# Preview

Australian Society of Exploration Geophysicists

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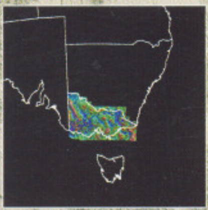

## New Total Magnetic Intensity Image of Victoria

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## ASEG Adelaide 2003

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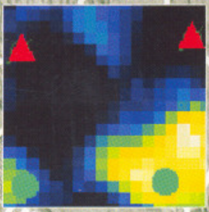

## Geophysics and Carbon Sequestration

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## Advertisers' Index



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## Adelaide Conference an outstanding success

There must be something about the timing of ASEG conferences. Straight after the 15th meeting in Brisbane the World Trade Center in New York was destroyed by Al Qaeda terrorists and now just after the 16th the US are bombing the guts out of Iraq with all manner of fearsome ordnance. Let us hope that by the time we go to Sydney in 2004 some common sense will be restored and we will not have similar happenings.

*David Denham*

Wars always add uncertainty and distraction to our normal lives and may well dim the memories of the excellent conference we attended in Adelaide.

Richard Hillis and Mike Hatch led a fine team at a superb venue to facilitate what must be one of the best ASEG conventions we have held. The figures speak for themselves:

- 674 registered delegates;
- Enough papers to fill five concurrent sessions;
- 62 exhibitors occupying 84 booths;
- 88 registered delegates to the 3D EM Workshop;
- 32 sponsors; and
- 140 people registered at the nine pre-conference workshops.

In addition 160 high school students visited the exhibition and 40 undergraduates together with 60 post-graduates attended the meeting.

Congratulations to the SA effort to deliver a first class convention.

## Margarita Norvill new contributor for WebWaves

I would like to welcome Margarita Norvill as the new compiler for WebWaves. Margarita completed her BSc with 1st Class Honours in Geophysics at Curtin University in 2001. She is currently a doctoral candidate at Curtin researching the "Use of Distributed Arrays in Electrical and Electromagnetic Imaging". Margarita has already published papers based on her Honours results and also serves on the ASEG's WA Branch Committee. When she is not working on things geophysical she enjoys photography, scuba diving, drinking beer, eating out, reading and cycling.

## In this issue

This issue focuses on the happenings at the Adelaide Conference and also Carbon Sequestration. Greenhouse gases are a major concern because of their link to climate change. It is important that we examine ways to reduce the concentration of these gases in the atmosphere so that global warming can be brought under control. If carbon sequestration can be made to work then geophysics will have a major role to play to implement this technology. The two papers presented at Adelaide, together with two short reviews on the main issues form the basis of the feature articles in this issue.

## Globalisation of Australian gold

It is good to see that the expenditure on both mineral and petroleum exploration has risen over the past two quarters (see Industry News). There is also hope that gold production will turn the corner and start to increase in 2003.

In 2002 production fell for the 5th year in a row down 3 per cent from 2001 levels to 275 tonnes. Peak production took place in1997 when 314 tonnes were produced. Perhaps of greater concern is that the top five mines in 2002 were all foreign owned. These are shown below:

| Mine | Owner | 2002 production, tonnes |
|---|---|---|
| Super Pit | Newmont/Barrick | 22.4 |
| St Ives | Gold Fields | 16.9 |
| Granny Smith | Placer Dome | 15.1 |
| Granites | Normandy NFM | 14.1 |
| Sunrise Dam | AngloGold | 11.9 |

Rationalisation of the world's gold industry has been taking place very actively during the last few years and Australian companies have been prime targets for overseas companies because of our low dollar against the US dollar.

Little seems to have been done by successive Federal Governments to reverse this trend, but they may have to act in the future for us to retain our jobs, research facilities and teaching institutions in Earth Sciences. If times get tough, then decisions on these issues made in overseas boardrooms may not necessarily be in the national interest

## Terry Crabb now Chairman of Publications

Andrew Mutton has stepped down from his position of Chairman of Publications after five years in that job. He has led the ASEG's publication activities with great skill and dedication since he took over in 1998, and the quality and robustness of the ASEG's publications owes a lot to Andrew's hard work, thoroughness and excellent people skills.

Terry Crabb has taken over from Andrew. Terry first served on ASEG Executive Committees in 1984, when the FedEx was in Adelaide, and has recently completed a review of Preview. He is therefore well qualified to take up this position and we hope to publish more on Terry and his plans in the next Preview.

***David Denham***

## Adelaide Conference a great success

The Adelaide Conference was an unqualified success on all counts, technically, socially and in meeting the ASEG's goals. It was apparent that the general feel of the Conference, fostered through its theme "Growth through Innovation", was upbeat in both the mineral and the petroleum sectors, and was confirmed by the large number of registrants (~670). This success is a tribute to the excellent and thorough work of the Adelaide Conference Committee and the co-chairs, Mike Hatch and Richard Hillis, which we, on the Executive Committee, applaud.

The time is opportune to address the question of what does this success means to the Society and its activities? Of special interest to us all is how the surplus is directed towards obtaining maximum value for the membership and the Society's future.

The answer to this is found in the outcomes of the various committee activities that occurred behind the scenes at the Conference. There were 9 individual committee meetings averaging 5-10 individuals, with the key ASEG Council meeting being attended by 36 members. These meetings are important to provide input to the deliberations and decisions that the Federal Executive makes on behalf of the membership.

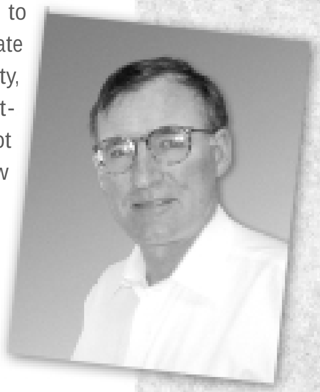
The Society is now in an excellent position financially, not only due to the success of the conferences, but especially due to the dedicated work that has been carried out in the last few years within the Finance and Publication Committees to target costs and improve efficiencies. We budget for a healthy surplus to meet expenses between conferences, consequently the success of the conferences are critical for our future viability.

## Publications

Publications are a continuing and major cost factor for the society amounting to $150-200k per annum. They also are a revenue earner from advertising of the order of $100k. The net cost of publications in a non-conference year is about $80k or about $60 per member. All areas of publication costs have been reduced during 2002, including the production of conference CDs and the careful management of Exploration Geophysics production costs. We are faced with falling advertising revenue and a continuing annual cost of Preview, so we have been addressing ways of minimising Preview's costs whilst maintaining the current quality standards and frequency of publication.

These are issues, which we gave attention to in our discussions. We looked at Preview, what it was doing and how it was received, and the feedback endorsed the value and content to our membership. The costs of $5 per member per issue were endorsed as a reasonable target. We are confident of where to put or efforts in future.

A key outcome of various discussions was a consensus to move towards electronic publication of Exploration Geophysics. The planning for this will be complementary with the specification of a web management system to improve the means by which we can communicate with each other. The trend is clear and is a necessity, highlighted by the advice of Walt Lynn (SEG past-President), who reported that if students cannot access articles they need from the web in a few minutes, those articles risk losing relevance.



*Kevin Dodds*

We are also at an advanced stage in discussions with SEGJ to prepare joint publications that will reach a wider audience in South East Asia for our geophysical expertise, and hopefully will facilitate our transition to electronic media.

## Membership

Our membership is declining slightly from year to year. This may have been anticipated by the economic circumstances, although we can report that this year renewals are well ahead of last year's figures, which augurs well for the future. We have sought to grease the machinery of the Society by completing a Procedures Manual and more importantly updating our constitution, to recognise the national identity of the Society.

## The future

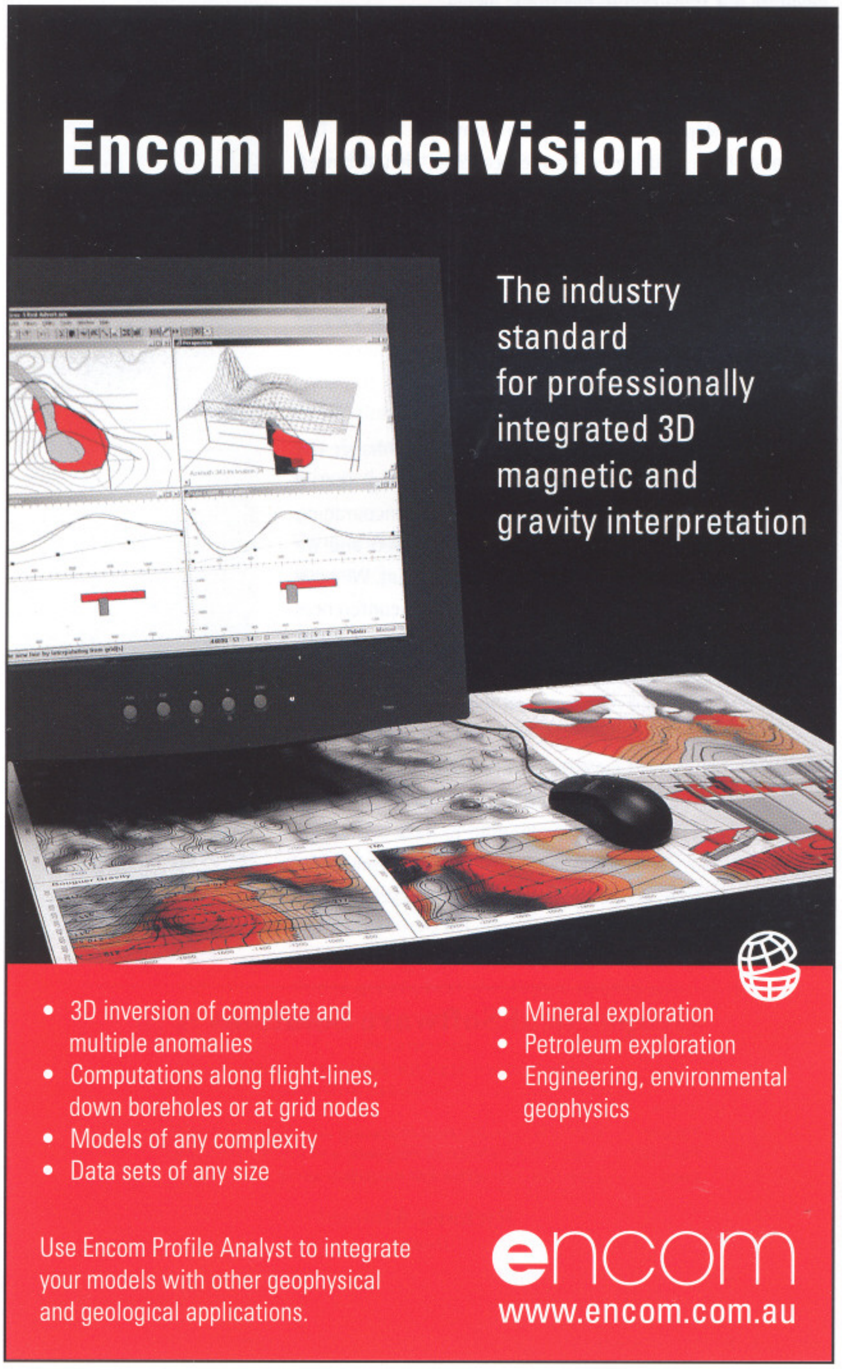
For the future we are focussing on initiatives to enhance the technical interchange of members in supporting special interest conferences and publications, and encouraging distinguished lecturers through our links with SEG and we are also looking to generate our own lecture circuit. We have looked ten years into the future in scheduling conferences and intend being smart about working with sister societies such as PESA and the GSA to improve our interaction and remain relevant to our members and industries' interests.

In closing, the current executive will report to the AGM to be held in Perth on 14th May, and pass the mantle to a new Executive at that time. We are planning to have a strategic review prior to the AGM so we can position ourselves for the "Growth" that was anticipated by the success of the Adelaide Conference.

## 2003

**May 27- 28**
ASEG Workshop
Theme: Interactive elimination of multiples, through the SEG Distinguished Lecturer Program
Venue: ARRC, 26 Dick Perry Ave, Kensington, Perth
Contacts: Cameron Crook, Andrew Long cameron.crook@woodside.com.au; andrew.long@pgs.com

**June 2-6**
65th EAGE Conference and Exhibition, Stavanger, Norway
Website: www.eage.nl




**June 16-18**
Symposium on Extreme Petroleum Operations
Hosted by: Curtin University's Department of Petroleum Engineering, the Centre of Excellence in Petroleum Geology and the WA Petroleum Research Centre
Venue: Sheraton Hotel, Perth
Contact: Jenny Dyer: motive@vianet.net.au

**October 13-15**
Water in Mining 2003
Theme: The role of water in a sustainable minerals industry
Venue: The Sheraton Brisbane Hotel and Towers
Sponsor: The AusIMM; Website: www.ausimm.com
Email: Conference@ausimm.com.au

**October 26-31**
SEG International Exposition & 73rd Annual Meeting, Dallas, Texas, U.S.
Email: meetings@seg.org

## 2004

**February 8-13**
Geological Society of Australia
17th Australian Geological Convention, Hobart, Tasmania
Theme: Dynamic Earth: Past, Present and Future
Website: http:www.17thagc.gsa.org.au

**August 15-19**
**ASEG, in collaboration with PESA**
**17th International Conference and Exhibition,**
**Theme: Integrated Exploration in a Changing World**
**Venue: Sydney Convention Centre, Sydney NSW**
**Website: www.aseg.org.au/conference/sydney**

## Preview Deadlines

*Preview* is published bi-monthly in February, April, June, August, October and December. The deadline for submission of all material to the Editor is the 15th of the month prior to issue date.

Advertising copy deadline is the 22nd of the month prior to issue date. Therefore, the advertising copy deadline for the **June 2003 issue will be 15 May 2003**. A summary of the deadlines is shown below:

| Preview Issue | Text & articles | Advertisements |
|---|---|---|
| 104 Jun 2003 | 15 May 2003 | 22 May 2003 |
| 105 Aug 2003 | 15 Jul 2003 | 22 Jul 2003 |
| 106 Oct 2003 | 15 Sep 2003 | 22 Sep 2003 |
| 107 Dec 2003 | 15 Nov 2003 | 22 Nov 2003 |

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*ASEG Silver Certificate Awardees will be listed in the June issue of Preview.*

### Western Australia – by Anita Heath

The WA Branch has allocated its 2003 officers and duties as follows:

President - Kirsty Beckett
Secretary - Megan Evans
Treasurer - Kim Cook
Web Maintenance - Don Sherlock
Membership - Levin Lee
Technical Speakers - Tim Cox, Peter Elliot and Anton Kepic
Media/Marketing - Anita Heath
Event Coordinator - Graham Jenke
Social Coordinator - Margarita Norvill
Sponsorship - Steve Mudge
DISC 2003 - Tom Kearney, Anita Heath, Don Sherlock, Brian Evans, and John Mc Donald

The newly elected committee has identified sponsorship and education as its goals.

### New South Wales – by Steve Webster

Meetings are held on the 3rd Wednesday of each month and we would be pleased to hear from any members travelling through Sydney who would be prepared to address the Branch.

Our AGM will be held on 16th April.

# New Members

We welcome the following new members to the ASEG. Membership was approved by the Federal Executive at its meeting on 25 February 2003.

| Name | Organisation | State |
|---|---|---|
| Alan Anderson | Santos Limited | SA |
| Yuzuru Ashida | Kyoto University | Japan |
| Volmer Berens | DWLBC | SA |
| Christopher Anthony Biesaga | Mallee Catchment Management Authority | Vic |
| Mark Alan Brokaw | Chevron Texaco | WA |
| Luke James Brown | Curtin University | WA |
| John Henry Cant | Makaira Geotechnical | WA |
| Lawrence Cho | WesternGeco | WA |
| Linda E Chung | De Beers Canada Exploration Inc | Canada |
| David Raymond Cousens | CSIRO Exploration and Mining | Qld |
| Richard George Cresswell | Bureau of Rural Sciences | ACT |
| Susan Katherine Dippel | WMC Fertilizers | Qld |
| Anthony J. Farmer | CSIRO - TIP | NSW |
| Ian Rees Garsed | MIM Exploration | SA |
| Michael John Gidding | ROC Oil Ltd | NSW |
| Richard R. Gosse | Anglo American | India |
| Scott Hammond | Bell Geospace Inc | USA |
| Michael Hartley | WesternGeco | Vic |
| Carol Hensley | BHP Billiton | Vic |
| Kathryn M. Holder | Flinders University | SA |
| Katie Marie Hulmes | University of Adelaide | SA |
| Matthew Fenton Hutchens | Adelaide University | SA |
| Joel Christopher Jansen | Minera Teck Cominco Chile Ltd | Chile |
| Booncherd Kongwung | PTT Exploration & Production PCL | Thailand |
| Matthew Lamont | BHP Billiton Petroleum | WA |
| A. Yusen Ley | Monash University | Vic |
| Sonny Lim | CTOC | Malaysia |
| Matthew Ludwig | University of Wisconsin | USA |
| Brigette Martini | HyVista Corp | NSW |
| Iain McLaren Mason | University of Sydney | NSW |
| William John McGaughey | Mira Geoscience Ltd | Canada |
| Benjamin Craig Mee | Woodside Energy Ltd | WA |
| Godfrey Ngaisiue | Geological Survey of Nambia | Nambia |
| Catherine Margaret Norman | Consultant | WA |
| MV Suwit Pabchanda | PTTEP | Thailand |
| Michael Joseph Raymondi | Conoco Philips Petroleum Australia | WA |
| Jan Rindschwentner | Santos Limited | SA |
| Glenn William Simon | Strike Oil | WA |
| Colin Peter Skidmore | Southern Cross Resources | SA |
| Craig P. Smith | CSIRO | Qld |
| Kurt Sorensen | University of Aarhus | Denmark |
| Andrew Hoon Wai Spyrou | University of NSW | NSW |
| S. Srinivas | Anglo American | India |
| Andrew Robert Stacey | University of Tasmania | Tas |
| King Seong Tan | WesternGeco | WA |
| Guy Taylor | CGG | WA |
| Matilda Thomas | Geoscience Australia | ACT |
| Jason Tilley | University of Adelaide | SA |
| Andrea Vizzoli | Monash University | Vic |
| Eric Carl Wedepohl | Geoforce | WA |
| Karen Andrea Weitemeyer | Australian Nation University | Canada |
| Adrian James White | NCPGG, University of Adelaide | SA |
| Nicholas Cory Williams | Geoscience Australia | ACT |
| Nanthawan Wisanuwong | | Thailand |
| Ian Andrew Wood | Subsurface Imaging | NZ |
| Changchun Yin | Fugro Airborne Surveys | Canada |
| Michael Wayne Zang | Anglo American Exploration | Canada |
| Lassina Zerbo | Anglo American | South Africa |
| Bing Zhou | Adelaide University | SA |

## USGS restricts public access to water resource data

One of the casualties of the so-called War on Terrorism has been the withdrawal from the public domain of several geoscience data sets in the US. The American Geophysical Union has reported (EOS, 11 February 2003) that "sensitive but unclassified" information such as the location of oil and gas pipelines, reservoirs and dams, and toxic or hazardous waste sites have been removed from publicly available maps. In 2002, the USGS requested that librarians in the US destroy CDs distributed by the Survey, which contained information about water resources in the country.

There is also a review being undertaken, at the behest of the White House, on US national space policy, including policies on commercial remote sensing, and foreign access to remote sensing space capabilities.

Will there be similar government responses in Australia?

