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SAYING GOODBYE TO A 2D EARTH — CONFERENCE ABSTRACTS 2015

INTERNATIONAL CONFERENCE, 2–7 AUGUST 2015
MARGARET RIVER, WESTERN AUSTRALIA

compiled by
M Jessell and K Gessner




Geological Survey of Western Australia

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Perth 2015

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Geological Survey of Western Australia

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This Record contains the abstracts, program of the conference 'Saying Goodbye to a 2D Earth' that took place in Margaret River, Western Australia, 2–7 August 2015. The posters and PowerPoint presentations are available to download as a zip file from the website. GSWA is releasing the conference volume as part of its Record Series to ensure a wider distribution of the conference presentations. The individual authors are responsible for the scientific content of the Record and the drafting of figures. No editing has been undertaken by GSWA.

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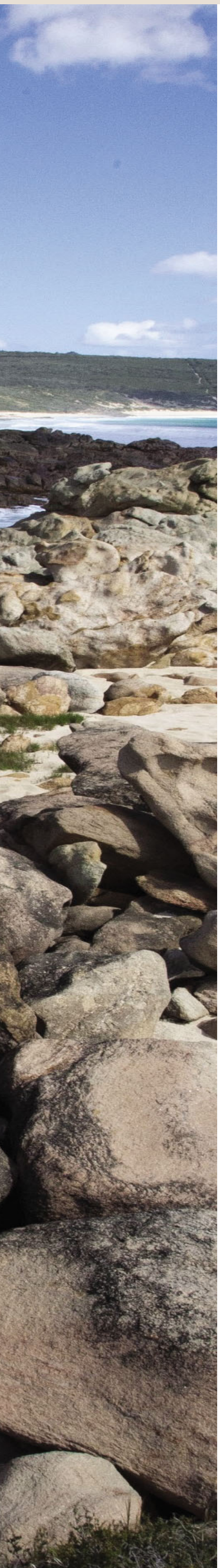

SAYING GOODBYE TO A 2D EARTH

INTERNATIONAL CONFERENCE AUGUST 2 - 7, 2015

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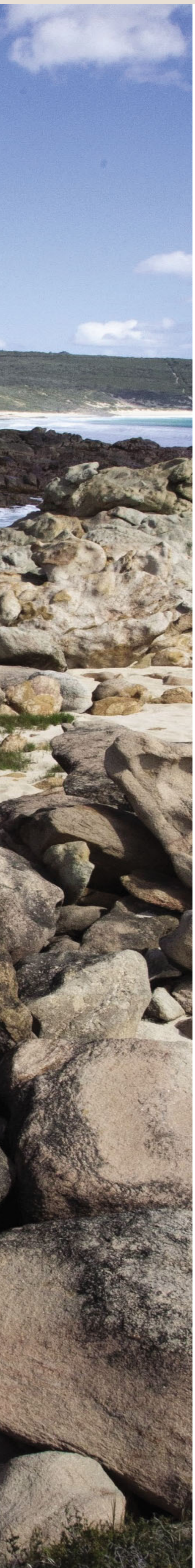

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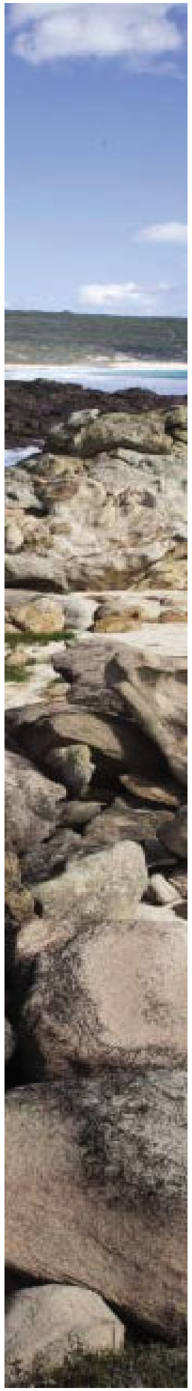
Participants

Brett	Adams	Spinifex Geophysics	badams@spinifexgeophysics.com.au
Laurent	Ailleres	Monash University - Australia	laurent.ailleres@sci.monash.edu.au
Coraline	Blaud-Guerry	Centre for Exploration Targeting	c.blaudguerry@gmail.com
Clare	Bond	University of Aberdeen - Scotland	clare.bond@abdn.ac.uk
Anaïs	Brethes	Geological Survey of Denmark and Greenland	aib@geus.dk
Lucy	Brisbout	GSWA	lucybrisbout@gmail.com
Graeme	Broadbent	Rio Tinto Exploration	graeme.broadbent@riotinto.com
Tim	Chalke	Mira Geoscience	timc@mirageoscience.com
Gabriel	Courrioux	BRGM, Orléans - France	g.courrioux@brgm.fr
Mawson	Croaker	Rio Tinto Exploration	mawson.croaker@riotinto.com
Karol	Czarnota	Geoscience Australia	karol.czarnota@gmail.com
Eric	de Kemp	Geological Survey of Canada	Eric.deKemp@NRCan-RNCan.gc.ca
Tania	Dhu	Northern Territory Geological Survey	tania.dhu@nt.gov.au
Klaus	Gessner	Department of Mines and Petroleum	Klaus.GESSNER@dmp.wa.gov.au
Jeremie	Giraud	Centre for Exploration Targeting	jeremie.giraud@research.uwa.edu.au
Javier	Gonzalez	University of Western Australia	jaggo84@gmail.com
James	Goodwin	Geoscience Australia	james.goodwin@ga.gov.au
Lachlan	Grose	Monash University	lachlan.grose@monash.edu
Hoshin	Gupta	University of Arizona - USA	hoshin.gupta@hwr.arizona.edu
Eun-Jung	Holden	Centre for Exploration Targeting	eun-jung.holden@uwa.edu.au
Mark	Jessell	Centre for Exploration Targeting	mark.jessell@uwa.edu.au
Jens	Klump	CSIRO	jens.klump@csiro.au
Nan	Li	Centre for Exploration Targeting	nan.li@uwa.edu.au
Mark	Lindsay	Centre for Exploration Targeting	mark.lindsay@uwa.edu.au
Roland	Martin	CNRS Toulouse - France	rackam_2000@yahoo.com
Stephan K.	Matthai	University of Melbourne	stephan.matthai@unimelb.edu.au
Mike	Middleton	WA Department of Mines and Resources	mike.middleton@dmp.wa.gov.au
Ruth	Murdie	GSWA	Ruth.Murdie@dmp.wa.gov.au
David	Nathan	Centre for Exploration Targeting	david.nathan@uwa.edu.au
Ian	Neilson	Model Earth	ian.neilson@modelearth.net.au
Malcolm	Nicoll	Geoscience Australia	malcolm.nicoll@ga.gov.au
Vitaliy	Ogarko	Centre for Exploration Targeting	vogarko@gmail.com
Evren	Pazyuk-Charrier	Centre for Exploration Targeting	evren.pakyuz-charrier@research.uwa.edu.au
Perla	Piña-Veras	Centre for Exploration Targeting	perla.pinavaras@uwa.edu.au
Thorkild	Rasmussen	Luleå University of Technology	Thorkild.Maack.Rasmussen@LTU.se
Mark	Rattenbury	GNS Science	m.rattenbury@gns.cri.nz
Peter	Schaubs	CSIRO Mineral Resources	Peter.Schaubs@csiro.au
Christian	Sippl	Australian National University	christian.sippl@anu.edu.au
Bernd	Striewski	Geological Survey of Western Australia	bernd.striewski@dmp.wa.gov.au
Sam	Thiele	Centre for Exploration Targeting	sam.thiele01@gmail.com
Nina	Triche	Department of Mines and Petroleum	nina.triche@dmp.wa.gov.au
Florian	Wellmann	RWTJ Aachen - Germany	jan.florian.wellmann@gmail.com
Stephen	White	Geological Survey of Western Australia	stephen.white@dmp.wa.gov.au
Jason	Wong	Centre for Exploration Targeting	jason.wong@uwa.edu.au
Ji	Zhang	Rio Tinto Iron Ore	uqji@hotmail.com

Saying Goodbye to a 2D Earth - Program



Sunday 2nd of August

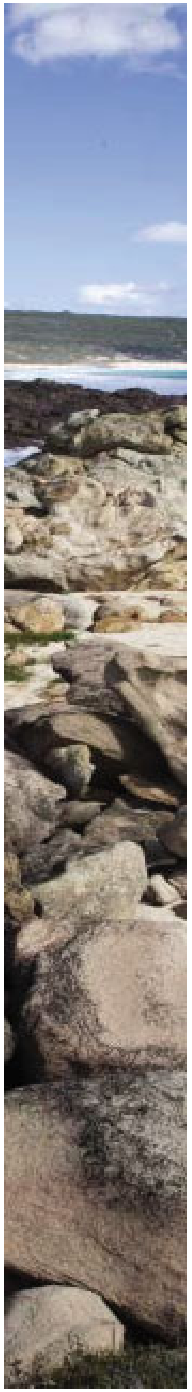
Conference Registration 18:00-19:00

Monday 3rd August Geological Modelling - Talks

			First Name	Last Name	Title
8:45	9:00	Welcome	Mark	Jessell	
9:00	9:30	Talk 1.1	Mark	Jessell	A history of 3D geological modelling
9:30	10:30	Talk 1.2 Keynote	Laurent	**Ailleres**	Uncertainty in 3D geological model and implicit modelling of multiple folding events
10:30	*11:00*	*Coffee Break*			
11:00	11:30	Talk 1.3	Tim	**Chalke**	Realising the benefit of integrated interpretation in minimising model uncertainty
11:30	12:00	Talk 1.4	Steve	**Matthai**	3D - 2D -1D and asynchronous in time: modelling and simulating sub-surface systems in a physically more realistic way with CSMP++
12:00	12:30	Talk 1.5	Charles	**Randle**	Quantifying and predicting interpretational uncertainty in cross-sections
12:30	13:00	Talk 1.6	Mark	**Lindsay**	Dips are important: geological uncertainty and mineral prospectivity
13:00	*14:00*	*Lunch*			
14:00	*18:00*	*Free Time*			
18:00	*19:00*	*Dinner*			
19:00	20:00	Talk 1.7 Keynote	Eric	**de Kemp**	Achieving Geologically Reasonable 3D Models

Tuesday 4th August - Case Studies - Talks

9:00	10:00	Talk 2.1 Keynote	Gaby	**Courriaux**	Pushing forward implicit modelling
10:00	10:30	Talk 2.2	Lachlan	**Grose**	Adapting geostatistical tools to a structural geology framework: with an application to fold modelling
10:30	*11:00*	*Coffee Break*			
11:00	11:30	Talk 2.3	Sam	**Thiele**	Topological Uncertainty
11:30	12:00	Talk 2.4	Ian	**Neilson**	Discovery of a Blind Gold Deposit via 3D Geology Model Targeting, Kalgoorlie, Western Australia
12:00	12:30	Talk 2.5	Anais	**Brethes**	3D modelling of the base-metal mineralized Jameson Land Basin (central East Greenland) using geologically constrained inversion of magnetic data
12:30	13:00	Talk 2.6	Ruth	**Murdie**	A 3D fault model of the NW Yilgarn
13:00	*14:00*	*Lunch*			
14:00	*18:00*	*Free Time*			
18:00	*19:00*	*Dinner*			
19:00	20:00	Talk 2.7 Keynote	Clare	**Bond**	Uncertainty in seismic interpretation - what factors influence interpretational ability?



Wednesday 5th August - Demo Day

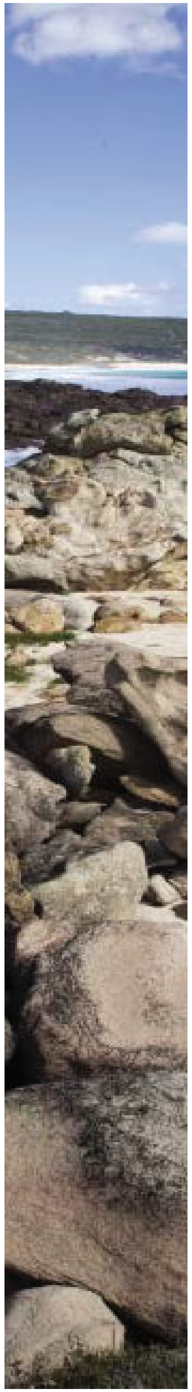
8:30	9:00	1 slide presentation	All
9:00	10:00	Slot 1	Geosoft, MIRA, Monash, UWA- Nan, UWA- Wong, Model Earth
10:00	11:00	Slot 2	Geosoft, GA, MIRA, RWTH, GSC, UWA- Wong, Model Earth
11:00	12:00	Slot 3	Geosoft, GA, RWTH, Monash, GSC, UWA- Nan, UWA- Wong, Model Earth
12:00	*13:00*	*Lunch*	
13:00	14:00	Slot 4	Geosoft, GA, MIRA, RWTH, Monash, GSC, UWA- Nan, UWA- Wong
14:00	15:00	Slot 5	Geosoft, MIRA, RWTH, Monash, GSC, UWA- Nan, UWA- Wong , Model Earth
15:00	16:00	Slot 6	GA, MIRA, RWTH, Monash, GSC, UWA- Wong, Model Earth
16:00	19:00	Open	
19:00	*21:00*	*Cocktail Dinatoire*	

Thursday 6th August geophysics - Talks

9:00	10:00	Talk 3.1 Keynote	Roland	**Martin**	Linear and non-linear techniques applied to joint inversions using TOMOFAST3D
10:00	10:30	Talk 3.2	Mike	**Middleton**	Understanding the Offshore Harvey Transfer Zone, Perth Basin, Western Australia
10:30	*11:00*	*Coffee Break*			
11:00	11:30	Talk 3.3	Clive	**Foss**	How can we make the most of magnetic data in building regional geological models?
11:30	12:00	Talk 3.4	Jason	**Wong**	3D Model and Feature Evidence Visualisation in the Integrated Exploration Platform
12:00	12:30	Talk 3.5	Perla	**Pina-Varas**	Welcoming 3-D magnetotelluric inversion without saying goodbye to 2-D: Kimberley Craton and Capricorn Orogen as example of 3-D cases
12:30	*14:00*	*Lunch*			
14:00	*16:00*	*Free Time*			
16:00	18:00	POSTERS			
18:00	*19:00*	*Dinner*			
19:00	20:00	Talk 3.6 Keynote	Hoshin	**Gupta**	Models, Data, Uncertainty and Learning: How Information is Coded into Dynamical Geophysical Models

Friday 7th August Delivery of 3D Models - Talks

9:00	10:00	Talk 4.1 Keynote	Florian	**Wellmann**	Uncertainties in 3-D Geological Models: Recent Developments and Future Outlook
10:00	10:30	Talk 4.2	Mark	**Rattenbury**	Delivering and curating 3D geology models
10:30	*11:00*	*Coffee Break*			
11:00	11:30	Talk 4.3	Christian	**Sippl**	Crustal models for the Albany-Fraser Orogen, Western Australia, from passive-source seismology – how can they be brought together with geological information?
11:30	12:00	Talk 4.4	Klaus	**Gessner**	The future of 3D modeling in Geological Surveys
12:00	12:30	Wrapup			
12:30	*13:30*	*Lunch*			
13:30	*16:30*	*Return to Perth*			



Posters

	First	Last	Title
Poster 1	James	**Goodwin**	3D Geological Model of the Grampians-Stavely Zone, western Victoria
Poster 2	Ruth	**Murdie**	The Capricorn Orogen Passive source Array
Poster 3	June	**Hill**	GeoLena – Synthetic Data Models
Poster 4	Vitaliy	**Ogarko**	Non-linear 3D electrical capacitance tomography inversion
Poster 5	Malcolm	**Nicoll**	EarthSci – A new tool for 3D data visualisation, integration and distribution
Poster 6	Evren	**Pazyuk-Charrier**	Geological models need error bars
Poster 7	Coraline	**Blaud-Guerry**	3D modelling of the Bryah and Padbury Basins, southern Capricorn Orogen, Western Australia: understanding the structure of the Robinson Range
Poster 8	Juan	**Alcalde**	Where is the Fault? – An experiment to understand differences in seismic interpretation
Poster 9	Peter	**Schaubs**	3D Architecture of the Jervois Cu-Pb-Zn deposit, Northern Territory, Australia
Poster 10	Lucy	**Brisbout**	Preliminary results of gravity inversion and forward modelling in the Madura Province

1.1 A History of 3D Geological Modelling

Jessell, M.W.

Centre for Exploration Targeting, The University of Western Australia, 35 Stirling Highway, Crawley, 6009, Australia

Mark.Jessell@uwa.edu.au

The 3D geological modelling problem, which has been recognised since at least the late 1800s, consists of several elements:

a) The model has to match all the observed geological observations,

b) The model can be visualised to allow 3D spatial relationships to be better understood

c) The model constructing methodology does not limit the possible outcomes.

The first 3D models were physical (wood, wire, clay…) and provided partial solutions to three elements listed above, and continued up until the 1970s. The boom in the use of computers in 3D geological modelling dates from the 1980s, drawing upon in-house systems developed in the large oil & gas and mining companies. First examples of most of the currently-used model construction and visualisation techniques were already in place by 1990. The evolution of research into computer assisted 3D geological modelling can be imagined as a series of waves (Figure 1):

1) 2D modelling (maps or sections)
2) Analysis of geological observations
3) 3D Visualisation
4) Model Construction Algorithms
5) Uncertainty Analysis.

The different modelling systems currently available, either as commercial or research codes, are tailored to specific geological environments (mines, basins, regional, global) and many of the challenges that geomodellers face come from using or adapting tools that were designed for a different environment. In 2015 the most challenging geological environment is the regional-scale cratonic setting as none of the available tools were originally designed for this environment, and thus they fail criteria a & c above. This is compounded by the fact that geophysical imaging techniques as constraints cannot at present be used at the regional craton scale in a form that adequately retains geological meaning.

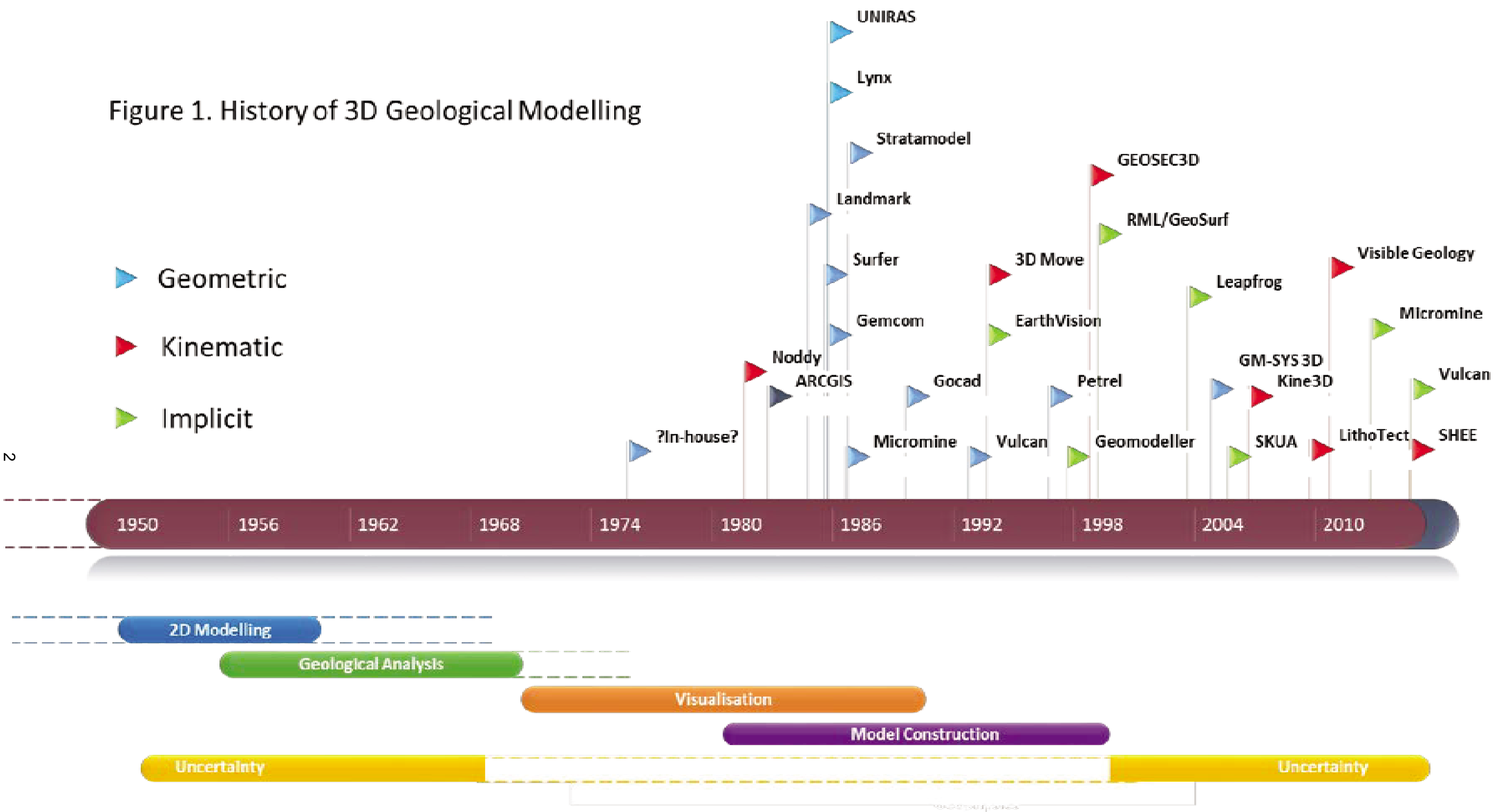


Figure 1. History of 3D Geological Modelling

1.2 Uncertainty in 3D geological model and implicit modelling of multiple folding events

Ailleres[1], L., Grose[1], L., Carmichael[1], T.C., Jessell[2], M.W., Lindsay[2], M., Laurent, G[1,3]., Armit[1], R., Kolin[1], V.

[1] School of Earth, Atmosphere and Environment, 9 Rainforest Walk, Monash University, VIC 3800.

[2] Centre for Exploration Technology, 35 Stirling Highway , The University of Western Australia, Perth, WA 6009

[3] Research for Integrative Numerical Geology Project (RING) - ENSG – Georessources, Universite de Lorraine, 2 Rue du Doyen Marcel Roubault - TSA 70605, VANDOEUVRE-LES-NANCY, 54518, France. (ex Gocad Research Group).

Laurent.ailleres@monash.edu

Recently developed implicit modelling techniques (Lajaunie et al., 1997; Mallet, 2004; Moyen et al., 2004; Aug et al., 2005; Calcagno et al., 2008) allow for repeatable and consistent geological model building with reduced subjective user input. The resulting models are built consistent with input data and knowledge and the ability to construct a series of models from a perturbed initial input data set allows assessment of model variability and uncertainty. (Jessell et al, 2010; Wellmann et al., 2010; 2011; Lindsay et al., 2012; Lindsay et al., 2013a and b; Wellmann et al., 2013). Biodiversity concepts adapted to geoscience (termed geodiversity – Lindsay et al., 2013a) help characterise geometrical differences between models within a model suite and multivariate statistics (PCA and SOM [Kohonen, 1997]) are used to classify models within the entire model space. Outlier models and most common models can be identified (Lindsay et al., 2013a).

We present a review of uncertainty characterisation research (Jessell et al, 2010; Wellmann et al., 2010; 2011; Lindsay et al., 2012; Lindsay et al., 2013a and b; Wellmann et al., 2013) using examples from the Gippsland basin in Victoria, the Ashanti belt in Ghana. We also investigate the source of uncertainty related to both input data uncertainty (Grose et al., 2014) as well as upscaling of data necessary before any geological modelling (Carmichael et Ailleres, in press).

The main findings of the research are:

1. Data are inherently uncertain (obviously). We present the result of map variability analysis based on 40 maps produced during the 3rd year mapping camp at Broken Hill (Grose et al., 2014). Use of geodiversity methods identify geoscientist behaviours and interpretation variability. Although not as thorough with respect to “expertise”, this work is similar to the work of Bond et al. (2007; 2012)

2. Data upscaling has a major influence on the initial variability of the input data and consequently on the 3D geometries produced. However, the method proposed by Carmichael & Ailleres (in press) allows to optimise upscaling and model-data consistency.

3. Uncertainty can be estimated and visualised (Wellmann et al., 2011; Lindsay et al., 2012)

4. Geodiversity allows to characterise the model space and identify most common models as well as outlier models (Lindsay et al., 2013a & b)

5. Characterisation of the model space may provide a series of reference models for further geophysical inversions (Jessell et al., 2010; Lindsay et al., 2013b, 2014; Wellman et al., 2013).

However, geophysical inversions will need to geologically constrained using e.g. a geological objective functions (Jessell et al., 2010)

The results presented above are applicable to layer cake stratigraphic models and do not take into account all of the available data collected during structural mapping. Folds in particular are ignored unless manually drawn onto sections prior to modelling (Maxelon et al., 2009) or are a conceptual representation (Vollgger et al., 2015).

