3D geological mapping and potential field modelling of West Arnhem Land, Northern Territory

Richard Lane
Geoscience Australia
Canberra, ACT, Australia
richard.lane@ga.gov.au

Geoff Beckitt
Cameco Australia Pty Ltd
Darwin, NT, Australia
Geoff_Beckitt@cameco.com.au

Mark Duffett
NTGS (presently University of Tasmania)
Hobart, TAS, Australia
Mark.Duffett@utas.edu.au

SUMMARY

A regional scale 3D geological map of the upper crustal sequence in the West Arnhem Land region, Northern Territory, was compiled from surface mapping, limited drilling information, and liberal amounts of geological inference. Modelling of the gravity and magnetic field response of this map was proposed as a means of evaluating the viability of this geological hypothesis. A relatively large number of mass density and magnetic property measurements were available to constrain the transformation of 3D geological maps into property models in preparation for potential field modelling. The presence of numerous magnetic dykes, sills, and stratigraphic horizons provided many challenges for producing geologically-realistic magnetic property models at a regional scale. Modelling of the gravity field at this scale was far more straight forward and successful. After completing various forward modelling experiments, a stochastic procedure will be used to derive a large number of geological maps by making small changes to the highly uncertain interpretive parts of the original 3D geological map. It is expected that a subset of these derived geological maps will have associated mass density models that can adequately reproduce the gravity field observations. The common characteristics of the geological models in this subset will be isolated using statistical techniques and used to refine our representation of the regional scale 3D geological features.

Key words: 3D, gravity, magnetics, inversion, West Arnhem Land.

INTRODUCTION

The West Arnhem Land region is one of Australia's prime exploration areas for uranium mineralisation (e.g., Beckitt, 2003; Ahmad, 1998). A 3D geological mapping and potential field modelling project was initiated to gain a better appreciation of the 3D geological architecture of the region and to test the unique functionality of the GeoModeller software package.

The software utilises geostatistical co-kriging methods to interpolate geological boundary, structural orientation and fault plane observations in 3D (Lajaunie et al., 1997; Chiles et al, 2004). Employing a stratigraphic approach to mapping, geological age and boundary relationship definitions are used to resolve the conflicts that arise in the resultant overlapping distributions of mapped units. These semi-automated mapping methods relieve the user from the responsibility for precisely defining the extent of the volumetric regions occupied by each unit, thus raising the possibility of significantly decreasing the time required to construct or modify 2D or 3D geological maps (e.g., Maxelon and Mancktelow, 2005; Putz et al., 2006). However, this promise is contingent on the user providing an adequate number and spatial distribution of geological boundary, structural orientation and fault plane observations, and on the suitability of the underlying interpolation conditions for representing the actual geological situation. In a typical situation where the supply of specific geological observations is inadequate to define a geological architecture that is deemed viable according to general geological understanding of a region, potential field information in the form of gravity and magnetic data can be used to investigate different permissible geometrical configurations and to inform the user of those with a higher likelihood (Lane et al., 2007). This approach relies on the quality of the potential field data, the ability of a rectangular prism mesh to represent the geometry of the geological units, a facility to define the relative uncertainty for different aspects of the geological map, a capability to produce multiple viable geological configurations, and the definition of appropriate mass density and magnetisation property distributions for the mapped units.

The West Arnhem Land region presents many geological challenges, due in part to the wide spacing between primary surface observations, the deeply weathered state of the Archaean and Palaeoproterozoic outcrops, and a short supply of subsurface observations. With very few exposures of the key boundary relationships, it proved difficult to propose a coherent hypothesis of the 3D geological architecture of the region for this project. Beyond this conceptual difficulty, a number of recurrent data management and computational load issues were evident to us. The efficiency of transferring geological information held in 2D cartographic form in government agency and exploration company data stores to the software applications was substantially reduced by the need to manually re-interpret and re-structure the digital data. We were then challenged by the computational demands of carrying out comprehensive 3D gravity and magnetic modelling of regional geological and geophysical datasets. Although the project is still a work-in-progress, we describe the work that has been carried out to date and discuss some of the issues that have arisen.

DATA COMPILATION

Project region and surface topography data

The volume-of-interest (VOI) for 3D geological mapping was from 240000mE to 360000mE, 8590000mN to 8665000mN, and -5000mAHD to +500mAHD (NB: Unless otherwise indicated, all of the coordinates given in this paper are in reference to an MGA53 projection, GDA94 horizontal datum and AHD vertical datum). The geological mapping was carried out within a larger volume from 220000mE to 380000mE, 8570000mN to 8695000mN, and -18000mAHD to +12000mAHD. The inclusion of a padding region of at least 10 to 20 % ensured that geological information beyond the VOI could be included in the calculations and hence provide constraints for the results on the margins of the VOI. Geological observations were supplemented by ‘interpretation’ and ‘construction’ points that were largely confined to zones above and below the VOI to produce specific geological configurations.