## National Science Stocktake starts

In February 2003 Dr Brendan Nelson the Minister for Education Science and Training, asked Robin Batterham, the Chief Government Scientist, to undertake a review of Australia's science and innovation system, including the strengths, which should be maintained and developed, and weaknesses and gaps, which need to be addressed.

### Scope

The objective of the study is to take stock of the state of Australian science, technology and innovation by developing a comprehensive overview in terms of resources, players, linkages and performance.

The study will cover key aspects of the science and innovation system including:

- Australia's ability to generate ideas for innovation in science, engineering, technology and related research and development (R&D);
- The utilisation and commercial application of R&D and other innovation and the conditions which support this; and
- The development and retention of relevant skills for science, innovation and internationally competitive enterprise.

### Outcomes

The study will highlight the main features of Australia's science, engineering, technology and innovation system and map how the elements of that system interact. In addition the study will identify the key issues in Australia's science and innovation system:

1. Strengths which should be maintained and developed;
2. Weaknesses and gaps in science and innovation performance which need to be addressed;
3. Complementarities and areas of possible greater cooperation on Commonwealth and State/Territory government activities.

A report will be provided to the Prime Minister to assist in planning the future strategic directions for science and innovation.

### Stakeholders and consultations

A Reference Group of twenty, chaired by the Chief Scientist and including representatives from stakeholder groups including industry and the research community has been established. As far as I can see the only geoscientist on the Group is Bruce Hobbs, former Deputy CEO of CSIRO and currently Chief Scientist of Western Australia.

### Process

The plan is for an interim report to be released in May 2003 and the final report to be completed in late 2003.

This process could form the blueprint for post BAA funding of science in Australia in time for new programs to be included in the 2004/2005 forward estimates, so it should be taken seriously. However, with the tight timetable, and a restricted consultative process it will be difficult for the outputs to have any positive impacts. Cynics may think that it will be all about re-cutting the same sized cake, rather than making the meal more nutritious.

## CRC Program also under review

Meanwhile the Federal Minister for Science, Peter McGauran has instigated an evaluation of the Cooperative Research Centres (CRC) Program.

He said: "It is important that it continues to provide the most effective means and support for research that will benefit the Australian community, environment and economy".

There will be two elements to the evaluation. The first will assess the effectiveness and efficiency of the CRC Program in meeting its objectives and make recommendations for any improvements required. The second element will assess the clarity and appropriateness of the objectives for the CRC Program and make recommendations about possible future strategic directions for the Program including in relation to changes to key program design features and any associated change management strategies required.

The evaluation will involve wide community consultation and is expected to be completed around the middle of this year.

The CRC Program had its largest ever-funding round in 2002, providing more than $478 million, as a result of the additional funding committed by the Federal Government under Backing Australia's Ability, and from July 2003 the number of CRCs will grow to 71.

## Linkage Fellowships for researchers to move between industry and university announced

Dr Brendan Nelson announced in March that funding of up to $100 000 will be available for outstanding individual researchers to move seamlessly between universities and industry, as part of the Commonwealth's $90 million Linkage program.

This will be operated by the Australian Research Council (ARC) and will provide up to $100 000 support for outstanding researchers to base themselves in industry or public sector research organisations for a period of 3 to 12 months.

This initiative promotes research mobility as a pivotal factor in transferring information, ideas and expertise between the academic and industry sectors.

The Commonwealth funded Linkage Industry Fellowships will attract experience and expertise into universities from the private sector as well as increasing the involvement of senior academics in innovation and change in industry.

The Fellowships will enable private sector researchers to return to Australia's universities to educate and motivate the next generation of innovators, as well as encouraging high achieving university researchers to focus on the challenges of industry.

So if you think you can benefit by going from universities to industry or from industry to university, now's your chance.

## HECS debt to rise to nearly $12 billion

Almost 2 million students have been assisted to access university study through the Higher Education Contribution Scheme (HECS).

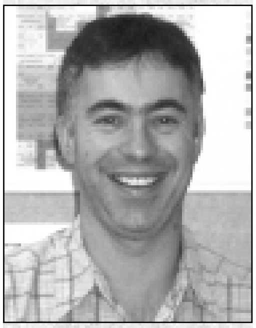
New data from The Australian Taxation Office (ATO) has revealed that more than 1.7 million people have taken advantage of the interest-free loan scheme since it was introduced in 1989.

The data show that 1 077 675 people currently have a HECS loan. Australian taxpayers are carrying the cost of these loans, which is currently around $9 billion but is forecast to rise to $11.5 billion by 2006 as more people take up loans, including through the Postgraduate Education Loan Scheme (PELS).

The Commonwealth Government funds the students' debt, but the current scheme clearly discriminates in favour of those who can pay their way without incurring debts.

***Eristicus***
*23 March 2003*

# People



*Richard Brescianini*

## Richard Brescianini appointed Director of Northern Territory Geological Survey

Congratulations to ASEG member Richard Brescianini who, in February this year, was appointed to the position of the Director of the Northern Territory Geological Survey.

Richard said "I'm absolutely delighted and feel privileged to be given the opportunity to lead Australia's best Geological Survey, am keen to accept the challenge, and that I couldn't have asked for it to passed on in better shape, having been moulded over the last 4 years into a highly focused organisation by Dennis Gee."

Richard Brescianini graduated with a BSc (Hons.) in geophysics from the University of Tasmania in 1985 after completing his undergraduate degree in geology and physics at La Trobe University. He joined BHP Minerals in Brisbane as an exploration geophysicist in 1987. Over the next 12 years he worked with BHP on base and precious metal exploration programs and was based in various locations throughout Australia, Canada and the US. During that time he was involved with successful discovery teams at Eloise (Cu-Au) and Cannington (Ag-Pb-Zn). He joined the Northern Territory Geological Survey (NTGS) in mid-1999 as Chief Geophysicist, coordinating all geophysical programs within the framework of the Northern Territory Exploration Initiative.

He thanks Dennis Gee, Richard West (BHP Billiton Vancouver), and Doug Price (Infofield Consulting - ex BHP) for providing the inspiration for management leadership, and Mike Asten for technical guidance and mentoring over the years.

Richard has been a member of the ASEG since 1987, and we wish him well in his new challenge.

## NTGS

NTGS has recently released four new products. These are:

1. The 2003 Elevation Map of the Northern Territory, produced by Roger Clifton. This product is available in both digital (100 m grid in ERS [ER Mapper] format on CDROM) and hardcopy (1:2.5M scale) format.

Also included on the CDROM is a spatial index outlining full specifications of all component datasets (both airborne and otherwise). The digital product is provided in GDA94 MGA53. The hardcopy version is in an Albers Equal Area projection. The 2003 Elevation Map of the Northern Territory can also be viewed on the NTGS Image Web Server at:
http://www.dme.nt.gov.au/ntgs/ecw/NT_magnetics.htm by simply choosing "Elevation" on the drop down menu. Place your order now for both digital and hardcopy versions of the 2003 Elevation Map of the Northern Territory through: geoscience.info@nt.gov.au

2. Approximately 255 000 line km of located and gridded magnetic, radiometric and elevation data from the Buchanan and Georgina airborne surveys, flown on behalf of NTGS during 2002. Survey locations are shown at: http://www.dme.nt.gov.au/ntgs/downloads/geophysics/m00-096.pdf.

Both surveys were flown at 80 m MTC along 400 m spaced N-S flight lines by Fugro Airborne Surveys. The spectrometer crystal volume utilised for both surveys was 33 litres. New flying occupies approximately 70% of Buchanan and 90% of the Georgina survey area. Reprocessed existing private sector airborne data (200-300 m line spacing; 1984-1997 vintage) has been incorporated over the remainder. Please be advised that raw 256 channel radiometric located data is also available upon request. The 256 channel data will not automatically be sent to you as part of a regular data order. In addition, there is no need for you to re-submit an order for Buchanan or Georgina if you had placed an earlier order.

Survey location, specifications and located images for Buchanan, Georgina and all other NTGS surveys are available on the NTGS Image Web Server at: http://www.dme.nt.gov.au/ntgs/geophysics/air_map/air_geo_map.html.

Order your CD copy of located and/or gridded data for Buchanan and Georgina from geoscience.products@nt.gov.au.

3. The 2003 Magnetic Map of the Northern Territory, produced by Roger Clifton. This product is available in both digital (100 m grid in ERS [ER Mapper] format on CDROM) and hardcopy (1:2.5M scale) format. The Magnetic Map of the Northern Territory comprises all datasets as indicated on the diagram. Also included on the CDROM is a spatial index outlining full specifications of all component airborne datasets. The digital product is provided in GDA94 MGA53. The hardcopy version is in an Albers Equal Area projection.

The 2003 Magnetic Map of the Northern Territory can also be viewed on the NTGS Image Web Server at: http://www.dme.nt.gov.au/ntgs/ecw/NT_magnetics.htm.

4. The 2003 Radiometric Map of the Northern Territory, also produced by Roger Clifton.

This was released at the Adelaide ASEG Conference, and comprises its component grids – potassium, thorium, uranium, total count and the high-pass filtered total count.

Included is all NTGS high-resolution data, mainly flown at 400 m line spacing between 1974 and 2002. The Map also includes high-resolution surveys flown by AGSO (now Geoscience Australia, formerly BMR) over Tennant Creek (1998), Port Keats (1994) and Mt Theo-Highland Rocks (1993). The high-resolution grids are merged in with the backdrop of some regional scale grids, flown by BMR in the 1970s. These grids, as well as many high-resolution uranium and total count grids, had to be decorrugated before merging.

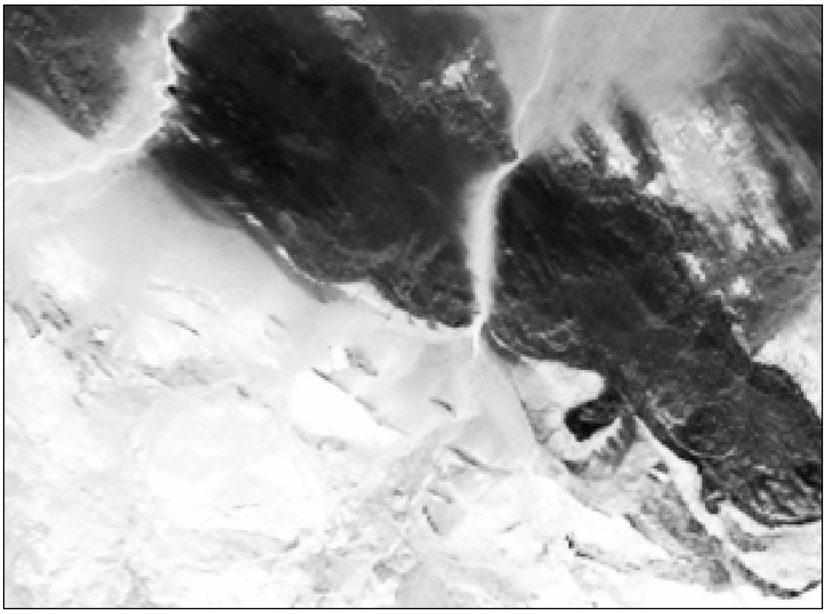
Decorrugation turned out to be the main solution to the stray variance, which interfered with the scaling of the component grids. There were more than a hundred source grids for each of K, Th, U, and TC, so full reprocessing for all datasets was simply not feasible.

In addition, spline-gridded data often failed to mate with minimum curvature-gridded data, so that required regridding too. The extra variance implied by the spline method seemed to have affected the scaling and may even have been anisotropic, affecting cross-grain joins differently to those along the grain.

Surveys younger than 1997 purport to be calibrated, but often mismatch. Where available, calibration of a survey is applied to a central subset and its flanges warped to meet the neighbours. Although quite crude, this method allows calibrations to be propagated across the surveys of the state.

Adjustment, that is the warping of the separate grids, has been conducted at degree two. The severity of the adjustment is somewhat less than the standard deviation of the signal, so uncertainty exceeds 50%. Clearly the calibration is incomplete and grid values are ballpark rather than accurate. To some degree, all grids of a survey run high or low together, so relative concentrations, represented as hues in the Map are more consistent than the values of the separate elements.

The dynamic range, that is the difference between bright areas and dark, is considerable, more than a printer can



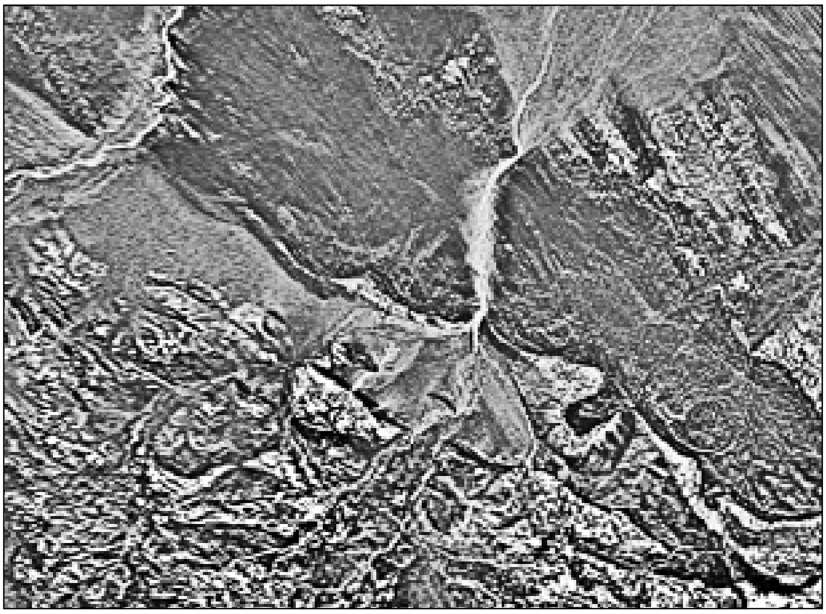


*Fig. 1. (Top) Subset of the total count image, equalised over the whole NT. The range of light and dark is so great as to render the printed image useless. The area, near 22.5 degrees S and 135 degrees E, is about 100 km across.*

*Fig. 2. (Above) The same area, with a high-pass filter run through the total count. Soil units are clearly delineated. With K, Th, and U in the red, green and blue tints, units of interest can be identified and traced.*

express and still show detail. Moreover, this range is the least reliable feature of the stitches.

Spatial variations however, are reliable on scales shorter than the survey widths less than 100 km or so. It seemed desirable to filter out the long wavelengths and enhance the more useful, shorter wavelengths. As the eye only registers one intensity rather than three, the high-pass filter was applied just to the total count. Edges of radiating units are now quite sharply defined, the boundaries appearing as the shortest wavelength detail.

By substituting the total count, high-pass filtered, as the intensity layer and potassium, thorium and uranium conventionally assigned to red, green and blue, the result is effectively a statewide soil map.

Users can zoom in and download their subset of interest from the "KUThTC_RGBI" image on the NTGS image webserver at: http://www.dme.nt.gov.au/ntgs/ecw/NT_magnetics.htm

The Radiometric Map is a companion product to the 2003 Magnetic and Elevation Maps of the NT and 2002 Geological Map. All three products are available in both digital (ER Mapper ERS & ALG, and MapInfo TAB formats on CDROM) and hardcopy (1:2.5M scale) formats.

The NTGS believes that this is the first successful attempt at a contiguous radiometric mosaic on such a scale.

Also included on the CDROMs is a spatial index outlining full specifications of all 133 component airborne datasets, which date from 1975 to 2002 (150-3000 m line spacing).

The digital product is provided in GDA94 MGA53 and the hardcopy version is in an Albers Equal Area projection.

Various Territory-wide radiometric, elevation, magnetic and gravity images can be viewed on the NTGS Image Web Server at: http://www.dme.nt.gov.au/ntgs/ecw/NT_wide.htm

***Roger Clifton,***
***NTGS***

# Preview Classified Advertising

ASEG understands that with the mineral exploration industry experiencing tough times, members continue to seek new and cost effective ways of delivering a focused message to their potential customers.

Preview Classified Advertising has been designed with this in mind and, at just A$55 (including GST)** provides an economical medium through which companies can advertise their services and contact details.

Conditions apply when advertising in Preview Classified Advertising so, for more information, contact Will Butun on +61 8 9446 3039 or email will@oilfield.com.au.

# New 3D visualisation centre opened by Esso in Melbourne

Esso Australia has just completed the installation of a state-of-the-art Visualisation Centre in its Southbank office that greatly enhances its interpretation capacity.

The installation of the Visualisation Centre has coincided with a decision by Esso Australia's parent company to establish a new South-East Asian/Australasian geoscience group in Melbourne. The new 15 member group is responsible for identifying and evaluating new exploration and venture opportunities for the company in the South-East Asia / Australia / PNG region. It consolidates smaller teams which were previously located in Melbourne, Jakarta and Malaysia.

"We have assembled an outstanding team of experienced geoscientists who bring a mix of specialised expertise and extensive local knowledge to our quest for prospective new exploration acreage in this part of the world," said Dr Doug Schwebel, Exploration Director, Esso Australia. "Once we have completed our evaluation of a project we hand it over to the various in-country geoscience teams for progression."

The Visualisation Centre allows Esso's geoscientists to display images from both, or either of the Unix and PC dual screen desktops on to a 2.4 m by 4.8 m screen through two high-resolution, high-brightness, digital light processed (DLP) projectors. Alternatively, the system can take feed from a visitor's laptop.

This greatly assists the collaborative process of interpreting seismic data. It means a large group of geoscientists can sit together to discuss subsurface formations while manipulating the images on screen. By utilising the internet and 'virtual meeting' programs the group can even be extended to involve participants from overseas said Doug Schwebel.

In the past a group discussion would involve putting together a PowerPoint presentation to be displayed in a meeting room. This limited the data being looked at to pre-determined static displays. Because we can now work with the live, on-line datasets, the discussions can be far more interactive, and able to respond in real time to 'what-if' questioning" said Dr Schwebel.

The quality of the projection system in Esso's new Visualisation Centre allows the images to be displayed in daylight and, coupled with special headsets, in three dimensions for selected 3D enabled applications.

The 3D effects are similar to the 3D images at the Imax theatres. The reservoir formation image comes right out of the screen and can be manipulated in any number of ways. Anything we can do on our desktops can be done on this screen, plus we have the added advantage of the 3D visualisation. The Visualisation Centre has also proved to be an excellent training tool and has even been used to run training sessions from Esso's parent company in Houston.

Esso is currently working on the analysis of the vast amounts of 3D seismic data collected in 2002 by it's $55 million Northern Fields survey, the largest 3D seismic survey ever undertaken in Bass Strait.

# New total magnetic intensity image of Victoria

In 1994 the acquisition of detailed (down to 200 metre line-spacing) airborne magnetics and radiometrics commenced as part of the Victorian Initiative for Minerals and Petroleum (VIMP). The airborne geophysical program, which covered all of Victoria, was completed in 2001. The grids and located data from these surveys are available free of charge. Changing acquisition specifications and processing capabilities during 1994-2001 led to data being provided to the Department in varying formats and quality.

To overcome these variations, the located data of the VIMP, company and Geoscience Australia surveys were converted to ASEG-GDF format, and then improved grids of the TMI data were produced to a uniform standard. The cell size and origin of each TMI grid were chosen to avoid re-sampling when the individual surveys were merged together. In addition, each TMI grid was further processed to produce a first vertical derivative (1vd) TMI grid, reduced to the pole (rtp) TMI grid and a 1vd rtp grid. The new survey grids of the magnetic data show significantly fewer gridding and processing artefacts when compared to the original survey data.

Examples of the variability of original survey grids are presented in Figures 1a, 2a and 3a with corresponding improved grids in Figures 1b, 2b and 3b. Each image below is approximately 10 km x 10 km.

The improved TMI grids have now been merged and stitched together to form a seamless coherent TMI grid for the whole of Victoria (Figure 4).