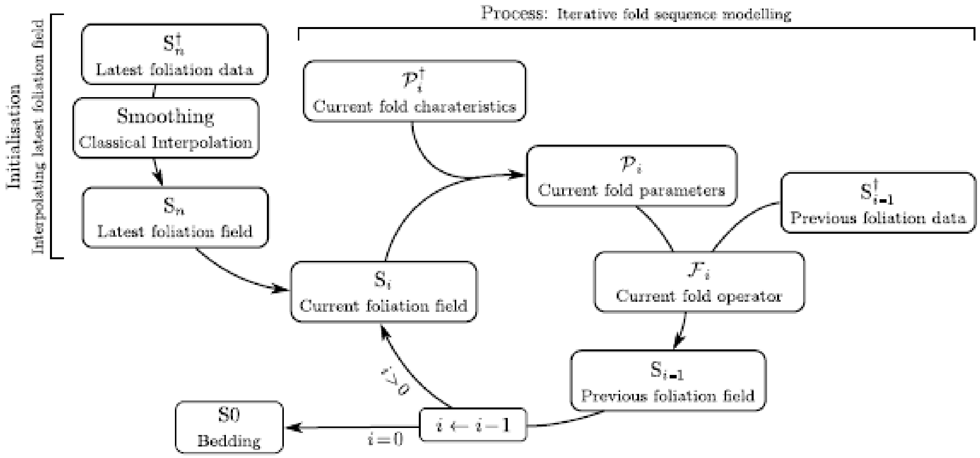


Figure 1: Iterative fold sequence modelling process. The process is initialised by modelling the latest foliation field with classical interpolation approach. Foliation fields are then iteratively used with other fold characteristics to derive any previous geological foliation (from Laurent et al., 2014).

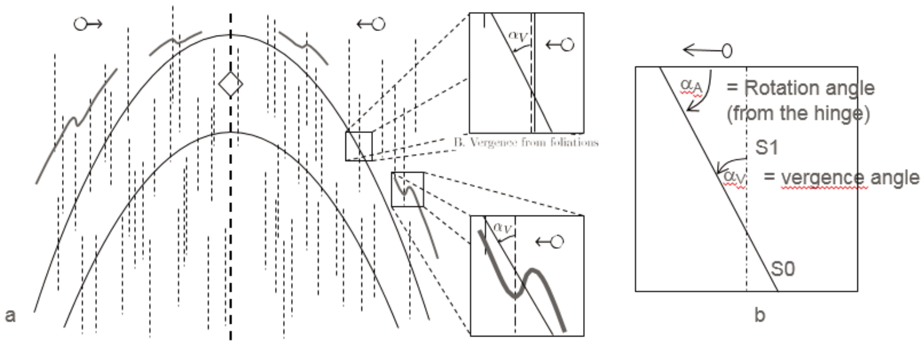


Figure 2: a) classical concept of vergence, defined by the angular relationship between a folded foliation and the axial surface of the fold and/or asymmetry of parasitic folds (S and Z) and b) the concept of Fold rotation angle which allows the characterisation of fold geometry (rotation angle = 0 in the hinge; maximum and minimum at inflection points of both limbs) [adapted from Laurent et al., 2014].

We present a new method (Laurent et al., 2014) accounting for poly-deformation as well as structural elements associated with each deformation event. Each folding event is represented by a set of scalar and vector fields associated with the fold axial surfaces and fold axes either measured or inferred from intersection lineations. Our approach is based on structural geology and we model the most recent event first (Fig.1). The fields thus calculated are used to constrain the interpolation of the next most recent deformation event fields until the field of bedding can be estimated. This approach is data driven and makes use of structural geology concept such as vergence and its complementary angle termed “rotation angle” (Fig.2). Once the field of Sx (axial surface of fold generation x) has been calculated, the vergence of Sx to Sx-1 can be estimated in the modelled volume combining this field with actual measurements of Sx-1.

In the case of scarce data, s-plots (Grose et al., 2015 - this volume) allowed picking of fold geometries and propagation of the folded structures throughout the model. This tool also allows stochastic simulation of the fold parameters and the creation of a series of poly-deformed models that can be subjected to geodiversity and uncertainty analysis.

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1.3 Realising the benefit of integrated interpretation in minimising 3D model uncertainty

Tim.W.J.Chalke[1], John McGaughey[2]

[1] Mira Geoscience Asia Pacific Pty Ltd

[2] Mira Geoscience Ltd

timc@mirageoscience.com

Abstract

The modern mineral exploration context is increasingly one of targeting at depth or under cover. This requires moving beyond traditional interpretation of data and its map representation towards interpretation of 3D models. In mineral exploration, the fundamental purpose of a model is to convert data, concepts and interpretation into an actionable construct. 3D models are as varied in purpose, resolution, construction and content as the geological environments they represent and the project objectives they serve.

Historically, 3D models have predominantly been utilised in a mining environment where interpretation is facilitated by large volumes of information obtained through dense drilling and underground mapping. Models were typically built solely on the basis of direct geological observation. On the other hand, away from the mine site and its abundance of direct observation, 3D earth models have been based primarily on geophysical inversion. With any of these 3D models — geological wireframes or geophysical inversions — uncertainty is ubiquitous due to insufficient data and non-uniqueness. Multiple model realisations based solely on either geological or geophysical data give no assurance of adequately or sensibly sampling the model space. This is particularly the case when other data types are available, which may provide significant constraint to shape, depth, volume, and other aspects of model components.

An integrated interpretation framework in which the construction of the 3D model is consistent with conceptual understanding and demonstrably quantitatively consistent with geological, geophysical, geochemical and petrophysical data, provides the best model that one can reasonably hope to achieve. As a basic test of model fitness, we contend that a geological wireframe model not be accepted until the model volume has been attributed with plausible physical properties that are demonstrated to forward-model to whatever geophysical data is available. Uncertainty is thus reduced in a practical manner through the constraints provided by multiple, independent data sources. Although model uncertainty is not quantifiable in absolute terms, constraining the model space through a quantitative reconciliation of multiple, independent data is more useful than analysis of uncertainty in a model with limited inputs. From a practical point of view it is preferable to invest the time required for quantitatively integrated interpretation, through which we know in a concrete way that everything possible has been done to ensure that we can act on the model with confidence, as opposed to working to characterise uncertainty in a model which is limited in input.

1.4 3D - 2D -1D and asynchronous in time: modelling and simulating sub-surface systems in a physically more realistic way with CSMP++

Stephan K. Matthai[1]

[1] Chair of Reservoir Engineering, Department of Infrastructure Engineering, The University of Melbourne, VIC 3010, Australia.

Stephan.matthai@unimelb.edu.au

Oral

First order technical deficiencies of contemporary tools for the large-scale simulation of combined flow - thermal - mechanical and chemical processe are:

1.Lack of geometrical flexibility to capture geological detail. For current engineering practice this implies that many important geologic features and structural details of the storage complex must be ignored to obtain a workable simulation model. Key obstacle: the use of structured grids. These dictate a uniform resolution and regularized geometry that makes it impossible to represent oblique large aspect ratio features such as faults, layer pinch-outs etc. Furthermore the grid cannot be refined to resolve local details of interest and / or achieve a uniform distribution of discretization errors.

2. Oblique faults or fracture corridors cannot be represented. This is the well-known problem of non-neighbour connections. Displaced or truncated layers usually are represented by offsets in the structured grid, and the grid is aligned with such boundaries. Thus, faults as such have do not have a discrete grid representation. Cross-flow or flow in the fault plane can only be approximated with ad-hoc cell connections. When inclined faults are represented using stair-step arrays of grid-blocks, this fails to create oblique flow continuity because the finite-difference stencils only consider transmissibilities along the principal axes of the grid. Finally, unless a prohibitively fine resolution is used, fault thickness tends to be over represented. If so, this distorts flow velocities and leads to a different flow-focussing potential.

3. Implicit wells. The lack of spatial adaptivity and refinement also precludes a discrete representation of wells in conventional simulation models. In stead, semi-analytical well representations are used to relate source / sink terms to corner point pressures. For wells in structurally complex reservoirs, this treatment is inadequate and it precludes model inclusion of near-wellbore flow physics.

4. Key phenomena / features of the flow are not resolved. The inability to refine regions of interest implies that most reservoir simulation models locally are insufficiently refined. If, for instance, highly permeable strata are represented by a single layer of grid-blocks, internal processes, like gravity-tonguing or override, that have a decisive impact on production, will not show. In this case, also the unique properties of the layer will be smeared along the vertical grid axis because of harmonic averaging with adjacent layers in the transmissibility calculations.

5. Deficiencies associated with 2-point flux approximations. Although higher-order FD stencils and/or so-called multipoint flux approximations are available in most commercial reservoir simulators their application is not straightforward. Also, such stencils cannot be applied near material boundaries. Engineers therefore use 2-point flux approximations, accepting severe grid-orientation effects, suppressed flow focussing, and artificially stable displacement fronts. Given the goal to accurately

predict processes like the spreading of a CO2 plume in the subsurface, this lack of fidelity in the representation of the flow processes is unacceptable.

6. Smearing of material interfaces. The classical (point-based) FD or FV methods require averaging of flow properties across material interfaces. Not only does this blur the representation of material interfaces in the model. If different flow physics apply on opposite sides of such boundaries, these averages are physically meaningless.

7. Globally driven time-stepping. In conventional reservoir simulation, the so-called Courant-Fredrich-Levy condition dictates the size of time steps (the discretization of time continuous time). However, the size of optimal time steps decreases with flow rate and the latter varies over tens of orders of magnitude within a single reservoir: Saturation fronts in the far field move at a speed of tens of centimetres per year, while velocities near the wellbore approach meters per second. Therefore any global time stepping scheme cannot be optimal. In addition, only a few tens of years of behaviour need to be simulated / forecast for hydrocarbon reservoirs, while thousands of years are mandatory for CO2 storage complexes.

8. Inability to do multiphysics. Since there is no single numerical method that solves multiphase advection, diffusion, and mechanics problems equally well, hybrid methods that combine different discretization approaches are required to implement rigorous internally consistent multiphysics simulators. To date no such tools exist in the (subsurface) reservoir engineering application domain.

9. No goal-based simulation yet. Any numerical estimate of a physical quantity should come with an error bar and an uncertainty quantification accounting for the natural variability and limited knowledge of the input parameters. However, numerical error estimates for water breakthrough or recovery rate are rarely presented in reservoir simulation studies because errors cannot be quantified for complex simulations where gradients vary over time and the grid might be optimal for one of the equations that are solved, but not for the others. It follows, that the simulation engineer cannot prescribe target accuracy, i.e. set prediction goals determining the computational effort. Such goal-based simulation is highly desirable and already a standard in Computational Fluid Dynamics where unstructured grids are adapted dynamically over the course of a simulation until the target accuracy has been achieved with the side benefit that subgrid-scale features are captured. Goal-based simulation carries a high potential for reservoir simulation but has yet to be introduced in this domain.

10. Limited parallelism. Moore's law no longer applies to CPU clock speed. Thus, dramatic speed gains are possible only by making use of improved hardware parallelism. For billion-cell geologically realistic models, short runtimes can only be achieved if they are implemented in a highly granular way on dedicated massively parallel hardware like GPUs. This has not happened yet.

In summary, while conventional tools like reservoir simulators are conservative by default, highly optimized to minimize computational cost, and although, in many cases, they can match sparse dynamic data after extensive calibration and the benefit of hindsight, their lack of physical realism / spatio-temporal adaptivity, makes this generation of tools poor candidates for predictive and physically realistic simulation of subsurface processes.

This talk presents the Complex Systems Modelling Platform (CSMP++) as an alternative suite of tools, supporting spatially and temporarily adaptive goal-based simulation. CSMP++ is a novel hybrid finite element – finite volume technology invented by the author in 1995. By contrast with standard reservoir simulation technology, this framework can be deployed on adaptively refined unstructured grids, facilitating a discrete representation of all interpreted geologic and engineered features in field scale models. Proof of concept simulations have already shown that CSMP++ can resolve process nonlinearities with the spatio-temporal detail needed to capture emergent behaviour: injection front instabilities due to viscous- or heterogeneity induced fingering, gravity override, clogging by salt precipitation, flow localization due to mineral dissolution / precipitation, alteration of in situ stress by cooling of the injection site, pressure build-up, and buoyant CO_2 accumulation below cap-rocks. CSMP++ also is interfaced with a range of geometry preprocessing tools like Gocad, SKUA, Petrel and ANSYS and public domain visualisation tools like Visualisation Toolkit / Paraview. Respective workflows are also demonstrated in the presentation.

1.5 Quantifying and predicting interpretational uncertainty in cross-sections

Randle[1], C.H., Bond[1], C.E., Monaghan[2], A. A., Lark[3], R. M.

(1) University of Aberdeen, Aberdeen, United Kingdom
(2) British Geological Survey, Edinburgh, United Kingdom
(3) British Geological Survey, Nottingham, United Kingdom

Contact: charles.randle@abdn.ac.uk

Poster

Cross-sections are often constructed from data to create a visual impression of the geologist's interpretation of the sub-surface geology. However as with all interpretations, this vision of the sub-surface geology is uncertain. We have designed and carried out an experiment with the aim of quantifying the uncertainty in geological cross-sections created by experts interpreting borehole data. By analysing different attributes of the data and interpretations we reflect on the main controls on uncertainty.

A group of ten expert modellers at the British Geological Survey were asked to interpret an 11.4 km long cross-section from south-east Glasgow, UK. The data provided consisted of map and borehole data of the superficial deposits and shallow bedrock. Each modeller had a unique set of 11 boreholes removed from their dataset, to which their interpretations of the top of the bedrock were compared. This methodology allowed quantification of how far from the 'correct answer' each interpretation is at 11 points along each interpreted cross-section line; through comparison of the interpreted and actual bedrock elevations in the boreholes. This resulted in the collection of 110 measurements of the error to use in further analysis.

To determine the potential control on uncertainty various attributes relating to the modeller, the interpretation and the data were recorded. Modellers were asked to fill out a questionnaire asking for information; such as how much 3D modelling experience they had, and how long it took them to complete the interpretation. They were also asked to record their confidence in their interpretations graphically, in the form of a confidence level drawn onto the cross-section.

Initial analysis showed the majority of the experts' interpreted bedrock elevations within 5 metres of those recorded in the withheld boreholes. Their distribution is peaked and symmetrical about a mean of zero, indicating that there was no tendency for the experts to either under or over estimate the elevation of the bedrock.

More complex analysis was completed in the form of linear mixed effects modelling. The modelling was used to determine if there were any correlations between the error and any other parameter recorded in the questionnaire, section or the initial dataset. This has resulted in the determination of both data based and interpreter based controls on uncertainty, adding insight into how uncertainty can be predicted, as well as how interpretation workflows can be improved. Our results will inform further experiments across a wide variety of geological situations to build understanding and best practice workflows for cross-section interpretation to reduce uncertainty.

1.6 Dips are important: geological uncertainty and mineral prospectivity

Lindsay, M.D.[1], Aitken, A.R.A., Metelka, V., Occhipinti, S.A., Jessell, M.W., Hollis, J.A.[2] [1] Centre for Exploration Targeting, The University of Western Australia, Crawley, WA, 6009

[2] Geology Department, Ministry of Mineral Resources, Imaneq 1A 201, 3900 Nuuk, Greenland

markdlindsay@gmail.com

Mineral prospectivity modelling provides a means to display the degree of overlap between different geological features thought permissive for mineralisation. Occhipinti et al. (2015) separate features into lithospheric architecture, geodynamic throttle, fertility, depositional site and preservation (Fig. 1). Of these, lithospheric architecture includes major strctures such as faults and shear zones that act as pathways for mineralising fluids, or as physical traps for deposit formation (e.g. damage zones, fault bends and intersections). Fault maps thus provide an important input to mineral prospectivty studies as they not only define discrete regions through which fluids may migrate or be trapped, but also drastically constrain areas of high prospectivity. These constraints on modelling are enforced simply due to the geometry of faults in nature, being discrete linear features that are usually represented as lines in digital data sets. Faults then have a large influence over the reliability of the final prospectivity models, and it is important to represent them appropriately in our modelling.

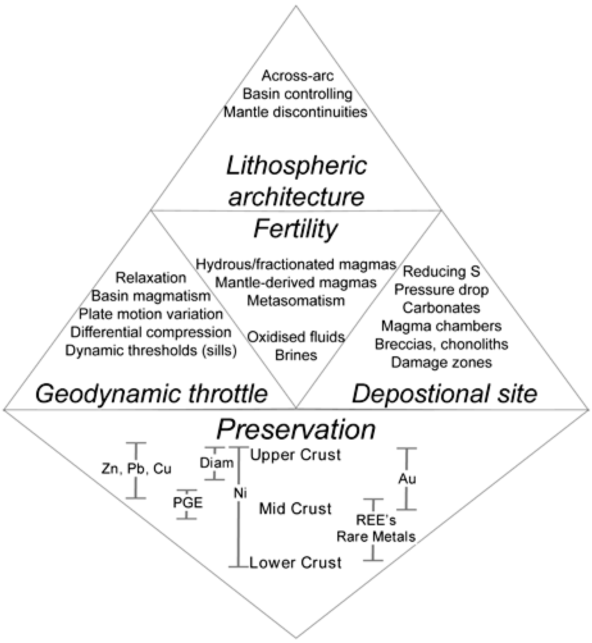

Figure 1. Conceptual arrangement of key mineral Systems components illustrating which are required to form and preserve the a variety of mineral deposits. From Occhipinti et al. 2015.

We address two major considerations: that uncertainty (or 'confidence' as is usually labelled) to the geometry of the fault is a subjective measure; and that the orientation of the fault geometry is not taken into consideration when used in prospectivity modelling. Uncertainty in prospectivity modelling is applied as a weighting value that modifies the final result. A fault considered important for orogenic gold mineralisation may be given a weight of 0.9 (from a range 0 to 1). The location of the fault may be uncertain as it was interpreted from geophysical data, and the entire length of the feature may not completely imaged. Further, the dip angle of the fault may not be well imaged in the data, so a confidence weight of 0.6 (also a value between 0 and 1) may be used to modify initial weight of 0.9 to a value of 0.54 ($0.9 \cdot 0.6 = 0.54$). This value is assigned for the entire fault based on a considered, but nonetheless subjective, assessment by the geoscientist. The given confidence value has a large effect on the resulting prospectivity score, and a more detailed examination of the uncertainty associated with the feature is justified.

The orientation of faults is not acknowledged in current propsectivity techniques. The potential effect of a fault on mineralising the surrounding rocks is represented by a buffer of given distance from the fault. This buffer is symmetric, and gives each side of the fault equal weighting. This approach implies that the dip and dip direction of the fault is unimportant, and may also be valid where the fault is vertical or the extension of the fault at depth is irrelevant for the mineralisation style under analysis. In a large number of cases these assumptions are not valid, and can result in unreliable results being produced.

We examine the King Leopold Orogen (KLO) in the west Kimberley, northern Australia for orogenic gold mineralisation. The KLO is dominated by the Paperbark Supersuite, a Paleoproterozoic set of granitic to granodioritic intrusions that were intruded during the 1870-1850 Ma Hooper Orogeny. The 1855 Ma Whitewater Volcanics are linked to the Hooper Orogeny and intrusion of the Paperpark Supersuite rocks. The c. 1872 Ma Marboo Formation, an amphibolite facies metaturbiditic package also forms an important part of the KLO, and are intruded by the metadoleritic sills of the Ruins Dolerite. To the north of the KLO are the c. 1835 Ma Speewah and c 1800 Ma Kimberley basins. The Kimberley Basin unconformably overlies the Speewah Basin, and includes the basaltic Carson Volcanics. Intruding both the Speewah and Kimberley basins is the c. 1797 Ma Hart Dolerite, which together with the Carson Volcanics forms a Large Igneous Provinces.

The boundary between the KLO and Speewah and Kimberley basins is marked by the Ingliss Fault, a north-east dipping thrust fault determined to be a deep-crustal scale feature by Lindsay et al. (2015). The Ingliss Fault is considered to be old, and to have been reactivated over the tectonic history of the west Kimberley. The Ingliss Fault is also thought to be a major conduit for deep metalliferous fluids. The Ingliss Fault being old, deep, reactivated and therefore a likely fluid conduit means determining its geometry and any uncertainties are critical concerns for any mineralisation associated with it.

Uncertainty can be located and quantified in 3D models (Lindsay et al. 2012; Wellmann et al. 2010). We use these techniques to determine the uncertainty associated with the Ingliss Fault (Fig. 2a), and specifically, with the hanging wall (Fig. 2b). Fig 2c shows what is typically done in prospectivity analyses, with symmetric distance buffers from the fault and failing to show that the fault dips moderately to the NE. Fig. 2d shows asymmetric distance buffering, with thinner buffers on the foot wall side of the Ingliss Fault.

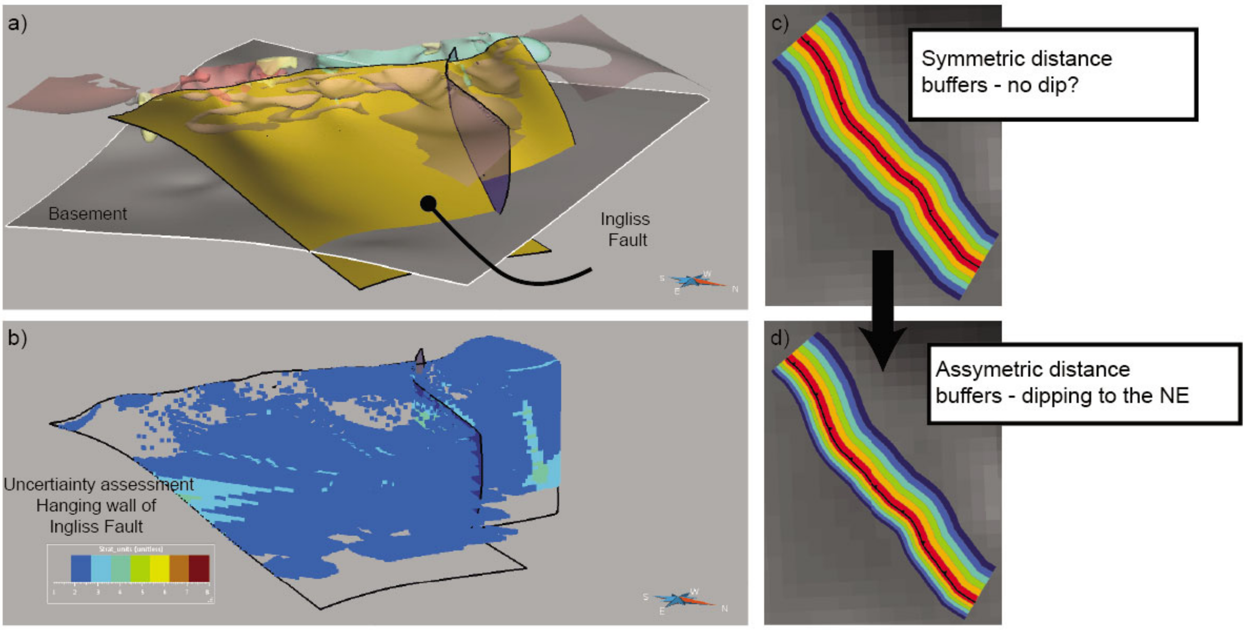

Fig. 2. a) 3D model of the west Kimberley as viewed from the NE– highlighted is the Ingliss Fault. b) uncertainty associated with the hanging wall of the Ingliss Fault. c) Symmetric distance buffers (500m interval) around a portion of the Ingliss Fault typically used in prospectivity analysis. d) NE dip direction of the Ingliss Fault is honoured here, with the larger distance buffers on the hanging wall side of the fault inferring greater prospectivity.

By combining geological uncertainty and the geometry of geological features, prospectivity analyses can include valuable information that can better inform mineral explorers. The results will honour fundamental features shown in the geology, such as dipping structures, while acknowledging that the location these features at depth are uncertain. Calculating uncertainty in this way precludes the need for a subjective assessment of uncertainty, and recognises that assigning a single value for an entire structure is likely misrepresentative.

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1.7 Achieving Geologically Reasonable 3D Models

de Kemp, E.A.

Geological Survey of Canada, Ottawa, Canada
(edekemp@nrcan.gc.ca)

Summary

The tool-kit for creating more complex 3D geological models is expanding each year. On several fronts such as the ability to integrate more geological and geophysical constraint types (Corrioux et al. 2006, Hillier et al. 2014), heterogeneous and sparser data distributions and more complicated geological histories (Aillères et al., Laurent et. al. 2014). Importantly more implicit algorithms are available (Jessell et al. 2014) as well as ways to characterize the uncertainty and complexity of the calculated models (Grose et al. 2014, Pellerin, J., et al. 2015). Geophysical inversion techniques, structural restoration, forward modelling codes and various flow simulators have all developed and continue to evolve into mature commercial software (Caumon 2014). There is increased activity in supporting 3D data infrastructure for storage, workflow optimization and interoperability between models and data (Le et al. 2014). These tools are being applied in a wide range of fields (resources, environmental, and hazards) as well as supporting scientific studies at many scales from the micro to global scales. The 3D geological modelling domain is also benefiting from the exponential rates of computer hardware evolution, supporting ever more realistic renderings, faster model calculations and real time interactions (Jessell et al. 2014). With all these impressive advances in hand, it may be a worthwhile exercise to see what is still truly needed to be done to make even more progress.

