read in the evenings when the falling temperature of the evening was reversed by the heat of the gas lamps. A disadvantage of this procedure was the extra time needed to observe the temperature long enough to detect its natural reversal.

Figure 6 is one example of three tables of observations given in the T-P paper as "Specimen Observations". The observations were made in Sydney on December 20, 1898 (the fifth last reading ever shown in the T-P paper, as it happens). It is one for a 'natural maximum', the others being a 'natural minimum' and

NATURAL Maximum. December 20th, 1898.

Time. P.M.	Temperature of instrument.	Readings of end of level.	Circle reading.	Remarks.
h. m. s.	°C.		° ′ ″	
1 1 0	21·509	...	...	Air temperature 22°·1
2 12 0	21·779	...	...	" " 22°·4
2 42 0	21·890	...	...	" " 22°·5
3 53 20	22·033	6·1 41·1	81 26 50	
3 57 30	22·033	6·2 41·1	81 26 50	
4 2 30	22·033	6·2 41·1	81 27 0	Lever continues to rise, but temperature is steady
4 21 0	22·033	6·2 41·1	81 27 20	
4 24 0	Begins to fall			
4 26 0	22·31	6·2 41·1	...	Lever turned, air temperature 21°·6

Aneroid 28·2. Lever clamped at 85°
Level reversed. B end to eye-piece. Readings of bubble 6·2 41·1
" " A " " " " 6·2 41·1
" " B " " " " 6·1 41·1

Figure 6. *A table from the T-P paper shows the "Circle", or sextant, readings, in degrees to 10s of seconds, rising to a maximum while the instrument temperature is read to a precision of 0.001°C for 3.5 hrs.*

an 'artificial maximum'. Here the temperature reading began nearly three hours before it was observed to level out and the first reading of the Sextant began. In that case, the temperature was the same (to within 0.001 of a degree) for 28 minutes while the lever reading continued to rise. The sextant was read over a period of 28 minutes.

Readings were quicker when the balance was artificially heated with a gas burner or lamp. This meant the observer(s) controlled the temperature change and could read at a maximum temperature in less time than for natural changes. However this procedure led to some erratic readings at the same place over one month. T-P also believed this to be "barbarous treatment" of the instrument and chose in future to only read at natural changes. Also, it was noted that the temperature could be "disturbed considerably by the presence of the observer".

Thus, a complete reading of sextant angle, pressure and temperature, with the levels checked, could take several hours and the shortest time overall was 90 minutes. This is still a quicker than the time to read the Eötvös pendulum, the instrument most in use in the 1920s. A modern meter is read in one minute or less.

About the results

T-P proposed "two conditions which a balance of this kind must fulfil for it to be a working instrument – firstly, it must give accordant readings at any one place from day to day; and secondly, the readings must not be affected by the vibration inseparable from transport". At any one place, the readings will differ due to two causes: temperature changes, which, for comparisons, are reduced to a common temperature by the application of the temperature coefficient, and "the slow elastic after-working of the thread and its supports". The latter produced a daily drift, not uncommon to modern instruments, which at first was too high but was later improved by changes to the instrument to be, finally, less than the repeatability value (see 'Specifications').

The results of the latest surveys (from June 1897 to December 1898) are illustrated in 'Plots' 2-9 in the T-P paper, as grids of time in days on the abscissa and sextant angles in minutes on the ordinate[12]. Figure 7, as "Plot 4" from the paper, is an example (one of the better ones) of the eight plots of results. It

[10]Such a bold project may have proved too difficult to achieve given the modes of transport available and, possibly, the departure of Threlfall to England in the following year (see 'About the authors').

[11]"Lamp room" reminds us that electricity was not yet available even in Sydney until 1904. Until then, light was by gas lamp.

[12]These plots may be viewed at the URL listed in References for the T-P paper.

shows readings taken in Sydney and Springwood in the period October – November, 1897. The readings at Sydney shown here are almost one per day, a density that ensures that the daily drift at this time is well determined, in this case 2.3 sextant minutes (in the following, 'sextant minutes' is abbreviated to "sm" which also avoids confusion with minutes of time).

Such was not the case for the first trip to Melbourne, in June 1897, where only single readings are shown in each place of observation (in T-P's "Plot 2"). The differences between Sydney and Melbourne, going and on return, were 78 sm and 58 sm respectively (see below where the mean of 68 sm is used). For the last trip to Armidale, in September 1897, (T-P "Plot 3") only three readings at Sydney over five days produced a doubtful daily drift value that was then applied across the only two readings over two consecutive days shown at Armidale, thus making the difference between the two stations very uncertain. This would consequently make any determination of 'g' at Armidale uncertain too.

Also illustrated in Figure 7 is an offset, or 'tare', on 6 November 1897 of 5 sm. Such offsets of more than 2 sm were attributed to "when the instrument was travelled [sic]" and in one case in particular, "to the looseness in the joint fixing the lever to the thread". It can also be noted from Figure 7 that the repeat readings on the same days in Springwood differ by 2-3 sm. This same difference is also shown on other plots on the rare times when repeat readings on the same day are shown which is contrary to T-P's claim of no more than 1 sm for repeats. The much smaller difference in readings between Springwood and Sydney on the third occasion in late November 1897 compared to the other two earlier times, which give a consistent difference of 35 sm, was attributed to "a permanent change taking place due to the travelling".

"Satisfactory observations were made in Melbourne" on the second trip in October 1898 "with a view to finding the sensitiveness [sic] of the instrument". Single readings on each of three days in Melbourne (T-P "Plot 5") gave the difference to Sydney at the same time (as extrapolated from an uncertain drift line) as a doubtful average of 63 sm. Together with the (only) other value of 68 sm (itself the mean of two differences) obtained before, in June 1897, T-P chose to use a somewhat arbitrary value of 60 sm as the final difference "until the difference has been more accurately determined". Maybe T-P believed that since readings were becoming more reliable, any subsequent differences would trend to this lower amount. However, no further trips to Melbourne were reported in the paper to provide more confidence in this value. With the difference in gravity between Sydney and Melbourne given by Love (see 'About the theory') as 277 mGals, using 60 sm meant that one sm equalled 4.6 mGal, or as T-P have "a change in the value of g of 1 part in 100,000 would be represented by a change in reading of 2.12 sextant minutes"[13]. Here then is the ratio from theory of 277/60 (see 'About the theory') as the sensitivity constant to be used for relating the reading in Sydney to that of an unknown place. It is unfortunate that this important constant was not established with more assurance.

Providing the constant was unchanged and readings were generally reliable, T-P claimed that eventually "we may say that the value of g at any station may be determined relatively to that

[13] The value of gravity at Sydney Observatory from Love was "979.639" and "979.916" at Melbourne Observatory.

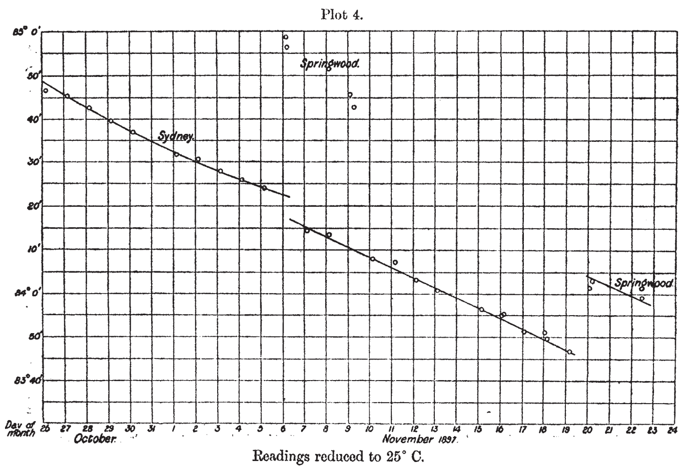

Figure 7. *An example of the method of plotting the results from 'Plot 4' of the T-P paper, a plot of the readings in Sydney and Springwood from Oct. 26 to Nov. 24, 1897. It shows a near-linear daily drift and a 'tare' on Nov. 6.*

at some standard station by a single observation… with certainty to one part in 100 000". Given their results, I believe this to be optimistic. No new values of 'g' at an unknown place were attempted to be determined by applying the theory other than in the case of Hornsby, the last location for field measurements and after "the readings are not now affected by travelling". Also, by then the daily drift was the lowest ever at ~0.2 sm/day. Using differences from Sydney from three separate trips, T-P claimed "a maximum difference [between the three readings] of 0.4 sextant minute, or to less than 1 part in 500 000 in the value of g"[14]. However, I dispute this accuracy as one of the three values is itself a mean of two readings on the same day and the difference could therefore be as much as 0.6 sm giving an accuracy of more like one part in 300 000 or < 3 mGals (it was not unusual for T-P to be somewhat relaxed with their conclusions from the results, as seen elsewhere).

At no time was any attempt made to correct gravity readings for latitude, elevation, density or terrain. The accuracy of the determination of 'g', at an unknown site, was not sufficient to justify any further such processing.

Specifications

A list of specifications of the instrument and its performance, as we have with modern gravity meters, is not provided and apart from the weight and the overall dimensions being inferred as above by me, such performance factors as resolution, accuracy and drift are scattered throughout the paper. For the factors given in the following, the equivalent values for a Scintrex CG-5 gravimeter (see 'References') are in brackets.

T-P consider the error of the final reading as made up of the error in measuring the temperature, the angle of twist and the levelling. "If all these three maximum errors conspire, we shall obtain a value of g in error by one part in about 300 000". That translates to about 3 mGal in Sydney. T-P state that the "accuracy of a determination of g … depends on the possible deviation of a single observation from the mean".

Only at the end of the discussion of results did T-P address the sensitivity of the meter and a relationship between readings and

[14] It was this accuracy that McCaughan (1988) claims of Pollock that "astonished his contemporaries" (see 'About the authors').

values of gravity suggested as, 1 sm equal to 4.6 mGal. Therefore, the best resolution of 10 seconds of angle represents 0.77 mGal (CG-5: 0.001mGal). The repeatability of readings in the same place was generally, from their plots of results, about 1 -2 sm, equivalent to less than <10 mGals. (< 5 microGals).