The new TMI grid of Victoria and other geoscientific products will form part of the 15th VIMP data release and seminar in Melbourne on 26 May 2003. For information on this release contact Alan Willocks (03) 9412 5131, Department of Primary Industries.

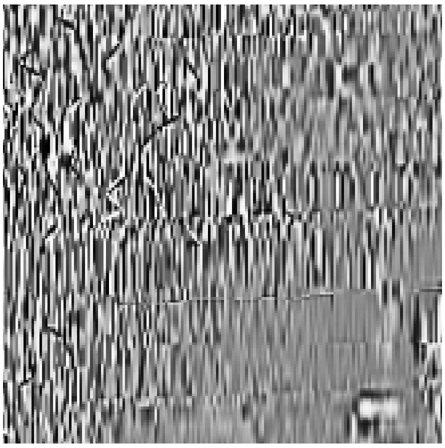


*Fig. 1a.*

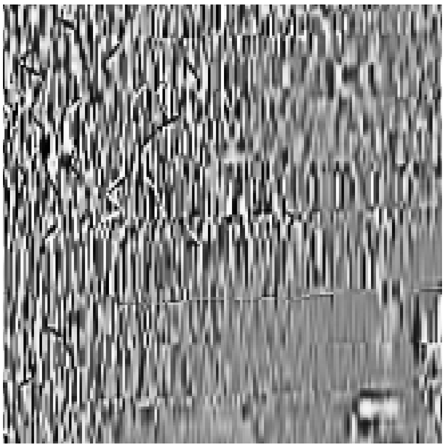


*Fig. 2a.*

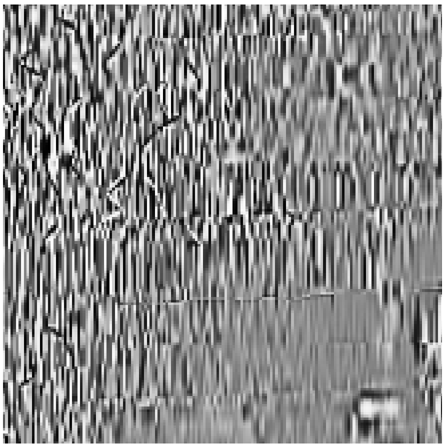


*Fig. 3a.*

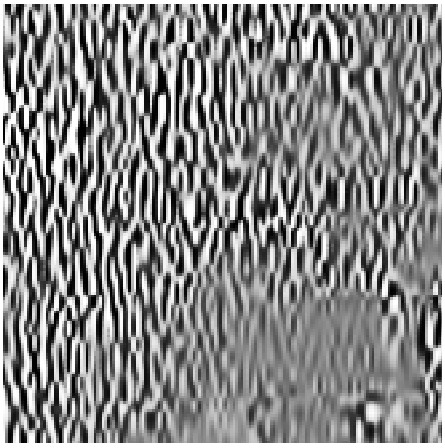


*Fig. 1b. Relevelling and gridding over basalt showing improved resolution of bedrock window.*

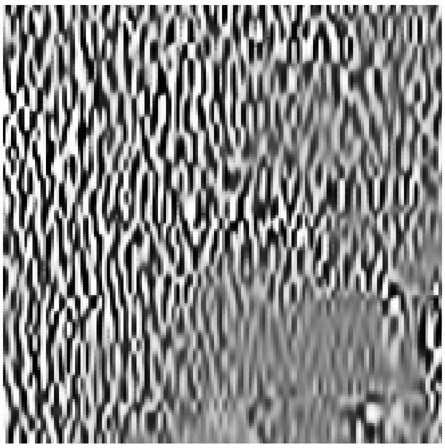


*Fig. 2b. Relevelling and gridding improved extents of dyke.*

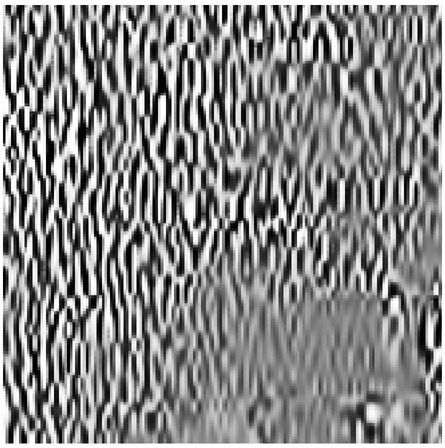


*Fig. 3b. Relevelling and gridding improved granite and palaeochannels.*

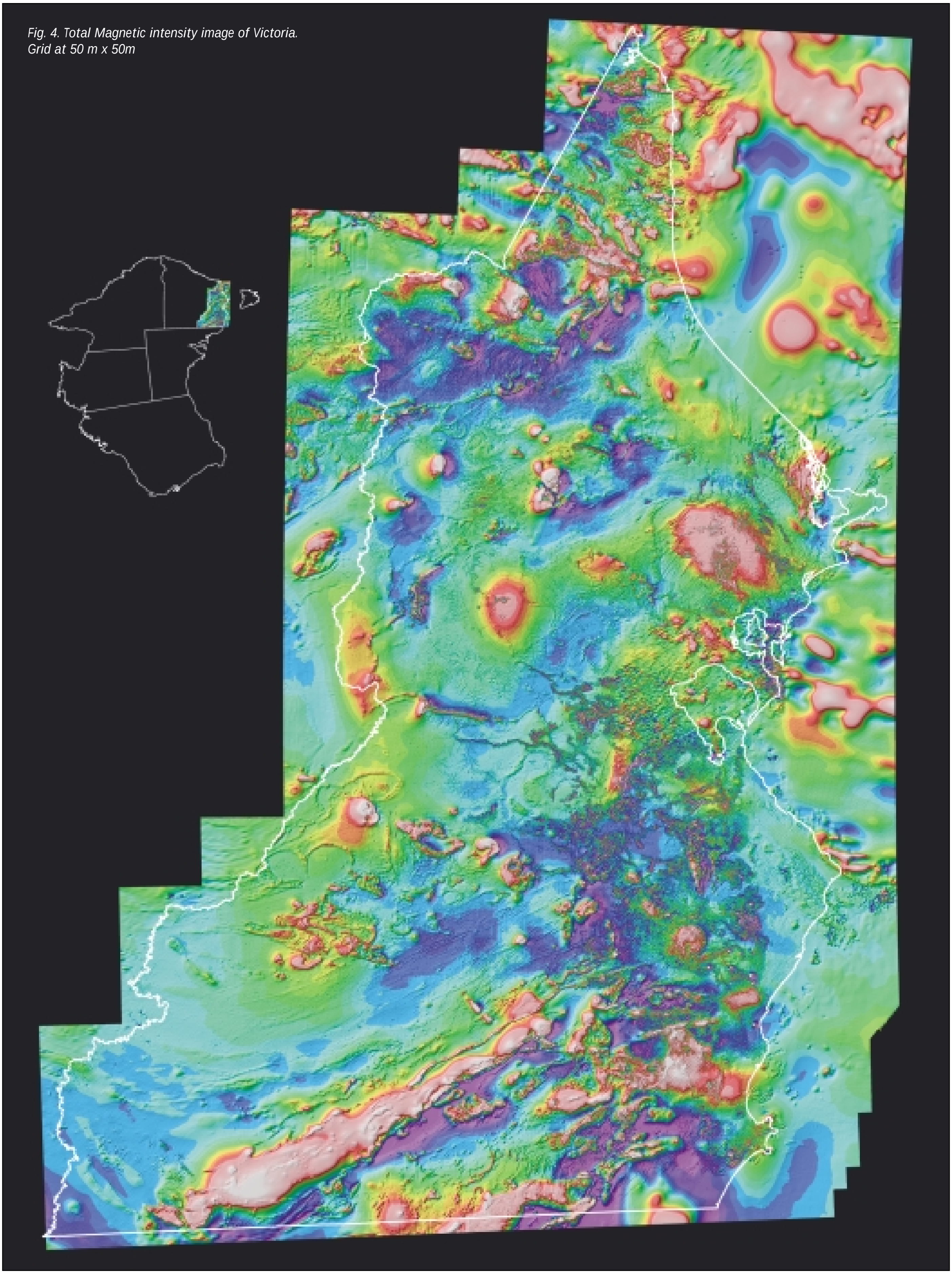


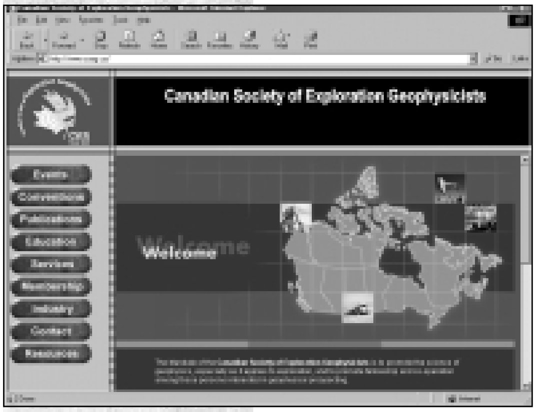
Fig. 4. Total Magnetic intensity image of Victoria.
Grid at 50 m x 50m

# International Geophysical Societies (Part 1)

International geophysical societies consist of three main types Professional, Exploration and Solid Earth. Professional societies deal with licensing, professional standards and ethics. Exploration societies are concerned with the search for oil, gas, minerals and water, with the intention of economic gain. Solid Earth societies relate to the study of the Earth, its environment and the solar system. These cover a range of disciplines including: geodesy, atmospheric electricity, geothermometry, hydrology, oceanography, meteorology and techonophysics. The major Exploration Societies are described below:

## Exploration Geophysics

CSEG – Canadian Society of Exploration Geophysics
★★★★★
http://www.cseg.ca/




The CSEG was established 1949 to promote the science of geophysics, specifically exploration, and to promote fellowship and cooperation among those persons interested in geophysical prospecting.

***All of the CSEG journals may be viewed and downloaded for FREE on the web***. CSEG journals include the '*Recorder*' and the '*Canadian Journal of Exploration Geophysics*'.

A joint conference with the Canadian Society of Petroleum Geologists (CSPG) is to be held at Round-Up Centre, Stampede Park Calgary, from June 2nd to 6th 2003.

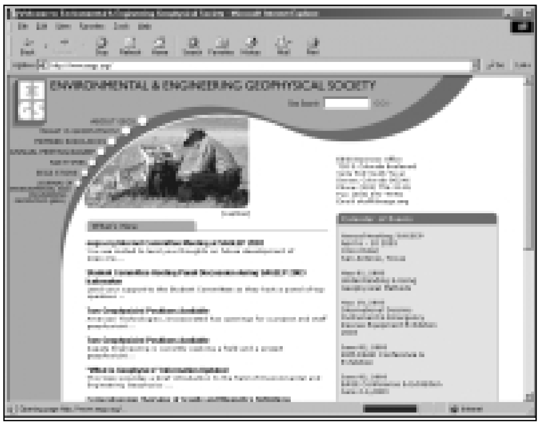
EAGE - European Association of Geoscientists and Engineers
★★★★½
http://www.eage.org/


EAGE looks after combined interests of those active or interested in the application of geosciences and related engineering disciplines to solutions of problems in petroleum exploration and production, in mineral industries, for water production, environmental protection or civil engineering. Today EAGE has two divisions, the Oil and Gas Geoscience Division and the Near Surface Geoscience Division.

The EAGE publishes the following journals; *Near Surface Geophysics*, *Petroleum Geoscience*, *First Break*, and *Geophysical Prospecting*.

Stavanger, Norway is the location for the 65th EAGE Conference& Exhibition, 2nd to 5th of June 2003.

EEGS - Environmental and Engineering Geophysical Society
★★★★½
http://www.eegs.org/




Founded in 1992 in the USA, EEGS is affiliated with the ASEG. There is also a European section. EEGS publishes the '*Journal of Environmental and Engineering Geophysics (JEEG)*' and '*FastTimes*'. All FastTimes Issues may be viewed on the web. This is an excellent site for an introduction to geophysics, with the 'What is Geophysics' page.

A Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP) will be held from the 6th to the 10th of April 2003 at San Antonio, Texas.

KSEG - Korean Society of Exploration Geophysics
★★
http://www.seg.or.kr

A difficult website to explore as everything is written in Korean, for a free translation check out http://world.altavista.com/

KSEG up and coming conference at Seoul National University, entitled "*International Symposium on the Fusion Technology of Geosystem Engineering, Rock Engineering and Geophysical Exploration*" will be held from the 18th to the19th of November 2003.

SAGA - South African Geophysical Association
★★★
http://www.sagaonline.co.za

SAGA was founded in 1977 to encourage the development of Geophysics in South Africa and has since grown to over 350 members worldwide. SAGA publish the '*South African Geophysical Review*', the 8th SAGA Biennial Technical Meeting and Exhibition "*Tracking down the Big Five*" will be from the 7th to the 10th of October 2003 at Pilanesberg Notional Park, South Africa. The big five, are; diamonds, ferrous metals, fossil fuels, gold, and platinum.

SEG - Society of Exploration Geophysics
★★★★½
http://www.seg.org/


Probably the most well know geophysical society in the world, the SEG was established in 1930. It has more than 16 536 members working in 110 countries. Take the time to look at the Sections and Societies page; it has links to many other SEG sections world wide, such as; Vietnam SEG, Uzbekistan SEG, Azeri SEG, Romanian SEG, SEG Russian Section and much more.

Journals published by the SEG are '*Geophysics*' and '*The Leading Edge*'. The 73rd annual meeting of the SEG will be "*Geophysics – An International Language*" Dallas, Texas, 26th to 31st October 2003. Watch out for the 76th Annual Meeting in New Orleans in 2006.

SEGJ - Society of Exploration Geophysics Japan
★★½
http://www.segj.org/index_e.html

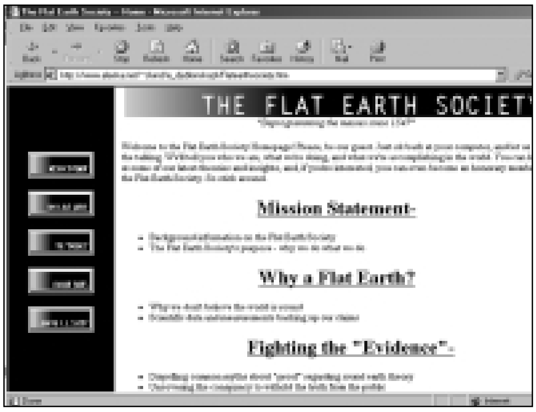
The Society of Exploration Geophysicists of Japan (SEGJ) was established in 1948 with the objectives to promote the science and technology of geophysical and geochemical exploration as well as to encourage mutual communication among the members.

SEGJ was initially composed of 416 members and 18 corporate members. The first issue of the journal of '*Butsuri-tanko*' (Geophysical Exploration) was published a month after the establishment. The name of the journal was renamed '*Butsuri-tansa*' in 1986. The SEGJ currently consists of 1623 members and 182 corporate members.

The 7th International Symposium on Recent Advances in Exploration Geophysics (RAEG) was held in Kyoto Japan in January this year.

## A site of interest

FES - The Flat Earth Society
★★★★
http://www.alaska.net/~clund/
e_djublonskopf/Flatearthsociety.htm




Deprogramming the masses since 1547. For over five hundred years humanity has believed the 'round Earth'. A small but diligent band of individuals has preserved the knowledge of our planet's true shape. The FES wish to spread the truth that it has forever been Flat. Using whatever means necessary and relying heavily on a callous disregard for the lives and well-being of there members, they have slowly but steadily been spreading the news. To become a member of the Flat Earth Society, there is a rigorous testing process, in which you have to answer questions such as: favorite jellybean flavour, favourite radioactive isotope, and favourite eastern European nation. After submission you must wait to here if you have passed or failed.

## Star Rating

The star rating is calculated from estimates of the following parameters:

| | |
|---|---|
| Content/information available on web pages | 2 |
| Navigation friendly | 1 |
| Aesthetically Pleasing | 1 |
| Currency | 1 |
| TOTAL | 5 |

In the June *Preview* more international geophysical society sites will be reviewed.

# The Opening Ceremony

It was good to have contributions from our sister societies at the Opening Ceremony. The SEG was represented by Walter Lynn a former President, the EAGE was represented by its Secretary-Treasurer Henk van Montfrans, and the SEGJ by its President Yuzuru Ashida. Summaries of the opening remarks are given below, and Walt's keynote address will be in the June Preview.


*Walt Lynn (top) and Henk van Montfrans (above)*

## Henk van Montfrans, EAGE

On behalf of the members of the EAGE I have come to extend our best wishes. I also congratulate you with this 16th Conference and Exposition with the theme "Growth by Innovation". A key factor in innovation is the global nature of our profession. New ideas and techniques are created in universities, research institutions and of course industry. Their dissemination takes place through new products of industry but also by Associations as ours, namely through the journals and big gatherings like this conference. By actively and mutually supporting these conferences we further improve this process.

EAGE's objectives are to promote the development and application of the geosciences and relating engineering subjects, and to foster the communication between those that are active in these fields. Our membership is steadily growing and now around 7000. We have a strong basis in Europe and we are proud to serve some 200 Australian members.

EAGE differs somewhat from its sister organizations. We are an integrated association. There is horizontal integration in two ways:

- We encompass research and the application of existing techniques.
- We deal with exploration issues and with production/engineering oriented ones.

There is also vertical integration because within EAGE we have now two divisions:

- The Oil and Gas Geoscience Division, with geophysicists, petroleum geologists and reservoir engineers. The journals are Geophysical Prospecting and Petroleum Geoscience.
- The Near Surface Geoscience Division, which was created when the Environmental and Engineering Geophysical Society – European Section recently joined the EAGE. Its journal is Near Surface Geophysics.

(The journal for the whole of the EAGE is *First Break*)

We are convinced that these "deep" and "shallow" oriented professionals, that have so little contact in their day-to-day life, will strongly benefit from being members of one and the same organization. There is much scope for cross-fertilization between these two job focuses.

Let me conclude by wishing you a very successful conference and exhibition here in Adelaide. Good luck.

## Yuzuru Ashida, SEGJ

*Yuzuru Ashida*

On behalf of SEGJ, it is my pleasure to contribute to the 16th ASEG Conference.

I would like to introduce the activities and projects related to the geophysical and geo-technical field in Japan. These are as follows:

### 1. High level radioactive disposal

This problem is very serious in Japan. According to the procedure to final disposal regulated on 2002, geophysical, geological and geo-technical surveys and tests will be carried out during next 20-30 years. Among them, the geophysical survey is expected to occupy a main role.

### 2. Exploration and development of methane hydrate

The Japanese government is carrying out the fundamental research at the Mackenzie delta in Canada with the USGS, Canada and Germany. Judging from a recent report they recovered methane from hydrate by injecting hot water.

In the Nankai trough, we recovered methane hydrate from core sample in the well drilled in 2000.

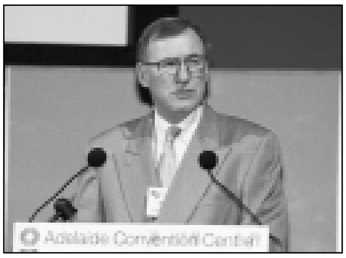
In offshore Japan, we have detected many BSR phenomena, carried out 2D and 3D seismic reflection surveys and will drill several wells in near future.

In this field, geophysical techniques are essential.

### 3. Geo-sequestration

The project of geo-sequestration that injects the extracted $CO_2$ from a steam power plant into the coal seam and recovers the replaced CH4 has started this year and will continue for 5 years.