The current implicit modelling schemes purport to provide rapid model solutions, which in many simple geological scenarios is a very welcome development. However, in ancient shield and orogenic terrains, where much of our mineral wealth is located, we need to push these schemes to perform much better. Many 3D models, especially the more complex ones, in the initial stages of development lack geological credibility. This is particularly true when data is sparse, which is common for regional settings producing the well-known 'bubble gum' or 'tunnelling' effect. This is a known problem when using current implicit schemes as they have as yet no internal mechanism that guarantees topological correctness and hence geologically meaningful solutions. They are designed primarily to provide smooth spatial interpolations on densely scattered datasets. Interpolants are obtained by solving a linear system of equations, generated from data constraints and a user chosen distance-dependent basis function. Determined solutions can be characterised as the smoothest solution fitting the data for a given basis function. This may result in unreasonable solutions, surfaces with non-geological topologies. To counteract this, the geologist-modeller adds interpretive constraints to make things work a bit better. Depending on experience, this tends to become a more or less painful exercise with mixed results in geologic credibility. Practically this puts these interpreted constraints at the same model weighting as hard observational data, which solves some geologic problems but starts to embed user bias on the model. This can be a good thing, especially with high levels of expertise, but if only one model is going to get built because the interpreter is too exhausted to do another one, it is back to the traditional map construction approach, except in 3D. To move forward, 3D geological modelling will need to move beyond this approach. The user should not be required to insert more interpretive points, or re-use interpretive features from existing maps to make the model work. There should be enough data and knowledge available to efficiently develop a model without extensive human intervention to make a geologically reasonable model.

Geological reasonableness is the essential quality of a model which allows the geologist to say 'yes, that seems reasonable given the geologic environment'. Achieving geological reasonableness is indeed one of

the most difficult aspects of 3D geological modelling, familiar to anyone who has had the task of building more complex models. This is perhaps an as yet un-quantified authenticity attribute embedded in our models which speaks intuitively to most geologists. This reasonableness factor is more than just assessing if the model or its components are geometrically consistent with all the various data sets. Perhaps it is a component of a global conceptual uncertainty. Given our existing tools for uncertainty characterization we may still have the possibility of having a high degree of certainty in a model but things just look wrong geologically or the model infers a false process such as thrusting instead of normal faulting (Wellman 2014).
How do we judge if a given model realization is geologically reasonable? This is not an unfamiliar problem, if we acknowledge that 2D maps are models and that a 3D model is just a 3D map, albeit created with a quite different workflow. It is the same problem for any 2D geological map or cross-section, namely, how to assess their geological meaningfulness? The core difference which tends to get overlooked is that geological maps need to make sense right from the start, whereas a 3D model calculation doesn't. The geological map is generally an interpretation, and that makes all the difference. The knowledge embedding is done at the interpretive level. It is an intelligent realization utilizing all available knowledge that extends, interpolates and reconciles contact and overprinting features to fit the geologic history and process drivers. It is still wrong, in that it may never be an accurate real world representation, but it is believable and until it can be falsified, it is acceptable. On the other hand the interpretive map, if it is 'geologically reasonable' will respect the feature observations, physical properties and gradients. Most importantly the 'reasonable' map solution respects the age relationships of all observed features, and expected recurrent patterns seen in other situations formed by similar earth processes. In the end the 'good map' is an extension of the observed geological relationships demonstrating familiar patterns we see throughout earth history. It just makes geological sense.

A current GSC development project called MapSim tries to formalize some of the core notions from the 2D mapping paradigm. Initially attempts focus on capturing the knowledge component of the mapping process by encoding the geological relationships directly from the observation set. These relationship encodings can then provide the sequential framework for implicit or other estimation steps.

In addition to making geologically reasonable models, it will need to become standard practice to be able to produce more than one model. 3D geological modelling will have much more impact scientifically and predictively if several 'geologically reasonable' scenarios are possible with much less effort. This will mean a greater emphasis on simulation techniques to produce 2D maps and sections as well as 3D and 4D models. Perhaps there will be possibilities of combining simulation and traditional estimation techniques from other application areas for example using support vector machine or spatial agents.

In order to develop 2D and 3D models in a simulation approach, all essential geological features and feature relationships must be encoded before computer estimations are undertaken. A simple binary encoding of single feature to single feature over-printings (Schetselaar and de Kemp 2006) and a dependency legend graph is suggested for this process (Harrap 2001). These feature relationships form the basis for the geologic topology that defines the map or model. Internally each observed or inferred relationship will need to be stored in a relationship data base that will act as a rule set to keep the computation process geologically reasonable. Each geological history and the features involved can be encoded from the geological observation data. Each step of the history results in modified or new features with expected pattern ranges and topology (genus). Once computed, the map or model can be examined to determine how well the geological relations and history are respected, as well as the expected patterns, shapes and topologies, forming a kind of geologic reasonableness indicator. In a simulation approach all models below a given geologically reasonable threshold are excluded and those above are kept.

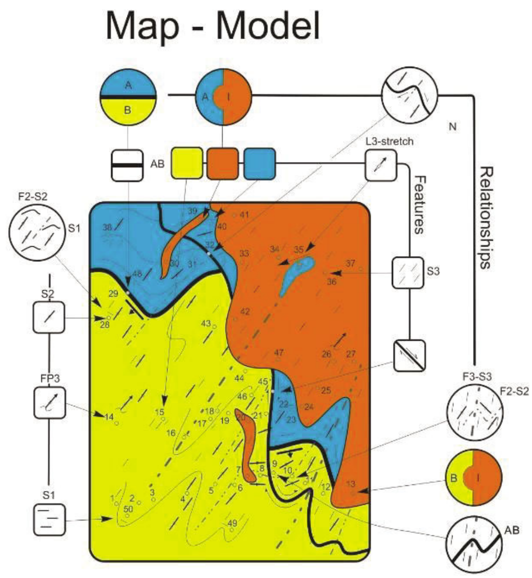

Figure 1 – Example of encoding of observations of geologic features (rounded squares) and feature binary relationships (circles) for MapSim a 2D map and section simulation development. Yellow and blue are supracrustal units, orange is an intrusive, N indicates a normal fault. Small circles on map are field observation stations with site numbers. Synthetic example.

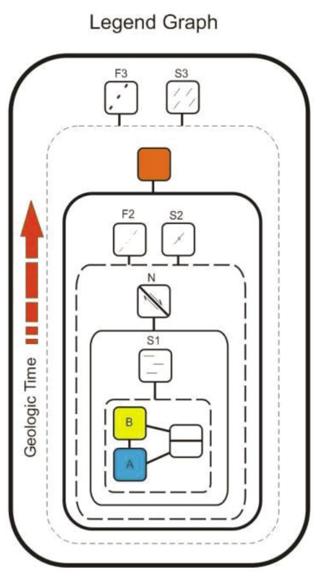

Figure 2 – A dependency legend graph approach for encoding consistent geologic history from relationships between map patterns and the geologic legend adapted from Harrap 2001.

The advantages of this approach is that algorithms can be adapted to suit the geologic feature and relationship being estimated, they can use close feature relations to provide geometric support and it releases the estimation engine from having to calculate a global solution with all constraints in one go.

Saying ‘goodbye to a 2D earth’ will not result in abandoning 2D geology representations, these will always be needed. In fact we need to better understand how geologically meaningful maps actually work to move forward into 2D & 3D geologic model simulation. What seems more the intent is to be ‘saying good-bye’ to the approach that only results in a single 2D, 3D or 4D map solution. And most definitely for any approach that doesn’t use and respect all the available data and knowledge reflecting the whole geological history.

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2.1 Pushing forward implicit modelling

Gabriel Courrioux, Bernard Bourgine, Antonio Guillen, Simon Lopez

BRGM, BP36009, 45060 Orléans Cedex 2, France.

This talk aims at presenting some new developments and ideas on implicit modelling in the frame of the potential field and gradients co-kriging method (Lajaunie et al. 1997, Calcagno et al. 2008, Guillen et al., 2008). The leading idea is to show how taking more advantage of implicit form of co-kriging to enhance the possibilities of geological modelling in a way that they better fit to multiple geological constraints.

Different subjects will be considered:

- Folds modelling.
  Some preliminary results will be presented on how incorporating a varying anisotropy field in the co-kriging method in order to model folds whose axes and intensities are varying in space.

- Faults modelling.
  Some issues and ideas of improvement on fault modelling will be discussed, as accounting for complex situations, faults displaced by faults, "in echelon" faults, or "bizarre" fault shapes.

- Meshing and simulations.
  Recent works on meshing implicit volumes and their application to simulation will be presented.

- Uncertainty estimation.
  The use of Standard co-kriging error is subordinated to the correct choice of a covariance model. Though some theoretical work has already been carried-out on estimating the potential covariance from gradient variogram (Aug, 2004), this aspect has been so far neglected in the modelling process and it is time for rehabilitation. We will show an example of comparison between model variability (realisation of multiple models) and co-kriging error estimation.

- Geophysical inversion
  The main issue is that in current geological-geophysics joint inversion methods, the link between geological data and parameters is lost during the inversion process. We will present some ideas on how breaking this limitation. At this stage this appears as a long term innovative research.

2.2 Adapting geostatistical tools to a structural geology framework: with an application to fold modelling

Grose[1], L.J., Laurent[1], G., Ailleres, L.[1], T. Carmichael[1]

[1] Monash University, School of Earth, Atmosphere and Environment

lachlan.grose@monash.edu

Oral

A new approach to implicit modelling in poly-deformed terranes involves iteratively modelling each folding event using geometrical characteristics of folds such as wavelength, asymmetry, amplitude and tightness. These parameters need to be derived from available data and specified to the interpolator. We present an adaptation of geostatistical tools to structural geology for quantifying these geometrical characteristics of folds.

In this framework, each fold is described with a fold frame based on structural elements (fold axial surface, stretching lineation and intersection lineation). We use the angle rotating the direction of the folded foliation towards the surface of the structural element defining the fold axial surface (fold rotation angle). The fold rotation angle can be calculated in two ways: (1) angle between younger foliation, S_n and older foliation S_{n-1} or; (2) angle between S_n and S_{n-1} form line around the fold axis Ln. We present three adaptations of geostatistical tools where cartesian space is substituted for the foliation scalar field of the younger foliation (S_n): a cross plot of fold rotation angle and the scalar field (S-Plot); a variogram of fold rotation angle (S-Vario); and a h-scattergram of fold rotation angle (S-Scattergram). Using these plots it is possible to characterise the geometry of folds such as the origin, wavelength, tightness, asymmetry and periodicity, for a single fold or a fold series. This approach is applicable to complex poly-deformed terranes because we use the foliation scalar field representing the state prior to deformation. Our method provides a robust method for identifying these parameters from observations and provides the framework for automated fold modelling. We expect a number of different applications of this approach and present an application to parametric fold modelling.

Acknowledgements

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2.3 Topology and Uncertainty in 3D Geology

Sam Thiele, Mark Jessell, Mark Lindsay, Steve Micklethwaite
Centre for Exploration Targeting, The University of Western Australia, 35 Stirling Highway, Crawley, WA, 6009, Australia

Florian Wellmann
RWTH Aachen University, Schinkelstraße 2, 52062 Aachen, Germanywellmann@aices.rwth-aachen.de
Introduction

Introduction

The topology of the 3D subsurface geology of the Earth refers to those geometric properties preserved during continuous deformation such as folding. The topology of geological features is a scale dependant property that reflects the physical processes that form and modify distinct geometric features. It also plays a role in determining the complexity of a region, with consequences for the modelling approach taken (Pellerin et al. 2015). Topology will also be an important element of any analysis of the economic value of a region (Pouliot et al. 2008), and its deformation history.

This study focuses on the topology of meso-scale models within the crust. A number of recent studies have examined the variations in permissible geometries that can arise from imperfect knowledge of 3D geology (Bistacchia et al. 2008; Caumon et al. 2007; Jessell et al. 2010; Wellmann et al. 2010; Lindsay et al. 2014; Cherpau et al. 2011) and this study extends these works by examining the variations in topology that can also arise.

Topological variations within the crust can provide important constraints on fluid flow and electrically conductive pathways. Connectivity of pathways is critical for transporting metal-rich fluids from the mantle to the crust via deep-penetrating faults. Conversely, non- connectivity is critical when metals are to be deposited in or around damage-zones, fault jogs and/or fault intersections. In addition, many geophysical inversion schemes use prior geological models as inputs, but are limited to exploring the parameter space within a single topological system. Finally this analysis provides the possibility to test possible models against neighbour relationships in boreholes.

The most commonly used 3D modelling systems can provide triangulations or voxel models of lithologies, however the topological information needed for a complete description of the system is not generally provided. In this study we have used the Noddy modelling system (Jessell, 1981) as it is capable of providing systematic information in the lithology, the nature of the contacts between lithologies, and the relative ages of the these contacts. Although it is too simple to provide a complete 3D modelling environment it is ideal for this sort of study as calculation times are very fast and the source code can be altered at will if new information is required.

A full topological description of a 3D geological model includes information on the spatial and temporal neighbour relationships between all contiguous volumes (faults, unconformities or stratigraphic contacts, and igneous contacts). The evolution of the geology provides time as an important constraint (Lowner and Becker 2013). Although it could be argued that the nature of the contact is not a piece of pure topological information, it is so fundamental to understanding the system that we have included this information in this study, which otherwise reduces to a set Egenhofer relationships (Egenhofer 1989; Zlatanova et al. 2004).

Evolution of Topology in 2D

Geological events have an inherent topological nature (Perrin et al. 2005), and superimposing these for a given topology provides insight as to the number of possible topological outcomes. In the first example we simply follow the evolution of a 2D geological model (for simplicity of display) as it evolves from a layercake stratigraphy, to a faulted layer cake, to one faulted and intruded by a dyke, and finally to one where the previous geology is partially truncated by an unconformity and its associated stratigraphy (Figure 1a). Two of the most commonly-used visualisations for analysing topologies are network diagrams and adjacency matrices (Godsil and Royle 2001).

Network diagrams (Fig. 1b) portray the pairwise relationships between features, in this case we show the relationship between contiguous lithological volumes, where the nodes in the diagram represents the centroids of each contiguous volume, and the lines joining the nodes (rather confusingly called 'edges') represent the surface that separates the two volumes. In these visualisation the nodes are coloured by lithology, and the edges by the type of contact, although other colouring schemes are possible (e.g. colouring edges by the surface area of the contact). A second network representation is also possible, where the nodes represent the contacts, and the edges the lines of intersection between surfaces, however this is less intuitive when trying to describe the full system.

In Figure 1b we can see that the network evolves with the geology, first becoming more complex, and then reducing in complexity as some of the model is removed by the unconformity.

Adjacency diagrams represent a second approach to analysing topologies, which are more compact and therefore have some advantages, and are closely related to Younging Diagrams (Potts and Reddy 1999). Adjacency diagrams show the all possible neighbour relationships between the lithologies seen in the model, with each axis showing the complete set of lithologies in a model, and row/column pairs representing the contact between two such lithologies. Again several variations are possible: a simple binary diagram that shows if two lithologies contact each other; diagrams that show what surface area two lithologies share along their contacts; or as shown in Fig. 1c, we colour the diagram according to which types of contacts are found in the model (as some lithologies may be neighbours with each other as a result of more than one contact type (stratigraphic and faulted for example). As the model evolves, the adjacency matrices become more complex. Although the adjacency matrices are easier to compare the full network description of a model such as those in Fig.1b can be used to derive the associated adjacency matrix, but not vice versa.

Topological Uncertainty

The use of Monte Carlo simulations to generate multiple testable 3D hypotheses provides a powerful tool for understanding the limitations building under-constrained 3D geological models. In this example we have built 1000 models of a simplified Gippsland basin model (Lindsay et al. 2012) by varying the dip and strike input parameters that define the geometry of geological interfaces. Each of these dip and strike inputs where varied by ±5° from their original values. For each model, we then constructed network diagrams and adjacency matrices (Fig. 2a). By analysing the adjacency matrices we found that for 1000 instances of the 3D model, there are 107 unique topologies. This emphasises the importance of considering topology as a metric for model geodiversity.

Of the 27 lithological neighbour pairs that are found in at least one model (out of a theoretical total of 153 pairs), 13 are found in all models, and 14 are only found in some models, or do not always share the same type of contact (Fig. 2b,c). We can also investigate the average surface area of contact as ways of estimating the likelihood of a particular surface occurring in a model (Fig. 2d). This information provides an important constraint if and when new data is collected, as it can quickly eliminate a subset of the models if the new data is inconsistent with their topologies, without the need to build a full new model.

Discussion

Although we have used Noddy models as a proof of concept, any implicit code should be able to produce the necessary information to allow this sort of analysis. In the future, topological variations should provide an important extra metric for geodiversity analysis.

Using this approach we can show which types of surface are always found (Fig. 2b), regardless of which model is used, and those surfaces which are only found in some models (Fig. 2c). In this model the split between constant and variable surface types was about 50:50. Finally we can analyse the average surface area of each contact pair for all models. More detailed comparisons may be possible building upon analogous studies in molecular biology (Brohée 2012).

The analysis of topology allows us to describe the complex geometric relationships in 3D models in a much reduced form. As new data are collected, (e.g. drillhole data), we can compare the neighbourhood relationships seen in the drill core with the multiple model topologies to eliminate incompatible models.

Acknowledgements

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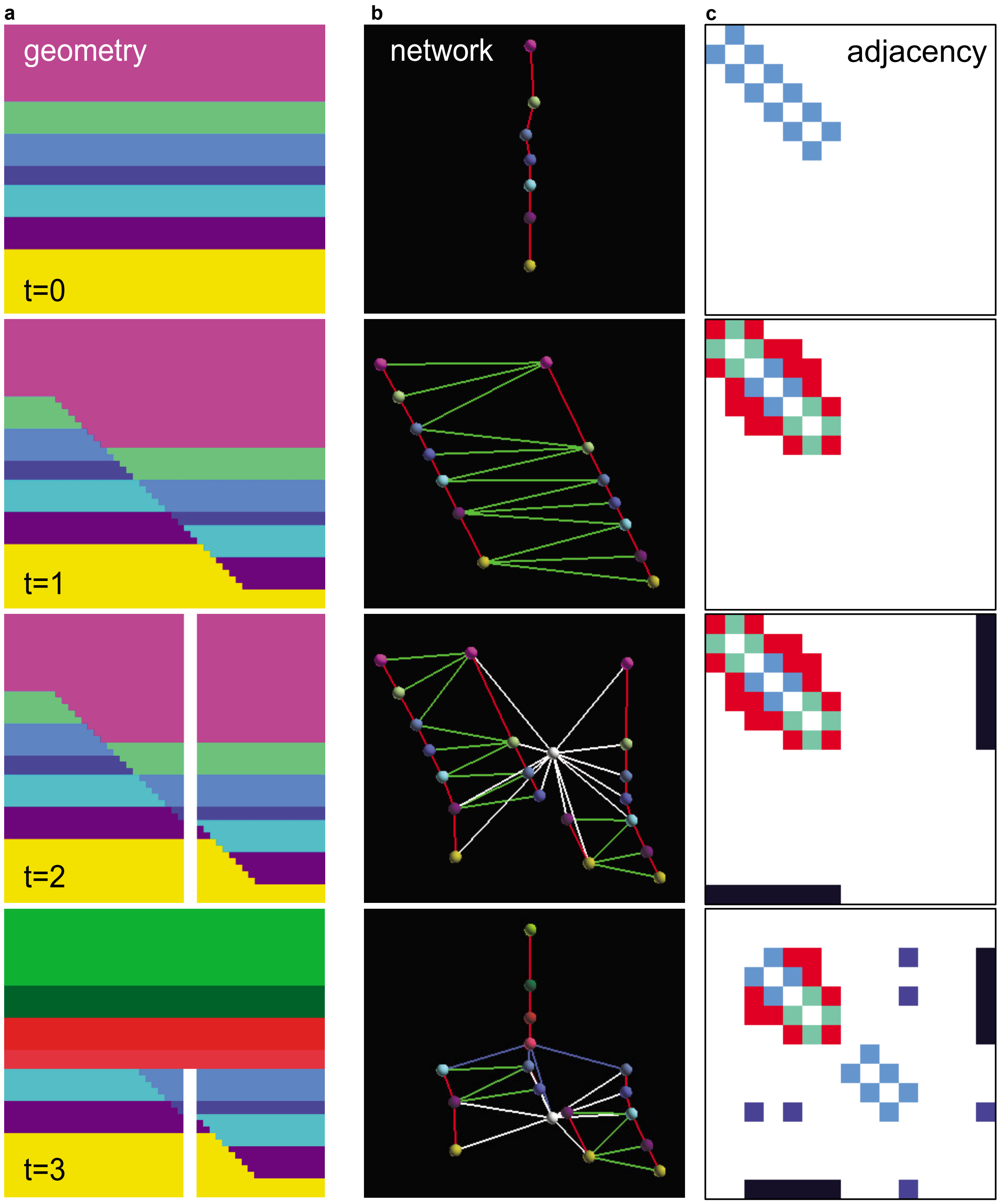


Figure 1. a) Left column shows progressive four-stage evolution of a two-dimensional geological model, showing successive stratigraphic, fault, dyke intrusion and unconformity. b) Central column shows equivalent enhanced network diagrams showing a node for each contiguous volume (sphere colour coded by lithology) and edges (contacts colour coded by type: red=stratigraphic contact; green=fault contact; white= igneous contact; blue=unconformity). c) Right-hand column shows the equivalent adjacency matrix for each time step, coloured according to the type of contact between two lithologies (white=no contact between lithologies; light blue=stratigraphic; red=fault; green=fault and stratigraphic; black=igneous; dark blue=unconformity).

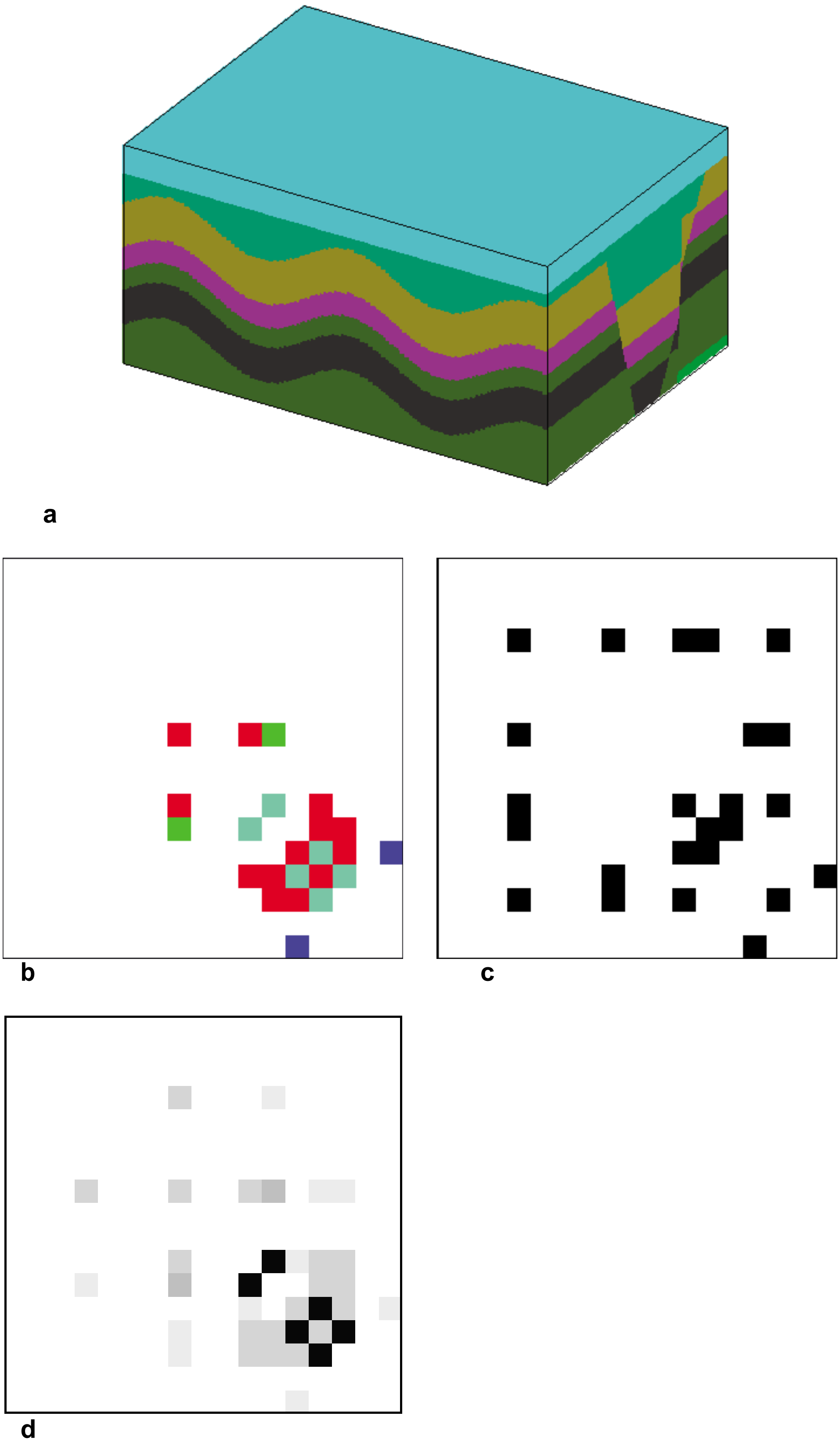


Figure 2. a) Test model from which 1000 variations were derived. b) Adjacency matrix showing only those neighbour pairs that occur in all 1000 models. (white=no contact between lithologies; light blue=stratigraphic; red=fault; green=fault and stratigraphic; black=igneous; dark blue=unconformity). c) Adjacency matrix showing those neighbour pairs that occur in only a subset of the 1000 models. (white=no contact between lithologies; black=contact found in all models). d) Average surface area for each lithological pair, black shows highest surface area.