Observed discontinuities (or offsets) can be of the order of 5 sm, equal to about 20 mGals. ('Tares" are less than 5 microGals). The daily drift, was finally 0.2 sm in December 1898, or about 1 mGal. (<0.02 mGals).

Instrumental development

"Appendix B" of the T-P paper titled, "Notes on experiments made with various forms of gravity balances" is 6 pages of a very detailed chronology of all the challenges and trials T-P experienced from September 1888 to June 1897 together with the innovations they devised to overcome them.

At first T-P made calculations as to the "sensitiveness" of the balance and then made "several" experimental balances 'on the bench' (in this case "on an old watchmaker's lathe-bed"). "The thread and levers were massive [then] compared with those we now employ". "By May, 1891, [after 2 plus years] we had sufficient experience to hope to detect the lunar disturbance of gravity" (the 'tidal effect'). At this time a mirror was mounted on the lever and the balance was read in a cellar on a stand weighted down "with sand and stones". During the latter part of 1891 T-P used a "Michelson's arrangement of interference mirrors" (see more on Michelson in 'Famous names'). This system "presented no advantages in practice" and "By March, 1892 [another ten months later] we became convinced that it was hopeless to attempt to disentangle the lunar effect from the instrumental irregularities…" and "The research was therefore abandoned".

Investigations into constructing a portable instrument started in May 1892. This led to the present form of the instrument, which was ready in July 1893, and a thread, made by the 'catapult method', was mounted in September 1893. In October, 1893, while the instrument that was "practically destroyed" in Armidale was repaired, another instrument "intended as a trial instrument" was built "in which the whole of the working parts were immersed in mineral sperm [whale] oil", presumably to test the oil's damping ability. This in itself led to two years of "subsidiary" experiments testing the resistance of different cements when immersed in oils. In order to see whether it would be possible to observe at sea, the instrument was mounted in a swing whereupon they satisfied themselves "that no amount of damping would enable accurate measurements under such circumstances".

When the repaired instrument was deemed to be "worse than the one that had been broken…an experimental thread was mounted on "yet another balance", in January 1894. Then for "two months of incessant work we struggled with fine threads" leading to "a separate experiment on another balance" with the realisation, in August 1894, that "The very fine threads have not been a success". Initially they were too thin, often only 0.001 cm in diameter, with many breaking, and "it was not till March 1895, that we succeeded in obtaining a thread to satisfy us". However, this was broken in November 1895 while making other repairs and two more months were spent getting another satisfactory one, until July 1896 "when it was pleased to break" (no reason was given in this instance).

After the bad experience with very fine threads, in August 1894, "we abandoned the lever and mirror in favour of a microscope, and also brought the arrester to its present form". In September 1895 the theodolite, given to T-P by the Surveyor-General of NSW was replaced "by a sextant arc".

Yet another "new thread was got in September 1896, after some weeks of shooting. This thread is still in use and is the best we ever got [sic]". Then, after "a great deal of trouble in stopping leaks in the apparatus" and effects due to "wear in the bearings", the instrument was again "considered to be fit to travel" to Bowenfels in May 1897. This was after two years spent drawing more ideal threads and after five years altogether developing the portable instrument, admittedly with some subsidiary distractions along the way.

Many of the difficulties they faced would now be solved easily in other ways. For example, when an air-tight seal was required on the turning shaft they used 'tallow' (animal fat) and mercury, and because of the different air pressure the mercury drove the tallow through the joint. This was the basis of the "stuffing boxes" (see 'Some observations on the published paper').

Comparison with modern gravity meters (see for example the Scintrex CG-5 "Autograv" Gravimeter)

Some of the elements that T-P devised in building a meter for the first time have carried through to modern meters. As we have seen in 'Description of the T-P meter', some current meters still use fused quartz material, a pointer ('lever'), a microscope and a clamp ("arrester"). Many of the technicalities that T-P had to overcome to obtain reliable readings are still present in modern gravity meters. For example, temperature effects were dealt with by accurate measurements of the ambient temperature and the temperature inside the chamber by a sophisticated platinum thermometer involving an electrical circuit of resistors able to measure 0.001 0C. However, modern meters have electronic temperature compensation and, if necessary, separate heaters, and have solved T-P's effects due to varying air pressure by employing vacuum-sealed chambers. Drift, which T-P finally improved to an acceptable level, is almost eliminated today. Modern meters no longer suffer 'tares' as did T-P through rough handling. They are much more rugged and smaller (e.g. 30 × 22 × 21 cm) and lighter (8 kg or less). The T-P meter lacked the modern attributes of digital reading displays, digital storage or remote control.

About the authors

Threlfall, Sir Richard (1861–1932)

According to Home (1990), Threlfall was born in Lancashire, England in 1861 and before coming to Australia in 1886 worked as a demonstrator in the Cavendish Laboratory under his friend J. J. Thomson (see 'Famous names') who regarded him as "one of the best experimenters I ever met". In 1886 he was appointed to the Chair of Physics at the University of Sydney whereupon, according to Home, "his research developed along three separate lines", one of which was to develop "a quartz thread torsion balance…gravity meter" with "his [then] student and friend, J. A. Pollock". Two publications by Threlfall are referenced in the T-P paper, both in relation to the drawing of the quartz thread and its characteristics. One, "to refer the reader to" is a book entitled "Laboratory Arts". According to Home (1990), Threlfall left Australia in 1898 to work as Director of Research at Albright & Wilson in Oldbury, England and was elected a Fellow of the Royal Society, London in 1899 (before the T-P paper was submitted). Also, it can be noted from the T-P paper that the meter was being used up to December 22, 1898.

Pollock, James Arthur (1865–1922)

According to McCaughan (1988), Pollock was born in Cork, Ireland in 1865 and migrated to Sydney in 1885. Specialising in physics and mathematics, he graduated from the University of Sydney in 1889 with a B.A. and University Medal and in 1890 was appointed demonstrator in physics assisting Professor Threlfall. McCaughan (1988) states that "he published jointly with Threlfall and worked independently in optics, using the Michelson-Morley technique". This expertise was made use of in early trials of the balance (see 'Instrumental development'). McCaughan (1988) also states "an accuracy of 1 part in 500 000 achieved for the relative value of the acceleration due to gravity astonished his contemporaries". This order of accuracy is indeed claimed in the paper but only in the second last paragraph and is doubtful in my opinion (see 'About the results').

In 1899, Pollock succeeded Threlfall as Professor of Physics and in 1916 was elected Fellow of the Royal Society, London. His enlisting in the Australian Imperial Force in 1916 at the age of 51 (!) is particularly interesting for geoscientists, as he served in France with Professor (Sir) Edgeworth David in the Mining Corps, where he helped to design listening apparatus to foil German countermining measures. Pollock died in office in Sydney in 1922.

Famous names in the T-P paper

Some idea of the scientific atmosphere of the times in which the gravity meter development took place is provided by the famous physicists listed in the T-P paper's "Bibliography". Here names are listed with references to specific papers and reports, some from the British Association, dated 1886 and 1887. In the following text the underlined names are just as they appear in the T-P paper. First is Herschel (with a reference, "Outlines of Astronomy" not dated), is presumably Sir John Herschel (1792-1871), the English polymath who, in 1849, proposed the possibility of measuring gravity using a mass on a string (Garland, 1965); Siemens, C. W. (with a reference dated 1876) is presumably Carl Wilhelm Siemens (1823–1883), the German engineer whose brother, Werner von Siemens lent his name to the S.I. unit of conductance; Poynting (with a reference dated 1886) is presumably, John Henry Poynting (1852–1914), the English physicist who published on the determination of the universal gravitational constant; and Lord Kelvin (with a reference dated 1886) is the British physicist (1824–1907) of thermodynamics and absolute temperature fame.

Also discussed in the paper is an early system T-P tried using "Michelson's arrangement of interference mirrors" no doubt the Michelson (1852-1931) of the famous Michelson-Morley pair. This is confirmed by McCaughan (1988). In addition, the paper was "Communicated" to the Royal Society by Professor J. J. Thomson, F.R.S. (1857–1940). Professor Thomson discovered electrons and Threlfall worked under him in the Cavendish Laboratory (Home, 1990).

Epilogue

Information on any subsequent use of the balance after publication of the T-P paper is provided in another paper co-authored by Threlfall, when he was in England, and titled "Further History of a Quartz Thread Gravity Balance" (Threlfall and Dawson, 1933). In that paper it is revealed that, on the departure of Threlfall to England in 1898, the instrument was to be left in the charge of Professor Pollock "and that he should continue the work in so far as his duties as Professor of Physics enabled him to do so. Unfortunately, an opportunity never occurred, and the balance was stored in one of the cellars of the Physics Laboratory of the University till 1923." We may excuse Professor Pollock from making any further use of it, particularly as he did service in WWI during that period and died in 1922 (see 'About the authors'). Nevertheless, this meant that further use of the instrument was delayed for 25 years.

Threlfall and Dawson (1933), also reveal that it was suggested by the then Director of Research at the British Admiralty, Sir Frank Edward Smith, that the balance be sent to England for possible further use. Accordingly, in 1923, it was "mounted in the Magnetic Annexe of the National Physical Laboratory" at Teddington, near London. Threlfall and Dawson (1933) then describe how, after 25 years had elapsed, there was some deterioration of parts and oils, etc., requiring a virtual reconstruction of the instrument. I would expect that the 'tallow' would need replacing for one thing. Observations were made in 1928 in Teddington and Kew Observatory with results tabled in the paper. Finally they conclude with a discussion "on the design of a new instrument", listing all the improvements that 25 years of advancement could provide. However, as it was now approaching the 1930s, other more sensitive rivals were beginning to appear.

Some observations on the published paper by Threlfall & Pollock

The paper consists of 44 pages including 2 figures, 3 tables of sample observations, 9 "Plots" of results and 2 separate "Plates"[15]. The latter consist of scale drawings of parts of the assembly including a horizontal section of the balance (see Figure 3) and two "photographs" of the interior and exterior of the meter (see Figures 4 and 5). Overall, the paper would have benefited from some editing.