Geophysical surveys are required to obtain the structural and physical information concerning with coal seam, and the possibility of micro-earthquake occurrence due to the injection of $CO_2$.



*(Far left) Kevin Dodds making an impact at the Opening Ceremony.*

*(Middle) John Ellice-Flint explaining the technical issues and challenges for Santos and the geophysical industry in Australia.*

*(Left) Roy Woodall explains what it takes to be a good manager, as well as a successful geophysicist.*

4. Earthquake prediction

Unfortunately, we had the serious Hanshin-Awaji earthquake in 1995.

This occurred, where the Japanese government had predicted a major earthquake.

Many geophysical surveys by shallow reflection methods, electrical soundings and magnet-telluric surveys have been undertaken in order to examine whether faults exist or not, and to identify where these faults intersect the surface for determining the location of the trench.

5. Public utilisation of shallow subsurface zones in urban areas

In 2000, the law of public utilisation of shallow subsurface zone in cities was published in Japan. The deeper zone either 40 m or the support layer +10 m is utilized for freeways, tunnels, railways or aqueducts and so on. The geophysical surveys are performed to link the depth of the support layer identified by well data.

6. Evaluation of soundness of road slope

Since almost 30-40 years have passed after the construction of many freeways in Japan, the maintenance and management of slopes and tunnels using the geophysical techniques are required in order to prevent landslides and slumping.

As mentioned above, our SEGJ has the tailwind and acts positively in order to respond to social requirements such as energy supply, civil engineering, environment protection fields.

We hope to have the support from ASEG and I thank you very much for your attention.

We then heard from Kevin Dodds, President of the ASEG, John Ellice-Flint, Managing Director of Santos Ltd and Roy Woodall, former Director of Exploration Western Mining Corporation. Photographs showing their participation are shown above.

# ASEG Awards at Adelaide 2003

## Lindsay Ingall Memorial Award for ***the promotion of geophysics to the wider community***

### Mike Smith

It is most appropriate that Mike Smith should receive this award for several reasons. Lindsay Ingall is remembered for his *energy* and *enthusiasm* and these are the very same words that immediately spring to mind with regard to Mike. Lindsay admired Mike greatly and vice-versa.

Mike overlapped with Lindsay on the Australian Institute of Geoscientists (AIG) where he has been a Councillor since 1992. During this time he was AIG President for a record 3 years from 1993-96 and is especially known for his advocacy for and then establishment of the mechanism for registration of Australian geoscientists. He remains Chairman of the AIG's Registration Board.

Along with his energy and enthusiasm, Mike also impresses all who know him with the tireless *effort* and extreme *dedication* that he applies to the many activities he undertakes. In all of these he is continually promoting geophysics to geoscientists, politicians, the media and the general public.

Currently he is doing this by being, all at the same time, the Chairman of the Australian Geoscience Council (AGC) for the past four years, the geoscience representative on the Board of the Federation of Australian Scientific and Technological Societies (FASTS), an active Councillor on the AIG and a very active member of the ASEG. Mike received the ASEG Service Medal in 2001 for his "extraordinary and outstanding service to the ASEG over many years".

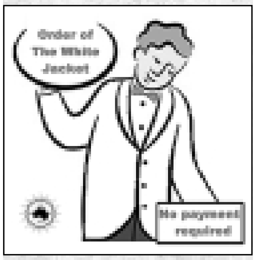
*Mike Smith (right) receives the Lindsay Ingall Award from President Kevin Dodds*

As if this is not enough, he has participated for two years in sessions of "Science Meets Parliament", in Canberra, to promote the value and concerns of geophysics to Federal politicians, and through the Geological Society of Australia (GSA), he has lobbied the NSW Department of Education to include Earth Sciences in the secondary school's curriculum.

Typical of his very pro-active involvements is his personal establishment of FAST'S first newsletter, "Science News". It is distributed to members and the general public informing of the latest events and activities in Australian science. Of course, Mike ensures that this includes items on geophysics.

Because he felt recently that GSA conventions should have a special session on the application of geophysics to geology, at the last convention in July 2002 he single-handedly organised the first of what will now be a regular feature at all future GSA conventions.

As he is not one to waste a moment, during his time as President of the ASEG in 1999, Mike gave interviews to the media on the current situation in mineral exploration whilst playing golf.




What is this? See page 20 for more information.

Through his extensive knowledge and interest in geology and geochemistry as well as geophysics, Mike has developed strong associations throughout the geoscience community. He is respected by many geologists as one who is able to converse in the same language and also able to convince them of the appropriateness of geophysics. One very prominent geologist described Mike as "the geologist's geophysicist".

At the symposia sponsored by the Sydney Mineral Exploration Discussion Group (SMEDG) in 1993, '96, '97 and '98, he was responsible for organising sessions involving geophysics. To many geologists he is recognised as a long-time promoter of aeromagnetics and CSAMT. He has been particularly effective in this throughout the Pacific region and has co-authored several papers with many prominent geologists in non-geophysical journals as part of these activities.

As he is always anxious to learn more geology, Mike will eagerly join geology excursions, but not without arming himself with a portable conductivity meter and proceeding to interest all other members of the group with his rock measurements. With groups of students, he has to be restrained from enthusing them to death.

As Mike's impressive enthusiasm shows no signs of diminishing, we can be hopeful that he will continue to promote geophysics to the wider community so very effectively for many more years to come.

## The Grahame Sands Award for ***Innovation in Applied Geophysics***

### Graham Boyd

Graham Boyd receives his Graham Sands Award from President Kevin Dodds, while Mike Hatch (left) one of the Conference Co-chairs looks on.

This award is based on an endowment made by members of the ASEG and the geoscience profession in memory of Grahame Sands, who was tragically killed at the prime of his life and career, in an aircraft crash in 1986, whilst developing and testing new navigational equipment for geophysical survey aircraft.

Graham Boyd graduated from the University of Melbourne in 1972, with a BSc (1st Class Hons). He then did a stint at the ANU, working on a PhD, but pulled out, presumably because of boredom or monetary reasons. In 1975, he obtained a DipEd, and taught at high school for two years. Graham's geophysical career finally got underway when he joined the late Geoff Dickson at Newmont Holdings Pty Ltd in February 1978, based in Melbourne. At Newmont he worked with and held his own with such luminaries as Misac Nabighian, Colin Barnett and Maurie Davidson. From 1978 to 1985, Graham was actively involved in geophysical exploration throughout Australia, including the giant Telfer gold deposits. During this period he authored and co-authored several papers on transient electromagnetics and the Newmont ElectroMagnetic Pulse (EMP) system. He was Senior, then Chief Geophysicist, for Newmont Holdings Pty Ltd.

In May 1985, Graham moved to Tuscon, Arizona, to take up the role of Acting Director of Newmont's geophysical department. He returned to Australia in November 1987, as Chief Geophysicist of Newmont Australia Ltd. During his initial Newmont career, Graham became actively involved in the development of geophysical software and instrumentation. He converted most of the geophysical software from mainframe computers to PCs, worked on the development of the first fully digital version of the EMP system, and was responsible for the development of digital altimeters for elevation control in gravity surveying.

In early 1989, he left Newmont to become an independent consultant, commercialising the innovative *Geosolutions* geophysical processing and imaging software package.

His time as a consultant was appropriately cut short when he joined the emerging Poseidon Exploration Ltd, as Chief Geophysicist in late 1989, moving to Adelaide in 1990. Here, his brief was to establish an exploration geophysics group and to undertake leading edge research and development. Poseidon ultimately became the Normandy Mining Group and was taken over by Newmont Mining Corporation in early 2002. Thus, Graham finds himself back where he started all those years ago.

During his time at Normandy he was responsible for:

1. Rapid sampling magnetometers, based on Overhauser sensors;
2. Ground and drill hole time domain electromagnetic prospecting systems, known as the POSEM. These are synchronized via GPS timing and are capable of transmitting currents of up to 100 A;
3. A helicopter-borne magnetic/radiometric surveying system;
4. A high powered IP transmitter; and
5. A helicopter-borne transient electromagnetic prospecting system – the HOISTEM, for which this award is being presented.

Development of the HOISTEM system was, in part, a collaborative project with Newmont. Graham had seen, through his earlier developments, the benefits that could be achieved by a high-resolution TEM system, built with gold exploration in mind. It was from there the idea took flight by changing the slow and labour-intensive dragging of wires along the ground, to dragging them through the air and, in the process, increasing the sample density. The outcome was a system that was able to provide more detail than might ever be achieved on the ground, and at a cost that would enable projects, not prospects to be mapped and explored.

HOISTEM, consists of both newly developed equipment and modified instrumentation from Normandy's highly successful ground TDEM system. A single turn transmitter loop of 20 m in diameter is towed 30 m below the helicopter at a nominal terrain clearance of 30 m, with the receiver coil fixed in the center of the transmitter loop.

A transmitter current of 320 A is pulsed 24 times per second. The on-time is 5 ms, off-time 15 ms, with a shut-off ramp of 40 µs. The system records 140 channels, out to 14.3ms, at varying channel widths. With a helicopter speed of 35-45 knots, this gives a sampling interval of approximately 10 m along the flight line. The position and altitude are determined by GPS.

The system's wide bandwidth, low flying height and high spatial resolution allow it to undertake fine, near-surface mapping, that was once the realm of frequency domain systems, while its power provides a large depth of penetration thus giving the best of both worlds with the one system.

HoistEM has now been commercialised in Australia by GPX Airborne Pty. Ltd

When Graham is not conceptualizing new geophysical innovations, his leisure time is dominated by at least two other activities. These are building houseboats (he is currently on his second one) and consuming red wine. Well-sourced rumours have it that this second houseboat includes a wine cellar, strategically placed in one of the pontoons!

Graham's whole career has been about innovation in instrumentation design and construction and software development. He was a personal friend of Grahame Sands, who would be extremely pleased to see this award going to such a worthy recipient.

# Awards for contributions at ASEG 2003

## Laric Hawkins award for the most innovative use of geophysical techniques from a paper presented at the ASEG 2003 Convention

*Introduction to vector-processing techniques for multi-component seismic exploration*
by Natasha Hendrick and Steve Hearn.

## Best booth in the ASEG 2003 Exhibition

*Multiple booth*: Petrel
*Single booth*: Encom Technology Pty Ltd

## Best technical presentations

*Petroleum geophysics: A new model for fluid substitution in fractured reservoirs,*
by Boris Gurevich.

*Minerals and Environmental Geophysics*: *Airborne vector magnetics mapping of remanently magnetised banded iron-formations at Rocklea, Western Australia*
by Mark Dransfield, Asbjorn Christensen and Guimin Liu, presented by Mark Dransfield.

## Student Presentation

*Salinity monitoring of the Murray River using a towed TEM array*, by Brian Barrett, Michael Hatch, Graham Heinson and Andrew Telfer, presented by Brian Barrett.

*Natasha Hendrick and Steve Hearn receive the Laric Hawkins Award from Stewart Greenhalgh, Chair of the Technical Papers Committee, for the most innovative paper.*

*Brett Farquar (on the left) and Bryn Bender (in the middle) of Petrel, receive their "Best Booth Award" from Conference Co-chair, Richard Hillis*

*Dave Pratt receives Encom s Award for the best small booth in the Exhibition.*

*Guimin Liu receives the Best Paper Award in the Minerals and Environment category from Stewart Greenhalgh, Chair of the Technical Papers Committee*

*(Left) Boris Gurevich proudly displays his rewards for presenting the best Petroleum paper at the Conference.*

# The Order of the White Jacket

One of the highlights of the conference dinner was the presentation of the Order of the White Jacket Awards by Master of Ceremonies, Barry Long.

These were awarded to ASEG members who were present at the Adelaide dinner and had also attended all previous ASEG Conferences.

*Recipients of the Order of the White Jacket at the Adelaide Conference.*
*From left to right we have: Steve Collins, Peter Gidley, Nick Sheard, Jock Buselli, Bob Smith, Doug Roberts, John Denham, Brian Spies and of course, the Master of Ceremonies, Barry Long.*

Barry displayed a letter of support for the new award from the ASEG President Kevin Dodds, which contained the words:

"I have reviewed the material you supplied me for the new Award the "Order of the White Jacket" and feel that such an Award has been long overdue. I have acted in my Presidential autocratic manner and informed the other ASEG Committee members that this award is to be inaugurated at the Adelaide 2003 Conference."

He also displayed a letter from the President of the SEG which contained the following words:

"I am impressed with the concept of the new Award you have proposed for the ASEG.

I have sent a letter to your ASEG President, Kevin Dodds, and informed him that this new Award the "Order of the White Jacket" must definitely be supported.

The Awardees are shown in the photograph

It was proposed that all awardees would receive free registration at all subsequent ASEG Conferences. This has been put before the Conference Advisory Committee for consideration.

# At a Glance...

# ASEG/PESA
# 17th International Conference and Exhibition

15-19 August 2004
Sydney Convention Centre

On behalf of the 2004 Conference Organising Committee, you're invited you to attend the 17th Annual ASEG Conference and Exhibition in Sydney. The Conference is being jointly organised by the ASEG and PESA NSW and these societies will co-host the event at the Sydney Convention Centre, Darling Harbour, from 15-19 August 2004.

The theme is: ***Integrated Exploration in a Changing World***

## 2004 ASEG-PESA Conference Organising Committee

The key positions in the Organising Committee have already been appointed. You can see from the list below that it is a very strong committee and promises to be a great event.

| Positions | Person |
| --- | --- |
| Co-Chairmen | Barry Smith, Tim Pippett |
| Finance | Graham Butt, Max Williamson |
| Secretary (PCO) | Francis Child, Louise Pitney |
| Publicity | Toby Gilmour, Ken Grieves |
| Sponsorship Co-Chairmen | Mike Smith, Wes Jamieson |
| Technical Program Co-Chairmen | Peter Gunn, John Mebberson |
| Exhibition Co-Chairmen | Pat Hillsdon, Simon Stewart |
| Workshop Co-Chairmen | Dave Robson, Mark Hitchings |
| Student Liaison | Dave Schmidt |

# Geostatistics for seismic data integration in Earth Models

*To be held on May 2nd in Perth, May 5th in Brisbane and May 7th in Canberra*

## Summary

In recent years, the use of geostatistics has spread from the world of reservoir characterisation to that of velocity analysis, time-to-depth conversion, seismic inversion, uncertainty quantification, and more generally to that of seismic data integration in Earth Models. Nevertheless, many geoscientists still regard geostatistics as little more than a statistical black-box. By explaining the concepts and applications, this course aims to clarify the benefits of geostatistics and help spread its use.

The course will cover the use of geostatistics for interpolation (kriging...), heterogeneity modelling, uncertainty quantification (simulation...), and data integration (cokriging, external drift, geostatistical inversion...). A variety of applications and examples will be presented, including velocity mapping, time-to-depth conversion, heterogeneity modelling, and seismic data integration in stochastic Earth Models. The relationships between geostatistics and approaches more familiar to geophysicists, such as filtering or bayesian methods, will also be discussed, without entering into mathematical details. A number of case studies will be presented, covering examples from various parts of the world. This will be a lively course, illustrated by examples, exercises and discussion sessions.

This course comes at a time when the use of geostatistics is spreading in geophysics, as shown by the increase in the number of geostatistics papers submitted to Geophysics or Geophysical Prospecting. It should raise significant interest among ASEGmembers.

## Who should attend?

This is a great opportunity for those interested in solving practical problems involving data interpolation, earth modelling, multidisciplinary data integration or uncertainty quantification

## Biography

Oliver Dubrule obtained a PhD in Petroleum Geostatistics at Ecole des Mines de Paris in 1981. He then worked for Sohio Petroleum Company in the USA (1982-1986), Shell International in The Netherlands (1986-1991) and, since 1991, he has been with Elf and TotalFinaElf, working in France and in the UK.

He has authored more than twenty papers in the field of geostatistics and Earth Modelling and in 1991 he received the President's prize of the International Association of Mathematical Geology, for "Outstanding Contribution to Mathematical Geology by an individual 35 years or younger".

## Topics Covered in the Short Course

### Introduction

- Earth Modelling, the meeting point for data integration
- The role of geostatistics at different steps of the Earth Modelling workflow
- Basics of statistics

### Covariance and the variogram

- Stationarity vs non-stationarity, what does this mean practically?
- Variogram and covariance; interpreting the sill, the range, the nugget effect
- How to compute a variogram

### Interpolation

- Kriging, for property interpolation in 2D or 3D
- Error Cokriging and Factorial Kriging for velocity analysis and mapping
- Time-to-depth conversion using the External Drift method
- Collocated Cokriging, for integration of seismic attributes information in reservoir models

### Conditional Simulation for heterogeneity modelling and uncertainty quantification

- Conditional Simulation, what is it, and when should it be applied?
- Conditional Simulation for 3D geological facies modelling
- Stochastic Earth Modelling integrating all subsurface uncertainties

### Geostatistical Inversion

- Geostatistical Inversion, for acoustic impedance inversion at reservoir scale
- Geostatistical Inversion versus other geophysical inversion techniques

### Conclusion

- Geostatistical websites and software
- The «do's and dont's» of geostatistics
- The current and future role of geostatistics in the reservoir modelling workflow

## Registration

The cost of the course varies from venue to venues but will be approximately $100 for members of both the SEG and the ASEG - excellent value for money. To register, contact ASEG officers in Canberra, Brisbane or Perth or contact Klaas Koster on Klaas.Koster@woodside.com.au.

# Letter

Dear Editor

### Near Surface Geophysics

It was very pleasing to see a full afternoon session at the Adelaide ASEG Conference and Exhibition devoted to Near Surface Geophysics. I would hope, with my involvement in the forthcoming ASEG Conference in Sydney, that we could devote a full one-day session to Near Surface Geophysics.

With the increasing interest in near surface geophysics, some of the other geophysical societies such as the SEG and EAGE have formed Near Surface Sections to deal specifically with this area of our discipline. There is also the Environmental and Engineering Geophysical Society based in the USA and Europe, which fills an important role in this field.

I am interested to determine whether there are members of the ASEG who would be interested in forming a Near Surface Geophysics Section of the ASEG, to promote geophysics in the environmental and engineering market and fill a niche market in this area. I would anticipate that this group would undertake the following:

- Contribute to Preview, either having a Section on Near Surface Geophysics or writing articles;
- Provide a network for technical discussion, which might end up as a Newsletter;
- Run Seminars for Environmentalists and Engineers on Geophysical Applications; and
- Assist with Session Theming at ASEG Conferences.

If member are interested in such a proposal, please contact me at tpippett@alpha-geo.com or on 02 9542 5266.

Yours sincerely

*Timothy Pippett*

Alpha GeoScience Pty. Ltd.

# ASEG Research Foundation: Project Results

The ASEG Research Foundation has been supporting students in all facets of Applied Geophysics at the BSc (Honours), MSc, and PhD (or equivalent) levels for 13 years. In this issue of *Preview* we are summarising the research outputs from Honours students at Adelaide University during 2002.