2.4 Discovery of a Blind Gold Deposit via 3D Geology Model Targeting, Kalgoorlie, Western Australia.

Ian E. Neilson[1], Jonathan G. Standing[1], John Beeson[2], Sue Drieberg[3], Vanessa Beach[3]

1 formerly Jigsaw Geoscience, now Model Earth Pty Ltd
2 formerly Jigsaw Geoscience, now Geoscience Now Pty Ltd
3 formerly KCGM

Abstract

The Central Kalgoorlie 3D modelling project was a collaboration between Jigsaw Geoscience Pty Ltd and KCGM, in late-2009. The resultant Central Corridor 3D model is the first geological model built for Central Kalgoorlie that integrates historic and newly generated geologic data into a representative, functional and queryable 3D model. The fundamental tenet of this model is that it honours the data. The driving force behind construction of this 3D model is the need to be predictive about exploration targeting. The model integrates geology, alteration, structure, mineralisation and physical property data from both surface, pit, underground and drill core. The 3D model was delivered in mid 2010. Drilling of the first target (Town Fault target) began in early-mid 2011 with an intersection of 71.38m @ 4.99ppm Au returned in UNGD015 (Barrick Gold Investor Day presentation, 7 Sept 2011) early in its discovery. The Town Fault Target was reassigned Hidden Secret to due proximity of this historic mine, however they are unrelated. Drilling was ongoing from surface and underground throughout 2011, 2012 and into 2013. In September 2014, KCGM announced the discovery of the Hidden Secret resource of 76,000oz (0.66Mt @ 3.56ppm Au) (http://superpit.com.au/publications/information-sheets/). EPA approval (https://consultation.epa.wa.gov.au/seven-day-comment-on-referrals/kcgm-hidden-secret-project) for development of the Hidden Secret mine was granted in April 2015 with the orebody planned to be mined as an underground operation from Mt Charlotte over a period of 2 years.

2.5 3D modelling of the base-metal mineralized Jameson Land Basin (central East Greenland) using geologically constrained inversion of magnetic data

Brethes[1,2], A., Rasmussen[2], T.M., Guarnieri[1], P., Bauer[2], T.

[1] GEUS (Geological Survey of Denmark and Greenland)

[2] LTU (Luleå Technical University – Sweden)

aib@geus.dk

The N-S elongated Paleozoic – Mesozoic Jameson Land Basin in central East Greenland is explored for base-metals. The study presented here focuses on the eastern margin of the basin where stratiform stratabound and fault-bounded copper mineralization occur within Upper Permian and Triassic sediments which are bounded to the east by crystalline basement. The width of the basin is 80 km and maximum depths of 16 to 18 km are reached in its central part. In Tertiary time the basin was first affected by intense break-up magmatism accompanied by numerous sills and dykes intrusions. A later uplift of more than 1 km and subsequent erosion has resulted in very well exposed structures.

The basin architecture being essential for exploration targeting, an initial 3D geological model was built relying on a detailed mapping of the area from 3D-photogeology and a structural interpretation of aeromagnetic and electromagnetic data. To reduce uncertainty regarding the depth to the crystalline basement and the variation of the sedimentary unit thicknesses, 3D inversion was performed on aeromagnetic data. Most of the study area is covered by a combined transient electromagnetic (SkyTEM) and magnetic survey giving a high resolution dataset. It was merged with data from a GeoTEM survey and more regional data in order to take into account regional trends of the magnetic field variations and avoid edge effects in the modelling. For this purpose the VPmg 3D potential field forward modelling and inversion code from Fullagar Geophysics was used as it allows bringing into play a preliminary geological model made in GoCad software as a priori information. This initial model was built on the geological understanding of the area using data from the 3D-photomapping, fieldwork and drill cores. Eight holes were drilled in the area for a total of 1200m and with a maximum depth of 500m. The drill intersections with geological contacts were used as hard geometrical constraints in the model. Several geological units are taken into account, an heterogeneous crystalline basement, Early Triassic sediments composed of conglomerates and arkoses, Middle Triassic gypsiferous sandstones and mudstones, and Late Triassic sediments, mainly composed of mudstones and sandstones. Magnetic susceptibility was measured at every meter along the drill cores with a hand-held magnetic susceptibility meter. The magnetic susceptibility distribution was calculated for every lithology and geological formation and an average value was attributed to each geological unit in the model. A relatively low magnetic susceptibility contrast occurs between the basement and the overlying Early Triassic conglomerates made of meter-sized granitic boulders. Two different geological domains were therefore considered for the Early Triassic sediments, the conglomerates and the arkoses.

The initial model was subsequently updated both in terms of geometry and susceptibility using a trial and error forward modelling approach and followed by data inversion. A first geometric basement inversion was then performed with a homogeneous basement unit and one single sedimentary cover unit. The inverted geometry was used as input surface in a starting model for a heterogeneous property inversion of the crystalline basement which is mainly made of Caledonian rocks of different lithologies and magnetic susceptibilities. Simple geometry inversions were also performed on local anomalies due to dykes, sills or larger intrusions with the software Model Vision from Encom. The results were integrated into the Gocad model. Combined geometric and property inversions were later run by taking into account the different geological units to achieve a consistent geological and petrophysical model.

The resulting geologically constrained model shows the eastern margin of the Jameson Land basin to be composed of two main domains separated by a sealed NE-SW oriented Early Triassic fault down-faulting the northern block of at least 500m. The area to the south is modelled to have a relatively thin sedimentary cover of a few hundred meters thickness compared to the northern part which attains around 2500m thickness. Early Triassic arkoses are present both in the northern and southern blocks whereas the conglomerates seem to be only present in the north. A significant lateral thickness variation is observed between the down-faulted block in the north where at least 500m of early Triassic sediments were drilled, whereas less than a hundred meters are present in the southern part. The Middle Triassic sediments are not affected by this fault. Early Triassic sediments are onlapping the crystalline basement in the southern part while in the north the contact between the sediments and the basement is tectonic. The local modelling on isolated anomalies shows that the sill present in the northern part of the basin is more or less horizontal and its presence has therefore limited influence on the estimation of the sedimentary thickness of around 2500m. Further north in the basin, the early Triassic sediments are observed with a maximal thickness of 700m lying on top of a very thick sedimentary sequence comprising Devonian to Carboniferous continental deposits and Upper Permian carbonates. A Pre-Triassic sedimentary sequence could therefore be present in the study area between the early Triassic conglomerates and the crystalline basement and was therefore integrated into the model. This is of importance for mineral exploration as a thick sedimentary sequence is an important requirement regarding the metal source.

Other efforts were put in modelling a local anomaly which could be due to a relatively large and shallow intrusion. This is also of interest when considering the Malmbjerg porphyry-molybdenum deposit present on the western margin of the basin, associated with a Miocene granite intruded in Carboniferous sandstones. Several other intrusions in central East Greenland show molybdenum mineralisation and may offer economic potentials.

2.6 A 3D fault model of the NW Yilgarn

Murdie[1], R.E., T. Ivanic[1], Zibra[1], I. Gessner[1], K.

[1] Geological Survey of Western Australia

Ruth.Murdie@dmp.wa.gov.au

Until recently, very little was known about the crustal structure under the Youanmi Terrane and adjacent terrances of the northern Yilgarn Craton. In order to establish first-order constraints on this region's lithospheric evolution and mineralization potential, five seismic reflection lines have been conducted jointly by Geoscience Australia and the Geological Survey of Western Australia from 2010 to 2012 (see parameters in Table 1). We obtain an effective cratonic cross-section by linking these new lines with existing surveys in the Eastern Goldfields Superterrane (east of the Ida Fault; Fig. 1), moreover, it is the first time that seismic data has been obtained across the main terrane-bounding structures of the craton (e.g. the Ida and Yalgar faults). This contribution utilises the new seismic data and combines it with complete gravity and magnetic coverage of the area and extrapolates the important geological surfaces into 3D across the entire northern Yilgarn Craton.

We import interpretative structural elements from workshops presented in 2011 and 2014 and combine these with the latest geological mapping data across the Youanmi Terrane and new measurements for rock properties. We also import existing fault surfaces interpreted in the pmd*CRC study in the Eastern Goldfields Superterrane. The approximate 3D shape of the greenstones was inferred from density inversions performed using the VPmg software of Fullagar incorporated into Gocad. Where greenstones were traversed by the seismic lines, the gravity inversion was constrained by the seismic interpretation.

On a large scale, we incorporate the previously interpreted flat Moho across the region (except for the northwest margin of the craton where the Glenburgh Terrane is thrust under the Narryer Terrane and the eastwards deepening near the boundary with the Eastern Goldfields Superterrane) and the broad seismic divisions within the crust. The latter elements were noted for the contrasting character of their reflectivities and divided into the lower-middle crustal, highly reflective, Yarraquin Seismic Province (which has not yet been identified at the surface) and an upper-crustal, low-reflectivity layer, thought to be composed of metagranitic rocks which relate to rocks observed at the surface. The Yarraquin Seismic Province does not clearly outcrop, but in seismic data it shows a distinctly east-dipping anisotropy under the whole craton which is interpreted to reflect the occurrence of a pronounced east dipping fabric possibly composed of layered migmatite complexes (Zibra et al., 2014).

Source type	3 IVI Hemi-60 vibrators (Hemi-50 for GA10-SC1)
Source array	15 m pad to pad 15 m moveup
Sweep length	3 x 12 s
Sweep frequency	6-64 Hz, 12-96 Hz, 8-72 Hz
Vibration point interval	80m (plus 40m on GA10-YU1,2,&3 over greenstones
Receiver group	12 geophones at 3.3 m spacing
Group interval	40 m
Number of recorded channels	300
Fold	75 and 150
Record length	20 s @ 2 ms
Processed by	10GA-SC1 Velseis Processing Pty Ltd
	10GS-YU1, 2 & 3 Geoscience Australia
	11GA-CP3 Geoscience Australia
Ancillary data	Gravity measurements every 400m
	Magnetotelluric measurements, broadband stations every 5km and long period stations every 15km

Table 1. Shooting parameters for the reflection seismic lines and associated surveys.

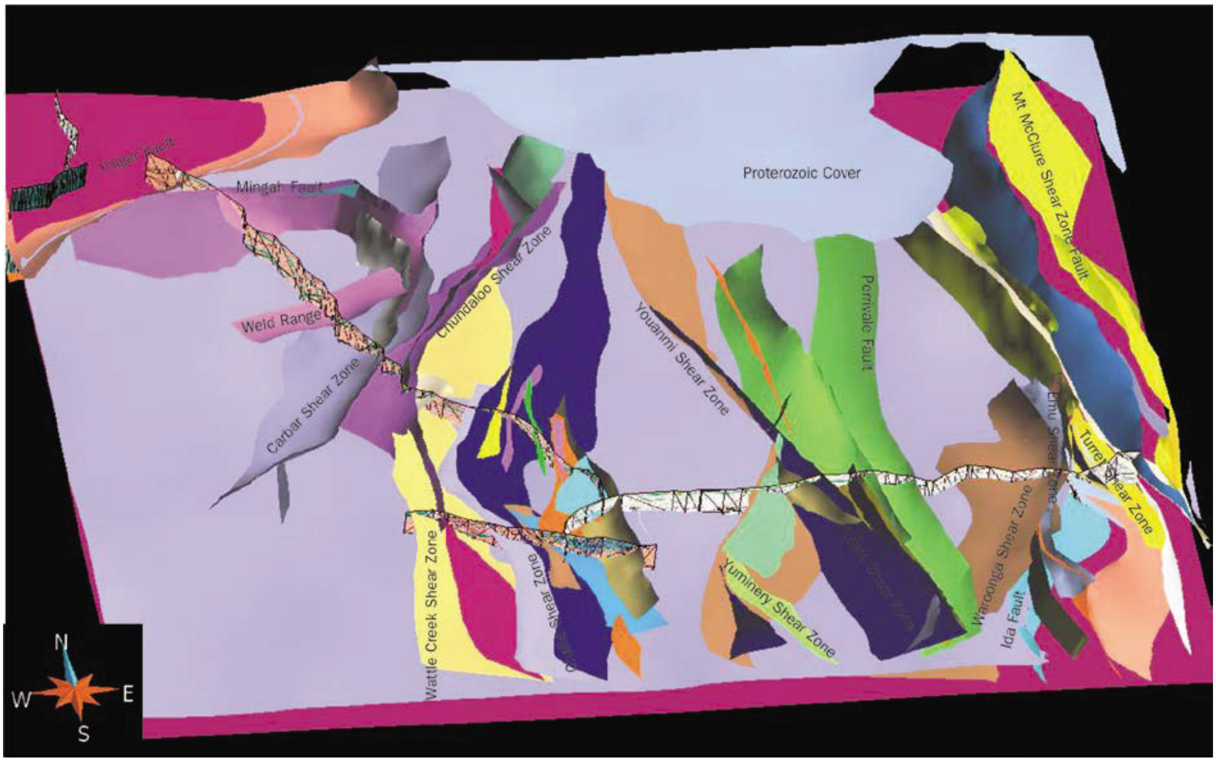


Figure 1. 3D model of the faults in the NW Yilgarn with selected faults named and the location of the seismic lines shown.

The model (Figure 1) shows the fabric of the Yilgarn craton. In detail greenstones are interpreted to reach down to maxima of between 2 and 7 km depth (e.g. Cue-Mt Magnet, Sandstone and Agnew greenstone belts and the Windimurra Igneous Complex) as imaged in the seismic lines.

Modelling using VPmg is currently being done to investigate the shape and depth of those greenstone belts not traversed by seismic profiles.

Faults in the north west appear to dip to the west eg Carbar Shear Zone, Chundaloo-Cuddingwarra Shear Zones. The faults here form a complex branching fault system that bound the greenstone belts and a series of stacked faults.

Going eastwards across the Wattle Creek Shear Zone, which is interpreted to extend through both the upper and lower crust, the imaged faults eg Challa Shear Zone, Cundimurra Shear Zone, appear to dip to the east with the subsidiary greenstone bounding faults only dipping to west. The Wattle Creek Shear Zone is interpreted in all three lines under the Windimurra Igneous Complex allowing more accurate dip estimates of the underlying fabric.

The next large, lower crustal-penetrating shear zone is interpreted to be the Youanmi Shear Zone which again dips to the east and is the bounding fault which separates the Murchsion Domain to the west from the Southern Cross Domain to the east. The Southern Cross Domain had been described by Chen et al (2001) as a region of arcuate structures generated by the impingement of competent granitoid blocks into less competent greenstone during progressive east-west shortening.

Further east again is the Ida Fault which is the terrane boundary between the Youanmi Terrane to the west and the Eastern Goldfields Superterrane to the east. Although it doesn't have a surface expression in this area, it probably is manifest in the Waroonga and Emu Shear Zones. Shear zones in the Eastern Goldfields have been taken from the predictive mineral discovery Cooperative Research Centre (pmd*CRC)(Blewett and Hitchman 2004).

Our conclusions are that: (1) we define greenstone-granite contacts and crustal provinces in 3D across the northern Yilgarn Craton; (2) we provide dip and surface geometries for the principal terrane and domain-bounding faults of the craton; (3) we show distinct changes in the fabric of the upper to middle crust as expressed as 60+ major faults and shear zones and delineate their truncations and depth extents and we highlight these as potential mineral exploration targets in 3D. (4) significant work is required to understand the full geodynamic implications of the geometries presented here.

2.7 Uncertainty in seismic interpretation – what factors influence interpretational ability?

Bond, C.E. School of Geosciences, University of Aberdeen, Kings College, Aberdeen, AB24 3UE

clare.bond@abdn.a.cuk

Geological exploration and production of hydrocarbon provinces requires a 3D picture to be built of the sub-surface. This picture is made up of remotely sensed information like seismic reflection data with limited resolution, and 1D point sources such as well bores which sample a relatively small amount of the subsurface volume of interest. Work on improving interpretation of these datasets has mainly focused on technological improvements to refine the imaging and processing of remotely sensed data to better illuminate the sub-surface architecture. But even with improved seismic imagery interpretations of the data and the subsequent models created are uncertain. This uncertainty equates to exploration and production risk. The risk results from the lack of constraint from the data to create a 'certain' predictive model, and is amplified by known biases that are applied during interpretation of resolution-limited datasets.

The uncertainties in geologists' predictions are insurmountable, as demonstrated by oil and gas exploration success rates as low as 20% (Loizou, 2002); providing a cautionary example of the uncertainties involved for the industrial geologist. The need to accept a significant *irreducible uncertainty* is true across geology and improving understanding of uncertainties, how to communicate them, and how to practically deal with uncertainty, *whilst getting on with the job*, are all key (but under-valued?) skills of an industrial geologist. This paper will highlight recent work on uncertainties in geology, with particular reference to structural geology; the methods used to elicit and reduce uncertainties in geological interpretation; the influence of media and public perception; and perhaps most importantly how to frame the questions to ask to address uncertainties without trying to reduce the irreducible.

A review of the state of knowledge in interpretation uncertainty, heuristics and biases is followed by an overview of a series of experiments undertaken by myself and collaborators. These experiments assess the role of different factors in the outcome of interpretations of seismic image data. Key findings include that: 1) multiple conceptual models can be applied to the same dataset (conceptual uncertainty); 2) even when the concept is universally recognised (e.g. fold-thrust belt) and the imagery is of good quality large uncertainties in fault placement exist and the resultant implied mechanisms of structural evolution cover a broad range; 3) experience is not a substitue for good technique use, or more specifically the application of geological reasoning skills; 4) use of effective techniques results in better seismic interpretation outcomes.

Loizou, N. 2002. DTI Oil and Gas Directorate (UK), Sharp IOR enewsletter, 3.

3.1 Linear and non-linear techniques applied to joint inversions using TOMOFAST3D.

Roland Martin[1], Vitaliy Ogarko[2], Mark Jessell[2], Mark Lindsay[2]

[1] GET/Geosciences Environment Toulouse Laboratory, CNRS UMR 5563, Midi-Pyrenees Observatory, 14 avenue Edouard Belin, 31400 Toulouse.

[2] CET, The University of Western Australia, 35 Stirling Hwy, Crawley, WA, 6009, Australia

Email : roland.martin@get.obs-mip.fr, roland.martin@get.omp.eu

Powerfull seismic data inversion techniques have been developped in the last decade based on adjoint method. Basically, a misfit function given by the difference between recorded displacements and those computed for a current model is minimized. The Fréchet derivatives of the misfit according to the models introduce an adjoint problem. The adjoint problem is solved as a forward problem in which sources are located at the recording stations and defined as the misfit between the recorded and the computed solutions. Then this adjoint solution is cross-correlated to the forward problem back-propagated form the last frame to the first one. This correlations are called the seismic sensitivity kernels. Based on this, least-square (LSQR) or quasi non-linear techniques (truncated Gauss-Newton, BFGS,...) can be applied to minimize the misfit function and to obtain a model at different resolutions or different scales. Of course the quality of the models depend on the choice of the initial a priori model and how it has been built and the density distribution of the seismic arrays. This is already done with our codes SPECFEM3D (spectral finite element methods) or SEISMIC_CPML (finite differences).

However, in some areas, seismic data are not available due to the nature of the ground or due to the financial cost to deploy dense seismic arrays. Therefore, other data can be chosen and inverted at lower costs like gravity and/or magnetic anomalies. Indeed, they can be inverted jointly to build an initial a priori model before designing any seismic survey. In this context a cross-gradient method is proposed here to invert both gravity and magnetic data under the constraint that the main geological interfaces are respected for both density and magnetic susceptibility models. Sharp interfaces are modelled as common jumps in the physical properties. This inverse problem becomes thus non-linear due to the cross-gradient constraint. Two ingredients are then necessary :

1. Initial « a priori » model are built by geologists: several initial models or family models are provided and tested according to uncertainties.
2. Non-linear algorithms for inversion and appropriate misfit functions are required.

The misfit function can be defined such that the solutions minimize the data misfit function for each kind of data, satisfy a cross-gradient assumption or not and are close to the initial model or not. These two last constraints introduce non-linearity in the inversion process. Parallelized inversion procedures are implemented in our TOMOFAST3D code. We will show how synthetic cases can be inverted by taking geologically plausible models and how the codes can be applied to real cases (South-West Africa, Western Australia). In some cases like the West African Craton in the southwest Ghana area the curvature of the Earth is not really important but at the scale of Western Australia it can be. A 150kmx150km area is studied and a 300x300x130 (11.7 million grid points) SW-Ghana model is inverted in less than 30 mns on a 500 processors and 10mns on 2000 processors of PRACE-GENCI multi-CPU/GPU clusters. Compression of the matrices involved allow to reduce calculations by a factor of 200 up to 500. We will also show how the damping parameters choice can improve the regularization of the solutions.

3.2 Understanding the Offshore Harvey Transfer Zone, Perth Basin, Western Australia

Middleton[1], M.F.

[1] Petroleum Division, Department of Mines and Petroleum, Western Australia

mike.middleton@dmp.wa.gov.au

This paper looks at two different conflicting geological and seismic data sets which require a reconciliation of the understanding of tectonic and structural geological concepts.

The Perth Basin was formed to the west of the Darling Fault, which is one of the largest elongate fault zones in the world. The Darling Fault separates the Precambrian Yilgarn Craton and various slivers of other Precambrian "docked" provinces (Pinjarra Orogen) from the Perth and southern Carnarvon basins to the west. It is commonly understood that Greater India separated from Australia in the Perth region at about 145.5 – 140 million years ago. This separation involved a series of oceanic transforms, which are recognised from mapped magnetic anomalies in the present-day oceanic crust. These transforms have been mapped to connect to transfer fault zones within the adjacent sedimentary basins. The separation occurred from north to south in a non-orthogonal regime with a north-west orientation. This can be simply interpreted to indicate that left-lateral movement generally occurred in both the oceanic and continental crust. Seismic interpretation suggests that this may not be the case.

One significant transfer zone is the Harvey Transfer Zone, which lies to the south of Perth in the onshore Perth Basin, and extends offshore to the west of Perth and Rottnest Island. This study presents the results of an investigation into the 3D subsurface extent of the Harvey Transfer and presents a investigation for apparently conflicting structural interpretations. Previous studies have proposed that the Harvey Transfer Fault entailed left-lateral strike slip movement, based on onshore seismic interpretations. A subsequent study of offshore seismic data has suggested the possibility of right-lateral strike slip movement of this same transfer fault. Figure 1 shows the interpretation of faults at the time of continental breakup, based on several generations of closely spaced 2D seismic data and a sparsely spaced collection of well data. Figure 2 shows the interpreted topography of the breakup unconformity.

Onshore seismic data indicates an uplift during the time of continental breakup (about 145.5 – 140 million years ago). The ubiquitously deposited Yarragadee Formation of Jurassic age has been uplifted and eroded over the onshore Harvey Ridge, the onshore extension of the Harvey Transform [based upon interpretation of 2011-acquired onshore seismic data suggests a significant uplift event to erode the Yarragadee Formation. These data may be interpreted to suggest compressional tectonics in an apparent extensional regime.

The offshore seismic data, which is presented in detail in this paper, also suggest a change of stress regime from the north-east to the south-west of the Harvey Transfer Zone. Significant uplift and erosion has occurred in the region to the south of the apparent transfer fault. The interpretation in this analysis of the Harvey Transfer suggests that different stress regimes may have occurred to the north and south of the transform zone that has influenced the Perth Basin.

A conclusion is drawn that accommodation space within the Harvey Transfer is a complex combination of compressional and extensional structural mechanisms. One of the biggest unknowns to be yet resolved is how this transform-transfer zone behaves at it hits the presumably stable

Precambrian craton. Some ideas are presented (a) dead-stop and re-bound of forces, (b) brittle-ductile inversion, (c) deeper unrecognised structural elements and (d) nature itself.