The first three pages start without a sub-heading, and are a combination of a brief introduction to the parameters of the design, a very brief summary of aspects of the construction and field operations and finally, acknowledgements of assistance. One acknowledgement recognizes the value to the meter's existence of Mr James Cook F.R.A.S. "mechanical assistant … who made the whole instrument, except the thermometric appliances" and without "his great mechanical skill and accuracy we should in all probability have failed in our undertaking". T-P also gave thanks to the Surveyor-General of New South Wales for "having placed a disused theodolite at our disposal".

The first sub-heading, starting at the bottom of the third page, is "Bibliography" (referred to above for its famous names), then "General Description of the Instrument and Preliminary Remarks" followed by "Instrument Details", where 11 pages are devoted to 12 individual components of the meter. Each has its own section including the most important Thread and Lever sections but also extensive details on the Microscope, Thermometry (consisting finally of a platinum wire thermometer and its associated Resistance box), The Arrester (which we now

[15]The "Plates" in the paper are numbered 1 & 2 (p. 258) but in the published paper they are Plates 13 & 14, respectively.

call a 'clamp'), the Stuffing Boxes (a type of air-tight seal on the rotating shaft), Thermal Insulation and finally, Packing and Transport. Even though I was a very interested reader of the T-P paper, I found some of this section in particular to be too detailed in the technicalities, making it hard to retain interest.

The following sub-headings in the T-P paper are, "Theory of the Balance", "Observations" (including the method of observing), "Discussion of Results" and finally "Appendix B" (despite there being no Appendix A included). A summary of Appendix B, is in 'Instrumental development'. As perhaps is usual for the time, references are not in a separate list at the end but at the bottom of the relevant page using an asterisk or other such symbol.

Because of some differences with dates between the main paper and Appendix B of the same events, some parts may have been written by only one of the authors. The language is often quaint with literary tendencies. For example, a thread doesn't just break but "it was pleased to break", and overheating of the instrument was "barbarous treatment".

Acknowledgements

I acknowledge Dr Ken McCracken and his good memory for alerting me to the existence of this paper and to some of its highlights. I am also grateful to Doug Morrison for providing further information on E. F. J. Love.

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Lapis lazuli – the most beautiful rock in the world

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Introduction

Lapis lazuli is a striking rock: intense, vivid, shimmering, deep blue (Figure 1). It is rare, semi-precious and non-metallic and has been found, so far, in only a few places. The main source of best material is Afghanistan where, at the 4000 m level, it has been mined for millennia and was traded along the Silk Road from Central Asia to the Mediterranean. It is valued to this day as a middle-ranking gem.

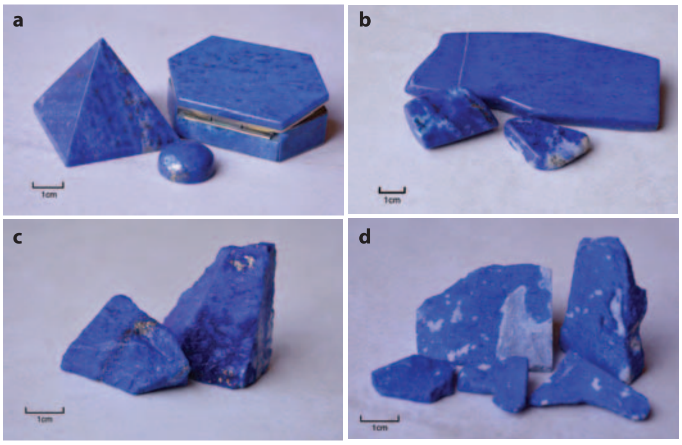

Figure 1. *(a–c) Average (medium) grade Afghan lapis; (d) Chilean lapis. (a) Crafted lapis lazuli. The pyramid's density is 3.01 g/cc. Pyrite occurs irregularly in disaggregated layers with grainsize 0.01-0.1 mm. The small hemisphere has less pyrite, the disseminated pyrite grains are ~0.2 mm diameter. In this, and in a jewellery box, inter-pyrite electrical continuity is absent. (b) Polished lapis lazuli. The large plate's density is 3.01 g/cc, and the disseminated pyrite has ~0.15 mm grainsize. The cylinder's density is 2.97 g/cc and its pyrite occurs in bands with pyrite grainsize ~0.3 mm, and in disseminations ~0.1 mm grainsize. The triangular plate, density 2.85 g/cc, has considerable carbonate (white), and sparse disseminations of pyrite ~0.2 mm grainsize. Inter-pyrite electrical continuity is absent. (c) Lapis from a block of somewhat better grade. The density of the right hand side piece is 2.84 g/cc. The left hand side piece (from the same block) is more pyritic, its density is 2.94 g/cc. In both, the pyrite occurs as grains (~0.1 mm diameter) and small grain clusters. There is electrical continuity intra-cluster but none between grains or between clusters. (d) Chilean lapis. The density of the larger right hand side sample is 2.71 g/cc. The larger left hand side sample's density is 2.76 g/cc. The three smaller sample densities are 2.76 g/cc. Note the white carbonate spotting and zoning. Sparsely disseminated pyrite occurs in all, with grainsizes varying from 0.01 mm to 0.1 mm approx.*

Lapis and its derivatives have been intrinsic to exquisite works of art and construction across cultures. Overlaying many of these and other mundane applications of lapis is a mystique of metaphysical attributes.

Many types of rocks can be dressed, shaped, and polished to an appealing sheen. They have been used to great decorative effect, on a large scale, in buildings, monuments, and tombs. Red imperial porphyry, for example, with red feldspar and manganiferous epidote imparting a sombre, rosy lustre, was much admired by the ancients. Magnificent marbles continue to grace many constructions, large and small. But only one rock, lapis lazuli, has exhibited a beauty so superlative that, in addition to building adornment, it has long been used in panels, inlays, necklaces, ring stones, and sculptured ornaments such as vases (Figure 2). When powdered it was the pigment for the stunning blue ultramarine[1] paint used in many a medieval painting (Figure 3). It is still employed by specialist artisans.

Through the ages lapis lazuli has indeed had an interesting history, and this is touched upon in this paper, briefly and selectively. The physical properties of this attractive material are sparsely documented so the results of some tests on Afghan and Andean Chilean lapis are also presented.

Figure 2. *Illustrations of carved artwork in lapis lazuli. (a) The Mughal elephant is 8 cm long. Photo by Adrian Pingstone (February 2003) and released to the public domain https://commons.wikimedia.org/wiki/File:Lapis.elephant.800pix.060203.jpg. (b) The urn in the State Hermitage Museum in Saint Petersburg is two meters high. Photo by Dezidor / CC BY 3.0 https://commons.wikimedia.org/wiki/File:Ermitáž_(28).jpg. (c) The bowl is from Iran and is dated to around the third millennium BC. Photo by SiefkinDR / CC BY-SA 3.0 https://commons.wikimedia.org/wiki/File:Lapis_bowl_Iran.JPG.*

[1] Ultramarine: of foreign origin, beyond the sea, as the raw material had to be imported into Europe.

Lapis mineralogy

The essential components of lapis lazuli are the azure-blue felspathoid lazurite, usually finely granular, and small amounts of fine grained pyrite which impart a sparkle (stars in the deep blue of the heavens). Calcite / dolomite is often present; the less the better. Gangue mineralogy can include amphibole, pyroxene, mica, and others. Some would regard pyrite as gangue. Excessive pyrite and calcite are certainly deleterious to the quality of lapis. Table 1 lists the mineral components. For a gemmy material lapis lazuli's hardness is not high, being ≤6 (impurity dependent) on the Moh scale, but it is durable enough and can be quite resistant to crushing.

Lazurite is a member of the sodalite-haüynite group of cubic felspathoid minerals. Minor amounts of other felspathoids often occur in lapis lazuli. These are gemmy minerals of relatively low density. Na, Ca and Mg are important elements in the mineral chemistry of lapis deposits. Sulphur, picked up from "impure" limestone (Ca) or dolomite (Ca, Mg), is essential for colour (Jones 2015). Gradations in chemical composition result in variations in colour (blue to green) and intensity of colouring. Impurities are quite common in the original sedimented carbonate, and, when metasomatised, can form suites of calcium and magnesium silicates including relatively dense amphibole, pyroxene, and Mg olivine. The fine detail of gem felspathoid genesis has yet to be formulated, so the origin of lapis is unclear.

Lapis geology

Finlay (2004) investigated lapis lazuli's history as the basic ingredient of medieval ultramarine paint and gives an absorbing account, with a good sketch map, of her travels to the historic mines at remote Sar-e-sang, south of Faisabad, in the Kokcha River valley, Badakshan Province, northeast Afghanistan, in the rugged Hindu Kush massif. There, in a valley lateral to the Kokcha, she saw the splendid sight of white country rock, speckled with blue, gleaming in the morning sun. Later she inspected hillside adits where lapis lenses were being mined. Voynick (2011), in a brief account of the mining history at Badakshan, mentioned that variable grade lapis occurs in lensoid bodies "several hundred feet long". Jones (2015) noted that the grey-white marble host is up to 400 m thick.

Kostov (2004) summarised the Badakshan geology as involving metasomatic processes associated with pegmatitic and aplitic granitoids intruding dolomitic marbles. Variably coloured lazurite mineralisation lenses can occur in Ca Mg alteration zones that contain a variety of silicates, or also in interbedded calcified formations with gneiss and amphibolite. So, the ore mineralogy and the host geology are both complex. Such deposits could perhaps be regarded as low Fe skarns. Pure lazurite, either massive or crystallised in rhombic dodecahedral form, is very rare. More commonly lazurite is the chief component of the rock lapis lazuli, and it is this rock that is herein discussed.

Lapis seems to be confined mainly to limestones and dolomites contact metamorphosed by igneous intrusions, according to Zöldföldi & Kasztovsky (2009) who provide a map indicating 13 occurrences of lapis worldwide. Deposits near Lake Baikal in Russia are thought by some to have been another important lapis source in ancient times. Chilean lapis, currently extracted from north of Santiago, is of paler hue. Other lapis sources have been reported in Central Asia, Canada, USA, Algeria, Angola, and Burma. The writer is not aware of any Australian contact metamorphosed carbonate localities that contain lapis.