## ASEG Research Foundation RF02M01

Project Title: Regolith to regional-scale magnetotelluric exploration in the Olary Domain and Gawler Craton, South Australia

This grant supported three Honours students:

| | |
|---|---|
| Host Institution: | Adelaide University |
| Supervisor: | Graham Heinson |
| Project Level: | Honours |
| Project Timing: | 2002 |
| Funding: | $5000 |

| | |
|---|---|
| Student: | Katherine Broxholme (nee Selway) |
| Honours Title: | Two-dimensional magnetotelluric responses of three-dimensional bodies. |
| Industry Mentors: | Steve Busuttil and Terry Ritchie, MIM Exploration |

### Project Summary

Magnetotelluric (MT) tensors have significantly different forms depending on whether the subsurface is one-dimensional (1D), two-dimensional (2D) or three-dimensional (3D). In subsurface geological structures that are not 1D, two-dimensionality is often assumed, as inversion routines for 2D earth models are computationally more tractable than those for full 3D media. In 2D, the MT tensor decouples into two independent modes, the transverse electric (TE) mode and the transverse magnetic (TM) mode. Often only one of these modes is acquired during commercial operations. Field data were collected with the Mount Isa Mines Distributed Acquisition System (MIMDAS) in the Deep Well prospect of the Curnamona Province in South Australia. The target for the survey was an elongate magnetic anomaly of a type that would normally be approximated as 2D but which has a finite strike length and is therefore a 3D body. With this in mind, the applicability of interpreting data defined as TE and TM were assessed using (a) Mohr circles galvanic distortion analyses, (b) determination of strike of local and regional geology, and (c) comparison of 2D inversion techniques. We show that the TM mode accurately delineates boundaries and that since boundary-charges are included in the inversion formulation, it also provides accurate values of apparent resistivity. The TE mode provides poor boundary delineation and underestimates the resistivity of the 3D body. Joint inversions provide only a small improvement upon TM-only inversions, but determination of dimensionality, strike and detection of galvanic distortion mean that collection of both data modes is still preferable.

(Right) Stephan deploying MT equipment south of Port Lincoln, South Australia. Stephan and Rob took part in a 19-site MT survey across the Kalijala Shear Zone in Eyre Peninsula, that formed the subject of Stephan's Honours project.

Kate, Stephan and Rob at Kalkaroo, Olary Domain, South Australia, Stephan in the middle. All three students took part in a 150km long MT survey across the Mundi Mundi Fault, that formed the subject of Rob Gill's Honours project). Here they are seen processing data in the evening.

| | |
|---|---|
| Student: | Stephan Thiel |
| Honours Title: | Electromagnetic induction studies of the Eyre Peninsula Anomaly and their relationship to the tectonics of the southern Gawler Craton, South Australia. |
| Industry Mentor: | Michael Schwarz, PIRSA |

### Project Summary

Long-period natural-source electromagnetic (EM) data have been recorded using portable three-component magnetometers at forty sites in 1998 and 2002 across the southern Eyre Peninsula, South Australia that forms part of the Gawler Craton. Site spacing was of order 5 km, but reduced to 1 km of less near known geological boundaries, with a total survey-length of approximately 50 km. Two profiles trending east-west were inverted for two-dimensional (2D) electrical resistivity models to a depth of 50 km across the southern Eyre Peninsula. The main features from the models are (a) on the eastern side of the Gawler Craton, the Donington granitoid suite to the east of the Kalinjala shear zone are resistive (>1000 Ω.m); (b) the boundary between the Donington granitoid suite and the Archaean Sleaford complex, which has much lower resistivity of (<10 Ω.m), dips at about 45º to the west; (c) two very low resistivity (< 1 Ω.m) zones in the top 5 km Hutchison group sediments correlate with banded iron formations, and are probably related to biogenic-origin graphite deposits concentrated in fold hinges; and (d) a second zone of higher resistivity (>100 Ω.m) is coincident with the Hall suite volcanics on the western side of the Eyre Peninsula. Such features suggest an extensional regime during the time period 2.00 - 1.85 Ga. We suggest that the shallow dipping resistivity boundary with the Donnington suite represents a growth fault, typical for rift systems that evolve into a half-graben structure. On the western margin a more steeply eastward dipping slave fault also marks the boundary with resistive basement rocks. In the graben basin, low resistivity shallow marine Hutchinson Group sediments were deposited. Folding of the metasediments during the Kimban Orogeny between 1.74 - 1.70 Ga has led to migration of graphite to the fold hinges resulting in linear zones of very low resistivity that correlate with banded iron formation magnetic anomalies.

Student: Rob Gill
Honours Title: A magnetotelluric profile across the Broken Hill and Olary Domains.
Industry Mentor: Stuart Robertson, PIRSA

### Project Summary

Seventeen magnetotelluric survey sites were occupied across the Olary and Broken Hill Domains in the Curnamona Province, Australia. Two-dimensional modelling along the magnetotelluric profile identifies the Broken Hill Domain as a zone of high electrical resistivity to a depth of 15 km. Gravity modelling along a coincident profile has also shown the Broken Hill Domain to be significantly denser than its surrounds. Seismic data have provided evidence of numerous faults and shear zones within the Pre-Cambrian Broken Hill Domain basement, and is indicative of compression during the Delamarian Orogeny. It is proposed that the majority of crustal fluids were removed from these rocks by granulite facies metamorphism and tectonic compression. The boundary of the Olary Domain appears to be delineated by the Mundi Mundi Fault with an order of magnitude increase in resistivity on the Broken Hill side. The location of the Flinders Conductivity Anomaly was also observed and a number of conducting mechanisms considered, including crustal fluids and graphite films.

*Rob and Kate with GPS at Kalkaroo.*

### Project Outcomes

All three students received 1st class Honours and Katherine Broxholme was the winner of the Newmont Prize for the top Geophysics student at the University of Adelaide in 2002.

### Publications


Broxholme, K., Heinson, G. S., Busuttil, S. and Lilley, F. E. M., 2003, Two-dimensional magnetotelluric response of three-dimensional bodies, proceedings of the 3DEM Workshop, Feb 2003.

Gill, R., 2002,. A magnetotelluric profile across the Broken Hill and Olary Domains. unpublished BSc (Hons) thesis, University of Adelaide.

Selway, K. 2002, Two-dimensional magnetotelluric response of three-dimensional bodies, unpublished BSc (Hons) thesis, University of Adelaide.

Thiel, S., 2002. Electromagnetic induction studies of the Eyre Peninsula Anomaly and their relationship to the tectonics of the southern Gawler Carton, South Australia, unpublished BSc (Hons) thesis, University of Adelaide.

*David Denham*
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# Greenhouse gases and climate change

Organic carbon buried in sediments as coal, natural gas and oil over hundreds of millions of years is being consumed as a result of human activities and returned to the atmosphere as carbon dioxide ($CO_2$) on a time scale of a few centuries. The energy harvested from this transformation supplies us with electricity, heat, transportation and industrial power. However, the $CO_2$ added to the atmosphere appears to be changing the Earth's climate, resulting in global warming (Sarmiento and Gruber, 2002).

Since 1751 roughly 280 billion tons of carbon have been released to the atmosphere from the consumption of fossil fuels and cement production. Half of these emissions have occurred since the mid 1970s (Marland *et al*., 2002). The 1999 fossil-fuel emission estimate for global $CO_2$ emissions, 6457 million metric tons of carbon, represents a 2.4% decline from 1998 and marks the second consecutive drop in global annual fossil-fuel $CO_2$ emissions (see Figures 1 and 2).

Globally, liquid and solid fuels accounted for 76.7% of the emissions from fossil-fuel burning in 1999. Combustion of gas fuels (e.g., natural gas) accounted for 19.4% (1251 million metric tons of carbon) of the total emissions from fossil fuels in 1999 and reflects a gradually increasing global utilization of natural gas. Emissions from cement production rose slightly to 218 million metric tons of carbon, a twenty-fold increase since the 1920s (Marland *et al*., 2002).

The numbers shown in Figures 1 and 2 correlate well with estimates of $CO_2$ in the atmosphere over a similar period as shown in Figure 3 from Hobbs (2002) and the estimates of northern hemisphere temperatures (Mann *et al*., 1999).

The challenge is how to reduce, or at least control the build up of carbon dioxide in the atmosphere. One strategy is to use carbon sequestration, whereby the carbon extracted form the ground is put back where it came from. This may sound simple but, as shown in the next three contributions, it is not an easy task. Peter Cook's article is a review of possible options in the sequestration challenge and the

*Cont'd on page 27*

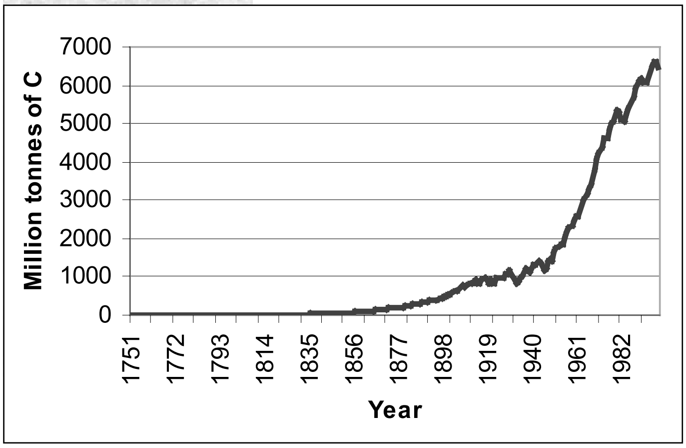


*Fig. 1 Annual carbon additions to the atmosphere estimated from the burning of solids, liquids and gases, and cement making (from Marland et al., 2002).*

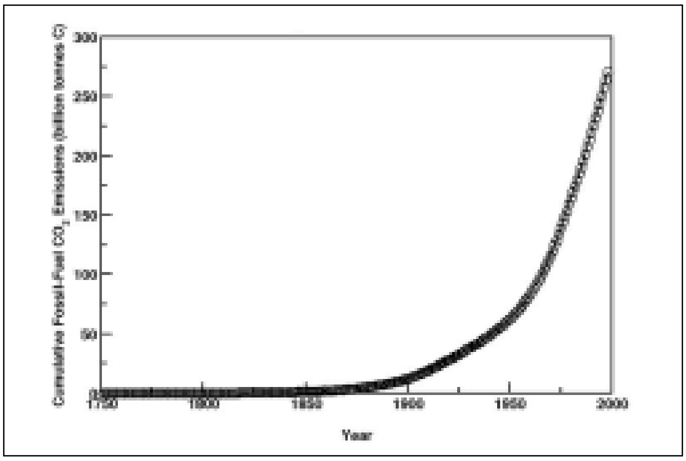


*Fig. 2. Cumulative global $CO_2$ emissions from fossil fuel consumption and cement production (from Marland et al., 2002).*

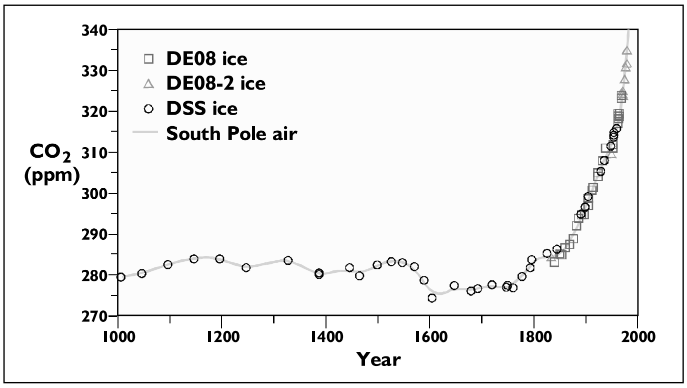


*Fig. 3. Historical concentrations of $CO_2$ in the atmosphere over the last 1000 years (from Hobbs, 2002).*

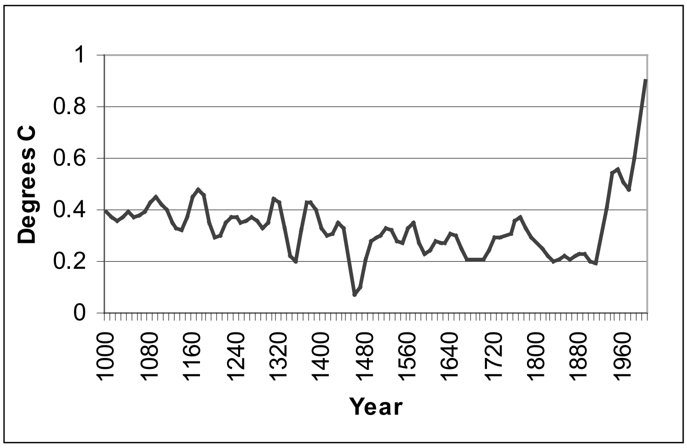


*Fig. 4. Temperature variations in the northern hemisphere (from Mann et. al., 1999), note the downward trend in the data until the middle of the 19th Century.*

# Some strategies to reduce $CO_2$ emissions[1]

Maintaining the benefits of access to low cost energy derived from fossil fuels, whilst at the same time significantly decreasing $CO_2$ emissions to the atmosphere, is a major challenge in the world today. The most promising technologies for significantly decreasing emissions from large scale stationary sources of $CO_2$ (coal-fired power stations, cement plants, gas processing facilities, etc) involve separating and capturing the $CO_2$, compressing and then storing it in geological or other locations where it will not leak back into the atmosphere.

## Capturing $CO_2$

Technologies for capturing $CO_2$ from emission streams have been used for many years to produce a pure stream of $CO_2$ from natural or industrial $CO_2$ emissions for use in the food processing and chemical industries. The gas industry routinely separates $CO_2$ from natural gas before it is then transported to market by pipeline. Methods currently used for $CO_2$ separation include:

- Physical and chemical solvents particularly monoethanolamine (MEA)
- Various types of membranes
- Adsorption onto zeolites and other solids
- Cryogenic separation

These methods can be applied to a range of industrial processes. However, their use for separating out $CO_2$ from high volume- low $CO_2$ concentration flue gases, such as those generated by conventional pulverised coal-fired power stations, is much more problematic. The very high capital costs of installing the huge post combustion separation systems needed to process massive volumes of flue gases is currently a major impediment to post combustion capture of $CO_2$. The second problem is the large amount of additional energy used to release the $CO_2$ from solvents or from solid adsorbents after separation.

Some major technical and cost challenges need to be addressed before retrofit (or new build) of post-combustion capture systems becomes an effective mitigation option. The present cost of post combustion capture of $CO_2$ is commonly quoted in the range of US$30-60 a tonne of $CO_2$. This would perhaps double the wholesale price of electricity. However, capture technologies will undoubtedly improve in the coming years, improving economics.

A key to achieving lower capture costs lies in the production of a more concentrated, pressurized stream of $CO_2$ (the average PF generator has only 10-14% $CO_2$ in the flue gas stream) by pre-combustion capture of $CO_2$ or oxyfuel combustion.

Pre-combustion capture is possible as part of integrated gasification combined cycle (IGCC), which involves first the combustion of coal or gas in air (or oxygen) to produce a CO plus $H_2$ gas stream, which is reacted with hot steam to produce $CO_2$ plus more $H_2$. The $H_2$ is then combusted in a gas turbine and the $CO_2$ is available for storage or use. Although IGCC plants are relatively common, few are used for base load power or incorporate $CO_2$ capture. Figures currently available indicate that – even allowing for the initial capital costs – 'new build' IGCC producing a pure stream of $CO_2$ is a cheaper option than the retrofit of a power station coupled with post-combustion capture.

An alternative approach is oxyfuel combustion, which relies on the relatively simple principle of burning coal in an oxygen-rich atmosphere to produce a pure stream of $CO_2$. Whilst the principle is simple, there are major issues to overcome, including the very high combustion temperatures and the cost of seperating out the oxygen. Oxyfuel combustion for power generation may be a future option though it has yet to confirm its operational and commercial viability. Much the same oxycombustion technique is used in steel making and consequently there may be no insurmountable technical barriers to $CO_2$ storage linked to oxyfuel power generation in the future.

As long as the main pressure on power companies is to decrease electricity costs, it is unrealistic to expect them to voluntarily retrofit post combustion $CO_2$ capture or move to IGCC or oxyfuels. However, if in the future the main pressure is to reduce $CO_2$ emissions, all technical options.

*Cont'd on page 28*

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*On 1 July 2003 Peter Cook will become the CEO of the CRC for Greenhouse Gas Technologies.*

*[1] This contribution is based on Peter Cook's article published in **Ecoal**, vol. 44, December 2002.*

*Cont'd from page 26*

next two articles are based on presentations made at the Adelaide Conference earlier this year. They shown roles geophysics may be able to play in any sequestration project.

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*Cont'd from page 27*

This may include post combustion retrofit, given that many countries have made massive investments in conventional thermal power stations.

## Storing $CO_2$

A number of $CO_2$ storage options are being considered at the present time – ocean storage, mineral storage and geological storage

### Ocean Storage

Ocean storage of $CO_2$ involves two main options: one is dispersal of $CO_2$ as droplets at intermediate water depths of around 500-1000 m; the other is disposal at abyssal depths (5000 m or more) as liquid $CO_2$. Given the ocean is an enormous sink for $CO_2$ and the system is strongly buffered, the injected $CO_2$ would probably have a negligible effect on the chemistry of the ocean as a whole. But it would result in a measurable drop in the pH of seawater in the immediate vicinity of the injection site and impact on marine organisms.

The ocean is an open system and it would be difficult, if not impossible, to monitor the distribution of the stored carbon in order to confirm residence times of $CO_2$. Also, the impact of elevated levels of $CO_2$ on marine ecosystems is poorly known and difficult to monitor. The potential application of the London Dumping Convention to ocean storage of $CO_2$ also raises legal uncertainties. For all these reasons, there is widespread opposition to ocean storage and it is most unlikely to be a $CO_2$ storage option in the foreseeable future.

## Geological Storage

The most comprehensively studied storage option is geological storage. For the past 30 years, the oil industry has been injecting up to 30 million tonnes a year of $CO_2$ (derived mainly from natural $CO_2$ accumulations in Colorado) into the subsurface of West Texas, for enhanced oil recovery (EOR). The Weyburn Project in Canada is a recently initiated example of an EOR project. However, most oils are not suitable for Enhanced Oil Recovery (EOR) and in fact much of the $CO_2$ used for EOR is not "stored" but re-used. Therefore the global opportunities for $CO_2$ storage and EOR are limited.

Enhanced Coal Bed Methane (ECBM) recovery is seen as a potential opportunity for sequestering $CO_2$ in unmineable coal seams and obtaining improved production of coal bed methane as a valuable by-product. A demonstration $CO_2$-ECBM project in the San Juan Basin produced a positive though modest enhancement of the rate of methane recovery. A new ECBM project (RECOPOL) has recently been initiated by the IEA Greenhouse Gas Programme in Poland and the results are awaited with interest.

The true potential of $CO_2$-ECBM is difficult to gauge at this time. Coal bed methane is an important energy source in the USA, but it has not to date been significant in most other countries because of the lack of existing infrastructure and expertise. An additional concern is that any increase in the leakage of methane as a result of ECBM, could counter the potential benefits of $CO_2$ storage.

By far the greatest potential for geological storage of $CO_2$ involves injection of compressed $CO_2$ into the subsurface, down to a depth of 6-800 m. The $CO_2$ is compressed to a dense near critical state; it is then very much denser than gaseous CO, thereby minimising problems posed by the large amounts of $CO_2$ that will need to be stored if this method is to have a major impact on current emission levels. Much of the $CO_2$ will initially remain in a super-critical state; some of it may react with the bedrock to form carbonate minerals; some will go into solution. Over time more will go into solution, but provided the injection site is carefully chosen, the $CO_2$ will remain stored for very long periods of time and can be monitored.

An obvious site for geological storage is depleted oil and particularly gas reservoirs. In the USA, it is estimated (by the US DoE) that the storage capacity of depleted gas reservoirs is about 80-100 Gigatonnes of $CO_2$ or enough to store US emissions of $CO_2$ from major stationary sources for 50 years or more.

Storing large amounts of $CO_2$ in deep saline water-saturated reservoir rocks, particularly sandstones, with the $CO_2$ stored as a result of hydrodynamic trapping, offers great potential. One major project to store $CO_2$ in a deep saline aquifer is already being conducted by the Norwegian company Statoil, in the sediments of the North Sea Basin. A million tonnes a year of $CO_2$ are being injected into the Utsira Formation at a depth of around 1000 m below the sea floor (see McKenna *et al.* paper on page 35).