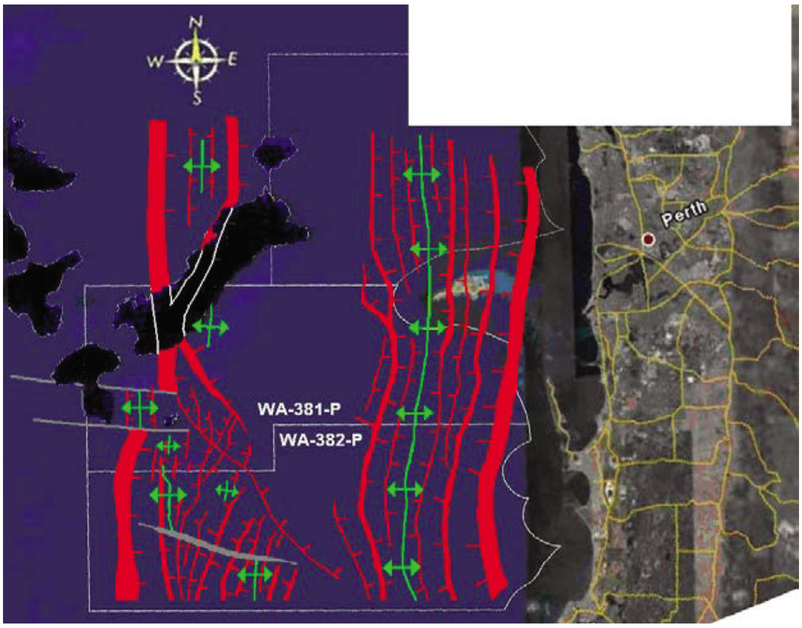


Figure 1: Major fault distribution around the offshore Harvey Transfer Zone. The fault system appears to show right-lateral movement across the transfer zone.

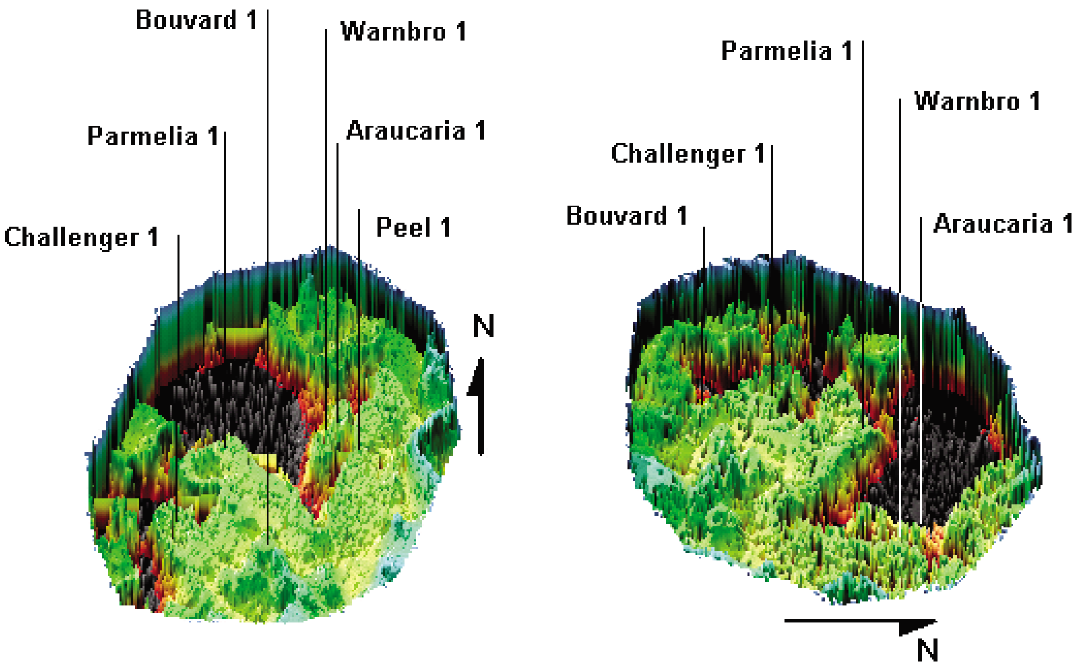


Figure 2: A 3D image of the situation at continental breakup (about 145.5 – 140 million years ago). The Figure shows the breakup Unconformity, looking from the south (right-hand-side) and looking from the east (left-hand-side).

3.3 How can we make the most of magnetic data in building regional geological models?

Foss[1], C.A., Meixner[2], A.J., and Austin[1], J.R.

[1] CSIRO Mineral Resources Flagship

[2] Geoscience Australia

Clive.foss@csiro.au

Oral

Regional magnetic datasets provide structural and lithological information that can be used to constrain the underlying geology, by providing an estimate of the thickness of cover obscuring basement over large areas of sparse or non-existent basement outcrop. It is important that we recover as much geological information as possible from the magnetic datasets, however that information only has value if its errors and limitations are understood. At present these data are imported directly into work flows from which the intended output is a model or models of the subsurface geology. Developing these models is a challenging and complex task, and it is difficult to optimise each step. We propose to undertake a semi-automated analysis of the magnetic data, firstly to isolate 'sweet-spots' which are rich in source information, and then to derive from these isolated anomalies models of the subsurface distribution of magnetisation at their corresponding discrete source locations. We suggest that this process will condense the most reliable information about subsurface magnetisation which is carried in the magnetic data. The resulting database of solutions will be available for the subsequent building of regional geology models of basement features. These complex models can then be developed with greater focus on the interpretive geological interpolation and extrapolation from well-determined control points at which they can be either tightly or loosely pinned. Alternatively, geological models produced directly from the magnetic data can be tested for agreement with these best-estimated control points.

Regional magnetic data are generally acquired with precise uniformity of sampling across a survey area, but the distribution of magnetic anomalies in that dataset is highly irregular, being dictated by the location of appropriate sharp magnetisation contrasts. Only at these favourable locations does the magnetic field carry usable information which can be recovered by inversion. Inversion of magnetic data generally involves the minimisation of an objective function such as the Root Mean Square (RMS) misfit between measured and computed fields. Figure 1 shows the RMS misfit as a function of depth between magnetic profiles over two ideal, tabular, homogeneous magnetisation models. In one case (the blue curve) the misfit is between magnetic profiles over identical bodies at different depths, illustrating the sensitivity in estimating the depth where the width and magnetisation are known. In the second case (the red curve) an inversion is run at each depth, offset to reduce the misfit by adjustment of the width and magnetisation of the depth-offset body. The greatly reduced sensitivity to depth of this second case represents the common geophysical problem where no parameters of a buried body are known, and all parameters must be simultaneously recovered via inversion. Where we apply this analysis to the misfit between a measured magnetic field profile and the computed curve of its best-fitting model, it is difficult to establish a sensitivity to the estimated depth less than 5-10%. This sensitivity to source depth falls rapidly with even modest misfit in matching the measured curve. Inherent non-uniqueness of the inverse problem precludes the derivation of standard error statistics for potential field inversion solutions. Estimates of model sensitivity do not include allowances for any imperfection of the field measurements or departures of geology from the ideal model assumptions, both of which decrease sensitivity of depth estimates. These sensitivities do, however, provide a means of quantifying the inherent limitations in estimating magnetic source depths, and of evaluating the capabilities of different algorithms used to perform this task. Currently used magnetic source depth estimators do not select the data ideally, do not perform rigorous data matching procedures, and have inferior sensitivities to source depth. Automated depth estimators, which use a standard window size for all anomalies, and regional inversions which simultaneously fit all the field variations in a dataset, can easily have depth estimation errors of 50% or more, while still producing a smooth fit to the data. If focus on matching the data at these individual 'sweet-spots' is traded for ensuring the geological validity of a model, then that model may have geological pedigree, but could easily be in error by over 50% in representing depths, even at these favourable locations.

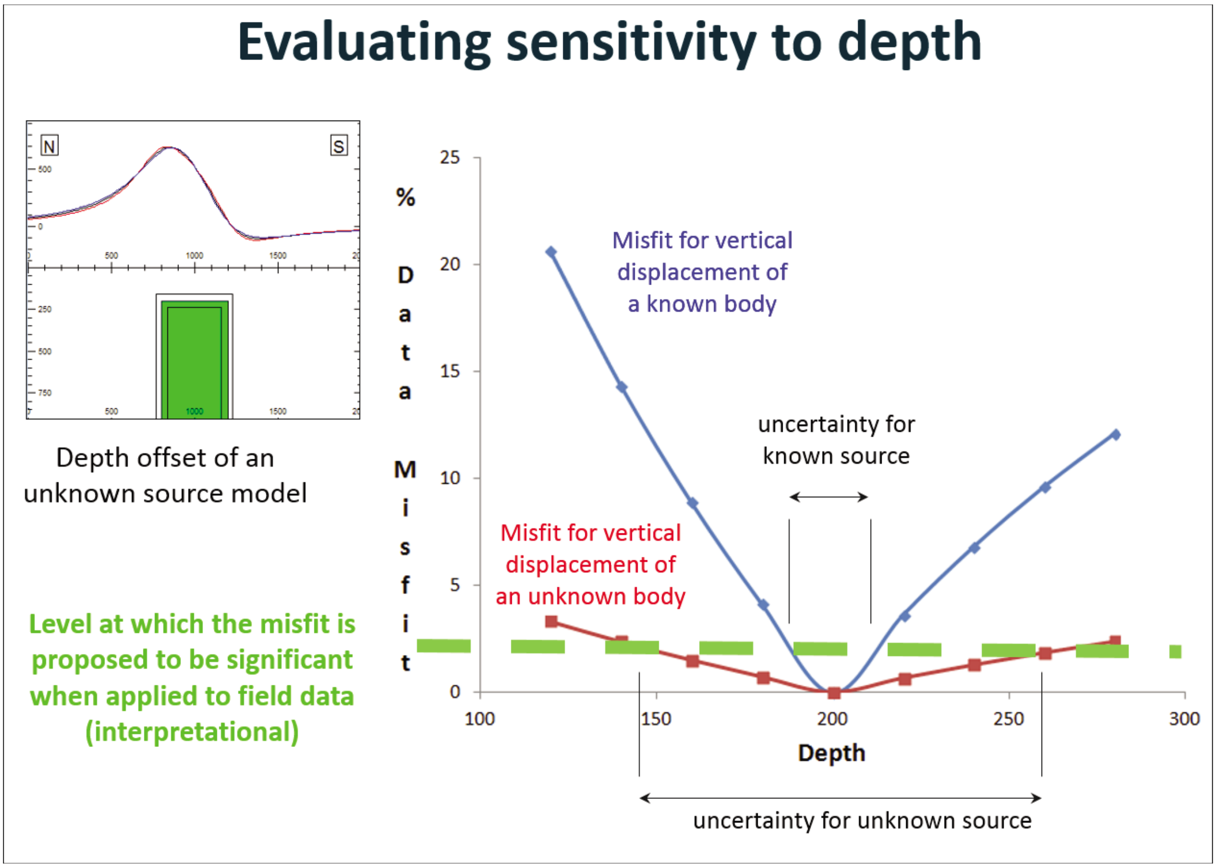


Figure 1 Schematic of the misfit (measured as % RMS) between two ideal model sources, where the same source is raised and lowered (blue curve), and where subsequent adjustments are made to width and magnetisation to minimise that misfit (red curve).

We propose a method that adds value to Australia's magnetic field data by developing a national-scale database of magnetic solutions, each attributed with sensitivity estimates derived by the process as illustrated in Figure 1. This database will be a resource for any interpretive use of the national magnetic field data, including the construction of regional geological models. Magnetic surveys are inherently more sensitive to shallower magnetisations, and in many areas most of the solutions will come from the termination of strong magnetisations at the top of crystalline basement, or from magnetisations within the cover sequence. In general, few deep magnetic sources produce surface anomalies that are useful in providing tight constraints on their depth and extent. Magnetic field data, therefore, contribute only sparse constraints in building models of deep geological structure, but this limitation should focus attention on optimising that information which can be recovered. Depth solutions derived by the methodology we propose to implement also have attributes of magnetisation intensity, thickness and dip, which should assist in the interpretive process of assigning those sources to geological units.

3.4 3D Model and Feature Evidence Visualisation in the Integrated Exploration Platform

Wong[1], J.C., Holden[1], E.J., Wedge[1], D., Nathan[1], D., Gessner[2], K., Murdie[2], R.

[1] Centre for Exploration Targeting, UWA, Western Australia

[2] The Geological Survey of Western Australia, Western Australia

jason.wong@uwa.edu.au

Poster

Introduction

Geological interpretation through integration of a variety of 2D and 3D data is a complex task. Along with the conventional use of surface data, vertical profile data (such as seismic and magnetotelluric data) and 3D models have become increasingly available in recent years. The challenge is in how these datasets can be visualised in an effective manner, and also combined in a way that maximises the utility of these datasets.

A collaborative research between the Geological Survey of Western Australia (GSWA) and the Centre for Exploration Targeting (CET) focuses on developing the Integrated Exploration Platform (IEP) with a specific aim to benefit the mineral explorers operating in WA, by providing them with a software platform to support their interpretation of GSWA datasets through innovative visualisation and intelligent interpretation assistive tools. The IEP is currently implemented as a plug-in to ESRI ArcGIS, running on version 10.0 and later.

Blending with 3D Data

Previous work has been done on visualising 2D datasets through a paradigm of interactive blending [1]. Blending provides a mechanism to combine multiple datasets in a visual way that maintains both the distinction of the contribution from each dataset, as well as the combined effect to identify correlations. Due to the variety of datasets geoscientists will pursue simultaneously, we have produced a suite of blending tools for datasets with different characteristics, such as multi-band data, orientation filtered data, and parameter blenders for filter outputs over a range of values.

We have extended this suite to include blenders for vertical profile data and 3D volumetric data. The initial prototype for blending with vertical profile data is a simple interactive offset that determines the displayed height of the vertical profile data in relation to the blended map-view datasets (Figure 1a). For 3D volumetric data, we introduce a single blender with number of visualisation modes that are geared toward exploring the 3D volumetric data (Figure 1b). Additionally, we have developed a prototype of a blender that allows for visualising two 3D models simultaneously.

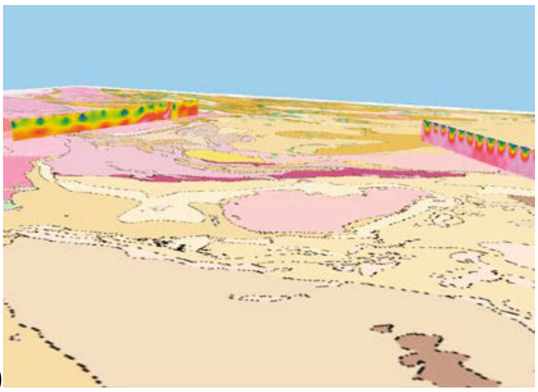
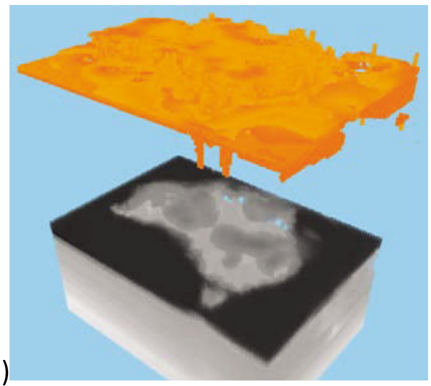
(a)  (b) 

Figure 1: Examples of the visualisation tools for vertical profile and 3D volumetric data in the IEP: (a) shows the vertical profile blending with user-controlled rendering height, and (b) shows a visualisation mode for 3D volumetric data that offsets a threshold range of voxels above the volume.

Visualising Feature Evidence Support

The IEP also provides computer assisted and user driven structural interpretation tools by harnessing the power of automated feature evidence analysis and expert knowledge of the user. A user may import pre-existing interpretation shape files, or annotate interpretation from scratch within the IEP. In either case, the user can visualise feature evidence to validate or to guide the structural interpretation of potential field geophysics data.

The feature evidence analysis is based primarily on automated lineament detection algorithms developed at the CET [2]. These algorithms detect ridge and valley features and edge features, all of which are useful for the structural interpretation of potential field data [3]. Feature evidence maps generated from these algorithms care used to provide objective feature evidence feedback to the user, both quantitatively and visually. The quantitative measure of feature evidence on interpreted structures can be useful as inputs into 3D implicit inversions to indicate a measure of confidence.

Visually, the feature evidence is presented in three optional modes: *full* feature evidence map, *on-lines*, and user *field-of-view* (FoV). The full map view is simply the full display of the feature evidence map on top of, and obscuring any other datasets (although the interpretation layer is still visible). The on-lines mode and FoV mode utilise a novel technique to combine information from the dataset being viewed, and the feature evidence layer. This is achieved through using the viewed dataset (which is being interpreted) as the source for the luminance component, and the hue is determined by the feature evidence layer. This results in a combined blend that displays information from both the viewed dataset and feature evidence layers.

More specifically, the on-lines mode(Figure 2a) renders the combined blend of dataset and feature evidence ‘windowed’ along each of the interpretation lines, with user-controlled variation of the windowed-width and opacity (the influence of the luminance). In particular, this is useful for a big picture view of the confidence across interpretation lines, and draws user-attention to lines that may not be particularly supported by feature evidence. Furthermore, interpretation lines could also be annotated whilst reviewing the feature evidence along the line as it is drawn.

The FoV visualisation mode (Figure 2b) allows for the display of the dataset and feature evidence blend in a ‘spotlight’ area centred at a location that can be modified using the mouse cursor in real-time. Further controls for the opacity and size of the FoV are also user-defined. This mode is particularly useful in allowing for the assessment of the extent of interpretation lines, in context to feature evidence, such as making decisions on whether to extend of shorten a line given the feature evidence.

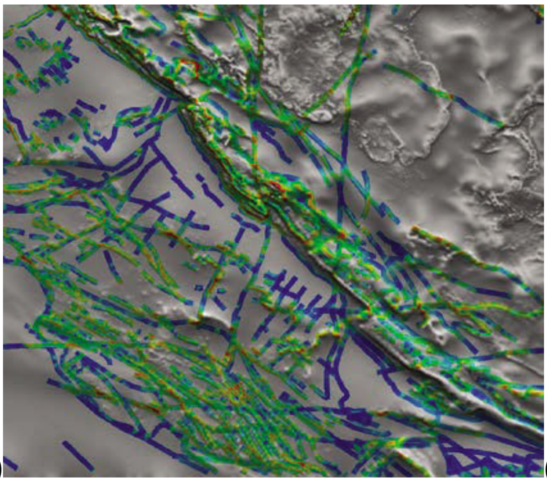
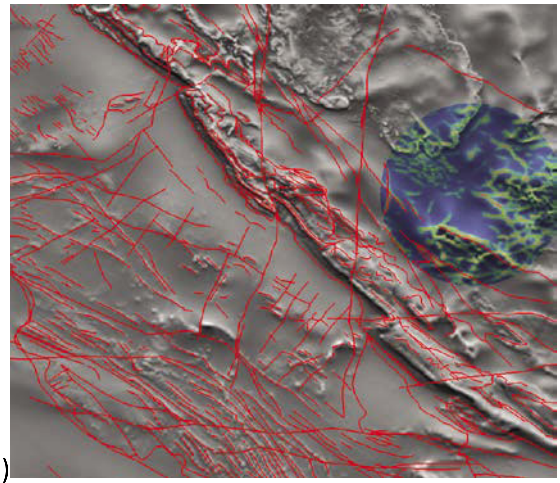
(a)(b)

Figure 2: Examples of two visualisation modes for feature evidence in the IEP: (a) shows the feature evidence 'windowed' along interpretation lines, and highlights the edge evidence strength in this example, and (b) show the FoV visualisation mode that enhances an area with the ridge evidence (in this example) strength.

Conclusion

The IEP takes a novel approach in developing tools for blending datasets and visualising feature evidence, with the aim to maximising utility of the broad range of datasets used in simultaneous perusal in order to create sound geological and structural interpretation. Blenders allow for combine 2D, vertical profile and 3D volumetric data, whilst the user-drive and computer assisted interpretation tools allows for more confident interpretations.

Acknowledgements

The authors would like to thank the continual support and collaboration with The Geological Survey of Western Australia and we acknowledge the funding support through the Exploration Incentive Scheme, and Australian Research Council via linkage grant LP140100267. We would also like to acknowledge the contribution of Mark Jessell through his WA Premier Fellowship, WA_In_3D.

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3.5 Welcoming 3-D magnetotelluric inversion without saying goodbye to 2-D: Kimberley Craton and Capricorn Orogen as example of 3-D cases.

Piña-Varas[1], P., Dentith[1], M. C., Spratt[2], J. E.

[1] Centre for Exploration Targeting, The University of Western Australia, 35 Stirling Hwy, Crawley WA 6009, Australia.

[2] Independent Consultant, Wakefield, Quebec, Canada.

E-mail: perla.pinavaras@uwa.edu.au

MT METHOD: DIMENSIONALITY

The magnetotelluric method (MT) uses naturally occurring electromagnetic field variations as a source for imaging the electrical resistivity structure of the earth. The orthogonal electric and magnetic field variations recorded at the Earth's surface are related to each other through the impedance tensor. This tensor contains the amplitude and phase relations between the measured horizontal components of the electric and magnetic fields.

The complexity of the impedance tensor depends on the dimensionality of geoelectrical structures. Consequently, an exhaustive dimensionality analysis of the MT data is necessary to determine which approach is more suitable: 1-D, 2-D or 3-D. Various measures of data dimensionality are used and only those data compatible with the dimensional capability of the modelling algorithm may be used. This can lead to significant amounts of a dataset being discarded.

It is very important to take into account that this dimensionality depends on the scale of the structure studied (ratio length of the anomalous body / penetration depth corresponding to the periods of interest), so 1-D and 2-D approaches are perfectly valid for some cases.

Furthermore, the dimensionality has an important role in the resolution of the final model and in the degree of equivalence of the potential models (non-uniqueness). In MT, due to its tensorial character, the degree of equivalence depends on the dimensionality of the model proposed. The ambiguity about the possible models which fit the data decreases considerably with the dimensionality of the model presented.

Consequently, although it still is very challenging, full 3-D MT inversion reduces this ambiguity and presents clear advantages over 2-D approaches in complex subsurface situations (Tietze & Riter 2013). Here we present two cases in which both 2-D and 3-D inversion models have been performed, highlighting the requirement and enhancements of the 3-D inversion models.

3-D vs. 2-D: KIMBERLEY CRATON AND CAPRICORN OROGEN

MT soundings at 155 locations throughout the **Kimberley** region have provided both 2-D and 3-D conductivity models of the crust and uppermost lithospheric mantle. Dimensionality and geoelectric strike analysis on these data reveal variable strike directions across the survey area, as well as with depth (Spratt et al., 2014). These variable electric strike directions suggest the need for 3-D modelling of the data. Nevertheless, this same analysis shows that locally 2-D models can be reliable. Therefore, 2-D inversion models were performed along several profiles, as well as a 3-D inversion model of the whole area (in progress).

The results show good agreement between the two kinds of models at shallow depths, whilst at depth 2-D and 3-D models show significant differences; although is important to keep in mind that under certain conditions some 3-D inversion codes seems to have problems to resolve deep structures. The models reveal a thin conductive near-surface layer, interpreted as Kimberley Basin sedimentary and volcanic rocks, up to 5 km thick and a general resistive upper crust (Spratt et al., 2014).

The discrepancies between 2-D and 3-D models could be related to different factors, such as the limitation in mesh size, the fact of disregarding strongly 3D data in 2D inversions, the changes in strike with depth mentioned above or to the effect of a finite strike. In this sense the major problem is when the profiles are located off the 3-D body, since the 2-D inversion can image phantom structures that are laterally offset from the profile (Ledo et al., 2002).

Similar to the 2-D models, the 3-D models image several upper crustal features that correlate with the location of fractures, faults, or boundaries between crustal terranes that are either mapped at the surface or inferred from gravity and aeromagetic data. The 3-D models provide a more accurate image of the geometry and orientation of these features and in some cases, allow us to trace their continuity between profiles. Along the eastern margin of the Kimberley craton, there still exist some large regional discrepancies in the lower crust and upper mantle between the 2-D and 3-D models. The 3-D results are currently not fitting the data well and the 2-D models are deemed more reliable, however continuing 3-D inversions are in progress in the attempt to further resolve this structure.

In the **Capricorn Orogen** area a total of 240 BBMT sites and 62 LPMT sites have been recorded. Data analysis shows a general 3-D dimensionality, but as in the case of Kimberley craton some 2-D inversion models were made by carefully selecting the data and the invasion parameters.

Only in the eastern part of the orogen both kinds of modelling have been performed to date. The 2-D inversion models were promptly discarded due to the high contribution from 3-D geoelectric variations to the data, and the general poor correspondence with known geology. Hence, 3-D modelling of the data appears as the only feasible solution for this region and 3D modelling produced geologically plausible results with the large scale crustal architecture well defined (Dentith et al., 2014).

Currently, a new 3-D model is being created in the south-east part of the Capricorn Orogen by the inversion of 62 MT sites, including some of those data inverted to obtain the previous 3-D model. Early results are consistent with the previous model, providing some confidence in the broad-scale architecture defined by this model.