Commercial lapis

Afghan best quality lapis, rich in lazurite, has three grades: indigo blue, sky blue, and greenish blue; all quite expensive. High quality lapis can sell for $5 or more per gm; medium grade fetches around a tenth of this price. Top grade blue pigment, milled and washed, is worth about $10 per gm. Lapis is a valuable material; it's value is directly related to the volume and blue colour intensity of the silicate lazurite. The best lapis is rich in lazurite with a homogeneous appearance and a minimum of accessory minerals, some of which have a relatively high density. Lower grades of lapis are textured, often banded, with significant and obvious amounts of carbonate and silicates. Pyrite is common to all grades, but can vary from sparse disseminations to heavier concentrations of clots, shards, grains, and veinlets. The mineralogy, and thus the value, of lapis lazuli rock can vary considerably.

Poor grade lapis lazuli can be enhanced (often unbeknown to the buyer) by dyeing, especially on the whitish carbonate spots, and then by paraffin impregnation to seal the dye and improve the polish. Such treatments are detectable by acetone or dilute HCl which often will wash off the dye. The use of a hot needle should detect any paraffin.

The application of HCl to lazurite should release H_2S leaving gelatinous silica; this is one of the tests for lapis. If HCl is put on sodalite, another somewhat similar bluish felspathoid, only gelatinous silica is formed. The presence of pyrite, even in small amounts, in a blue mineral matrix helps identify a sample as lapis.

Many synthetic versions of lapis have been made, e.g. dyed jasper. Most of them are pretty obvious as imitations on careful inspection. Synthetics are discussed by Anderson & Jobbins (1990), GIA (1995), and Schumann (2006).

Persian blue was used in glazes on mosque and palace tiles in the Middle East e.g. the vast Shah Mosque in Isfahan, Iran. This colour, derived from cobalt minerals plentiful in the region, represented or emulated the lapis colour and effect, but it is not lapis (Mishmastnehi & Holakooei, 2015).

Lithotherapy

Worries and troubles have ever distressed humankind. The Bible gloomily declares that man, born of a woman, lived briefly and miserably (Job, xiv, 1). Hesiod (~700 BC), the Greek epic poet, related in his *Works and Days* (100-1) the myth of Pandora's jar, a wedding present from Zeus, to explain the origin of toil and suffering. Pandora, the first woman, opened the jar and let slip a multitude of evils:

> *full the earth, and full the sea, of evils*
> *unbidden miseries, now by day, now by night,*
> *beset us of their own accord*

Minerals, for many, were the prophylactics to employ against these blights. Materials from the mineral kingdom, seemingly so inert, were seen to be wondrously dynamic: nondescript lodestone, powerfully magnetic; cool quartz, thermally quite conductive; resinous sphalerite, triboluminescent when scratched;

golden pyrite, sparking when struck; and lapis, viewed as the purest blue.

The veneration of minerals has a long history in myth, magic, and medicine. A beautiful gem, such as lapis, seemed to offer relief from life's woes to many. Gems still do – visit any crystal shop for an abundance of pocket fondling stones. Modern beliefs reflect those held in the Middle Ages and earlier. Marvellous powers, particular properties, and mystic virtues were believed to be divinely implanted in gems. Consequently gems provided a medium by which the divinity may be approached and ameliorating favours obtained.

Schumann (2006), in a concise account of the alleged curative powers of gems, notes that lapis is currently prescribed for headache, sore throat, and sciatica. George (2004) mentions several attributes reputed to be associated with lapis. These include: benefits in creative expression, vitality, virility and strength; alleviation of problems with the thyroid and throat; and the enhancement of psychic abilities. It will be shown that medieval writers believed in kindred qualities too.

Placebo comfort has always been, and still is, part of the human experience. Or is there more to all this?

The ancient world

Theophrastus (c.370-c.287 BC), Aristotle's pupil, in his treatise *On Stones* included lapis lazuli in the category of valuable stones. Lapis was known as *σάπφειρος* or *sapphirus,* in the ancient world and in medieval times too. A purer deep blue variety, low in pyrite, was known as *κύανος* or *cyanus*, a term which was also applied to other blue minerals, such as azurite (Caley & Richards, 1956). Transparent corundum in its blue gem form is now known as sapphire.

Lapis features in the Christian Bible as a precious item prominent in priestly and divine functions. Aaron's holy garments were fashioned for glory and beauty with lapis set in a second row of decorative stones (Exodus xxviii, 2, 18). In his vision of God, Ezekiel (i, 26) noted the likeness of a lapis throne in the firmament overhead. In St John's Apocalypse the foundations of the new Jerusalem's jasper walls were described as adorned with precious stones; the second foundation was of lapis lazuli (Revelation xxi, 18, 19).

Deep blue lapis was the premier blue pigment in Roman times. Azurite was popular too, but in time converted (or degraded) to green malachite (Voynick, 2015). Lapis lazuli, along with red garnet and amethyst, was also very popular in Roman jewellery (Hornblower & Spawforth, 2012).

The natural historian Pliny the Elder (AD 23–79), comparing azurite and lapis lazuli, commented, *Naturalis Historia* 37.119–120:

> *dividitur autem et haec [cyanus] in mares feminasque. inest ei aliquando et aureus pulvis non qualis sappiris, in his enim aurum punctis conclucet. Caeruleae et sappiri rarumque ut cum purpura. optimae apud Medos, nusquam tamen perlucidae. praeterea inutiles scalpturis intervenientibus crystallinis centris. quae sunt ex iis cyanei coloris mares existimantur.*

> *Azurite [blue copper carbonate] too is separated into male and female types. Sometimes a golden powder [cuprite?] occurs in azurite differing from that found in lapis lazuli where the gold glistens as spots [pyrite grains]. Lapis lazuli is also blue, and, rarely, purplish. The best comes from Persia [i.e. central Asia], but translucent lapis occurs nowhere. Furthermore lapis stones are impractical for engraving when knots of rock crystal get in the way. Lapis lazuli coloured like azurite is considered to be male.*

In antiquity stones had gender. Those with relatively more marked characteristics were male (darker, more brilliant), those with less (paler, duller) were female. In discussing sard, a dark red-brown chalcedony, Pliny, *Naturalis Historia* noted, 37.106:

> *et in his autem mares excitatius fulgent feminae pigriores et crassius nitent.*
> *among these stones too the males glow more intensely, but the females with a duller sheen are less lively.*

Medieval beliefs

Marbod (1035-1123), Bishop of Rennes in Brittany, in his famous book on gems, *Liber Lapidum,* devoted 26 lines of hexameter verse to lapis lazuli. Beckmann (1799) compiled and edited Marbod's mineral poems and supplied useful footnotes. The fifth poem (lines 103–128) is *De sapphiro*:

Sapphyri species digitis aptissima regum,
Egregium fulgens, puroque simillima coelo,
Vilior est nullo virtutibus atque decore.
Hic et Syrtites lapis a plerisque vocatur,
Quod circa Syrtes Lybicis permixtus arenis,
Fluctibus expulsus, fervente freto reperitur.
Ille sed optimus est, quem tellus Medica gignit.
Qui tamen afferitur nunquam transmittere visum,
Quem natura potens tanto ditavit honore,
Ut sacer et merito gemmarum gemma vocetur;
Nam corpus vegetum conservat et integra membra.
Et qui portat eum, nequit ulla fraude noceri.
Invidiam superat, nullo terrore movetur,
Hic lapis, ut perhibent, educit carcere vinctos,
Obstructasque fores, et vincula tacta resolvit,
Placatumque deum reddit, precibusque faventem.
Fertur et ad pacem bonus esse reconciliandam;
Et plusquam reliquas amat hanc necromantia gemmam,
Ut divina queat per eam responsa mereri.
Corporeis etiam morbis lapis iste medetur.
Scilicet ardorem refrigerat interiorem,
Sudorem stringit nimio torrente fluentem.
Contritus lacti superillitus ulcera sanat,
Tollit et ex oculis sordes, ex fronte dolorem;
Et vitiis linguae simili ratione medetur.
Sed qui gestat eum, castissimus esse iubetur,

Fine is the appearance of lapis lazuli – so very suitable for kings' fingers,
Splendid its glitter, so much like the unsullied heavens,
Inferior to none in miraculous powers and charm.
It is commonly called the stone of Syrtis
For around the Gulf of Sirta, mixed with Libyan sands,
Driven about by waves, in seething waters, it is found.
But the best stone is the one that central Asia produces.
Despite its documented opacity,
Powerful nature has enriched it with so much beauty,

That it is rightly regarded as the sublime gem of all gems;
For it keeps the body vigorous and the limbs healthy.
He who carries it cannot be injured by any crime.
He survives hatred, dread troubles him not.
This stone, so they say, releases the shackled from prison,
Unfastens closed doors and loosens applied bonds,
And appeases god who becomes well disposed to one's prayers.
It is said to be good for restoring harmony.
The art of divination esteems this gem more than mortal remains,
As, through it, the divine answers can be obtained.
This stone heals diseases of the body.
One can rely on it to relieve internal inflammation,
It limits sweating in excessive heat.
Ground up with milk, applied as ointment, it heals sores,
It recovers dirt from the eyes and banishes headaches;
Likewise it cures speech disorders.
But he who carries it about is bidden to be a most upright person.

So, in Marbod's view, the power and character of lapis offer impressive lithotherapeutic benefits: miracles, access to the divinity, energetic soundness of body, security in the face of malefactors and the envious, passage through barriers, promotion of serenity, and medication. Clearly, lapis must be the talisman of choice for the anxious, and even for the able.