A comprehensive regional analysis of the storage potential of saline reservoirs has been undertaken in Australia as part of the GEODISC project. This study has indicated a $CO_2$ storage potential for Australia, adequate to store $CO_2$ emissions for many hundreds of years at the current rates of emission. It is hoped that a major demonstration project will be under way in Australia in 2005-2006.

Commonly quoted storage costs are US$10 a tonne of $CO_2$ or less, suggesting that excluding the costs of $CO_2$ capture, the costs of geological storage are likely to be cost competitive with other sequestration options.

Where the cost of capture is factored into project costs, such as in the case of post combustion capture linked to a conventional coal-fired power station, then obviously total costs rise considerably. "New build" IGCC is likely to be a

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# Geophysical monitoring of subsurface $CO_2$

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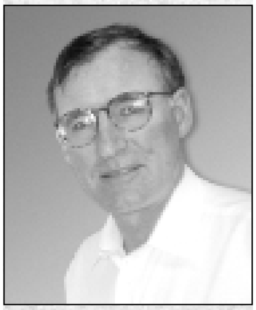

*Kevin Dodds*

## Summary

Geological storage of $CO_2$ will require accurate, high-resolution geophysical monitoring to map the subsurface flow paths and the phase state of the fluids. Existing and potential monitoring methods include seismic (both surface and borehole), electromagnetics, gravity, and well logging.

Seismic methods are expected be the main form of monitoring as they are cost effective and cover the whole area of interest. When used in a time-lapse sense, areal mapping of the injected $CO_2$ is possible with existing technology. However, improvements in resolution are required to detect leakage and identify preferential flow paths. Multi-component seismic acquisition may be necessary to discriminate between changes in saturation and pressure within the $CO_2$ reservoir. Passive monitoring of induced microseismic events may prove to be an effective way to evaluate the effects from the injection of $CO_2$ on the integrity of the cap rock and provide early warning of fracturing or fault reactivation.

Supporting geophysical methods will be needed for accurate quantitative interpretation of the seismic data. The geological setting and the availability of wells and pre-existing baseline data will have a profound influence on the choice of any additional geophysical methods. Electromagnetic methods have lower resolution than seismic, but are far more sensitive to changes in fluid saturation and may detect anomalies that are too subtle to interpret from seismic data alone. Gravity surveys are relatively cheap to acquire on land, but improvements in measurement sensitivity and constrained inversion methods are required before gravity can be of value for monitoring subsurface $CO_2$ in the supercritical state.

## Introduction

Geological storage of carbon dioxide ($CO_2$) will be an important component of Australia's efforts to meet greenhouse gas emission targets. The challenge of implementing such a program raises a broad range of technological issues including determining the most appropriate measures of storage performance assessment. If the objectives for performance confirmation require the phase state and subsurface flow paths of the $CO_2$ to be monitored, then high-resolution geophysical imaging techniques will need to be employed. Monitoring is also important for interaction with simulations of the storage performance to mitigate uncertainty associated with reservoir parameters and for validating the physics and mechanisms of storage.

After a brief description of the properties of $CO_2$ and the storage environments, this paper reviews existing and potential $CO_2$ monitoring methods, which include seismic (both surface and borehole), electromagnetics, gravity and well logging. We conclude with some recommendations for further research.

### Mechanisms of $CO_2$ storage

The density of $CO_2$ increases rapidly close to the critical point of 7.4MPa at 31°C. This occurs at depths between 500 m and 1000 m depending on temperature and pressure conditions. The density of subsurface $CO_2$ plateaus between 610 kg/m$^3$ and 720 kg/m$^3$, depending on the geothermal gradient. Depths greater than 1000 m are of little benefit in terms of storage density as the effects of higher pressure are offset by increasing temperatures.

$CO_2$ can be stored in geological formations by three principal mechanisms, referred to as hydrodynamic, solubility and mineral trapping (Hitchon, 1996). It is important to understand the rate behaviour of these processes, as they may be either faster or slower than the time span of injection.

### Hydrodynamic trapping

$CO_2$ can be trapped as a gas or supercritical fluid under a low-permeability caprock, similarly to the way that natural gas is trapped in gas reservoirs or that gas is stored in aquifer gas storage. In the short term, this is likely to be the most important mechanism for storage.

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*Cont'd from page 28*

more effective technology for power generation combined with $CO_2$ storage, but capture technologies will improve in the coming years.

Australia has recently made a major commitment to achieving this through the establishment of a new Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC). This centre which involves a number of major research partners (Adelaide, Melbourne, Monash, Curtin and NSW Universities, CSIRO, Geoscience Australia) and industry (ACARP, BHBP, BP, ChevronTexaco, Rio Tinto, Shell, Stanwell, Woodside) will be spending approximately A$120 MM over the next seven years on capture and storage of $CO_2$.

## Conclusions

Capture and storage of $CO_2$ is not a "silver bullet" that will overcome all the greenhouse gas problems. It is, however, one of the most promising options that we now have for decreasing $CO_2$ emissions, whilst enabling us to continue to benefit from access to widely available, low-cost fossil fuels .

### Solubility trapping

$CO_2$ can dissolve into the fluid phase. In oil reservoirs this lowers the viscosity and swells the oil, which provides the basis of one of the more common enhanced oil recovery (EOR) techniques. $CO_2$ is also slightly soluble in water. In the long term (10's to 100's of years) this will be the dominant form of storage, with solubility up to 50 kg/m3 for low salinity formation water at depths greater than 600 m (Rigg *et al*., 2001). The relative importance of solubility trapping depends on a large number of factors, such as the sweep efficiency of $CO_2$ injection, formation of fingers, and the effects of formation heterogeneity. It is probable that the flood-front velocity will be faster than the $CO_2$/water interaction front, so solubility is unlikely to be significant in early stages.

### Mineral trapping

$CO_2$ can react, either directly or indirectly, with the minerals and organic matter in the geologic formations to become part of the solid mineral matrix. In silicates, the dissolution of feldspars or clays releases divalent ions, which react with bicarbonate ions to precipitate carbonate minerals such as calcite or siderite. Under favourable conditions, the amount of $CO_2$ that can be sequestered by precipitation of secondary carbonates can be larger than $CO_2$ dissolution in the pore water (Pruess *et al*., 2001). Adsorption onto coal is another example of mineral trapping.

## Geological storage environments

### Deep saline aquifers

Sequestration into saline aquifers has the lowest storage efficiency of the geological sinks suitable for disposal of $CO_2$, with some estimates as low as 2% of the pore volume (van der Meer, 1995). This is due to unstable displacement fronts, or 'fingering', that occurs when the connate fluid is displaced by much lower viscosity $CO_2$ (Ferer et al., 2001). Also, the effect of buoyancy results in the $CO_2$ filling only the uppermost part of the aquifer at significant distances away form the injection well. However, saline aquifers appear to be the most economically attractive option currently available in Australia as they are widespread and have the largest ultimate storage capacity (Rigg *et al*., 2001).

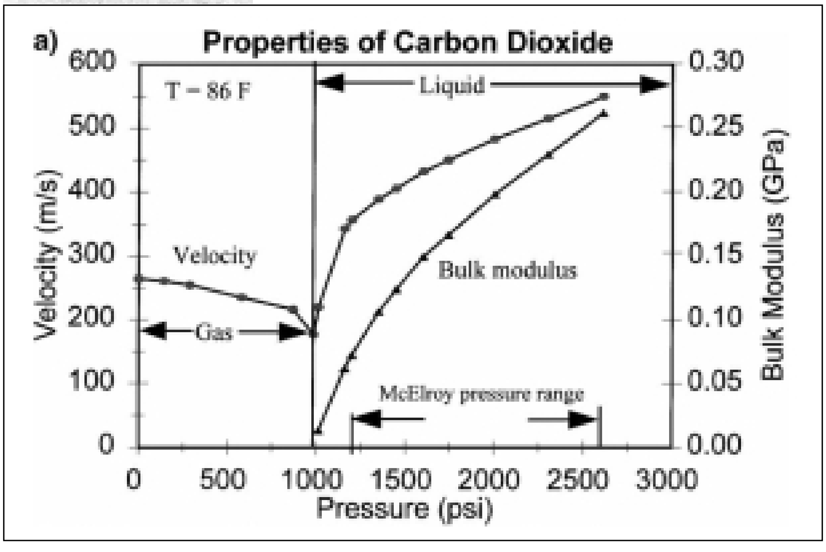


*Fig. 1. The velocity and bulk modulus of pure $CO_2$ as a function of pressure (from Wang et al. 1998).*

Saline aquifer storage will pose one of the biggest challenges for monitoring due to the lack of pre-existing data for characterisation of the reservoir. The petrophysical data required for modelling injection, migration and trapping of the $CO_2$ in the subsurface may be lacking if there is limited baseline information initially available from wells logs and geophysical surveys.

### Depleted oil and gas fields

The storage efficiency in depleted oil and gas fields is estimated to be much higher than in saline aquifers, with approximate storage capacity equal to the amount of hydrocarbons that have been extracted (Holloway, 1997). Depleted fields have limited capacity and availability and are less likely to be close to a large source of anthropogenic $CO_2$ in Australia. However, the availability of wells and baseline geophysical data, and the value of knowledge already gained during exploitation of the field may prove to be more important for reducing risk and uncertainty. Also, since depleted fields are known to have trapped hydrocarbons over geologic time, the vital issue of caprock integrity will be of much less concern.

### Enhanced oil recovery

$CO_2$ injection into suitable producing oil fields provides an economic incentive for storage in the form of enhanced oil recovery (EOR). In favourable circumstances, the $CO_2$ is miscible with the oil and improves the mobility through viscosity reduction and swelling. Storage efficiency is case specific and heavily dependent on the injection program that is implemented. Holt *et al*., (1995) estimated that storage efficiency could be anywhere between 13 and 68%. There are a number of other advantages of this method of storage. There has been significant experience gained from over 30 years of EOR operations, mostly in the US and there will usually be a substantial amount of good quality data available (Lewis and Shinn, 2001). As with depleted fields, caprock integrity will also be of less concern.

In the US at present, where there are no government incentives to reduce $CO_2$ emissions, EOR is the preferred method of storage as their motives are driven by the economics of incremental production. It is considered that combining sequestration with enhanced oil recovery is unlikely in Australia other than in exceptional circumstances (Rigg *et al*., 2001).

### Enhanced coal-bed methane recovery

Injection into coal seams that are too deep to mine is another possibility for geological storage, which is particularly attractive if it can be coupled with enhanced coal-bed methane recovery (ECBM). Injected $CO_2$ improves recovery by directly displacing methane that is adsorbed onto the coal. The $CO_2$ will remain sequestered as long as the coal is never mined or substantially depressurized (Gale and Freund, 2001). Coal beds provide the greatest storage density of $CO_2$ to depths of 600 m and are still competitive at greater depths. A key factor in favour of coal-bed sequestration is that in many cases coal seams are nearby to coal-fired power stations, resulting in low transportation costs from source to sink.

Large scale ECBM operations are now underway in the western United States and will soon begin in Alberta, Canada. One of the difficulties for ECBM is finding coal seams that are too deep to mine but are still permeable enough to inject. Low production rates and a lack of infrastructure restrict the applicability of ECBM methods in Australia (Rigg *et al*., 2001).

## Seismic monitoring

The velocity and bulk modulus of pure $CO_2$ is shown in Figure 1. The effect of $CO_2$ on the seismic velocities of rocks is unusual because, above the critical point, the density of $CO_2$ is similar to liquids, but the bulk modulus is much closer to that of a gas. Displacing brine with supercritical $CO_2$ will cause a reduction in the P-wave velocity. $CO_2$ injection also increases the pore pressure within the aquifer around the well, which contributes to the velocity reduction. Changes to the S-wave velocity will be mostly attributable to pressure changes.

If $CO_2$ is injected into a depleted oil field or used for EOR the relationship is more complex because the two phases become miscible and their capability to mix is also a function of pressure and temperature. Above the minimum miscibility pressure (MMP), which varies with the composition of oil but is usually around 9 MPa at 40°C, oil and $CO_2$ form a single phase whose properties are proportional to the properties of the individual phases. Unusual conditions can develop with $CO_2$ EOR. If the pressure is below the MMP, a methane rich bank can propagate ahead of the $CO_2$ front. Above the MMP, the increased pressure can force in-situ gas to re-absorbed into the liquid phase (Batzle *et al*., 1998). Fluid properties will vary substantially along the injection-production profile and input from compositional reservoir simulators is required to interpret the seismic response from this complex situation.

### Time-Lapse 3-D (4-D) Seismic

When 3-D surface seismic is used in a time-lapse sense, areal mapping of the injected $CO_2$ is possible with existing technology. This has been proven in case studies of both offshore and onshore surface seismic monitoring of $CO_2$ for both brine aquifer sequestration and EOR operations. Seismic methods will be the main form of monitoring as they are cost effective and cover the whole area of interest. However, improvements in resolution are required to detect leakage and identify preferential flow paths.

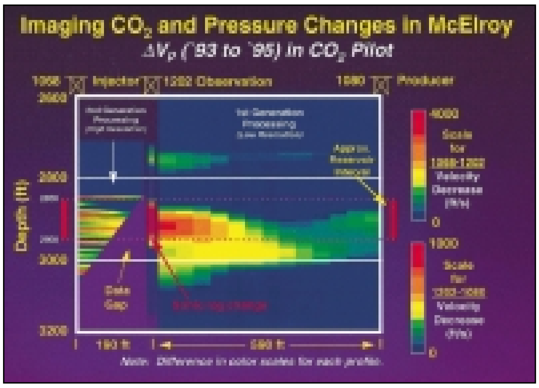


*Fig. 2. Tomographic image of the change in P-wave velocity between 1993 baseline crosswell survey and 1995 monitor survey recorded in the McElroy Field, West Texas. P-wave velocity decreases by more than 300 m/s near the $CO_2$ injector well. Away from the well, velocity changes are mostly within the reservoir interval (from Wang et al., 1998).*

### Borehole Seismic

Vertical seismic profiles (VSPs) and crosswell seismic provide progressively greater resolution than surface seismic at the cost of the portion of a reservoir volume they are able to image. VSP data proved to be valuable for confirming the existence of fractures within the Vacuum Field, New Mexico, which is currently undergoing $CO_2$ flooding for EOR, that were not resolvable on the surface 3-D seismic data (Michaud and Davis, 2000).

Crosswell seismic methods are an active area of research and there have been a number of commercial applications for monitoring steam and $CO_2$ floods. Crosswell reflection imaging uses VSP techniques to image reservoir boundaries between wells on the scale of 2 to 3 m, which are not detectable from surface seismic data (Cheng and Zhang, 2001). Processing of crosswell data has become very sophisticated for vertical wells, but processing data acquired between horizontal wells presents some new technical challenges (Washbourne *et al*., 2001). Depending on the velocity of layers above and below the reservoir interval, a number of different wave modes may arrive at the receiver at around the same time. Horizontal wells also introduce problems of positioning repeatability between time-lapse surveys. An example of a crosswell velocity tomogram from a $CO_2$ EOR project in the McElroy Field in Texas is shown in Figure 2.

Single-well imaging can be performed either using a borehole source and a separate array of clamped receivers, or with a specialised well-logging tool. The detection of both direct and back-scattered signals provides a 3D volumetric image

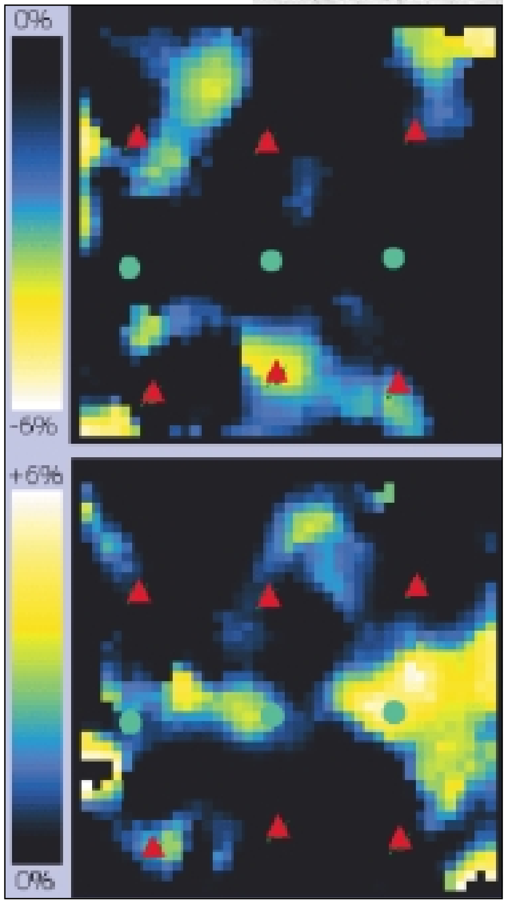


*Fig. 3. Velocity changes to the slow S-wave ($S_2$) in the Vacuum Field. The red triangles are the injector wells and the green circles are the producer wells. The upper picture shows areas of velocity decrease due to $CO_2$ injection. The lower image shows areas of velocity increase around the producer wells (from Duranti et al., 2000).*

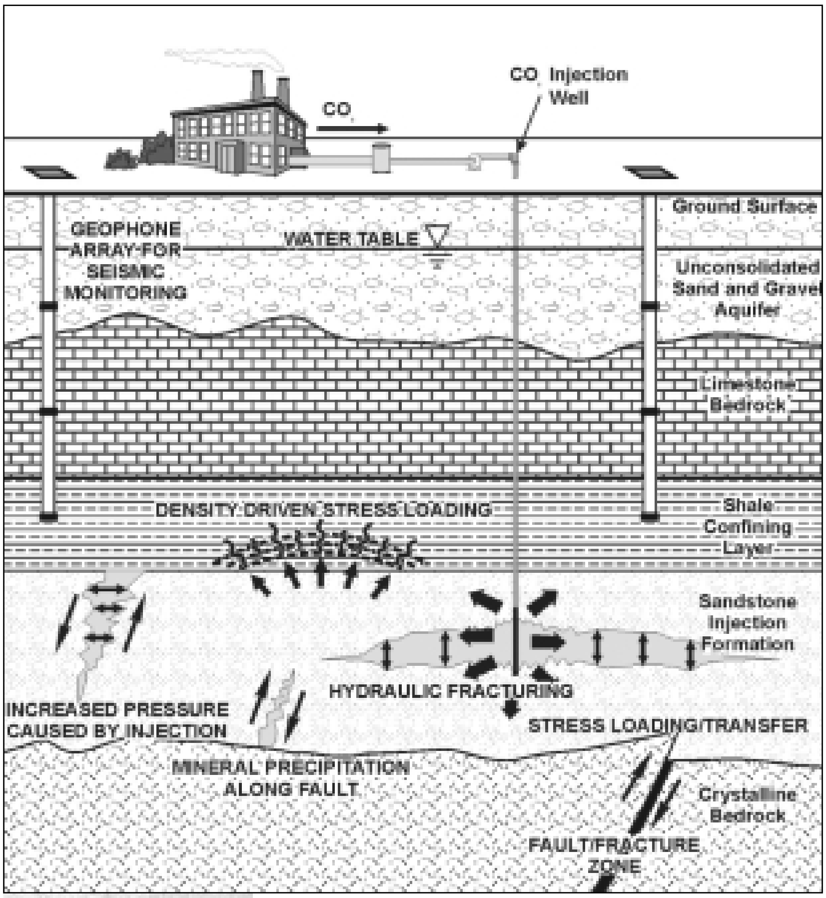


*Fig. 4. Conceptual figure illustrating the different processes that can induce microseismic activity when $CO_2$ is injected underground (from Sminchak et al., 2001).*

of the velocities and acoustic impedance of the geology surrounding a well. Single-well imaging is an emerging technology that shows promise and would probably be of most value in imaging distances between adjacent layers and changes to layer properties within horizontal wells. However, improvements are needed, particularly in data processing to cope with deviated well trajectories, washouts and to remove linear events (direct P-wave, P and S head-waves and Stonely waves).