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3.6 Models, Data, Uncertainty and Learning: How Information is Coded into Dynamical Geophysical Models

Hoshin V Gupta, Professor
Department of Hydrology & Atmospheric Sciences
The University of Arizona, Tucson, AZ 85705, USA
(*hoshin.gupta@hwr.arizona.edu*)

Keynote Address:
Inaugural 3D Modelling Conference "Saying goodbye to a 2D Earth"
Margaret River, Western Australia
(August 2-7, 2015)

Abstract

There is a clear need for comprehensive quantification of simulation uncertainty when using geophysical models to (a) '*learn*' about the world, and (b) support and inform decision-making. This need has become even more pressing as models have become progressively more complex. This talk will discuss the problem of building computational models as a process of '*learning*', which is classically approached as a problem of '*Estimation Theory*'. While conventional Estimation Theory, rooted in Maximum Likelihood and Maximum Aposteriori Bayes, provides a valuable theoretical foundation, my growing concern is that the strategies we use to implement it now fall short of our needs.

One way to address this problem is to develop a formal structured approach to characterizing how '*Information*', and hence '*Uncertainty',* is coded in both *data*, and in the *structures* of physics-based geophysical models (as physical principles, material and geometrical properties, assumptions and conjectures). By doing so, we can achieve a more systematic, robust and insightful basis for testing and improving Earth Systems Models, via a process of diagnostic evaluation at the model-data interface. A natural consequence will be to focus attention on the important role of *System Architecture* (and not just the *Process Parameterization*), thereby emphasizing the creative *Discovery* and *Learning* aspects of modeling as a vehicle for scientific investigation.

4.1 Uncertainties in 3-D Geological Models: Recent Developments and Future Outlook

Florian Wellmann, Graduate School AICES, RWTH Aachen University, Schinkelstraße 2, 52062 Aachen, Germany

Geological models are commonly built on the basis of a wide range of input data, ranging from direct geological observations in wells and outcrops, to inferred structures from geophysical measurements, to conceptual geological knowledge of a region. It is evident that geological models contain uncertainties due to the limited amount and quality of this information, and that each type of observation leads to specific aspects of uncertainties. Combining all of these facets of knowledge and uncertainties into one consistent modelling framework is a significant challenge.

We present here our recent work that addresses different aspects of this challenge through a combination of implicit geological modelling with stochastic simulations methods, an extension into a probabilistic framework, and the combination with novel approaches for the analysis and visualisation of uncertainties. Furthermore, we present first results on the combination of this modelling approach to include geophysical potential-field data to reduce model uncertainties. An interesting aspect is that our implementation enables the consideration of additional "soft" geological knowledge, for example about the general expected structural setting in an area. We believe that the implementation of all of these aspects into one framework provides a step forward on the way to the construction of meaningful geological models with an identification of uncertainties.

4.2 Delivering and curating 3D geology models

Rattenbury, M.S., Jones, K.E.

GNS Science, PO Box 30368, Lower Hutt 5040, New Zealand

m.rattenbury@gns.cri.nz

Oral

Geological surveys have traditionally held a curatorial role for geological information, including archives of geological maps of their jurisdictions. Printed paper geological maps have their own issues in terms of durability and storage space needs but if well archived, are resilient to technological change. The information in them, for the most part, remains readable and understandable. New Zealand has a historic archive of geological maps dating back 150 years and this archive is regularly revisited in the course of new geological mapping projects.

The mainstream use of GIS software technology for storing and managing geological map information has challenged us on how to ensure their contained information remains readable and understandable. Open exchange file formats and international data models are part of a solution for this but their longevity is not yet established. The relatively failsafe option is to store hardcopy paper representations of GIS data. For 3D geology models this is not an option, however. The last decade has seen remarkable growth in the number and capabilities of 3D modelling software and for the 3D geology models they enable, the curatorial challenge is that they are readable and understandable in one or two decades time. Geological surveys are increasingly building their own 3D geology models (as a logical extension of the geological map concept, Fig. 1) and/or are receiving 3D geology models from exploration companies on relinquishment of their permits.

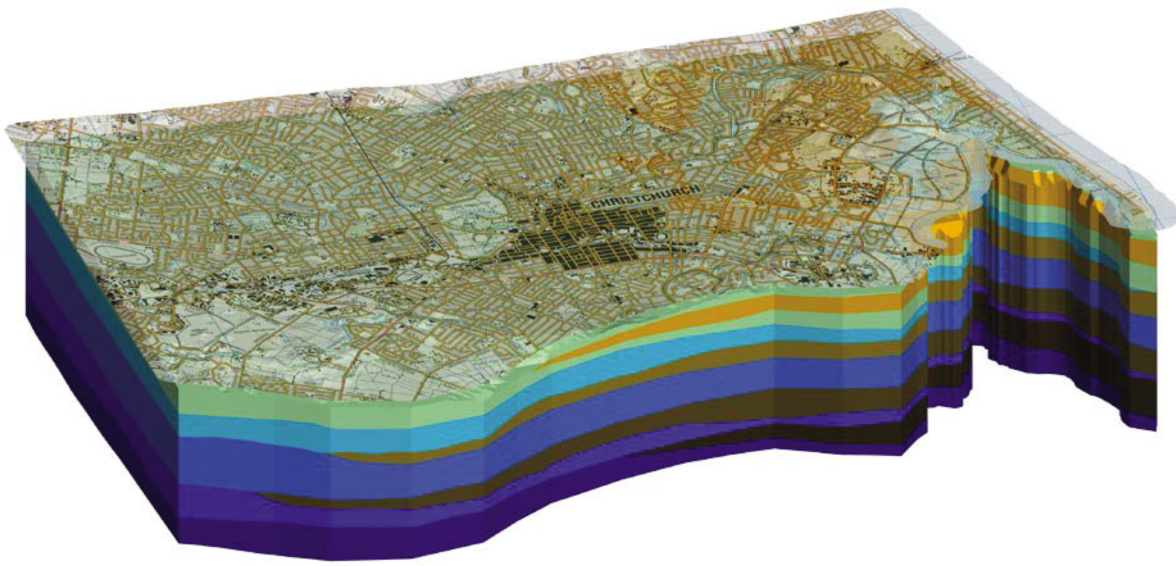

Figure 1. A 3D geology model of the Christchurch area (after Begg et al. 2015 in press). The model is based on regional interpretation of more than 12,000 borehole logs and highlights the cyclical interfingering of river gravels (blues/greens) with marine silt incursions (browns). The saturated upper silt deposits were prone to liquefaction during the devastating Canterbury Earthquake Sequence of 2010 and 2011. Layer information from this model has been used for restorative infrastructure planning.

Three dimensional geology models are an emerging part of a geological survey's product suite. GNS Science is just publishing 3D geology models as part of the 'Geological map of the Christchurch area' product (Fig. 1, Begg et al. 2015 in press). These 3D geology models have been built using Leapfrog Geo software. The product includes the viewer file derivative that can be accessed with freely downloadable Leapfrog Viewer software. Also included in the Christchurch product are Gocad T-surface and ArcGIS shapefile contour and grid format representations of base and top surfaces of modelled volumes, as well as their thickness (Fig. 2).

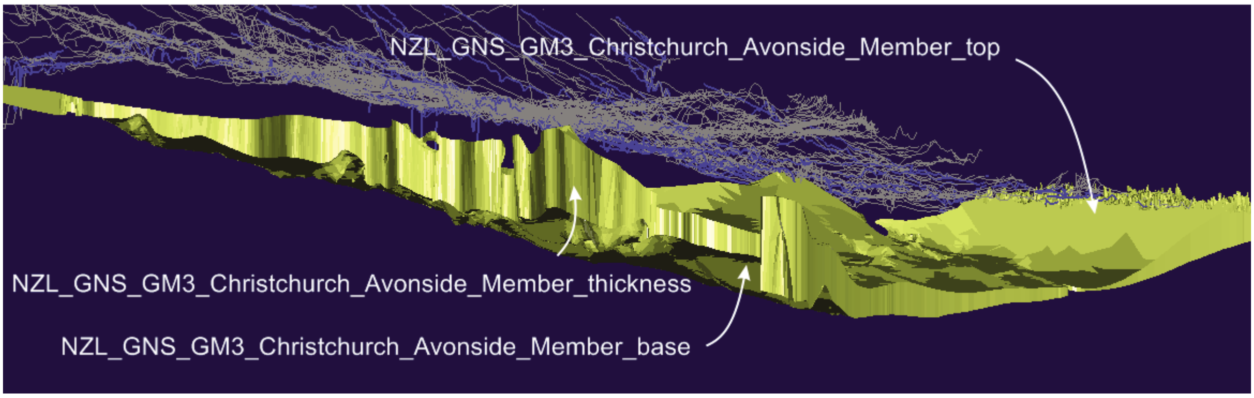

Figure 2. Each significant modelled volume in the Christchurch 3D geology model is defined by three separate components; its top and basal surface and its thickness. In addition to the Leapfrog Viewer model file, each component is delivered as an ArcGIS grid, with the base and thickness also as a contour shapefile and as a Gocad T-surface.

These derivative formats serve two purposes. Firstly they can be integrated with 2D spatial, non-geological datasets using GIS software where a large part of the client market sits (who have no intention of investing in 3D software technology). Secondly, delivering in these formats is an attempt to future-proof the 3D geology models. By breaking 3D geology models into their components, the expectation is that these components can be rebuilt later with updated or alternate vendor software. The aim is to retain as far as possible the information contained in the models in a sustainable readable form.

Development of 3D geology model standards may go a long way to solving delivery and curatorial issues for geological surveys. The CGI-IUGS-inspired, now OGC GeoSciML geology model is applicable to many different types of geometry, including 3D volumes. While not a standard itself, GeoSciML is capable of exchanging the geological information contained in 3D geology models. The fledgling Geo3DML data exchange format developed by the China Geological Survey is designed specifically for 3D geology models. As these standards mature, the longevity and accessibility of 3D geology models is expected to improve, the information they contain will persevere, and the models can better meet geological survey requirements for delivering and curating geological information.

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4.3 Crustal models for the Albany-Fraser Orogen, Western Australia, from passive-source seismology – how can they be brought together with geological information?

Christian Sippl[1], Hrvoje Tkalcic[1], Brian L.N. Kennett[1], Catherine Spaggiari[2], Klaus Gessner[2]

[1] Australian National University, Canberra

[2] Geological Survey of Western Australia, Perth

christian.sippl@anu.edu.au

Oral

In contrast to active seismic studies, which are most often performed along 2D transects and which retrieve surfaces of heightened seismic reflectivity, passive seismic studies can yield a variety of model types, depending on the employed analysis methods. Different types of seismic tomography retrieve 3D models of seismic wavespeeds, i.e volumes instead of surfaces. Depending on the utilized inversion approach, an uncertainty estimate can be included for each velocity node.

Their sensitivity to volume properties rather than surfaces as well as the typically lower resolution compared to active seismic studies makes tomographic models harder to integrate with geological data like fault locations/dips or block boundaries/sutures.

Other passive seismic methodologies (receiver functions, autocorrelation analysis, …) yield 1D models, e.g. seismic velocity vs. depth, beneath the sensor location only. These point measurements can then either be interpolated into surfaces (e.g. Moho maps) or used as additional constraints within pre-existing 3D models.

I will present preliminary crustal models for the Albany-Fraser Orogen in Western Australia as examples of what can be derived from passive-source seismology. The employed techniques will be outlined briefly, and the main focus will be on data types, uncertainty handling and what visualization methods can be used. With the recent acquisition of diverse geophysical datasets in this region as well as geological information available, integrating these data into joint models is a major task we will soon face.

This presentation is meant to showcase the types of models produced from passive-source seismology and invites discussion on how these can best be brought together with the different

3D Modelling at the Geological Survey of Western Australia

Gessner, K., Murdie, R., Brisbout, L., Yuan, H., Sippl, C.

[1] Geological Survey of Western Australia, 100 Plain St, East Perth, WA 6004

[2] ARC Centre of Excellence for Core to Crust Fluid Systems, Macquarie University

[3] Research School of Earth Sciences, Australian National University

Klaus.Gessner@dmp.wa.gov.au

The aim of the 3D Geoscience Section at the Geological Survey of Western Australia (GSWA) is to increase the knowledge of Western Australia's subsurface through the integration of geophysical, geological, and geochemical data in 3D structural models. 3D models are generated by the integration of depth data with high-quality surface data from the Survey's geological mapping program. Active and passive seismic surveys and magnetotelluric models add the third dimension to geological and geochemical mapping. It is crucial that models are tested against potential field data, gravity, and magnetics, to verify the validity of the model and to reduce uncertainties.

One challenge has been to develop the capability to build, manage, analyze, and store 3D models according to GSWA quality standards and stakeholder needs. Thus, collecting, archiving, and updating existing models involve ongoing effort. The variety of input data, the generation of a 3D database, a range of coordinate systems, the scale and accuracy of models are all issues that have to be addressed. Not only is GSWA generating its own models, we will also want to become the custodian for external regional Western Australian models and integrate them with existing data into a GSWA format, where possible. Examples of such 'inherited' models include the Eastern Goldfields model from Geoscience Australia, and the Kimberly region and Musgrave project models generated by the Centre for Exploration Targeting at The University of Western Australia (CET).

The next challenge is to disseminate these models to the public through an effective delivery system. A suitable platform that is accessible by the most number of users for either viewing or for manipulation of the model will be integrated into a digital data package and distributed in the same manner as the Survey's current 2D digital data packages.

Although 3D geological models can be generated at all scales, the GSWA focus is on regional structural models at the scale of the Earth's crust. For example, passive seismic studies carried out in collaboration with the Australian National University, Macquarie University, and the Centre for Exploration targeting at UWA are looking at whole crustal-scale structures using a variety of methods such as receiver-function analysis and ambient-noise studies. Current projects are based in the Albany–Fraser Orogen (with the Australian National University) and Capricorn Orogen (with CET and Macquarie University) regions. A review of existing passive seismic data has indicated the differences in crustal thickness and composition between the Yilgarn and Pilbara Cratons. The Pilbara Craton has a thin crust of felsic composition, whereas the Murchison Domain of the Yilgarn Craton shows a slightly thicker crust with a more felsic composition. In contrast, the South West Terrane of the Yilgarn Craton has a thicker crust with a much more mafic composition. The southeast edge of the Yilgarn Craton in the Fraser Zone of the Albany–Fraser Orogen comprises the thickest crust at more than 45 km, but further to the east the crust thins again slightly under the Eucla Basin. There is even an indication that a double Moho has been preserved where the Capricorn Orogen was thrust under the Narryer Terrane at the northwest margin of the Yilgarn Craton during the formation of the West Australian Craton. The current Albany–Fraser passive seismic network registered the Kalgoorlie earthquake of 14 February 2014, allowing for the first time a detailed analysis of Eastern Goldfields seismicity.

The fabric of the Yilgan Craton can be imaged by surface- mapping techniques, but also from GSWA-acquired seismic reflection surveys. On the surface, the synthesis of geological mapping with gravity and magnetic fields shows ductile shear zones that have accommodated shortening by oblique slip. This late orogenic shear network is overprinting older shallow-dipping structures having a northeasterly trend. The existence of this persistent trend, also shown in the seismic reflection surveys, is consistent with observations such as the structural grain in the Narryer Terrane (where some of the oldest rocks in the State are found), isotopic maps of crustal evolution, and the orientation of the 1.8–1.6 Ga Barren Basin rifting, which came to define the southeast margin of the Yilgarn Craton. On a more regional scale, areas such as the Windimurra Igneous Complex and the Sandstone greenstone belt have been modelled and then inverted against potential field data to produce 3D volumes (Fig. 2). These, with other models that have been submitted to GSWA, will be made available in our first 3D digital data packages scheduled for October 2015.

Poster 1. 3D Geological Model of the Grampians-Stavely Zone,

western Victoria Goodwin[1], J.A., McAlpine[1], S. R. B.,

[1] Geoscience Australia

james.goodwin@ga.gov.au

Poster Presentation

The Stavely Project is a collaborative project between Geoscience Australia and the Geological Survey of Victoria, which aims to provide a framework for discovery in the Grampians-Stavely Zone, western Victoria, primarily through the acquisition of pre-competitive geoscientific data. This includes the completion of fourteen stratigraphic drill holes which tested regional geological interpretations and recovered material for detailed lithological analysis (Schofield et al. in prep). The results have assisted in understanding the mineral systems potential under cover.

The new information derived from these stratigraphic drill holes has been incorporated into a 3D model which covers an area of 62 km × 94 km across the Grampians-Stavely Zone. The focus of this 3D model is on the geological units considered to be cover sequences that overly the prospective rocks of the Mount Stavely Supergroup. Within this area the cover units include regolith, the Murray Basin and various sedimentary and volcanic rock units such as the Grampians Group, Rocklands Volcanic Group and the Newer Volcanic Group.

GeoModeller 2014 software was used to create the 3D geological model. GeoModeller utilises an interpolator method for creating 3D geology that is based on potential field theory (Chilès et al., 2004; McInerny et al. 2005). The 3D geological model provides a space where interpretations from multiple datasets can be represented together. Information included in this model includes surface geology, stratigraphic drill-holes, and interpretations from seismic reflection, gravity and magnetic data.

The 3D model provides an estimate of the depth to prospective basement and presents the most recent understanding of the geological structure and evolution of the Grampians-Stavely Zone. The 3D geological model, although consistent with various input dataset, is still an interpretation. Therefore, after building a 3D geological model, inversion is recommended as a tool to test the validity of the model against gravity and magnetic data.

Two different inversion programs are used here and include the UBC-GIF GRAV3D v5.0 and MAG3D v5.0 codes (Li and Oldenburg 1996, 1998) and the GeoModeller 3D inversion tool (Guillen et al. 2004). The UBC-GIF codes although being deterministic (single solution results) are parallelised with MPI to run on the National Computational Infrastructure (NCI) supercomputer (hosted at the Australian National University, Canberra) and so are utilised to produce high-resolution, large-scale models. The GeoModeller 3D inversion process, however, is based on Markov Chain Monte Carlo formulation which allows many millions of models to be generated and used to report the inversion outcome in terms of probabilities, but is limited to the processing power of a desktop PC.

To further constrain the 3D inversion modelling, density and magnetic susceptibility data was extracted from Geoscience Australia's Rock Property Database (http://www.ga.gov.au/explorer-web/rock-properties.html).

This work supports the UNCOVER Initiative (Australian Academy of Science, 2012) which has been adopted by Geoscience Australia as part of its National Mineral Exploration Strategy. Specifically it addresses the depth and character of cover science challenge with the aim of assisting with the detection of mineral systems beneath cover.

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Poster 2. The Capricorn Orogen Passive source Array

Murdie, R. [1]**, Yuan, H.** [1,2,3]**, Dentith M.** [2]**, Johnson , S.** [1]**, Brett, J.**[1] **and Gessner , K.** [1]

[1] Geological Survey of Western Australia
[2] Centre for Exploration Targeting, University of Western Australia
[3] ARC Center of Excellence for Core to Crust Fluid systems

Poster

Overview

The Capricorn Orogen Passive source Array is the passive source component of a major SIEF program, "the distal footprints of giant ore systems: Capricorn case study". The passive source program focuses on the deep crustal and shallow lithospheric structure in the Capricorn Orogen, and with integration with other geological and geophysical datasets the overall goal is to produce 3D multiple scale seismic images across the orogen, providing direct constraints to local geological models for the timing and kinematic evolution of faults and shear zones in the region and its 4D metallorogenic history, as well as new findings in understanding the tectonic amalgamation processes of the Western Australian craton. The main tools of the project are seismic tomography (body waves and surface wave/ambient noise) and receiver function CCP imaging, two of the commonly used earthquake seismology methods that best fit a 2D design of the passive source project.

Structure of the orogen

Previous findings in the crustal structure of the Capricorn Orogen have greatly improved our understanding of the amalgamation processes of the Western Australian craton. For example recent active source survey through the orogen (Johnson et al. 2013) reveals three deep penetrating faults that separate four seismically distinct tectonics blocks, suggesting progressive and punctuated collision of continental blocks played an important role in the craton building process. Receiver functions (Reading et al. 2012) characterize a distinct orogenic crust which has patterns of upper crustal discontinuities, thickened crust and low impedance contrast across the Moho, favouring a weakened orogenic crust that has accommodated most of the horizontal deformation during the craton formation and reworking processes. Along the craton margins, an interesting observation is found from both active source profiling and MT studies (Johnson et al. 2013; Selway et al. 2009) that the sutures that separate the cratons and younger Capricorn orogen tend to dip towards the older craton side, suggesting a preferred subduction direction during the last stage of convergence within an orogen (e.g. Tyson et al., Geology 2002; van der Velden and Cook, JGR 2005).

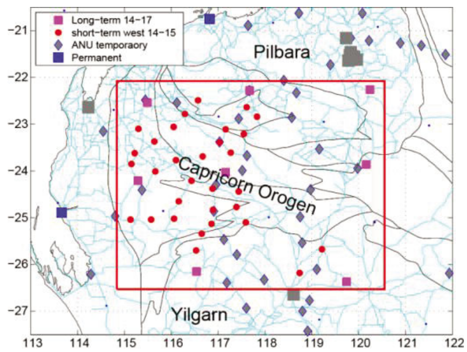

Fig. 1 Seismic deployment in WA. The COPA sites are: Long-term, 3 years from 2014-2017; short-term, 1.5 years for the western (red dots) and eastern (Nov. 2015-2017) orogen.

New 2D array

Up to date these studies are all based on line deployments; therefore it is essential to develop 3D seismic pictures to test whether these observations hold consistently throughout the whole orogen. With a careful design of a 2D array that takes advantage of previous passive source effort in the region, the proposed long-term and short-term deployments give us a 2D grid that spans nearly 500-km by 500-km surface area with roughly 40-km station spacing, and the 36-month in total deployment can guarantee enough data recording for 3D structure imaging using body wave tomography, ambient noise surface wave tomography and P- and S-wave receiver function Common Conversion Point (CCP) stacking techniques. Upon a successive instrument loan of 36 sets of seismometers from the ANSIR national instrument pool, 34 broadband seismometers (2 as backup) have been deployed in the western half of the orogen since March 2014.

Hypotheses to test

We will test several hypotheses that 1) distinct crustal blocks are seen continuously throughout the orogen (using ambient noise/body wave tomography); 2) distinct lithologies are present in the crust and upper mantle across the orogen (using receiver function CCP images); and 3) crustal and lithosphere deformation along craton margins in general follows the “wedge” tectonics (e.g. subduction of Juvenile blocks under the craton mantle, i.e. craton-ward dipping sutures; Snyder, Tectonophysics 2002). We expect ~40-km lateral resolution near the surface for the techniques we propose, which will however degrade to roughly 100 km near the base of the cratonic lithosphere (200-250 km depth) due to low frequency nature of earthquake waves.

Preliminary results in the crust

Up to June 2015, most the COPA sites have been in operation for almost over a year. Yet there are some down sites due to either instrument failure or harsh environment, resulting in loosing data in critical locations, i.e., there are nearly no data retrieved from one eastern long-term site and three short-term sites (Fig.2) .

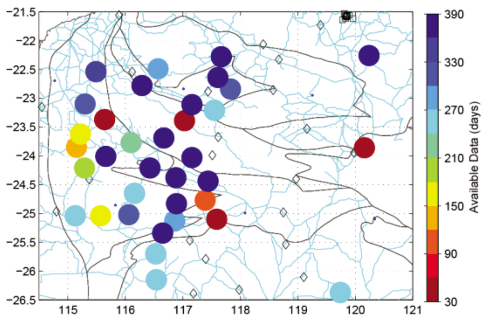

Fig. 2 Available data (in days) up to May 2015

The waveforms collected up to May 2015 enables several processes to carry out, including bulk crustal properties of the orogen by using receiver function technique (Yuan 2015 in review). Fig. 3 below shows the crustal thickness, the bulk composition (in terms of Vp/Vs ratio) and the average crustal P-wave velocities, respectively. These properties show spatial correlation with surface geology indicates. For instance, the crust is thicker in general in the orogen that in the Archean cratons; similarly the mean P-wave velocity is higher; the Yilgarn-orogen margin shows different seismic characteristics than the Pilbara-orogen margin; the paleo-Archean regions in both cratons are relatively felsic in composition (small Vp/Vs ratios), while the orogen shows quite large heterogeneities.

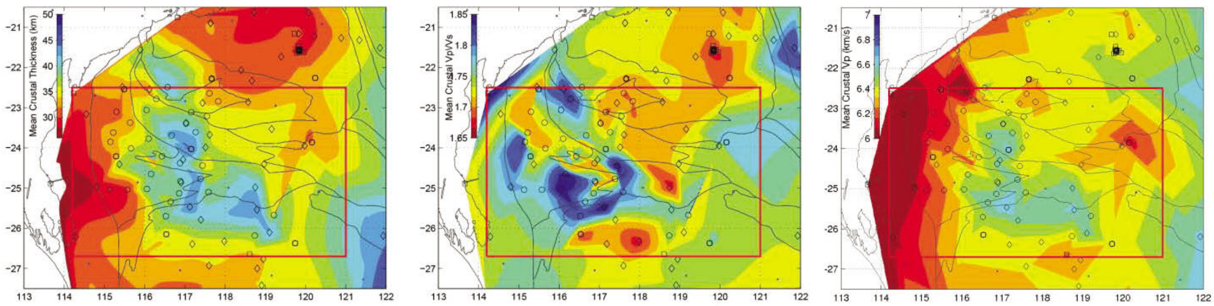

Fig. 3 Preliminary results showing bulk seismic properties of the Capricorn orogen. Left, crustal thickness (in km); middle, crustal composition in terms of P/S velocity ratio; right, mean crustal P-wave velocity.