Beckmann (1799) in his scholarly footnotes pointed out that: (1) in the first line of the poem Marbod's *sapphirus* was not a hard, dense, adamantine gem, rather it was lapis lazuli, whose location could not really be referenced to Libya where, it seems, Pliny had noted the occurrence of another mineral. (2) In the eighteenth line it is assumed that divination or necromancy is prophetic communication with the remains of the dead, especially those of saints, whereby the future, and the locations of hidden objects could be revealed, or enigmatic data interpreted, through trances or exalted states. This was real magic, although with unreal expectations. The cultish invocation of the dead was big business in Marbod's time. It is quite astonishing to see that talismanic lapis lazuli was put on par with a venerated body, or relic of a body, as an efficacious prophetic or propitiatory tool. In a footnote Beckmann cited an opinion that *necromantia* is the calling up of the ghosts of the dead. (3) Regarding the last line of Marbod's poem: Beckmann shrewdly noted that this was a canny proviso used by lithotherapists in the case of clients who failed to elicit the stone's powers, and then proceeded to deny those powers existed; obviously the clients were not holy enough. Presumably few would want to advertise the lax state of their souls, so the stone's reputation survived. Very clever.

Marbod's claims for the lapis lazuli were quite extraordinary, and surely must have raised the eyebrows, if not the ire, of the church hierarchy. To say that its agency mollifies god and results in prayers being answered favourably is extreme theology to say the least, even allowing for gems to be divinely impregnated material.

The double whammy of birth and death bracketed many a mentally bleak medieval life. At birth, it was defiled by original sin, according to St Augustine, ever admonitory; in death, it awaited punishment, according to the Apocalyptic visionaries. The ultimate forensic event, the Day of Judgement, as gruesomely depicted by Hieronymus Bosch, was a lifetime worry, if not dread. All were aware of the unending torment of the damned as portrayed by preachers and publications. So, although devotion to a stone may seem strange now, it helped then. Prominent among the available aids against damnation was lapis, along with icons, images, and the Rosary – the closed string of five decades of beads for counting repeated prayers. Lapis beads on a Rosary would have been quite desirable for aesthetic and eschatological reasons. Dire prognostications were believed and feared by medieval people. Their attitudes are utterly unlike the attitudes of most people today. Now scripted Armageddons regularly entertain blithe multitudes in movie theatres, and video games, around the world.

Later writings

Agricola (1546, *De Natura Fossilium VI*) in his early pre-modern mineralogy discussed lapis, but really only repeated Pliny. In evaluating the worth of sixteen leading gems he ranked the best quality lapis lazuli in seventh place, ahead of blue sapphire, and after diamond, pearl, emerald, opal, carbunculus (literally a small glowing coal, but possibly a red spinel or a ruby), and plasma (a bright green translucent chalcedony). The middle ranking of lapis lazuli more or less mirrors current valuations of gemmy materials, except that now good sapphire and aquamarine (gem beryl) would outrank lapis lazuli.

Lapis (after washing 50 times) was mentioned by Burton (1628) as a purging remedy for melancholy, but whether it should have been used as pill, powder, or potion was not stated. Kircher (1678), the Jesuit polymath, in a comprehensive book of pre-modern gemmology, described lapis as opaque blue, speckled with golden spots, and a rival in colour to sapphire. He listed powers peculiar to lapis such as curing fever, invigorating vision, inducing sleep, and relieving arthritis.

More precious than gold

Ultramarine owes its colour to the sulphur ion in the lazurite cubic lattice. As the charge on the ion varies, so does the lazurite tint. Pure lazurite being very rare, the colour was extracted from lapis lazuli. Thus lapis had a firm place in the visual arts culture of the Renaissance and the Middle Ages where it contributed to paintings, psalters, illuminated manuscripts, and frescoes (on plaster). It is still used in its natural form.

This medieval paint pigment was so scarce that it was more valued than gold. The deep blue of ultramarine was, and still is, fairly cheaply synthesised or imitated by various techniques. However, none can match the subtly impressive character of natural ultramarine with its virtually ineradicable content of associated minerals (see Table 1) interacting in nuanced plays of light that delight the viewer. Some connoisseurs consider its effects to be perfect, unsurpassed by any other colour or hue. This priceless pigment was often rationed to parts of a painting, such as the robes of the Virgin Mary, or as an overcoat to a base of cheap blue azurite. Diluted it served as an optical filter in a final varnish on a whole picture.

Kircher (1678) outlined the use of colour in the paintings of his time, and the special use of ultramarine ash (lower grade pigment) in a neutral transparent glaze, thinly applied, for optical enhancement of the subject and preservation of the work. *Mundus Subterraneus* 10, 13:

Table 1. Mineralogy of lapis lazuli

Mineral	Hardness (Moh scale)	Density (g/cc) (approx.)	Comments
Lazurite $(Na,Ca)_8(AlSi0_4)_6(SO_4,S,Cl)_2$ [the amounts of SO_4, S, Cl can vary considerably] *a rare and valuable mineral*	≤5½	2.45	Sulphur-related colour centres, deep azure-blue, waxy/vitreous lustre when polished, commonly granular massive, semi-translucent
Calcite $CaCO_3$	3	2.72	Inclusions and bands; transparent to opaque white-grey carbonate
dolomite $(Ca,Mg)CO_3$	≤4	2.85	
Pyrite FeS_2	≤6½	5.02	Disseminations – grains, shards; opaque sulphide, splendent yellow
Some other constituents (not all listed) may be present with varying degrees of translucency			
Afghanite	≤6	2.60	Na, Ca, K felspathoid, bluish, rare
Haüynite	≤6	2.50	Na, Ca felspathoid, blue-green, rare
Nepheline	≤6	2.60	Na, K felspathoid, greyish
Nosean	≤6	2.35	Na felspathoid, blue-green, rare
Sodalite	≤6	2.20	Na felspathoid, lavender blue
Albite	≤6½	2.62	Na plag. felspar, whitish
Marialite	≤6	2.55	Na scapolite (alt fels.), blue-grey
Mica	≤7	2.86	Phlogopite, K Mg silicate brown-green
Pyroxene	≤6	3.25	Diopside, Ca, Mg, silicate, white/green
Forsterite	ϖ6	3.20	Mg olivine, silicate, greenish
Lazurite can be regarded as a mixed crystal of the sodalite-hauynite felspathoid group			
Lapis lazuli's colour depends on its chemical composition: it is basically blue but can vary from marine blue to violet blue, sometimes greenish tinges are present; commonly it is opaque			
Lapis lazuli's density is ~2.75± g/cc depending on mineral components; note that lazurite itself is a relatively low density mineral			
Lazurite can exhibit short wave ultraviolet yellowish fluorescence – may vary; contained calcite may respond to long wave UV with pinkish fluorescence			
Lazulite or blue spar is a dense (3.06 g/cc) dark blue-green hydrous Mg phosphate that, despite the name, is not a component of lapis lazuli, nor is turquoise a blue Ca, Al, phosphate (2.70 g/cc)			

Propter immensum coloris ultramarini pretium non solent eo uti pictores, ut aliis coloribus, sed pingunt imagines, quas caeruleas volunt, communi caeruleo ex Armenio praeparato, aut ex vitro illius coloris, quod Smaltum vocant; deinde partes eas, in quibus lux haeret, cerussa, postmodum coloribus istis, ut res postulat, rite adhibitis iisque optime exsiccatis, ultramarino colore humectato oleo nucum, & spiritu terebinthinae totam illam picturam caeruleam tanquam vernice, ….. Hoc modo per obductum colorem tanquam per glaciem aut vitrum subjecti resplendent, pulchritudinem non solum excellentiorem a velamine nacti, sed & perpetuitatem, ut ne ducentis quidem annis, vel minima lucis, vel pulchritudinis portio decedat.

Owing to the enormous cost of ultramarine, painters do not usually use it as they do other colours, but they paint semblances with a common blue derived from prepared Armenium [azurite, copper carbonate], or from glass of that colour [derived from cobalt compounds] which is called Smalt. Next they paint those parts wherein brightness abides with white lead, and after that with those particular colours as the layout of the painting requires. When all these are properly applied and thoroughly dried, they smear a blue all over that picture using ultramarine colour moistened with nut oil and spirit of turpentine, like a varnish ….. In this way the subject matter of the picture glitters through the applied surficial colour as if through ice or glass, with not only outstanding beauty but also temporal durability. As a result not even in two hundred years does the least part of its brightness or beauty degrade

Kircher (1678) also provided a recipe for making ultramarine pigment extracted in solution from lapis lazuli. The procedure involving powdering, dissolving, leaching and filtering, must surely rate as a unique alchemical ritual for leaching a rock. *Mundus Subterraneus, Color ultramarinus Lazuli,* 10, 14:

Recipe lib.1.lapidis in tenuissimum pulverem redacti, ac cum aqua clara ad porphyrium triti, & impone scutellae vitriatae, donec pulvis in umbra exsiccetur, quem iterum, si in massam coierit, in pulverem redige; deinde habeas in promptu Resinae pini uniiii. Picis graecae, Mastiches, Thuris, ana uniii. Olivarum unii. Patellam vitream supra lentum ignem pone, ac primo imponas oleum, & cum bene calidum erit, adde resinam, postea picem, deinde thus, ac postremò mastichen, ac move optime: postea alteri *scutellae infunde, ut ebulliat parum. His peractis habeas ad manum aliud vasculum, in quod pones siccum lapidis pulverem, cui affundes unguentum dictum, paulatim movendo spatula, ut bona fiat mixtio. Tum relinque per diem mixturam, & cum auferre vis colorem, funde pastam supra aquam bullientem, ac move & agita optime materiam, & cum aqua incipit refrigerari, ejice, ac aliam calidam affunde; idque fac, donec aqua colorem trahat, atque repete toties, donec omnem colorem extraxeris. Singulas extractiones separare potes, ut distinctos colores habeas.*

Take one pound [327.45 gms = 12 unciae/ounces] of lapis stone reduced to the finest powder and ground with clear water until purple. Put this into a glazed dish away from sunlight until the powder has dried out. Reduce to powder a second time if the material coagulates. Then have ready four ounces of pine resin; three ounces (each) of turpentine resin [colophony/Greek pitch], mastic [pistacia lentiscus gum], and frankincense [boswellia gum resin]; and two ounces of olives [presumably oil]. Place the dish above a slow fire, put in the oil and when it is very hot firstly add the resin, then pitch, then frankincense, and lastly the mastic. Agitate thoroughly then pour into a second dish to bubble a little. On the completion of these procedures have ready another small vessel and place the dry lapis powder in it. To this add the specified aromatic grease gradually, stirring with a spatula, so that all is well mixed. Then leave for a day. When you wish to extract the colour pour out the doughy material on top of boiling water and stir and shake thoroughly. When the water begins to cool take it out [this contains suspended ultramarine pigment] and pour in another lot of hot water and continue to do this as long as the water keeps drawing out the colour. Repeat the process until you have extracted all the colour. You can separate the extractions, one by one, so that you have different shades of colour.