The surface topographic data were derived from SRTM Version2 3-second data (Farr and Kobrick, 2000; available from http://www2.jpl.nasa.gov/srtm/index.html). These data were projected from geographic projection for the WGS84 ellipsoid to an MGA53 projection and GDA94 horizontal datum. The grid was re-sampled from approximately 90 m cells to 500 m cells to avoid the significant computation overhead that can be incurred when a topographic grid is initially processed by the mapping software for storage and when rendering geological units onto this surface. It was not considered necessary to transform the SRTM elevation data from the supplied WGS84 EGM96 geoid vertical reference datum to the AHD vertical datum used in the mapping. Offshore areas were set to zero height. The topographic data covered an area at least 1 grid cell larger than the horizontal extent of the project to avoid introducing interpolation artefacts in the topographic representation around the edges of the map region

Geological mapping data

The 1:500,000 pre-Cretaceous solid geological mapping of Lally and Doyle (2005) was projected onto the topographic surface and used as the basis for the 3D mapping (Figure 1).

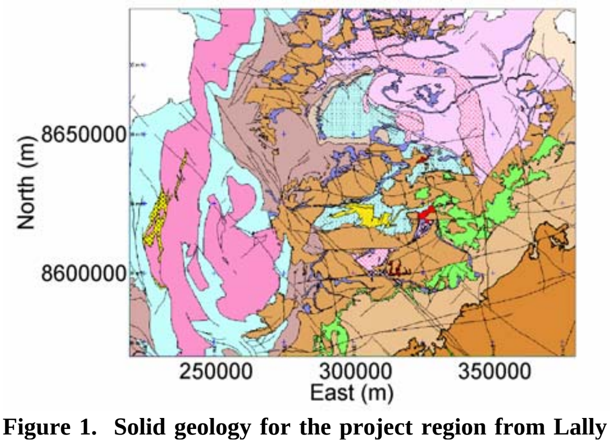

Figure 1. Solid geology for the project region from Lally and Doyle (2005). The colour legend is given in Table 1.

The oldest geological units exposed in the map region form the northeast edge of the Pine Creek Orogen (e.g., Worden et al., 2006; Carson et al., 1999; Needham, 1988). The Archaean Nanambu Complex is overlain by the Palaeoproterozoic meta-sedimentary and meta-volcanic rocks of the Kakadu Group, Cahill Formation, Nourlangie Schist and Myra Falls Metamorphics. These units are intruded by syn-orogenic granites of the Nimbuwah Complex and by the post-orogenic Tin Camp and Nabarlek Granites. Sedimentary and volcanic rock units forming the northwest edge of the Mesoproterozoic McArthur Basin unconformably overly the Pine Creek Orogen basement units. Oenpelli Dolerite dykes and sills intrude both the Pine Creek and McArthur Basin sequences. Neoproterozoic sediments belonging to the Arafura Basin overly both Pine Creek Orogen and McArthur Basin rocks in the northeast portion of the project area. Various Mesozoic and Cenozoic sediments of limited thickness are present, but were not considered during this exercise.

The choice of geological mapping units and their geological relationships depends on the scale and purpose of the mapping. The final selections considered to be appropriate at this regional scale are shown in Table 1.

Mass density and magnetisation properties

Estimates of the mass density and magnetisation properties for the geological mapping units were compiled from measurements made by various groups on hand samples as indicated in Table 2 and Table 3.

Geophysical data

Regional gravity and magnetic data sets were utilised in both a qualitative and quantitative fashion. Vertical gravity data (Figure 2) were derived from a combination of ground and airborne measurements (Lane, 2004). These data were upward continued to a height of 1300 m AHD, nominally 1 km above the average surface height of the region. The upward continuation operation was applied to attenuate any short wavelength features in the data that could not be adequately reproduced when modelling with a mesh of rectangular prism cells each 1 km in horizontal dimension.

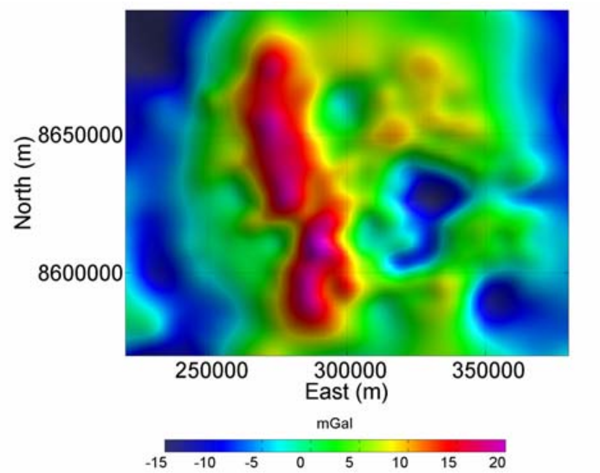

Figure 2. Vertical gravity data for the project region derived from the dataset described by Lane (2004).