On-going research

Velocity variations in both the orogen crust and shallow lithosphere are currently in the process using seismic tomographic methods. For the crust, an ambient noise tomography will give a whole crust 3D shear-wave velocity model with roughly 10-km and 2-km horizontal and vertical resolution across the orogen. This technique utilizes the diffusive energy (noise) generated at the ocean/continental margins and by stacking the cross-correlated waveforms between any two station pairs, it doesn't rely on earthquakes to provide path coverage as conventional surface wave techniques. Correlations with the permanent stations as well as the early ANU temporary deployment stations near the orogen are also considered which gives a good complement to the path coverage in the orogen. For the lithosphere, body wave tomography will provide constraints to both the P and S wave velocity variations in the orogenic lithosphere. The models from both tomographic methods are currently under construction. The raw traveltime residuals, however, show drastic changes are expected in the orogenic crust and along the Yilgarn-orogen boundary in the lithosphere (Fig. 4).

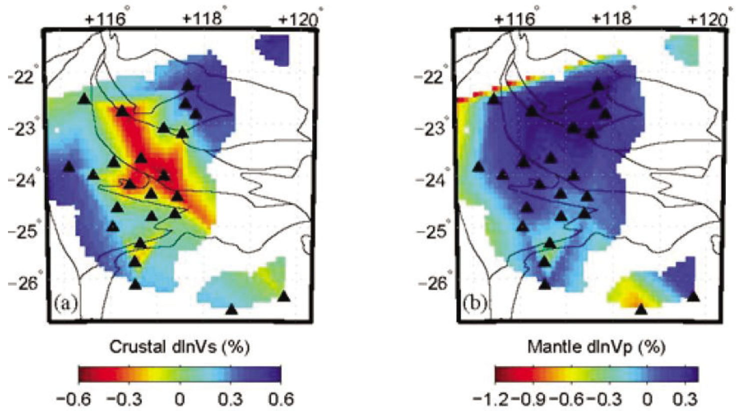

Fig. 4 Traveltime residuals for the crust (left) and shallow upper mantle (right) using a 7.5 Magnitude earthquake.

Poster 3. GeoLena – Synthetic Data Models

Hill, E.J.

CSIRO, 26 Dick Perry Ave, Kensington, WA

June.Hill@csiro.au

In minerals exploration and mining, drill holes are traditionally logged by geologists, but this is a time-consuming task and there are serious concerns about the consistency of logging between different geologists. New algorithms are being developed for analysing drill-hole data which are designed to assist the geologist to log faster and more consistently. However, we are unable to validate the accuracy of these algorithms because we do not know the real geology, only the geologist's interpretation of the true geology. This issue could be addressed by generating a realistic synthetic geology model, from which one could generate synthetic drill-hole data. The analysis of this synthetic data could then be used to validate the new algorithms by comparing their results against the known synthetic geology. The proposed GeoLena project is named after a popular image "Lena" used for testing and benchmarking image analysis algorithms.

Generating the synthetic model and simulating the measurement of samples is a challenging problem; it involves understanding the true spatial variability of rock properties on various scales and ensuring that all properties are consistent within a sample. In addition we need the ability to sample the synthetic model at different scales (e.g. 1 m interval geochemical assay or 1 cm diameter HyLogger spectral measurement), but it would be impractical to populate the entire model on the smallest scale of interest. To be useful, we would need a library of synthetic models covering a broad range of mineral deposit types. This is potentially a very large project and might be best undertaken as a collaborative effort between institutions and organisations. So what is the best way to attempt it? How do we fund it? Who has the skills to contribute to it?

Poster 4. Non-linear 3D electrical capacitance tomography inversion

Roland Martin[1], Vitaliy Ogarko[2], Mark Jessel[2], Dimitri Komatitsch[3]

[1] Laboratoire GET/Geosciences Environment Toulouse, UMR CNRS 5563, Midi-Pyrenees Observatory, 14 avenue Edouard Belin, 31400 Toulouse, France.

[2] Centre for Exploration Targeting, University of Western Australia, Crawley, WA 6009, Australia.

[3] CNRS, LMA UPR 7051, Aix-Marseille University, Marseille, France.

martinr@get.obs-mip.fr

Poster

Non-linear algorithms are generally used to improve the reconstruction of images in different fields of geophysical exploration and also the oil industry [1]. They allow to converge towards more suitable minima of a given misfit function between observed and computed data for a given current model. Seismic, acoustic or even electrical/potential methods are used. Here we make the choice of an electrical application where rings of electrical sources excite a medium at high frequencies. At high frequency the electrical potential field can be considered as static. In previous works, highly optimized simulated annealing (SA) algorithm have been applied to reconstruct permittivity images of 2D real two-phase gasoil flows or 2D granular materials through a cylindrical vessel using electrical capacitance tomography (ECT) [2]. In these cases only one ring of sources has been considered. ECT yields low-accuracy images but is robust, inexpensive and much faster than many other tomography processes. This non-intrusive method essentially measures nonconductive system distributions and is applied in oil industry processes such as mixing or stirring vessels, fluidized bed reactors, separator tanks and pipelines carrying multiphase flows. In 3D the SA method or any other stochastic method (genetic algorithms, neural networks etc...) are still computationally too expensive and classical linear/local optimization methods are smoothing solutions too much. Furthermore local minimization techniques are trapped in local minima.

Therefore, instead of a 2D configuration and only one ring, we perform the non-linear inversion in a 3D configuration with one and two rings of source electrodes and by using a MPI-based parallelized least-square approximation. A forward problem is solved using a finite volume technique at each step of an iterative algorithm in which the computed data are evaluate again for the new current model to solve the inverse problem. Comparisons of the solutions using different mesh resolutions and different damping/regularization parameters are made. In the finite volume discretization we use different kinds of interpolations in order to improve the calculation resolution of capacitances and also the sensitivity kernels necessary to linearize the misfit function. This discretization has the advantage of a conservative formulation as used in finite element methods and features the flexibility of mesh refinement close to the electrodes. Improvement of local accuracy due to high order interpolators is achieved without increasing prohibitively the number of mesh points. We show here how different numbers of gas bubbles in an oil matrix or different features can be retrieved for a reasonably high resolution mesh after a few tens of global iterations. The 3D inversion codes have been running on our 48 MPI-based PC cluster and can even be run on much more depending on the wanted resolution.

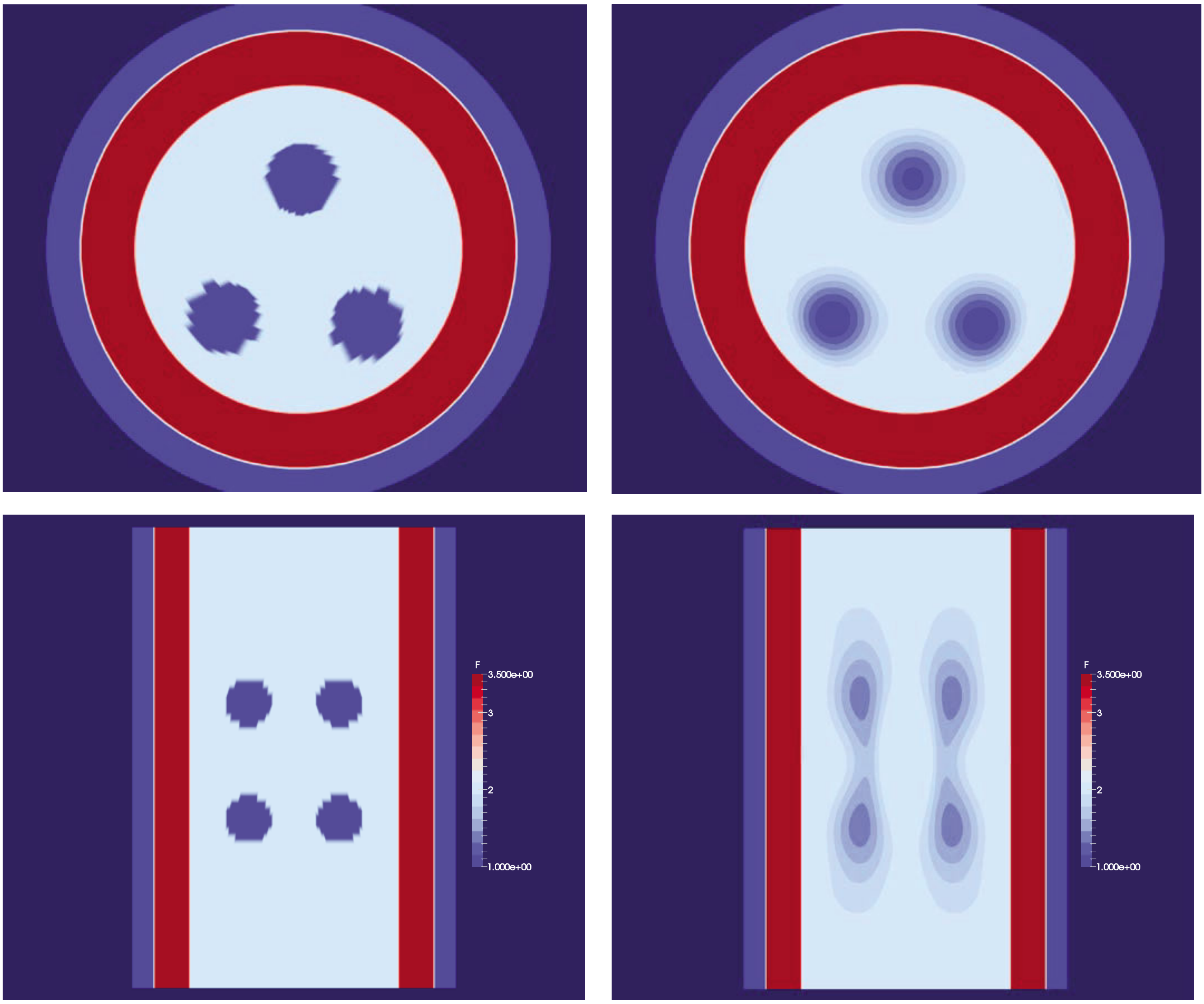

Figure 1. Comparison of the original models (left) and reconstructed images after 100 iterations (right), for systems with three horizontal bubbles (top), and four vertical bubbles (bottom) placed in oil. The permittivity of bubble ε=1, and the permittivity of oil ε=2. The model size is 72^3, and the number of data is 276 (i.e., 24 electrodes).

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Poster 5. EarthSci – A new tool for 3D data visualisation, integration and distribution

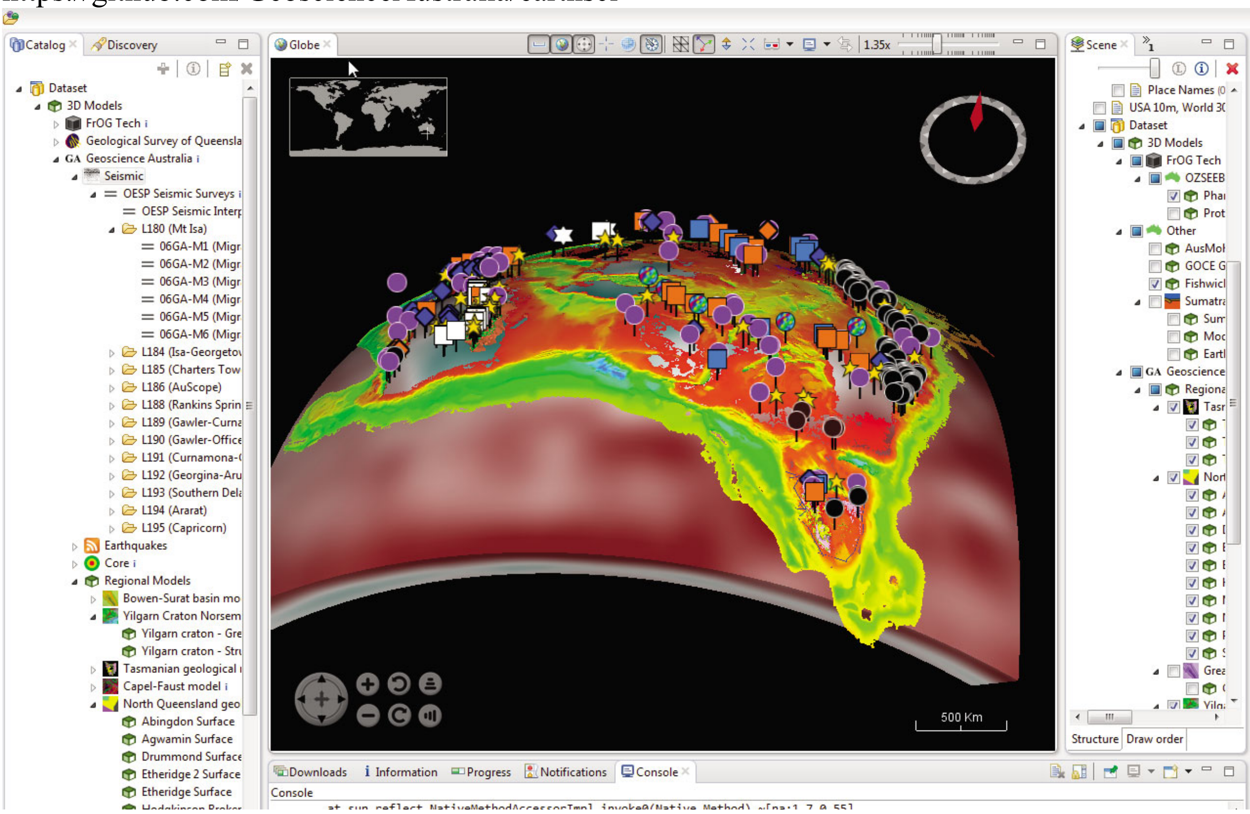
Nicoll, M.G., Cerini, E., de Hoog, M.

Geoscience Australia

Malcolm.nicoll@ga.gov.au

EarthSci is a powerful new tool for visualising earth science datasets in three dimensions. This 'virtual Earth'-style web application was originally developed by Geoscience Australia to assist its researchers to understand and present their findings. As demand for accessible data visualisation increased, the tool has been redeveloped to increase its useability and flexibility as a data integration and delivery tool. Importantly, EarthSci allows integration and visualisation of 3D datasets regardless of scale or coordinate system. Direct reads of popular file systems include including 3D, GIS, web services, tiled images and RSS feeds. An in-built animation function enables fly-throughs to be generated from within the tool and a presentation mode that enables journeys through the virtual globe environment to be constructed. This ability makes EarthSci stand out from other virtual globe environments. The latest version of the tool consists of modular design utilising Eclipse RCP and is freely open to developers in any field. Geoscience Australia welcomes collaboration with those interested in extending EarthSci's functionality as a scientific, communication and visualisation tool.

https://github.com/GeoscienceAustralia/earthsci



Poster 6. 3D geological models need error bars

Going from a single best guess model to multiple plausible models

Evren Pakyuz-Charrier[1]

[1] Centre for Exploration Targeting
School of Earth and Environment
University of Western Australia

evren.pakyuz-charrier@research.uwa.edu.au

3D geological modelling involves interpolating and extrapolating geological information (location of units and structures) in a 3D space mainly from surface data (maps, outcrop observations), cross-sections, drillholes and geophysical data. Geological models describe the geometry and nature of the subsurface in the same way that 2D geological maps describe the surface.

3D geological models have a wide range of practical applications from civil engineering to mining to fundamental research. They are necessary in any geology-related project as they reflect the geologists' knowledge of the subsurface and allow better understanding of complex relationships/geometry than static cross sections or maps. On the other hand, they are heavily impacted by uncertainty on many levels linked to human, conceptual and technical errors . It is then critical that any 3D geological model provides an estimation of its uncertainty and how it varies in space, in the same way that error bars indicate uncertainty for each element in a 2D scatter plot graph. The current 3D geological models public packages do not provide such "error bars", they are single "best guess" models obtained through deterministic interpolation. This is unsatisfactory as it may lead to false assumptions as these models do not give a proper rendition of how reliable our knowledge is.

Forward calculation of uncertainty is intricate but an alternative way to obtain uncertainty is by simulating it through a Monte Carlo simulation process. The method involves perturbing the input original data set using a probability distribution function to produce hundreds to thousands of different data sets. Each one of those altered data sets can then be used as an input to produce its own unique plausible 3D model. As all the models created this way are plausible they can be "merged" into a single global "fuzzy" probabilistic model which by its essence displays uncertainty.

The project's aim is to improve the current Monte Carlo based 3D modelling workflow developed at CET by integrating new algorithm to eliminate artefacts, reduce excess uncertainty, improve the uncertainty indexes usefulness and determine better the parameters of the probability distribution functions used to perturb the original input data.

Poster 7. 3D modelling of the Bryah and Padbury Basins, southern Capricorn Orogen, Western Australia: understanding the structure of the Robinson Range

C. Blaud-Guerry[1], M.W. Jessell[2], and M.D. Lindsay[2]

[1] Géosciences Environnement Toulouse, Université de Toulouse, Université Paul Sabatier – Toulouse III, UMR 5563, CNRS, IRD, UPS, Toulouse, France

[2] Centre for Exploration Targeting, The University of Western Australia, Perth, Australia

c.blaudguerry@gmail.com

The Bryah and Padbury Basins are located along the northern margin of the Yilgarn Craton in the southern part of the Capricorn Orogen, central Western Australia (Figure 1). The Bryah and Padbury Basins developed between 2.0 and 1.8 Ga. The Bryah Basin is divided in four formations: namely the Karalundi, Narracoota, Ravelstone and Horseshoe Formations. This basin is described as a rift to pre-collisional basin. The Padbury Basin is interpreted as a retro-arc foreland basin. The Padbury Group is divided in four formations: the Labouchere, Wilthrope, Robinson Range and Millidie Creek Formations. During the Capricorn Orogeny (1820-1770 Ma) the Bryah and Padbury Basins were deformed and metamorphosed at low metamorphic grade.

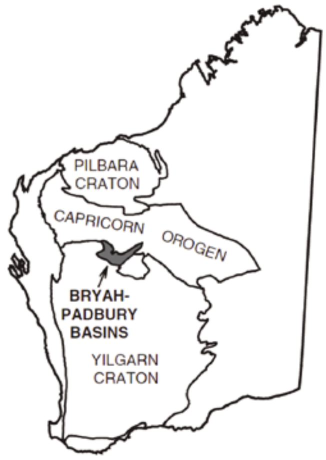


Figure 1: Location of the Bryah and Padbury Basins in Western Australia (after Pirajno, Occhipinti, & Swager, 2000)

In this area the basement is separated in two different domains. In first, the basement B2 (Figure 2) outcrops on the surface. B2 provided some geochronological information assigning an Archean age. B2 is considered as a part of the Narryer Terrane. In second, the basement B1 is situated deeper and could be a part of the Youanmi Terrane (Murchison Domain). The Narryer Terrane and the Murchison Domain are part of the Yilgarn Craton.

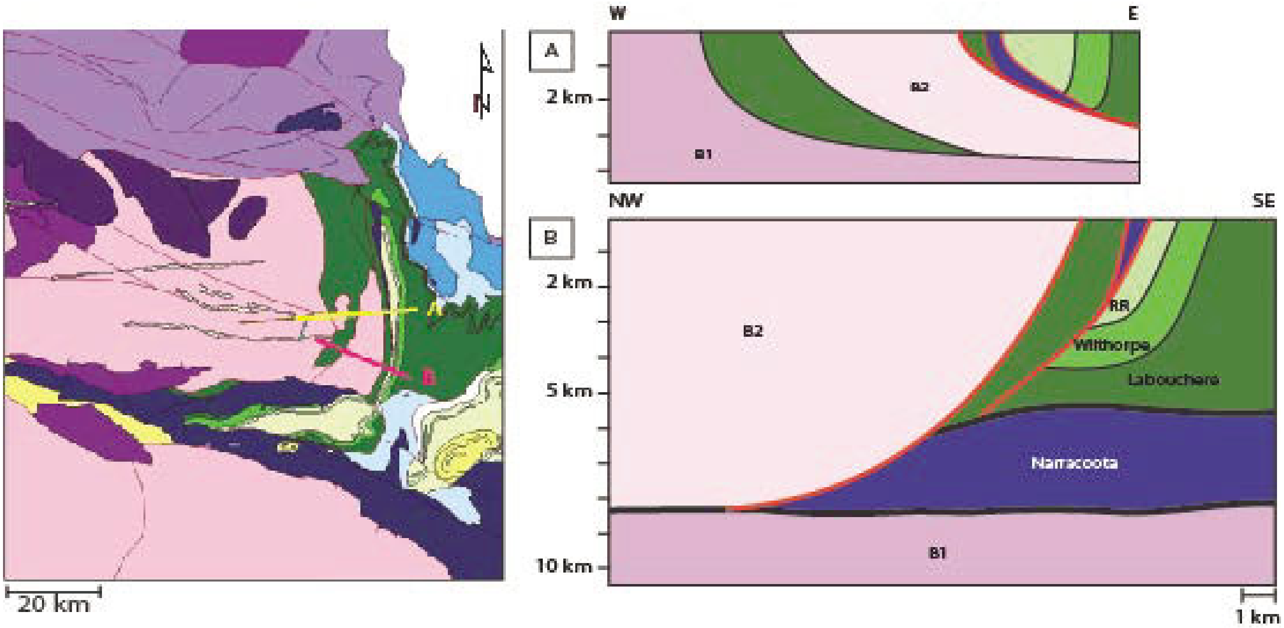


Figure 2: Location map of the Robinson Range area and the cross-section of Robinson Range area: A) Milgun Section B) Padbury Section. Pink: basement B1 and B2, blue: Bryah Basin, and green: Padbury Basin. Red fault: inverse, and black fault: decollement (modified after Swager, Myers, & Thorne, 2010 ; and Occhipinti, Swager, & Myers, 1997)

We built a three-dimensional model of this area using Geomodeller. The aim was to understand the main regional structures by highlighting the lithological distribution and the geometry of the main geological units.

On the cross-section published with the Padbury map (1: 100 000), (Occhipinti, Swager, & Myers, 1997), the major fault is west dipping, in contrast to the Milgun map (1: 100 000), (Swager, Myers, & Thorne, 2010) which is east dipping. Therefore, we had to revise the overall geological structure using geological knowledge and geophysical data such as magnetics and gravity data. After interpreting these data, the most probable scenario is that the fault is west dipping (Figure 2b). The presence of sub-vertical dipping, north-south striking layers in the east part of Robinson Range area shows an important faulting and folding deformation. This might, in part, be due to the presence of a part of the basement (B2) (Figure 2) on the west side of Robinson Range.

The first scenario which can explain the global structure of the Robinson Range and the presence of B2 (refer to Figure 2 caption) suggests that there is a dextral strike slip fault on the northern margin of the Yilgarn Craton. This fault is coupled to another a sinistral fault, parallel to the former, in the northern margin of the B2 block. These two strike slip faults induce the displacement of B2 in its actual place. B2 involved an east-west compression which can be at the base of a series of north-south west dipping faults. These west dipping faults add to the decollement induce the steepening of the layers of the Bryah-Padbury Basin in Robinson Range area. The decollement represent the separation between B2 and another basement B1. Nevertheless, the presence of the decollement has not been validated through the analysis of geophysics data such as magnetics or gravity. Questions remain about this structure: does it even exist, and if so how deep is it? To test the presence of the fault it will be necessary to observe a rock property contrast. We use magnetotelluric (MT) and potential field data to determine the location and magnitude of the contrast. The presence of this fault could augment our understanding of the tectonic evolution of this and the wider region.

Acknowledgements

Sandra Occhipinti, Franco Pirajno and Evren Pakuz-Charrier are thanked for their patience and for the long discussion as well about the geology, the geophysics data and the software.

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Poster 8. Where is the Fault? – An experiment to understand differences in seismic interpretation

Alcalde, J.[1], Bond, C.E.[1], Johnson. G.[2], Ellis, J. F.[3]

[1]Geology and Petroleum Geology, University of Aberdeen, School of Geosciences,
King College, Aberdeen, AB24 3UE, UK.
[2]School of Geosciences, University of Edinburgh, West Mains Road, Edinburgh, EH9 3JW, UK.
[3]Midland Valley Exploration, 144 West George Street, Glasgow, G2 2HG, UK.

juan.alcalde@abdn.ac.uk

Poster

Seismic reflection data is one of the most important tools for subsurface imaging. The interpretation of seismic datasets is strongly subjective, and is dependent not only on the characteristics of the data but on the skills of the interpreter. These skills rely on the experience, background and training received of the interpreters, and thus the final result is a product of the interpreters' ability to apply these skills to the interpretation. Consequently, the interpretation of the same seismic section can be profoundly different depending on who is interpreting the data.