### Multi-component seismic

Multi-component seismic acquisition (for recording both compressional and shear waves) is more expensive, but may be necessary to discriminate between changes in saturation and pressure within the $CO_2$ reservoir. The value of multi-component acquisition is evident in case studies such as the Weyburn and Vacuum Field tertiary recovery programs in Canada and New Mexico respectively. However, further theoretical and experimental work is required to satisfactorily explain some of the observed anomalies in the time-lapse data.

When vertical fractures are present in the reservoir, such as in the Vacuum Field, changes in the degree of shear wave splitting can be an effective indicator of pressure changes when the effects on P-waves alone are subtle (Davis and Benson, 2001). Figure 3 illustrates the correspondence between pressure and the slow S-wave in the Vacuum Field.

### Microseismic monitoring

Injection of $CO_2$ into oil and gas reservoirs will be accompanied by deformation in the region close to the injection well. In brine formations, the pressure build-up may be distributed over a broad area because injection will not be accompanied by fluid withdrawal from production.

Microseismicity reveals fractures and faults that have a propensity to slip due to their orientation with respect to the current state of stress. The increase in fluid pressure can reduce the frictional resistance along a fault plane and cause fault blocks to slip. Other processes can also induce seismicity, such as the transfer of stress to a weaker fault, hydraulic fracturing, mineral precipitation or dissolution along a fault, and density driven stress loading (Sminchak *et al*., 2001). These processes are all illustrated in Figure 4. Small displacement faults that are too thin to be resolved with surface seismic and do not have enough vertical throw to be detected from bedding discontinuities, may be revealed by microseismicity.

A vital aspect of any $CO_2$ injection strategy will be to avoid injection induced fracturing or fault reactivation. While serious earthquakes induced by injection activity are rare and can be prevented through proper siting and operation procedures, smaller induced seismic events are common and can potentially have serious ramifications. Fractures may occur in the overlying rock units providing a pathway for upward migration of the $CO_2$. Also, continual seismic activity may gradually weaken the well casing, or in the worst case scenario, fault or fracture movement may rupture the injection well casing, in which case containment will be lost (Sminchak *et al*., 2001).

Microseismic technology is still in its infancy, but passive monitoring of induced microseismic events may prove to be an effective way to evaluate the effects of deformation from the injection of $CO_2$ on the integrity of the cap rock and provide early warning of potentially disastrous fracturing or fault reactivation.

Borehole monitoring methods are initially expensive, particularly if wells need to be drilled for the purpose. However, recent advances in borehole technology, such as permanent fiber optic sensors that can be emplaced during drilling and completion, could make borehole monitoring cost effective in the long term. Permanent sensors that are integrated into a simultaneous surface and borehole acquisition system designed for both active and passive seismic monitoring would provide the ultimate in seismic data coverage at all scales. The improvements in repeatability of positioning and coupling that permanent sensors provide would also increase the sensitivity to subtle changes in time-lapse data.

Supporting geophysical methods and extensive laboratory testing are needed for accurate quantitative analysis of the seismic data. This also requires further development of the theoretical underpinning for the laboratory measurements. The geological setting and the availability of wells and pre-existing baseline data will have a profound influence on the choice of any additional geophysical methods.

## Electromagnetics

Electromagnetic (EM) data provides different and complementary information to seismic. It allows an image of the electrical resistivity distribution to be derived. EM methods have lower resolution than seismic, but are far more sensitive to changes in fluid saturation and may detect anomalies that are too subtle to interpret from seismic data alone. Over the range of typical reservoir conditions, the resistivity can vary by an order of magnitude whereas the seismic velocities may vary by just 10-20% (Wilt and Alumbaugh, 1998).

Crosswell EM methods have been used to monitor both steam and $CO_2$ flooding operations between wells up to 300 m apart and there are a number of recent efforts of simultaneous acquisition of crosswell seismic and EM data for improved interpretation of the flood performance. The successful application of crosswell EM has to date been limited to non-conductive fibreglass-cased wells. Steel casing poses a serious challenge but recent tests suggest it may eventually be possible if the dominating background effect of the casing can be removed (Wilt *et al*., 2001). Co-inversion of EM data with constraints determined from seismic offers the most potential to improve quantitative interpretation and further development of these techniques is required.

## Gravity

Changes to the gravity field or gravity gradient are a direct response to changes in subsurface density due to fluid displacement. Therefore, accurate time-lapse gravity data could be very complementary to seismic data, which has much more complex relationships.

Gravity surveys are relatively cheap to acquire on land, but at present are only viable for monitoring in the most favourable circumstance of shallow injection of large volumes of gas displacing water or vice-versa (Lewis and Shinn, 2001). Baseline gravity surveys have recently been acquired in gas fields in Alaska and the North Sea, with repeat surveys planned for monitoring purposes in several years time (Eiken *et al*., 2000, van Gelderen *et al*., 1999). However, substantial improvements in measurement sensitivity and constrained inversion methods are required before gravity will be feasible for monitoring volumes of subsurface $CO_2$ in the supercritical state. The resolution of surface gravity data is too poor to resolve preferential flow zones or detect small leakage pathways, although the addition of borehole gravity measurements may potentially address this.

## Well Logging

Well logging is a proven technology and current practices are adequate for monitoring saturation changes around the well within clastic and carbonate reservoirs. More value could be extracted from the fine detail provided by logs through integration with borehole and surface seismic data, to improve the resolution and quantitative interpretation of data recorded away from the well. Instrumentation of the injection well should include bottom-hole fluid temperature and pressure measurements and chemical analysis, in addition to the usual pressure measurements at the wellhead (Lewis and Shinn, 2001). The challenge will be to define the most cost-effective well monitoring program. New techniques need to be developed for monitoring coal-bed storage using well log data.

## Research

Research required for application of the geophysical method to the $CO_2$ monitoring can be grouped into two main areas: improved resolution and quantitative analysis of geophysical data, and reliable long-term simulations that couple all the processes involved (hydrologic, chemical, mechanical and thermal).

Improved resolution of surface data can be achieved through better ties with borehole data, which requires a better understanding of scaling and sensitivity issues. Accurate quantitative interpretation requires the development of improved interpretation methods that involve the simultaneous inversion of different types of geophysical data and calibration with laboratory measurements. This requires the development of existing or new theoretical models and numerical techniques.

The properties and phase behaviour of $CO_2$ in mixture with brine or oil vary greatly near the critical point for $CO_2$, and with a small percentage of impurities such as nitrogen or methane. Reliable approaches for modelling this behaviour and the subsequent effect on the seismic and electrical properties of rocks need to be developed and tested against experimental data.

## Recommendations

A research program that would lead to improved volumetrics and storage performance monitoring must include theoretical and numerical modelling with laboratory experimentation. This includes the following technical issues:

- Phase behaviour of $CO_2$, brine and oil near the critical point
- Distribution style of the fluids (i.e. viscous fingering, patchy saturation)
- Effect of $CO_2$ on seismic, electrical and flow rock properties
- Pore pressure/saturation discrimination

- Influence of impurities on the phase behaviour, flow properties and geochemistry
- Scaling issues
- Long-term experiments to take into account geochemical changes
- Calibration of experimental data to numerical models
- Joint inversion of seismic and electromagnetic data

## Conclusions

Mapping the distribution of free phase supercritical $CO_2$ in the subsurface should be possible with existing time-lapse seismic technology in most environments. If requirements for storage monitoring also include verification of stored volumes and the phase state, then supporting geophysical methods and further research will be required.

The main research needs for predicting and monitoring the behaviour of subsurface $CO_2$ are improved resolution and quantitative interpretation of geophysical data, and reliable long-term simulations that couple all of the processes involved. It is recommended that a key focus for research should be on experimental measurements that are important to validate numerical modelling of the storage performance and the geophysical response.

## Acknowledgments

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# Forward modelling the long-term seismic response to $CO_2$ storage in a saline aquifer

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## Summary

Geological sequestration of $CO_2$ into brine-saturated reservoirs is an immediate option to reduce anthropogenic $CO_2$ emissions into the atmosphere. It is anticipated that time-lapse 3-D seismic technology will form the foundation for monitoring $CO_2$ migration within the subsurface. The success of seismic monitoring will be determined by the magnitude of the change in the elastic properties of the reservoir during the lifecycle of $CO_2$ storage. In the short-term, there will be a strong contrast in density and compressibility between 'free' $CO_2$ and brine. The contrast between these fluids is greater at shallower depth and higher temperature. The change in the elastic moduli of the reservoir will enable time-lapse seismic methods to readily monitor structural trapping of $CO_2$ below an impermeable seal. However, because the acoustic contrast between brine saturated with $CO_2$ and brine containing no dissolved $CO_2$ is very slight, dissolved $CO_2$ is unlikely to be detected by any seismic technology, including high-resolution borehole seismic. The detection of porosity increases associated with dissolution of susceptible minerals within the reservoir may provide a means for qualitative monitoring of $CO_2$ dissolution. Conversion of aqueous $CO_2$ into carbonate minerals should cause a detectable rise in the elastic moduli of the rock frame, especially the shear moduli. The magnitude of this rise increases with depth. Forward modelling suggests that the optimal reservoir depth for seismic monitoring is between 1000 and 2500 m. Higher reservoir temperature is also preferred so that 'free' $CO_2$ will resemble a vapour.

## Introduction

The burning of fossil fuels has caused a significant increase in global atmospheric emissions of $CO_2$. One of the immediate solutions to reduce anthropogenic $CO_2$ emissions is long-term storage within shallow underground brine-saturated reservoirs. If $CO_2$ is to be sequestered within the subsurface, a rigorous monitoring program will be required to confirm that $CO_2$ storage is safe and secure. Time-lapse 3D (TL3D) seismic technology is expected to form the foundation for most monitoring. However, TL3D seismic technology is not applicable in all production scenarios and a feasibility assessment must be conducted prior to project commencement to ensure success.

The world's first geological sequestration project involving $CO_2$ injection into a brine-saturated reservoir was commenced in the Sleipner Field of the North Sea in 1996 (Kongsjorden *et al.*, 1997). The sequestration reservoir is the Utsira Sand and it was selected because of its shallow depth, large extent, high porosity and high permeability (Zweigel *et al.*, 2000). The objective of this study is to assess the feasibility for repeated seismic measurements to monitor long-term storage of $CO_2$ within an unconsolidated reservoir similar to the Utsira Sand.

## $CO_2$ lifecycle

The injection of $CO_2$ into sandstones saturated with brine will cause significant changes within the reservoir over time. The primary trapping mechanism of free $CO_2$ will be structural trapping below an impermeable seal (Johnson *et al.*, 2001). After the $CO_2$ has been locked within the reservoir for some time, it will begin to dissolve into the brine (solubility trapping). The effectiveness of seismic methods to monitor the flow of $CO_2$ will be dependent on the contrast between these fluids under reservoir conditions.

The dissolution of $CO_2$ into brine releases excess hydrogen and bicarbonate ions into the formation water (Johnson *et al.*, 2001). This reduces the pH of the reservoir and the induced acidic conditions will dissolve susceptible minerals within the rock frame, causing porosity to increase slightly. The breakdown of these minerals will release metallic cations into the formation water such as calcium, magnesium and iron. These cations can then combine with free bicarbonate anions to form carbonate minerals such as calcite, dolomite or siderite. This process is referred to as *mineral trapping* of $CO_2$.

## Rock physics model for Utsira Sand

Forward modelling the seismic response to long-term $CO_2$ storage can determine the most favourable reservoir conditions for seismic monitoring. This analysis requires a mathematical model that can anticipate the effect of fluid and mineral substitution, as well as changes in porosity, on the seismic properties of the reservoir.

In an isotropic porous medium consisting of m isotropic mineral components and saturated with a mixture of *n* immiscible fluids, P-wave $V_p$ and S-wave $V_s$ velocities are dependent on the bulk modulus $K_{sat}$, shear modulus $\mu_{sat}$ and density $\rho_{sat}$:

$$V_p = \sqrt{\frac{K_{sat} + \frac{4}{3}\mu_{sat}}{\rho_{sat}}} \qquad (1)$$

and

$$V_s = \sqrt{\frac{\mu_{sat}}{\rho_{sat}}} \qquad (2)$$

| | $V_p$ (m/s) | $V_s$ (m/s) | $V_p$ /$V_s$ |
|---|---|---|---|
| Utsira Sand | 2056 | 640 | 3.2 |
| Krief *et al*., 1990 | 2688 | 1450 | 1.85 |
| Nur *et al*., 1995 | 2412 | 1193 | 2.02 |
| Walton, 1987 (rough spheres) | 2216 | 1050 | 2.11 |
| Walton, 1987 (smooth spheres) | 2013 | 678 | 2.97 |
| Dvorkin and Nur, 1996 (uncemented sand) | 2175 | 1046 | 2.08 |
| Dvorkin and Nur, 1996 (cemented surfaces) | 3044 | 1963 | 1.55 |
| Dvorkin and Nur, 1996 (cemented contacts) | 3627 | 2344 | 1.55 |

*Table 1. Gassmann velocities calculated for the brine-saturated Utsira Sand. The effective grain elastic moduli were calculated from the average of the Hashin-Shtrikman bounds for the mineral aggregate ($K_{grain}$ = 38.92 GPa, $\mu_{grain}$ = 38.89 GPa). The dry frame elastic moduli were estimated from various empirical and theoretical trends developed for varying degrees of cementation.*

Formation density $\rho_{sat}$ can be calculated from the weighted average of the mineral and fluid densities:

$$\rho_{sat} = (1-\phi)\sum_{i=1}^{m} f_i\rho_i + \phi\sum_{i=1}^{n} f_i\rho_i \qquad (3)$$

where $\varphi$ is overall porosity, $\rho_i$ is density of $i^{th}$ mineral (fluid) component, and $f_i$ is its volume fraction within solid (fluid). The bulk and shear moduli of the saturated porous rock at low frequencies can be calculated using the Gassmann (1951) equations:

$$K_{sat} = K_{dry} + \frac{(1-\frac{K_{dry}}{K_{grain}})^2}{\frac{\phi}{K_{fluid}} + \frac{1-\phi}{K_{grain}} - \frac{K_{dry}}{K_{grain}^2}} \qquad (4)$$

and

$$\mu_{sat} = \mu_{dry} \qquad (5)$$

In equations (4-5), $K_{dry}$ and $\mu_{dry}$ are the bulk and shear moduli of the dry porous rock (frame moduli), $K_{grain}$ is the (effective) bulk modulus of the solid grains; $K_{fluid}$ is the bulk modulus of the composite fluid, which at seismic frequencies is given by the harmonic average.

### Effective Grain Moduli

According to the theory developed in mechanics of composite materials, effective elastic moduli of a solid composed of *m* isotropic minerals always lies between the so-called lower (-) and upper (+) Hashin-Shtrikman bounds. These bounds define the lower and upper limits of the effective elastic moduli of the mineral aggregate. When the difference between the elastic properties of the mineral constituents is not very large (as is the case for the Utsira Sand), the separation between these bounds is small. In this case, a simple average of the two bounds provides an adequate approximation of the effective grain moduli (Mavko *et al*., 1998).

### Effective Dry Rock Moduli

The largest uncertainty in the Gassmann equations (4) lies in the estimation of the frame moduli for porous materials. As porosity increases, the more compliant the material will become. For most porous materials there is a *critical porosity* ($\varphi_c$), which separates their mechanical and acoustical behaviour into two distinct domains (Mavko *et al*., 1998). When porosity exceeds $\varphi_c$, the fluid is the load bearing phase and the effective elastic moduli will typically follow the Reuss lower bound of the fluid-solid mixture. For porosities less than $\varphi_c$, the grains are the load bearing

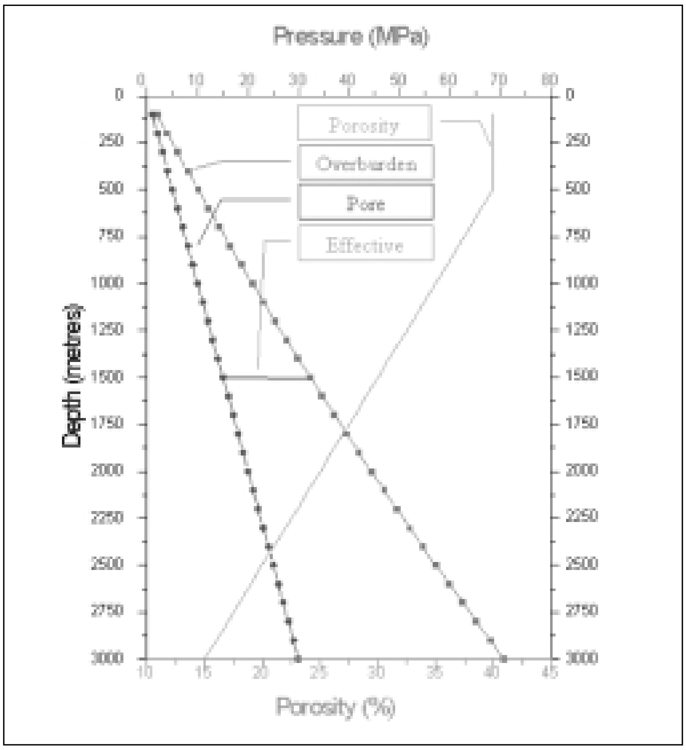



*Fig. 1. Synthetic porosity and pressure gradients of the unconsolidated reservoir model with depth.*

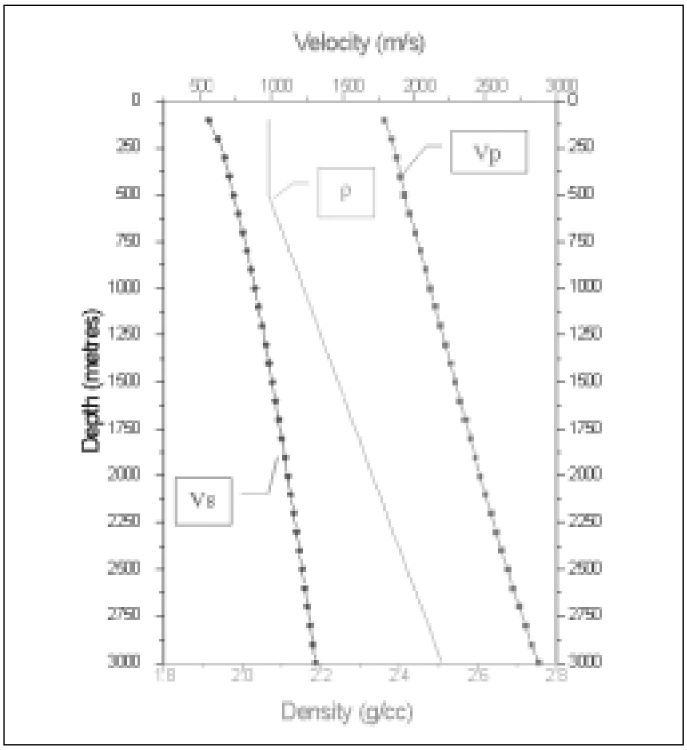



*Fig. 2. Original brine-saturated density and velocity profile of the unconsolidated reservoir model with increasing depth (at 60oC).*

phase and the elastic moduli will lie between the Hashin-Shtrikman bounds of the fluid-solid mixture.