The writer is not too sure about the chemistry and physics of this involved mineral processing operation. Used in Kircher's time, among other similar techniques, it is no wonder that the pigment cost a fortune given the ritual of its preparation and the very high cost of the lapis lazuli. The manufacture of natural ultramarine requires high quality lapis, then, and now, not always available. It also requires skill, patience, and thoroughness to produce the compelling tone and brilliance of a colour with the character that is so attractive in artwork.

Gazo (2015) extracts pigment powders from Afghan lapis in four grades using, after much research, a modified version of another recipe found in Cennino Cennini's treatise on painting, written in Italian ~1390. Gazo kneads milled and washed lapis with beeswax, mastic, and pine resin and then extracts the ultramarine colour in solution in a painstaking, lengthy, manual operation. Gazo's top grade Fra Angelico pigment and his minimally treated plain lapis lazuli powder are shown in Figure 3. Some tests were carried out on these materials.

The beautiful ultramarine effect can be seen in Figure 3 in two famous works of art: Girl with a Pearl Earring by Vermeer (~1665), and the Virgin in Prayer by Sassoferrato (~1645). The eye immediately focuses on the blue. Evidently, the ultramarine preparation techniques of earlier times resulted in a quite satisfactory product.

Figure 3. *Illustrations of ultramarine pigment and it's use in two famous paintings. (a) The dish on the left contains the highest grade "Fra Angelico" ultramarine produced by Master Pigments of California and the dish on the right contains the basic material – Afghan lapis lazuli ground to powder. Reproduced with permission, Gazo, A/Copyright 2015 MasterPigments. http://www.masterpigments.com/categories/pigments/lapis-lazuli-pigments.html. (b) The Girl with the Pearl Earring was painted by Johannes van der Meer (Jan Vermeer, 1632–1675). Photographer unknown/Public Domain https://commons.wikimedia.org/wiki/File:Johannes_Vermeer_(1632-1675)_-_The_Girl_With_The_Pearl_Earring_(1665).jpg. (c) The Virgin in Prayer was painted by Giovanni da Sassoferrato (1609–1685). Photograph Web Gallery of Art/Public Domain https://commons.wikimedia.org/wiki/File:Sassoferrato_-_Jungfrun_i_bön.jpg.*

The Renaissance bishop

Robert Browning was a Victorian man of letters, and one of the great English poets. Lapis lazuli has a key role in his masterly *The Bishop orders his tomb at Saint Praxed's church* (Kenyon, 1912). The poem is a withering commentary on the vanity, hypocrisy, materialism, and immorality of a Renaissance bishop deemed to be typical of a corrupt time. Saint Praxedes was reputed to be a Roman virgin, of exemplary compassion and charity, who sheltered Christians during the 2nd century persecutions of Marcus Aurelius. She has a church in Rome, but the bishop of the poem is not buried there; he is fictional.

Browning's unrhymed iambic pentameters are the perfect medium to convey the rambling monologue of the dying bishop. He exhorts his sons to do him proud in ensuring that he has an ornate burial vault befitting his exalted status. This must be more elaborate than that of his predecessor Gandolf, a rival, who much to the bishop's vexation died first and secured the best niche in the church. However, Gandolf's tomb is only of a modest stone and this is a consolation. Fading from life he thinks not of repentance, but of revenge on Gandolf who will have to look at his splendid tomb for all eternity. The bishop also takes satisfaction that Gandolf envied him for the woman he had as his lover, and will now envy him in his tomb. The lapis verses, in part of the poem, follow:

Draw close: that conflagration of my church
-What then? So much was saved if aught were missed!
My sons, ye would not be my death? Go dig
The white-grape vineyard where the oil-press stood,
Drop water gently till the surface sink,
And if ye find…ah God, I know not, I!...
Bedded in store of rotten fig-leaves soft,
And corded up in a tight olive-frail,
Some lump, ah God, of lapis lazuli,
Big as a Jew's head cut off at the nape,
Blue as a vein o'er the Madonna's breast…
Sons, all have I bequeathed you, villas, all,
That brave Frascati villa with its bath,
So, let the blue lump poise between my knees,
Like God the Father's globe on both his hands
Ye worship in the Jesu Church so gay,
For Gandolf shall not choose but see and burst!
Swift as a weaver's shuttle fleet our years:
Man goeth to the grave, and where is he?
Did I say basalt for my slab, sons? Black –
'Twas ever antique-black I meant! How else
Shall ye contrast my frieze to come beneath?

Previously the bishop had stolen a large piece of lapis from a church destroyed by fire. Now he wants it retrieved as the piece de résistance for his tomb. The hallowed Christian figures of John the Baptist (Jew's head) and the Virgin Mary (Madonna) are mentioned not for their goodness, but as violent and prurient yardsticks for the size and quality of his lapis. The wish for the lapis to be placed between his knees (under his loins) seems to have been inspired by God the Father holding a large globe of lapis in an adornment on the altar of the Jesuit Church of St Ignatius in Rome.

In death the bishop is the centre of attention, and the focus is the lapis stone. The tomb is an emblematic extension of his vain life and intended to be venerated. The lapis is the chief drawcard.

In his damning depiction of a repellent prelate, Browning did not choose gold, or silver, or diamonds, or pearls, but the rock lapis, as a suitably powerful symbol of human vanity. This compelling poem has become a much discussed classic since it was published in 1845.

Perhaps enough has been said of the reputation of lapis, now for some facts.

Some physical properties of lapis lazuli

As little seems to be known about the physical properties of lapis lazuli rock, the author investigated some samples. The test techniques are referenced in the bibliography. Average grade Afghan and Chilean lapis rock chip samples were cut and shaped into discs and prisms. The various tests used different subsamples i.e. an individual subsample did not necessarily undergo each test. The lazurite in each subsample was checked by HCl (releasing H_2S, a standard identification test) and applied to a streak plate (to show a blue streak). All the Afghan samples were textured i.e. they showed either coarse or fine banding. Most were cut in a direction oblique to any such foliation.

The Afghan lapis produced a yellowish fluorescence (to short wave ultraviolet) which had an irregular appearance owing to the presence of non-fluorescing gangue minerals. However, the Chilean lapis did not respond at all, except for some of its carbonate that fluoresced pink (long wave ultraviolet).

In non-destructive testing by prompt gamma activation analysis, to obtain chemical elements profiles of S and Cl, Zöldföldi & Kasztovsky (2009) showed that Afghan and Chilean lapis were different, with the Chilean variety having higher S/Si and Cl/Si ratios. Principal component analysis showed the Chilean lapis to be quite different, chemically, from Afghan lapis.

Mass properties

Following vacuum saturation with fresh water, and oven drying, water-accessible porosities of 0.9% and 1.5% were determined as averages for the Afghan and Chilean subsamples respectively. These porosities are low, so air dry and oven dry and saturated densities are similar. However, although the porosities are not high, they are finite, and typical for skarn material (Emerson, 1986). The porosity may be associated with alteration, microcracking, and, perhaps, incipient weathering, as the samples came from high altitude. Some of the porosity could be "blind" or dead end. It is thought that the porosity may be mainly associated with the carbonate in the lapis, especially the Chilean lapis. The residual water saturation in the porosity was estimated to be around 50% i.e. the porosity had air and water in comparable amounts.

Given the altitude of the deposits, it seems best to quote air dry bulk densities (BD), which include minor residual pore moisture, assumed to be fresh water. The Chilean BD's averaged 2.77 g/cc from 8 subsamples. For a carbonate gangue subsample, with minor sulphide content, BD was 2.93 g/cc; this sample appeared to be at least partly dolomitic. For 27 subsamples of Afghan material the BD average was 3.00 g/cc, which is on the high side of the usual lapis lazuli density range. The total density range for all samples was 2.70 to 3.08 g/cc. For the materials tested, Chilean lapis appears to have a lower density than Afghan lapis, which has a variety of silicates and is generally more pyritic.

Zöldföldi (2011) investigated the densities of 38 lapis beads from the Qaṭna royal tomb. For 23 of these the densities ranged from 2.4 to 3.0 g/cc and were deemed to be true lapis. Those with densities under 2.4 g/cc were thought to be imitation lapis. Attempts to manufacture artificial lapis have been known from the second millennium BC, such was its value.