We designed an experiment in order to analyse and understand the interpretation of seismic sections. In this experiment, the same seismic section, either in two-way travel time (TWT) or in depth, was given to 196 participants. The participants were asked to interpret the seismic section, paying special attention to a major fault located in the middle of the section. The interpreters' proficiencies were highly diverse, and their experience ranged from unexperienced students to specialists with more than 30 years of experience.

The interpretation results show a large range of fault geometries (Fig. 1) and horizon offsets that indicate different tectonic settings (Fig. 2). The interpreted geometry of the fault and its orientation were disparate, especially when comparing interpretations completed in TWT with those in depth. The results of this experiment showed that 37.1% (26 participants) of those that interpreted in TWT constructed a normal fault in comparison to 28.6% (36 participants) of those that interpreted a depth section. Furthermore, those interpreting in TWT created a narrower range of fault geometries than participants interpreting in depth (Fig. 1).

The majority of the interpreters (62 participants, 31.6%) correctly interpreted the main fault as normal (Fig. 2). However, the results of the interpreters self-considered as specialist in structural geology (19 participants, 9.7%) showed that only the 15.8% (3 interpreters) correctly interpreted the normal fault setting. This contrasts with 52.6% of the self-considered experts in structural geology (10 interpreters) that interpreted the setting as inversion.

In summary, there is a remarkable difference in the results obtained in TWT and depth and there are important discrepancies between the interpreted tectonic settings and the interpreters' self-assessment of ability. These results provide valuable knowledge on the way interpreters approach the interpretation of seismic datasets and evaluate their own skills. The outcomes of this work can be used to improve the interpretation workflows carried out in the industry.

a)

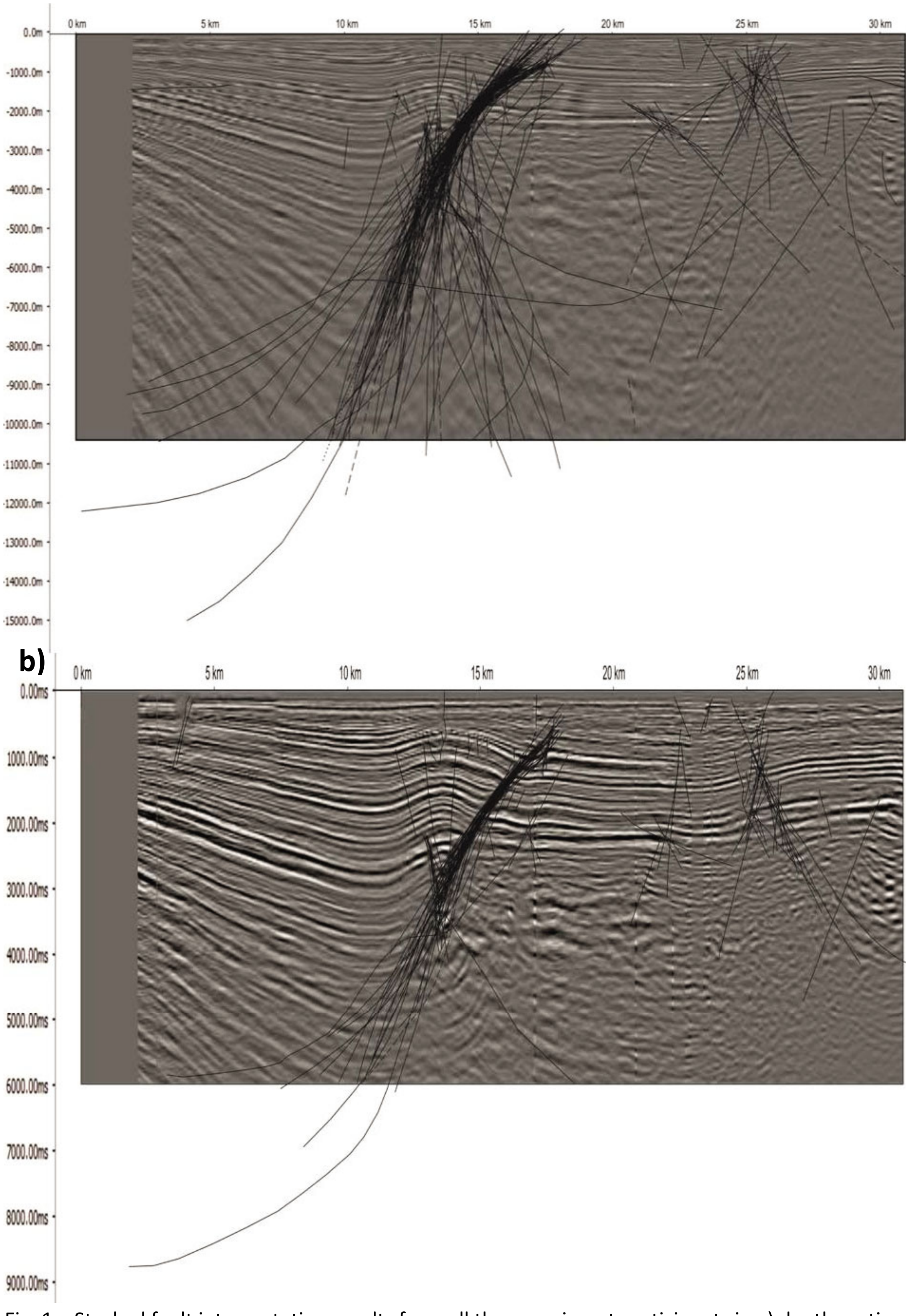


Fig. 1: Stacked fault interpretation results from all the experiment participants in a) depth section; and b) in two-way travel time (TWT) section. Note that the faults interpreted in the TWT domain are less spread in the deeper part of the section compared to the results in depth.

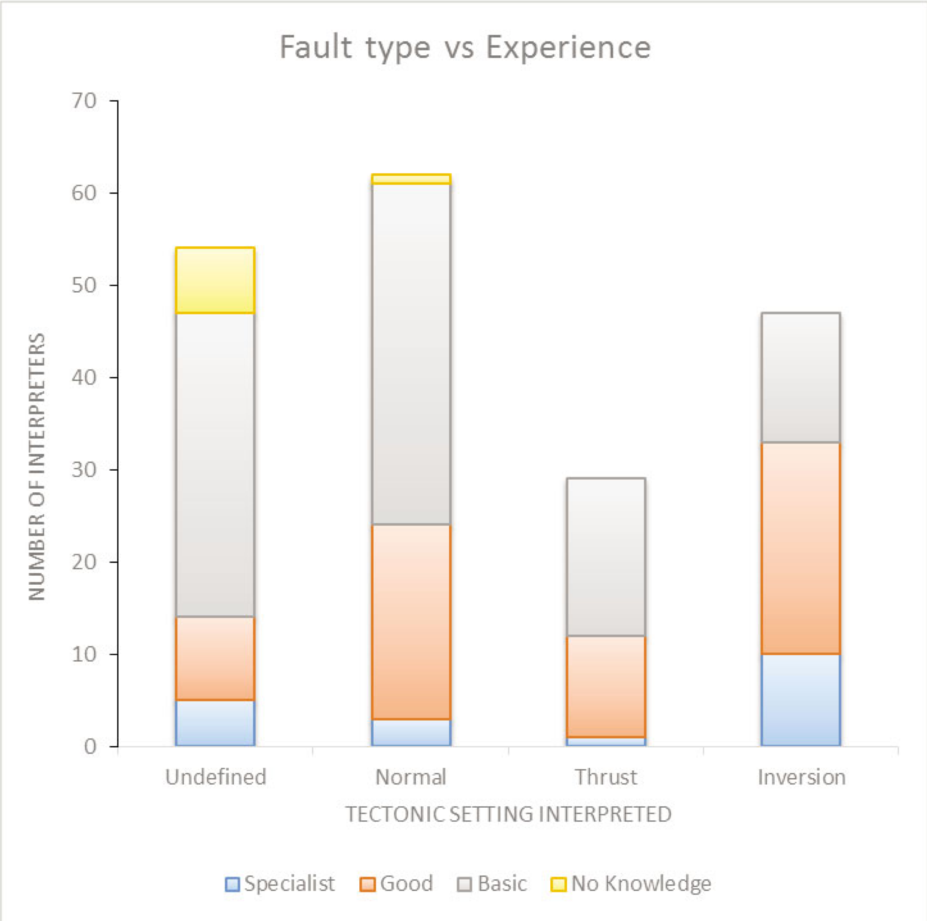


Fig. 2: The range of tectonic settings interpreted from the seismic sections. The colours represent the participants own assessment of their proficiency in structural geology.

Poster 9. 3D Architecture of the Jervois Cu-Pb-Zn deposit, Northern Territory, Australia

Schaubs,[1] P.M., Schmid,[1] S.

[1] CSIRO Mineral Resources Flagship, Kensington, Western Australia, 6151

Peter.Schaubs@csiro.au

Poster

The Jervois deposit is situated in the Arunta Region within the southern part of the Northern Territory, approximately 350 km E of Alice Springs. The majority of mineralisation is hosted in the Bonya Metamorphics (ca 1780 Ma) which comprise a range of upper-greenschist to middle amphibolite facies metamorphic rock types including muscovite schist, cordierite marble, calc-silicate rock and meta-quartzite.

Structural analysis from outcrop and core observations show that three deformation folding events occurred in the Jervois district resulting in a complex multi-folded stratigraphy with repeating mineralisation. Faults and fractures are related to the youngest deformation (syn–post D3) and offset the mineralisation, forming an en echelon pattern. Bedding is represented by the contacts of distinct marker units such as marble, meta-sandstone and tourmalinite that can be traced along strike across the Jervois 'J-fold'.

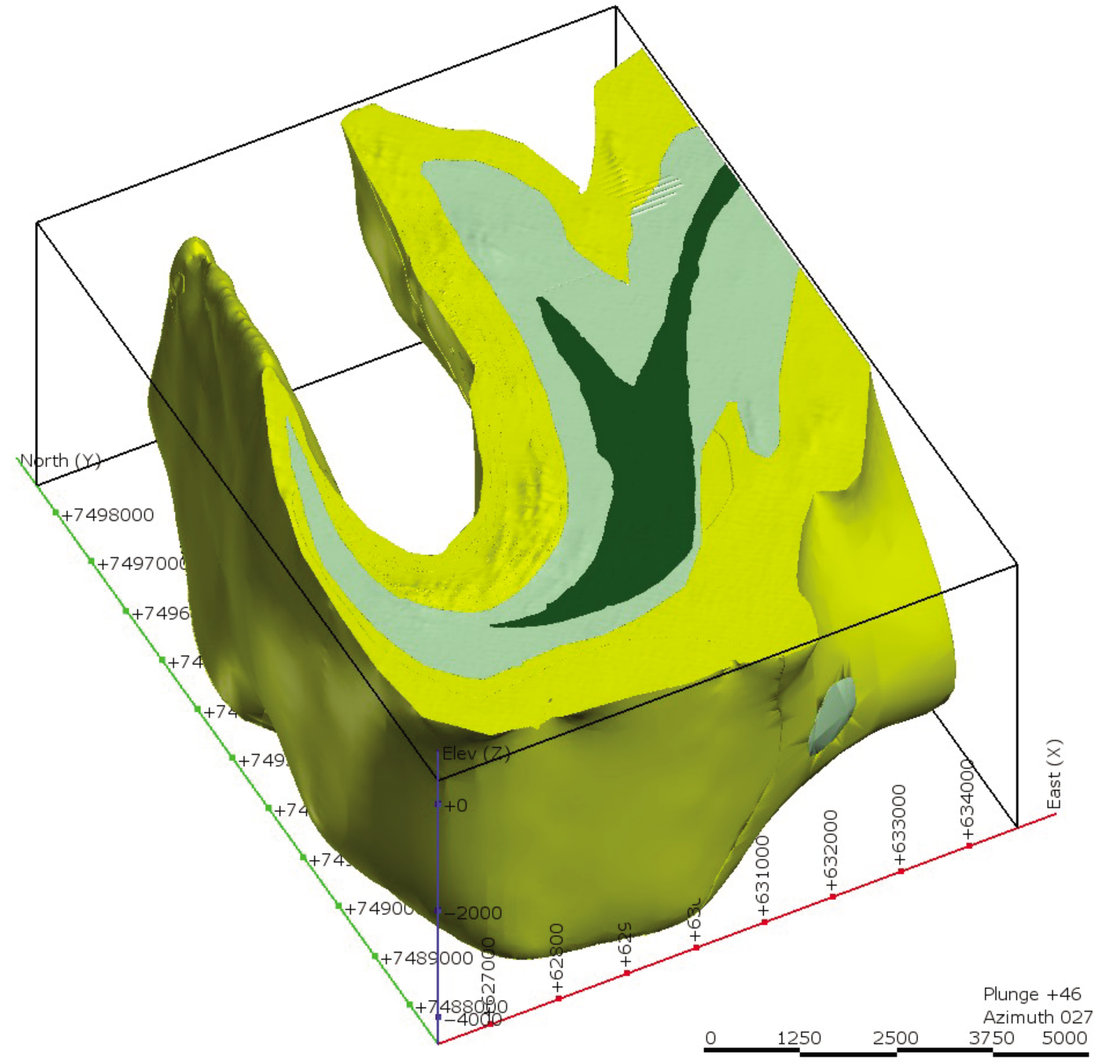
The trends in Cu-Pb-Zn mineralisation show that zones of mineralisation are repeated as a result of isoclinal folds in both the Bellbird and Marshall-Reward areas. Zonation of Cu, Pb and Zn is parallel to the marble/calc-silicate and quartzite marker units and bedding suggesting that mineralisation predates deformation and was originally distributed parallel to. Minor secondary remobilisation can be seen along faults and fractures offsetting the primary mineralisation.

The overall shape of the Jervois deposits is defined by the youngest ductile deformation identified at Jervois which is here termed D_3 and is represented at the map scale by the prominent F_3 synformal J-fold which covers the tenement area and plunges to the north.

Structures associated with D_2 are the most common features observed at Jervois, in particular the ubiquitous steeply dipping S_2 axial planar cleavage. S_2 is parallel to, or defines in part, the shape of the J-fold at Jervois and as such the orientations change from the northerly at Morley/East Reward to southerly at Bellbird North. In outcrop F_2 folds occur as sub-horizontal to moderately plunging tight to isoclinal folds with wavelengths of 1-3 m. Their plunge is also variable which may be in part due to their interaction with older F_1 folds. At the map scale tight to isoclinals folds defined by key marker beds such as marbles, calc-silicates, and tourmalinites are interpreted to be F_2.

Structures attributed to D_1 deformation are the most cryptic at Jervois. S_1 is very rarely identified in the field and it is interpreted that in most cases S_1 and bedding have been transposed into parallelism. In some rare cases F_2 crenulations are observed and these deform a fabric which is sub-parallel to compositional layering interpreted to be bedding. F_1 folds are interpreted to be steeply plunging and are most commonly found in marbles and calc-silicates rocks where they are defined by quartz rich layers, which are deformed into tight to isoclinal folds.

The 3D model of the Jervois area presented here was constructed in LeapfrogGeo and is based in part on previous interpretations with additional constraints from recent drill core data, a detailed magnetic survey and associated independent interpretation, including field observations from this study. The model is dominated by three major folds: one overturned F_1 anticline which is folded about an upright F_2 anticline and both of these are folded about the F_3 'J-fold'



Poster 10: Uncovering the Eucla basement: Preliminary results of gravity and magnetic inversion in the Madura Province, Western Australia

Brisbout[1], L.I., Brett[1], J.W.

[1] Geological Survey of Western Australia

Lucy.brisbout@dmp.wa.gov.au

Preliminary results from unconstrained gravity inversions have provided initial 3D geometries for mafic bodies in the upper crust of the Madura Province. These bodies include the Loongana intrusion and the Haig and Rodona bodies, all of which are associated with high amplitude Bouguer gravity anomalies (Fig. 1). These bodies, and the Madura Province, are located beneath up to 500m of cover and our geological understanding is based on sparse drillcore information mostly obtained during Ni and PGE exploration (Fig. 1). The mafic rocks intersected in drillcores at the Loongana and Haig prospects (Bunting and Myers, 2003; Tillick and Hunt, 2010) have been interpreted by Spaggiari et al. (2014) to be part of an oceanic magmatic-arc accreted onto the margin of the Albany–Fraser Orogen during the Mesoproterozoic. Unconstrained gravity and magnetic inversion, using Geosoft's VOXI Earth Modeller (version 8.3.2), has been used to produce 3D density and susceptibility models, respectively, of the Loongana intrusion and the Haig and Rodona bodies (Fig. 1).

The inverted density model suggests that the southwest end of the Loongana intrusion has a symmetric, synformal geometry (Fig. 2a) and a northeast-plunge. A useful way of visualising the density model is with isosurfaces that represent assigned densities. The geometry of the Loongana intrusion predicted in the density model is broadly consistent with gravity forward models, that have been constained by specific gravity measurements from drillcore and Bouguer gravity and aeromagnetic image interpretation. The synformal geometry of the inverted density model is also broadly consistent with the results of the inverted susceptibility model, except the susceptibility model suggests the synformal Loongana intrusion has a southeast inclined geometry.

The relationship between the inverted density model and the gravity worms is less straight forward. The northeast plunge of the Loongana intrusion is consistent with northeast dipping gravity worms. However, the steep, bowl-shaped geometry of the Loongana intrusion is not consistent with gravity worms, which show the margins of the Loongana intrusion dipping outward. The combined analysis of aeromagnetic images and magnetic worms suggest that the Loongana intrusion contains a c. 6 km wide, northeast-plunging tighly folded magnetic horizon. The plunge direction of the folded magnetic horizon is subparallel to the plunge of the Loongana intrusion.

The inverted density model of the Haig and Rodona study area has been visualised by assigning isosurfaces of 2.77 g/cm^3 and 2.60 g/cm^3, assumuing a background density of 2.67 g/cm^3 (the crustal density average). The 2.77 g/cm^3 isosurface possibly represents mafic rocks mixed with metasedimetary and/or metagranitic rocks and the 2.60 g/cm^3 isosurface possibly represents lower density felsic granites. The density model shows that the Haig and Rodona bodies appear to form the eastern and western limbs, respectively of a c. 50 km wide, northeast-closing fold in the hanging wall of the Rodona Shear Zone (Fig. 2b). The smaller size of the Rodona body compared to the Haig body could be explained by shearing of the Rodona body in the Rodona Shear Zone. The density model also shows that the 2.77 g/cm^3 isosurface is truncated by north and northeast trending structures and, in the hinge, by circular 2.60 g/cm^3 isosurfaces that most likely represent granites (Fig. 2b).

One of the limitations of unconstrained geophysical inversion is that the resulting models are just one of an infinite number of physical property models consistent with the observed data (non-uniqueness). In future work, constraints will be imposed on the upper and lower densities of units, using specific gravity data from drill core, and on the geometry of units, using major structures interpreted from deep crustal seismic sections.

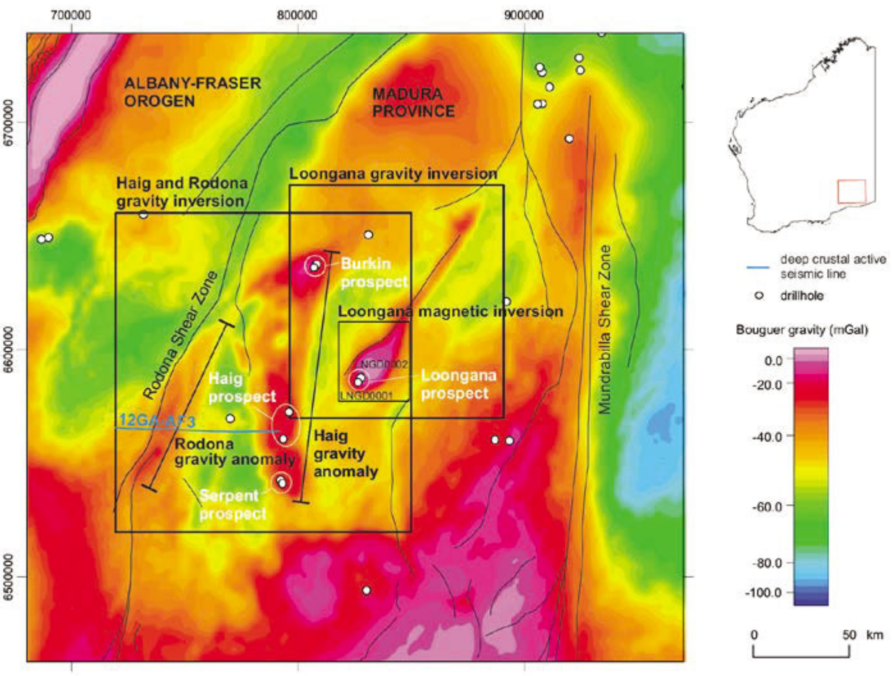


Figure 1. Bouguer gravity image of the Madura Province showing the location of the gravity inversions, the Loongana intrusion and the Haig and Rodona gravity anomalies. Also shown are the locations of drillholes and 1:500 000 structures (Geological Survey of Western Australia, 2014).

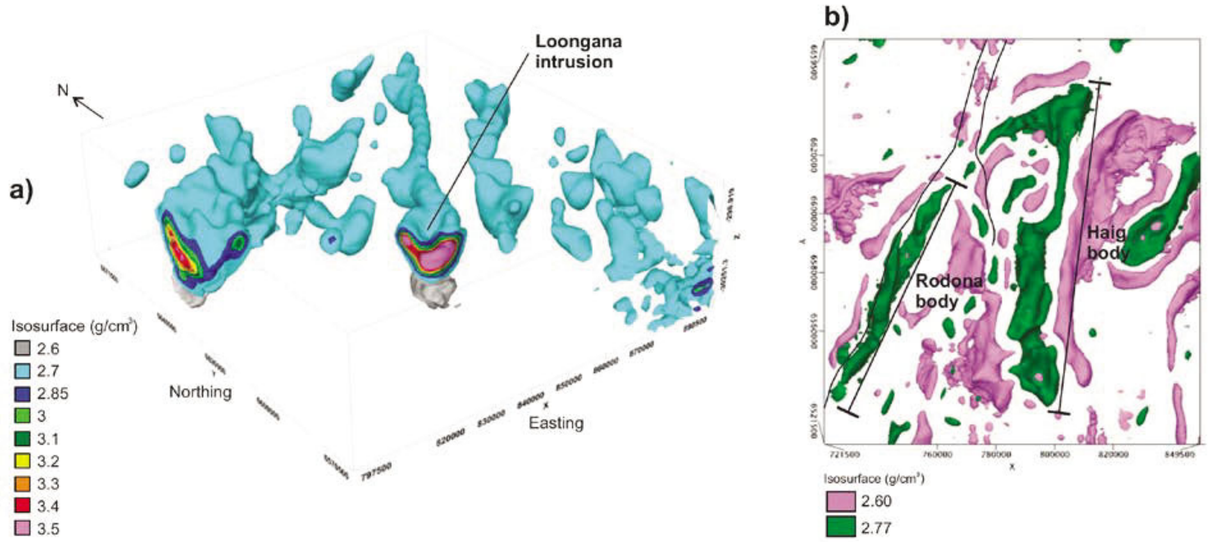


Figure 2. Density models represented by isosurfaces, produced by unconstrained gravity inversion using Geosoft's VOXI Earth Modeller: a) Loongana study area, showing isosurfaces that represent the Loongana intrusion, sliced northwest (perpendicular to the northeast-strike of the intrusion), b) Haig and Rodona study area, showing isosurfaces that represent bodies with densities of 2.77 g/cm^3 (mafic dominated bodies) and 2.60 g/cm^3 (possibly low density granites).

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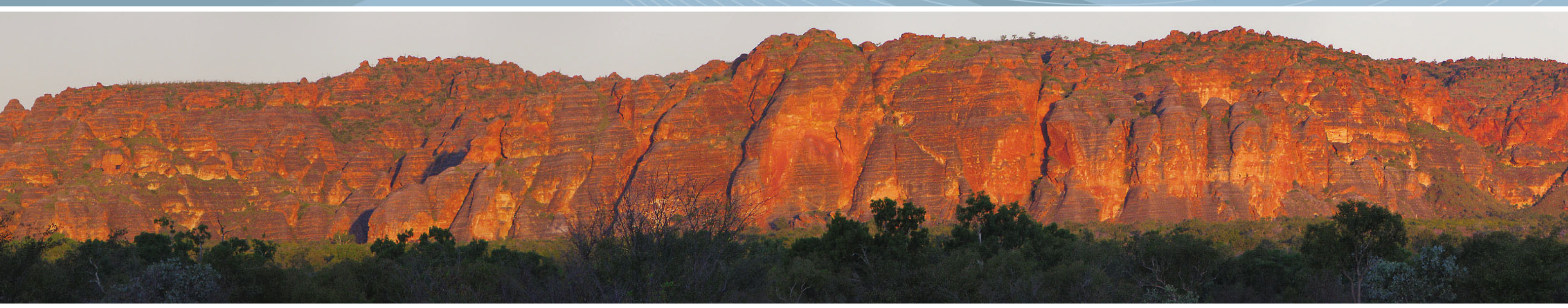

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