Most porous sands and sandstones within the subsurface have porosities less than $\varphi_c$. A number of empirical relationships and theoretical models have been developed to estimate the frame moduli of porous sands and sandstones as a function of porosity. The Utsira Sand is comprised predominantly of well-rounded quartz grains, has very high porosity and is unconsolidated. Therefore, we would expect the frame moduli of such a reservoir to be best predicted by granular theory. Walton (1987) developed two limits to the effective elastic moduli of dry granular materials. The first models minimum slip between adjacent grains during the period of a passing seismic wave (infinitely rough grains) and the second models maximum slip (infinitely smooth grains).

To test the validity of the Walton model to estimate correct frame moduli of the Utsira Sand, the sonic log P- and S-wave velocities (brine-saturated) were compared against Gassmann velocities calculated using a number of models to estimate the frame moduli (Table 1). This comparison confirmed that Walton theory is the most appropriate model to predict the frame moduli of the Utsira Sand.

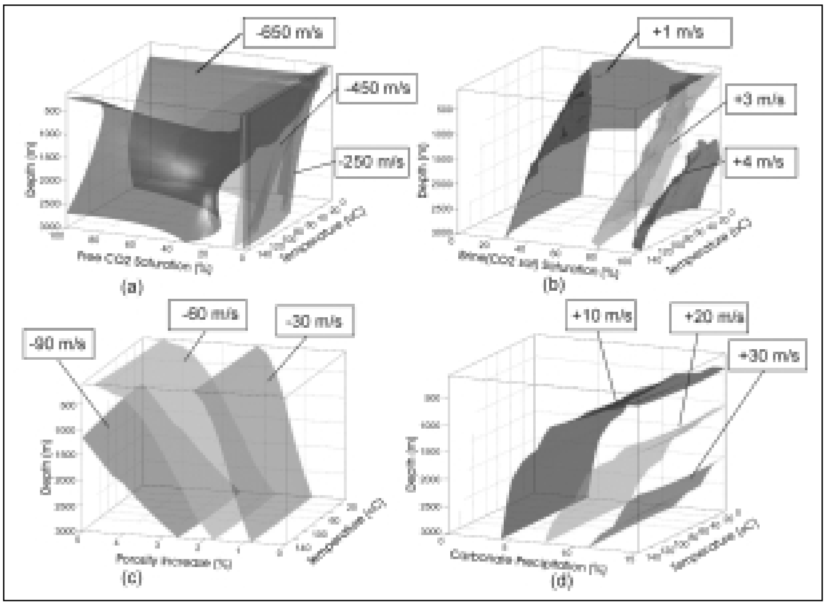
Thus, a combination of the harmonic average of the various fluid components; the Hashin-Shtrikman average of the individual mineral constituents; and Walton theory (to estimate the frame moduli), describes a complete mathematical model for the Gassmann equations. Using this model, it is possible to assess the change in the seismic properties of an Utsira-like reservoir during long-term $CO_2$ storage under a range of pressure-temperature conditions.

## Modelling the seismic response to $CO_2$ sequestration

### Baseline Conditions

The original mineralogy of the reservoir was altered slightly from that of the Utsira Sand and comprised of 70% quartz, 10% feldspar, 5% illite, 5% clay, 5% muscovite and 5% pyrite. The effective grain elastic moduli ($K_{grain}$ = 41.33 GPa, $\mu_{grain}$ = 37.88 GPa) were calculated from the average of the lower and upper Hashin-Shtrikman bounds of the mineral constituents.

The dry elastic moduli of the reservoir were calculated from the average of the Walton (1987) models for infinitely rough and infinitely smooth spheres. This calculation requires both porosity and pressure of the reservoir to be known. Because porosity generally decreases with depth, the reservoir model was assigned a synthetic porosity gradient. The reservoir model was also assigned a synthetic overburden and pore pressure gradients with depth, simulating increasing effective pressure (Figure 1). These pressure and porosity gradients are considered typical of the shallow subsurface.



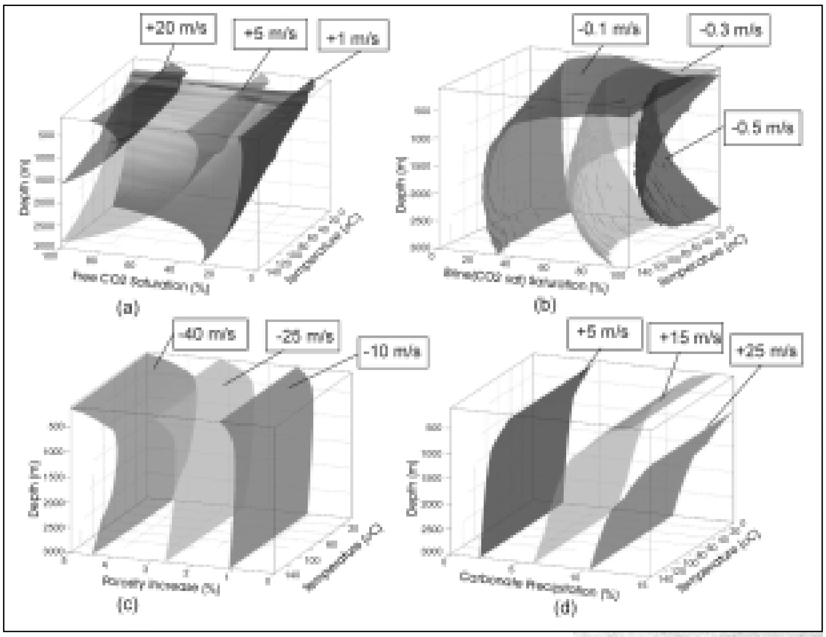




*Fig. 3. (Top) The surfaces illustrate the change in P-wave velocity caused by (a) structural trapping, (b) solubility trapping, (c) porosity increase and (d) mineral trapping of $CO_2$ stored within an unconsolidated saline aquifer under a range of temperature and pressure conditions.*

*Fig. 4. (Above) The surfaces illustrate the change in S-wave velocity caused by (a) structural trapping, (b) solubility trapping, (c) porosity increase and (d) mineral trapping of $CO_2$ stored within an unconsolidated saline aquifer under a range of temperature and pressure conditions.*

Calculation of brine-saturated velocities requires knowledge of the density and bulk modulus of brine. These properties are dependent on depth, temperature and salinity. A nominal salinity value of 35 000 ppm was used and the isothermal density and bulk modulus for brine were calculated using the equation of state. The brine-saturated velocity and density profile of the reservoir model with depth (at 60$^{o}$C) are shown in Figure 2.

### Structural Trapping

Because free $CO_2$ is more compressible than brine, the displacement of brine by $CO_2$ causes the P-wave velocity of the reservoir to decrease (Figure 3(a)). At shallow depth and high temperature, $CO_2$ saturation of just a few percent can cause a drop in $V_p$ in excess of 650 m/s. As the depth of the reservoir increases, higher $CO_2$ saturation and higher temperature is required to cause such a large change in $V_p$. The reduction in density caused by $CO_2$ displacing brine within the reservoir can also be significant at high $CO_2$ saturation. The reduction in density is greatest at shallow depth and high temperature where $CO_2$ resembles a vapour. Despite the Gassmann theory predicting constant shear modulus during a change of fluid, the reduction in density caused by $CO_2$ can be great enough to cause an evident change in the shear velocity of the reservoir (Figure 4(a)). The $V_p/V_s$ ratio of the reservoir will decrease when $CO_2$ is injected. This change is most apparent at depths shallower than approximately 2500 m. Thus, the displacement of brine by $CO_2$ will have a dramatic effect on seismic impedances, travel-times and AVO response.

### Solubility Trapping

The contrast in fluid properties between free $CO_2$ and brine reduces significantly when $CO_2$ dissolves into brine. $CO_2$ dissolution causes brine to become heavier and have increased rigidity. This in turn, will increase the P-wave velocity of the reservoir, but only slightly (Figure 3(b)). The maximum increase in $V_p$ (from baseline conditions) once the brine is fully saturated with $CO_2$ is less than 5 m/s. In similar fashion, the increase in density is extremely small, resulting in a negligible change in $V_s$ (Figure 4(b)). The combined change in $V_p$ and Vs has little impact on the $V_p/V_s$ ratio.

### Porosity Increase

The induced acidic conditions upon $CO_2$ dissolution into brine will cause the dissolution of susceptible minerals within the reservoir, increasing porosity. Increased porosity will reduce the effective elastic moduli of the dry rock and cause a decrease in $V_p$ (Figure 3(c)) and $V_s$ (Figure 4(c)). Although the actual increases in porosity will typically be less than 1% (Johnson *et al*., 2001), even such slight increases in porosity may cause a detectable change in the seismic response. Therefore, although the direct detection of $CO_2$ dissolution into brine may not be feasible using seismic technology alone, indirect monitoring may be possible through the detection of changes in porosity.

### Mineral Trapping

The precipitation of carbonate minerals will alter the mineralogy of the reservoir. The effective elastic moduli of the grains and frame must be recalculated to estimate the impact on the seismic response. Within this Utsira simulation, the feldspar and illite fractions of the sandstone were modelled as being dissolved and simultaneously replaced by equal fractions of dolomite, siderite and calcite.

Because the elastic moduli and density of carbonate minerals are higher than the respective elastic moduli and density of feldspar and illite, simple grain replacement acts to increase the effective elastic moduli and density of the grains. The effect on the seismic response will be an increase in $V_p$ (Figure 3(d)) and $V_s$ (Figure 4(d)). As porosity decreases with depth, the change in $V_p$ and $V_s$ as a consequence of carbonate precipitation increases with depth. It is significant to note that the increase in $V_p$ is almost matched by the increase in $V_s$, which must not be forgotten when planning a monitoring program. Because the fractional increase in $V_s$ is greater than the fractional increase in $V_p$, the $V_p/V_s$ ratio decreases as a result of carbonate replacement.

## Conclusions

The success of seismic monitoring of $CO_2$ sequestration into saline aquifers will be determined by the magnitude of the change in the elastic properties of the reservoir during the lifecycle of $CO_2$ storage. A preliminary feasibility assessment has shown that the strong contrast in density and compressibility between free $CO_2$ and brine (particularly at shallow depth and high temperature) will enable time-lapse seismic methods to readily monitor structural trapping of $CO_2$. However, the acoustic contrast between brine saturated with $CO_2$ and brine containing no dissolved $CO_2$ is very slight and dissolved $CO_2$ is unlikely to be detected by any seismic method, including high-resolution borehole seismic. Qualitative monitoring of $CO_2$ dissolution may be possible through the detection of porosity increases associated with dissolution of susceptible minerals within the reservoir. As dissolved $CO_2$ converts into carbonate minerals there may be a detectable increase in the elastic moduli of the formation, especially with respect to shear moduli. The magnitude of this change increases with depth. Forward modelling suggests that $CO_2$ injection between depths of 1000 to 2500 m will provide the optimal conditions for long-term seismic monitoring. Reservoirs with higher temperature will also be preferred so that free $CO_2$ will resemble a vapour.

## Acknowledgments

The authors would like to thank Jonathan Ennis-King for providing the fluid property database and the SACS consortium for providing basic data for the Utsira Sand. The Australian Petroleum Cooperative Research Centre GEODISC Program, Curtin Reservoir Geophysics Consortium, Australian Petroleum Production and Exploration Association, Petroleum Exploration Society of Australia and the Australian Society of Exploration Geophysicists are acknowledged for their financial support of this project.

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*Cont'd on page 39*

# Export earnings decline in the resource sector

Export earnings by the Australian minerals and energy sector fell by just over 1 per cent to $13.6 billion in the December quarter 2002, according to ABARE's Executive Director, Brian Fisher when he released the latest issue of Australian Mineral Statistics on 13 March.

The weaker performance mainly reflected lower world prices for most of the minerals and metals commodities exported during the quarter and significantly lower export volumes for crude oil.

Commodities for which exports fell by more than $50 million in the December quarter 2002 were:

- Crude oil, down $317 million (16 %) to $1629 million;
- Steaming coal, down $82 million (7 %) to $1161 million;
- Uranium, down $70 million (49 %) to $73 million; and
- Iron ore, down $54 million (4 %) to $1381 million.

Commodities that recorded falls of $5-50 million were: alumina, aluminium, refined gold, LNG, zinc and refined silver.

It is likely that the crude oil situation will continue to deteriorate as the Gippsland Fields are depleted.

However, Dr Fisher said there were also some major export commodities that recorded increases in export earnings during the quarter.

Commodities for which export earnings increased by more than $50 million in the December quarter 2002 were:

- Copper, up $103 million (25 %) to $515 million;
- Nickel, up $84 million (19 %) to $533 million; and
- Coking coal, up $78 million (4 %) to $1931 million.

Commodities that recorded increases of $5-50 million were: lead, refined petroleum products, salt, magnesia and LPG. Increases in these commodities were mainly the result of significantly higher export volumes.

# Exploration investment grows

Meanwhile both mineral and petroleum exploration activity increased during the 2002 December quarter.

## Minerals

Figures released in March 2003 by the Australian Bureau of Statistics showed a continuation of the turn around during in the September quarter. The trend estimate for total mineral exploration expenditure increased by 4.5% to $180.7M, following a large seasonally adjusted increase in the previous quarter. The trend estimate is now 13.5% higher than in December quarter 2001 (see Figure 1).

The largest increases occurred in Western Australia ($4.5M or 4.5% to $111M) and Queensland ($2.1M or 8.2% to $32 M). All remaining states recorded slight increases except Victoria, which fell slightly.

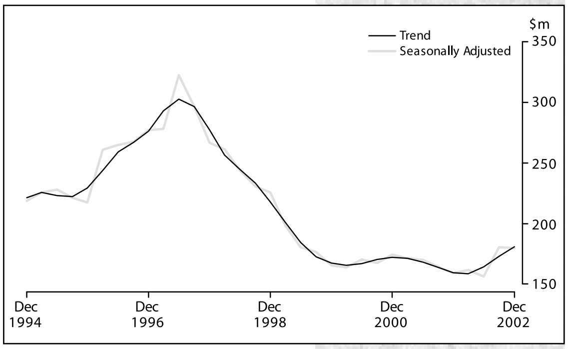


*Fig. 1. Trend and seasonally adjusted quarterly mineral exploration expenditure from December 1994 to December 2002 (provided by the Australian Bureau of Statistics).*

The overall increase was mainly due to exploration for coal in Queensland (up $7.4 M to $21 M), with a number of companies contributing to this increase. Gold exploration in Western Australia remained close to $70 M and in the Northern Territory increased by $2.7M to $8M.

The total metres drilled decreased by 25.4% in the December quarter 2002, to about 1000 km (down 19.6% in seasonally adjusted terms). This decrease was mainly due to decreased drilling on areas other than production leases, which contributed 79.4% to the overall decrease; in other words, a decline in Greenfield drilling. This followed a significant increase in metres drilled in the September quarter, with a number of businesses replacing drilling activity this quarter with other activities such as seismic surveys, geophysical mapping and geochemical analysis.

*Cont'd from page 38*

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## Petroleum

In the December quarter 2002, expenditure on petroleum exploration increased by $52.4M (24.0%) to $270.4M, which is a similar level to that recorded in the December quarter 2001. The increase this quarter was almost totally due to exploration on areas other than production leases.

Onshore exploration expenditure increased by $19.9M (39.5%) and offshore exploration increased by $32.5M (19.4%), with both drilling and non-drilling activity increasing in each case.

Western Australia was the main contributor to the increase in petroleum exploration expenditure, with expenditure this quarter almost doubling to $170.2M. Most of this increase was due to offshore expenditure on areas other than production leases. South Australia and Queensland also showed significant increases, while Victoria recorded a large decrease following a large increase in the previous quarter.

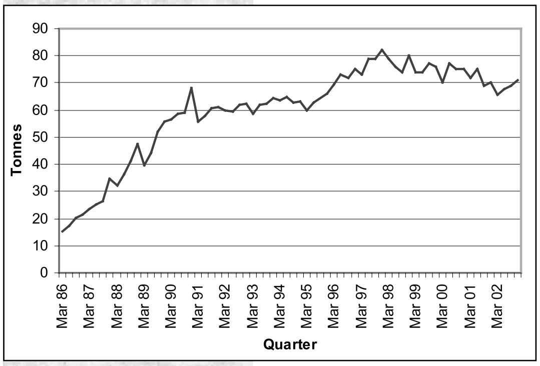


*Fig.2. Quarterly gold production in tones from Australian mines, 1986-2002.*

## And gold is still glittering

The boom in the gold price, now at close to US$340/oz has boosted exploration and gold production. On the exploration front five new Australian gold producers were added to the Australian Gold Council /Macquarie Gold Index in March. These were Oxiana Resources NL, Sino Gold Ltd, Dalrymple Resources NL, Dominion Mining Ltd and the recently listed, MPI Mines.

As a result of these new ventures the Australian gold production rose in the December quarter to 71 tonnes, and this figure is very likely to increase during the 2003. Figure 2 shows the variability in gold production in Australia from 1986 through 2002.

# Santos and Beach do well in the petroleum sector

## Record production in 2002 for Santos

Santos Ltd announced record production and sales volumes for the year ended December 31, 2002.

The company also achieved higher sales revenue of $1.48 billion – the second highest annual revenue for Santos since its formation nearly 50 years ago.

Increased sales in the Victorian market saw total gas sales quantities for the quarter rise 7.0% to 56.6 Petajoules (PJ) compared with 53.0 PJ for the last three months of 2001.

Santos Limited is a major Australian oil and gas exploration and production company with interests in all Australian hydrocarbon provinces. The Santos group also operates in the USA, Indonesia and PNG.

During the year, Santos also acquired the Esenjay interests in South Texas as well as a 20% interest in the Patricia Baleen gas project offshore from Orbost in eastern Victoria, which will be Santos' first offshore Victorian production.

## Timor Sea Treaty ratified

Santos received further good news in March when the Federal Government announced that it has concluded negotiations that will pave the way for $50 billion in petroleum developments in the Timor Sea.

Santos Ltd has welcomed the ratification of this Treaty by the Australian Parliament as a further milestone in the development of the liquefied natural gas (LNG) stage of the Bayu-Undan project. The Bayu-Undan gas and liquids field is located in the Timor Sea, 500 km north west of Darwin and Santos, with an 11.8% interest, was clearly pleased that the lengthy negotiations had been finalised.

Total revenue from the full development of Bayu-Undan is estimated to exceed $A30 billion.

### Beach Petroleum's best year ever

Beach Petroleum's emergence on the Australian oil and gas industry took a major step forward during 2002 with the company reporting record performances across its entire business.

The strong result included record oil and gas revenue of $16.76 million for the six months to December 31, 2002 - a half-year figure higher than total revenues for the whole of the previous year.

Production and sales volumes also climbed to record levels and along with the revenue, represented increases of more than 400% above the previous corresponding half-year period.

The results were powered by Beach's first full six months contribution from its ownership from July 1 last year of 100% from 22% previously, of the producing Bodalla and Kenmore oilfields in southwest Queensland.

A rise in petroleum production to a record half-year result of 443 990 barrels of oil equivalent (boe) for the first half of 2002/2003, compared with 99 367 boe in the previous corresponding half.

Average production rates for the last three months climbed to 2571 boe per day.

Beach Petroleum's Managing Director, Reg Nelson said the Company expected to recommence its exploration program in April or May this year, with up to 12 wells planned for Beach's Cooper Basin blocks in South Australia and Queensland.