Anderson & Jobbins (1990) state that 2.7 to 2.9 g/cc is the normal range for lapis and that fine pieces average about 2.8 g/cc. GIA (1995) specifies 2.75 ± 0.25 g/cc as the normal range for lapis. An appreciation of the straightforward, non-destructive property of density is useful in assessing this valuable and widely used material. Consider, by way of example, a notional lapis lazuli comprising 50% by volume lazurite, 15% other blue felspathoids, 10% pyroxene/mica, 10% pyrite, and 15% carbonate. Using the densities in Table 1, and ignoring porosity, the resultant composite density is 2.8 g/cc which would be typical of a good grade of pyritic lapis having plenty of blue minerals. If the proportion of blue mineral is diminished with corresponding increase in other minerals then densities exceed 3.0 g/cc. If the proportion of blue mineral is very high, as in a top grade lapis, then densities can be of the order of 2.5 g/cc. For a hard rock, as compared to, say, a granite, lapis lazuli is

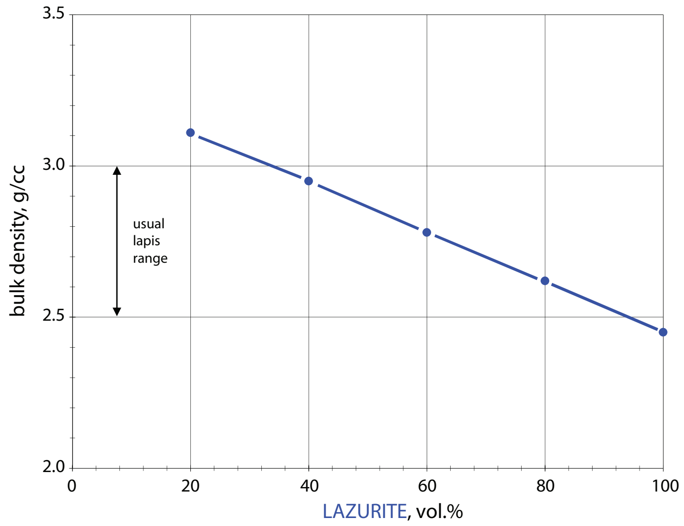

Figure 4. *Density variation in notional lapis lazuli. Increasing the amount of low density lazurite (and any other felspathoids) decreases bulk density and the quality of material would improve, provided that the overall blue colorations and textures are satisfactory. In the mineral mix presented here porosity is regarded as negligible; for 80% lazurite the amount of other felspathoids, carbonate, pyroxene et al, and pyrite were each assumed to be 5%; for 20% lazurite the amounts were each assumed to be 20%. See Table 1 for densities of components. This figure is simply illustrative of one range of mixes, it is not definitive for lapis assessment. The density range measured for the 35 subsamples reported in the text was 2.70 to 3.08 g/cc.*

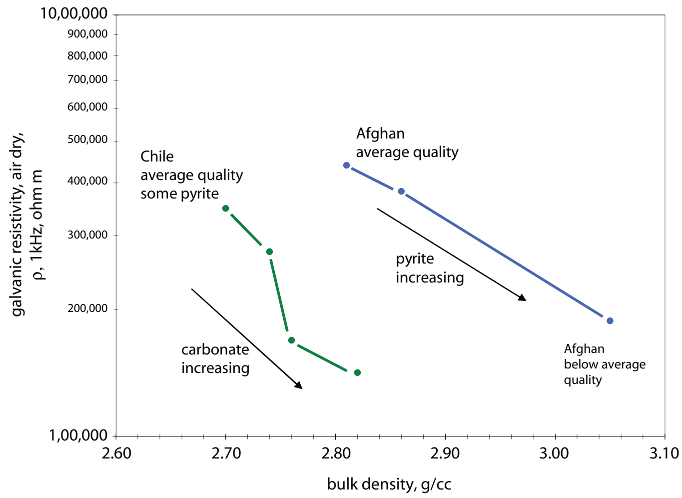

Figure 5. *Galvanic electrical resistivities measured air dry at 1 kHz. The materials are quite resistive and are changing into dielectrics, with high phase lags between voltage and current, at 1 kHz. Resistivities decrease as carbonate increases in the Chile samples and as pyrite increases in the Afghan samples.*

seen to have a wide density range; a sample's position in this range is an indication, but not a definition, of lapis lazuli grade. Figure 4 attempts to illustrate this with a synthetic mineral-mix. Many mineral mixes could be assumed and each would give a different plot. However, a common feature would be that as felspathoid content increases, and pyrite and pyroxene decrease, the density would decrease.

Inductive properties

Induction coil measurements at 400 Hz showed that the magnetic susceptibility of subsamples was near zero (actually some were diamagnetic, i.e. slightly negative). Some Fe infused skarn deposits can be quite magnetic (Emerson, 1986). However, it seems that Fe is not a feature of most lapis deposits, except in pyrite which itself has a very low magnetic susceptibility. Energisation at 2.5 MHz failed to produce electromagnetic conductivity responses from pyrite grains. It is possible that higher frequency energisation could have excited a response from the disseminated pyrite, but this was not pursued.

Galvanic properties

The air dry materials could be considered dielectrics loaded with semiconducting pyrite grains (sparsely for Afghan, and very sparsely for Chilean subsamples). Their measured DC conductivities were of the order of nanosiemens/m to microsiemens/m. Galvanic resistivity measurements, carried out at 1 kHz, with impressed current generally oblique to any bedding, showed ohmic current was subordinate to displacement current i.e. large phase lags of voltage with respect to current were observed. The very high resistivities, as shown in Figure 5, seem to depend inversely on density. Resistivity decreases with an increase in pyrite content in the Afghan lapis. An increase in carbonate has a similar effect in the Chilean lapis; the carbonate is impure and contains minor amounts of sulphides and clays.

Galvanic micro probing showed intra-semiconductor particle electrical continuity at microscale in pyrite grains, shards, clusters but no inter-particle continuity at mesoscale as the semiconducting pyrites are isolated electrically. The pyrite grain etc. conductivities were estimated to be in the order of ~ 1000 S/m. So the galvanic electrical properties are dominated by the insulating silicates in the matrix. However, in the field, such high resistivities may not be observed or resolvable if host and country rocks (e.g. marbles) have similar features. Also, if moist or wet macrofractures or fault damage zones are present, and shunt current through or away from such highly resistive lithologies, then field electrode arrays, in such environments, may map structure, rather than lithology.

The effect of pyrite on the resistivity on a lapis block at mesoscale may be estimated roughly from Maxwell's Equations (Shuey, 1975) which, for heterogeneous media, give an approximation of a mixture's conductivity up to about 10% volume fraction of dispersed spheres in a continuous matrix. If pyrite is represented by conductive spheres and the silicates are the resistive matrix then the formula, $\sigma_c/\sigma_m \approx (1 + 2f)/(1 - f)$ suggests that, for 10% pyrite ($f = 0.1$), the mixture (σ_c) to matrix (σ_m) conductivity ratio would be of the order of 1.3 i.e. about a 23% drop in resistivity. However, other factors need to be considered such as actual grain shape. This subject will not be pursued further here.

Dielectric properties

The 1 MHz real permittivities were determined and are shown in Figure 6, where K' is seen to increase with density. K', the permittivity, is the relative dielectric constant, a measure of charge polarisabilities. The reference minerals are from Olhoeft (1981) – regard as approximate. Again pyrite content is inferred to have a significant effect, boosting polarisabilities beyond that expected of silicates and carbonates. Note that the concept of K for a conductor, such as pyrite, is meaningless but in the application of mixing laws, by convention, a high value (quasi K) can be ascribed to conductive particles to give the resultant composite effect

In the samples measured (Fig. 6) the average tan δ (K''/K') values for three groups were 0.07 (Chile), 0.03 (low pyrite

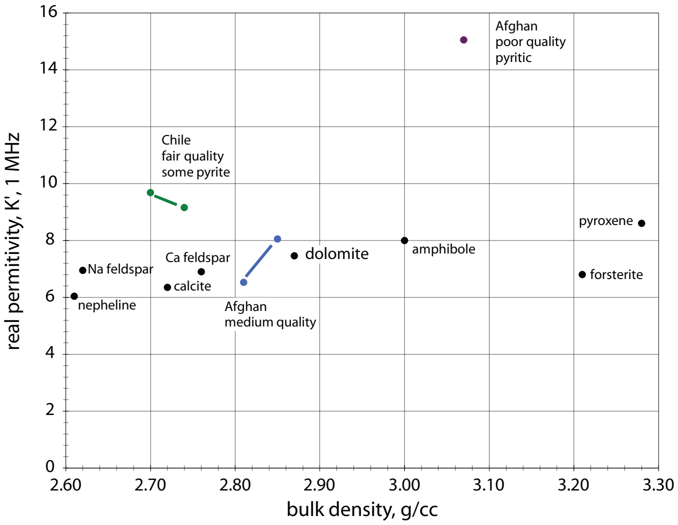

Figure 6. *Plot of real permittivity (relative dielectric constant) measured at 1 MHz on Chile and Afghan lapis samples in the air dry state. It is inferred that lapis of reasonable grade would have a permittivity similar to that of feldspar. The reference minerals are from Olhoeft (1981).*

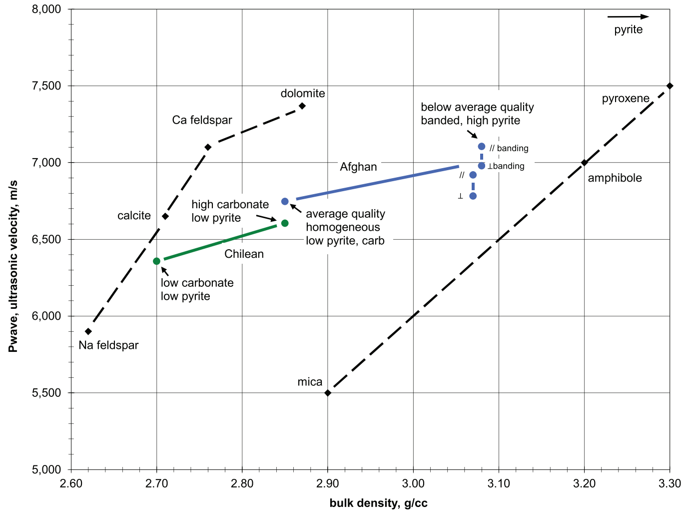

Figure 7. *Ultrasonic (200 kHz) compressional (P) wave velocities measured, under 10 kN uniaxial load, on five lapis samples. The results suggest a Pwave velocity of around 6700 m/s for an average quality lapis with minor amounts of pyrite and carbonate. The poorer quality Afghan material showed velocity anisotropy, (// = parallel to banding, ⊥ = normal to banding) and higher velocities. The reference minerals are approximate only.*

Afghan), 0.14 (relatively pyritic Afghan). K'' is the out of phase or imaginary permittivity which represents energy loss mechanisms associated with polarizations in the dielectrics. These loss mechanisms would be in phase with any galvanic (ohmic) loss. [Complex $K^* = K' - jK''$, $K = \varepsilon/\varepsilon_o$; ε is dielectric constant; free space dielectric constant $\varepsilon_o = 8.85 \times 10^{-12}$ F/m]

The dielectric effects observed were for frequencies below that usually employed in ground probing radar. At higher frequencies, in the field, the real and imaginary permittivities control EM propagation i.e. reflection and attenuation. The results given here are still instructive. The polarisabilities are thought to be associated with limitations imposed on charge movement by inhomogeneities (interfacial i.e. Maxwell-Wagner effects), and by charge carriers bound to attracting centres and capable of only very limited movement to a choice of immediately adjacent locations (dipole effects). The dielectric loss is the special type of friction associated with these limited movements of charge. Interfacial effects would include those associated with pyrite set in silicate; dipole effects would include those related to the molecular structure of silicates and carbonates, and to residual moisture bound to pore or crack walls or to hydrated alteration products such as clays (thought to be present in the Chilean lapis carbonate phase).

For the limited tests on the lapis, pyrite is seen to boost permittivities above those of the silicate / carbonate background. Lazurite and any associated felspathoids could be inferred to have a permittivity similar to albite (Na feldspar). The results here seem akin to work on epoxies (dielectric) loaded with aluminium (conductor) powder reported by Paipetis et al. (1983) who modelled their data with various mixing laws. Polarisation and loss increased with the volume of aluminium.

The pyrite content of the samples tested was within the range regarded as reasonable (i.e. not too much) for inferior to medium quality lapis. The pyrite, being effectively isolated, formed no semiconducting loops or threads to respond readily, in the form of conductivity responses, to induced (pyrite loops) or galvanic (pyrite threads) energisations. Electrically lapis could be viewed basically as an insulator with a low, but variable, semiconductor content. At meso-scale its best regarded as a leaky dielectric when the effects of the pyrite and any moist porosity are considered. At macroscale it would be resistive, but the rock mass resistivity, as seen by field arrays, could diminish if wetted macrofractures transect the rock mass.

Acoustic properties

Ultrasonic (200 kHz) compressional (P) wave velocities were measured under 10 kN uniaxial loading. The very limited test results shown in Figure 7 seem explicable in terms of silicate and carbonate mineralogy, and the pyrite content. Velocity increases with density for two types of lapis. Again it is inferred that lazurite and related feldspathoids may have a velocity similar to feldspar. It is possible that useful velocity or acoustic impedance (VxBD) contrasts could exist between lapis and any carbonate host if the lapis has a lot of pyrite and amphibole / pyroxene.

Pigment powders

Three grades of ultramarine pigment powders ground to ~25 μ (+/-) were obtained from Master Pigments: top grade Fra Angelico (Figure 3), ultramarine ash which is a low grade used in the surface glazing of a painting, and raw lapis lazuli (Figure 3). XRay Diffraction scans were run on these materials and the results are presented in Table 2. The solid material composite grain densities were obtained by pycnometry.

A feature of the results is the spread of eight mineral phases in the ash, and nine in the Fra Angelico and lapis; the dominance of dense diopside in the ash and lapis and its large presence in the final pigment; the significant amounts of blue or bluish feldspathoids (mainly lazurite) and the small amounts of pyrite for this particular type of Afghan lapis. This is a rich mineral mix producing blue pigment of quality.

Density, especially in the ash and lapis, is increased not by pyrite but by phlogopite and diopside. Pyrite is less than 2% by volume in this lapis. The volume percentages of mainly blue feldspathoids are 58%, 20%, and 26% approximately for the Fra Angelico, ash, and lapis, respectively. In the lapis trace amounts

Table 2. Lapis pigment powders; XRD results

Mineral	Fra Angelico weight %	Ultramarine ash weight %	Lapis lazuli weight %
Felspathoids			
Lazurite	32.4	12.4	14.1
Nepheline	10.4	2.8	4
Sodalite	2.7	0.9	1.4
Nosean	1.9	–	–
Afghanite	3.5	–	0.9
Feldspar			
Albite	3.6	1.8	2.3
Altered feldspar			
Marialite	4.2	1.2	2.6
Other Silicates			
Diopside	37.3	67	62.7
Phlogopite	4	13.2	9
Sulphide			
Pyrite	–	0.5	3
Pycnometry			
Grain density solid phase	2.74 g/cc	3.03 g/cc	3.01 g/cc

of carbonate were detected by HCl, but the carbonate content was below the XRD detection limit.

Summary

Lapis lazuli, being a mix of physically ordinary silicates with subordinate pyrite and carbonate, does not have any salient physical properties (except for colour in outcrop) to contrast with likely host and country rocks, especially in complex skarn settings.

Density, carefully interpreted, is a convenient, simple, and non-destructive indicator of lapis quality, especially if the mineralogy can be ascertained.

The inference that gemmy felspathoids are probably similar in some physical properties to feldspars is not surprising, given that felspathoids, chemically, can be regarded as silica deficient-feldspars.

Concluding remarks

Lapis lazuli is an intriguing material valued by many over the ages. It has been used, ornamentally, religiously, and medicinally, from the earliest times. Accordingly, it has been a well-represented species in the history of gemmology. Afghanistan still supplies markets with diverse materials some of which, of average quality, have been investigated. Lapis is the only gemmy material that is a rock, and the very limited results presented here suggest that, except for colour and optical character, it is a silicate-carbonate-pyrite rock of an unexceptional physical nature. Basically, when pyrite is low, as in the better grades of lapis, it has silicate / carbonate features. Chilean lapis lazuli seems to be a different variety. The non-destructive density test is useful and serves as an indicator of quality, in a supplementary role to visual and other techniques. In exploration, the application of geophysics would seem to be better devoted to locating possible favourable geological environments, regionally and locally, rather than attempts at direct detection of lensoid bodies of the peculiar blend of silicates that constitute grade lapis lazuli.

Perhaps geophysicists inspired by the third line of Marbod's poem could carry a nice piece of lapis around in their pockets and be blessed in their exploration endeavours. It may be worth a try, in the solidly empirical spirit of scientific testing, of course. However, the questing he, or the searching she, should bear in mind the last line of the poem.

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Lapis with pyrite & calcite. Lazurite polie (first page) photo by Parent Géry / CC BY-SA 3.0. https://commons.wikimedia.org/wiki/File:Lazurite_polie_-_53_mm_-_(Afghanistan).JPG.

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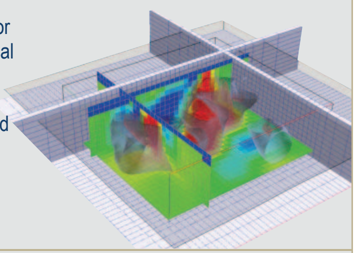

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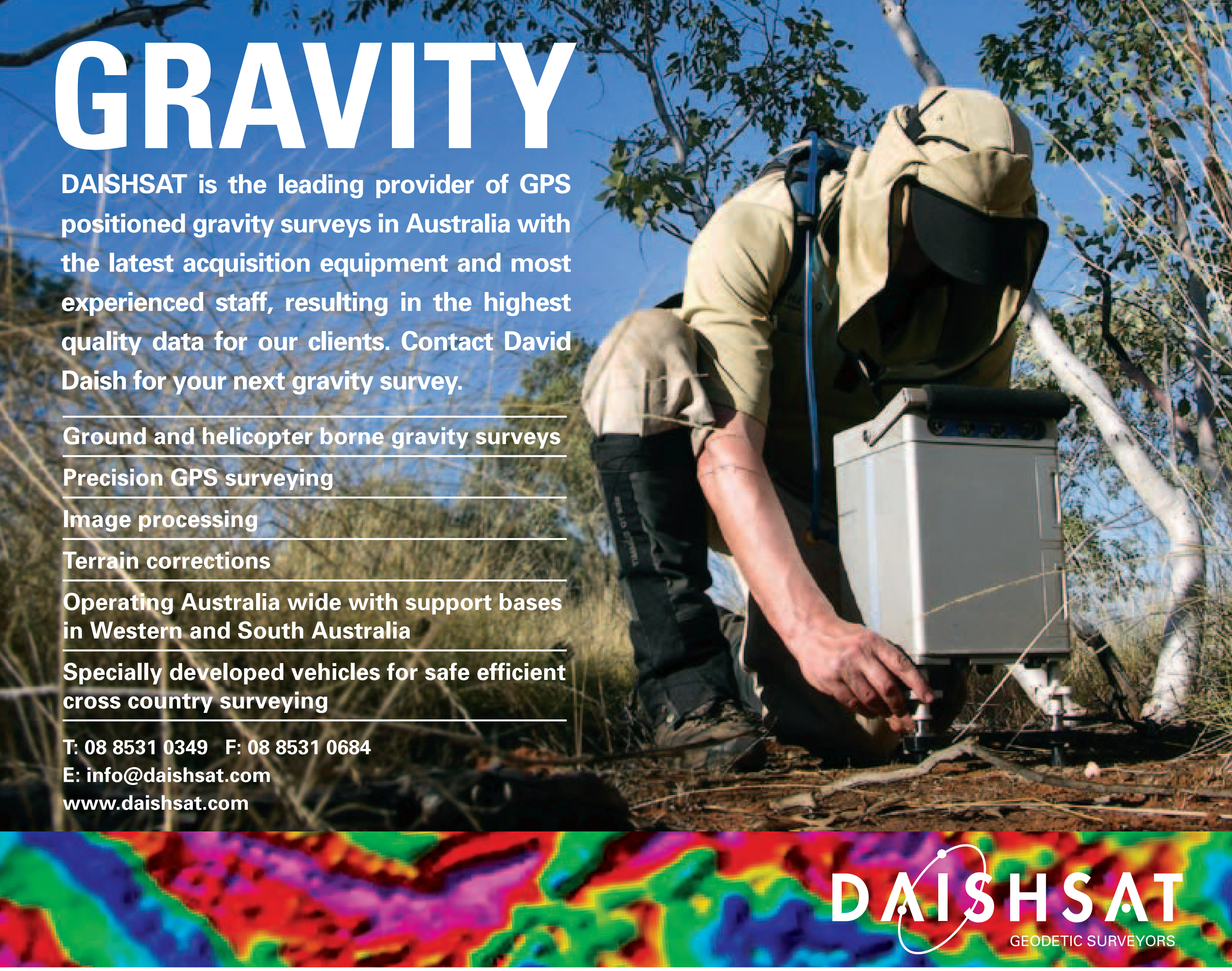
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