Total magnetic intensity (TMI) data were extracted from regional compilations produced by Geoscience Australia and the Northern Territory Geological Survey and upward continued to a nominal height of 1300 m AHD. These data are shown as an image of TMI reduced-to-the-pole (TMI RTP) (Figure 3).

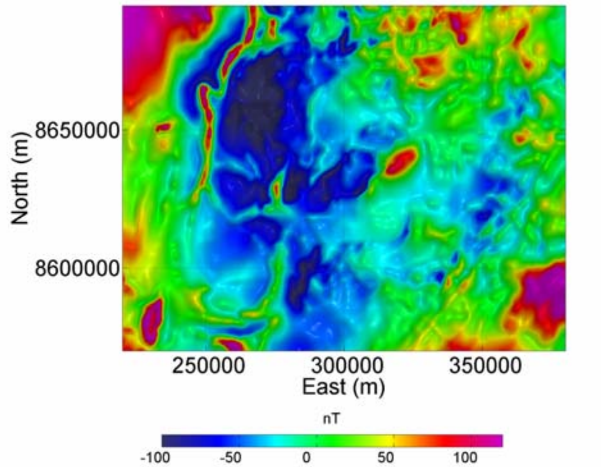

Figure 3. TMI RTP image for the project area.

To illustrate the considerable detail available in the original data, an image of the first vertical derivative of TMI RTP (TMI RTP 1VD) is shown in Figure 4. Upward continuation was not used in this instance.

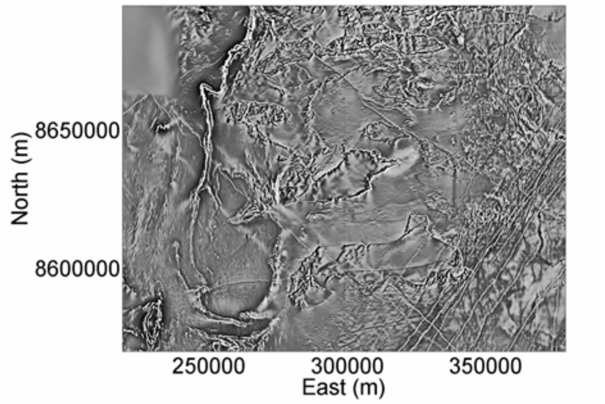

Figure 4. TMI RTP 1VD image for the project area. Note that the bland expression in the north-west corner is due to the absence of airborne data in this part of the project area.

QUALITATIVE ASESSMENT OF POTENTIAL FIELD DATA

Analysis of the rock property information and qualitative interpretation of the potential field data was carried out as an integral part of the process of creating the initial 3D geological map. In a strict sense, this preliminary use of the potential field data to aid production of the 3D geological map compromised the independence of the potential field data for use during the evaluation phase. However, this action was considered to be justified to reduce the source ambiguity inherent in the potential field data and to expedite subsequent inversion procedures. First order compatibility between the potential field data and the geological proposition put forward as an inversion constraint was virtually assured by this approach to the mapping.

Qualitative assessment of the magnetic data

The magnetic images in Figure 3 and Figure 4 illustrate the complex geometry and varied geological origins of the magnetic sources. A very fine mesh would be required to adequately represent the geometry of the sources, and in most cases, the map units would need to be subdivided to provide geometrical constraints for the sources. Unlike the vertical gravity data that reflect the bulk properties of the entire 3D geometry of the mapped units, the TMI RTP and TMI RTP 1VD data largely reflect the presence of narrow magnetic horizons within several of the mapped units and the response is strongly influenced by the depth-to-top of the shallowest sources at each horizontal location. The extensive additional work that would be required to formulate a complete set of geological constraints across the project region for quantitative magnetic modelling was not deemed warranted for this regional 3D geological mapping exercise. Instead, the magnetic data were used to provide qualitative constraints for the 3D geological mapping.

The presence within the Cahill Formation of narrow BIF units with moderate to steep dips is inferred from a set of curvilinear magnetic anomalies. These features are restricted to the margins of the Nanambu Complex despite the presence of the Cahill Formation in the Nimbuwah Domain. This is possibly a metamorphic effect reflecting the change from lower amphibolite grade in the Nanambu Domain to upper amphibolite and lower granulite grade in the Nimbuwah Domain, but is thought more likely to reflect a primary depositional difference in the two domains.

Concentric oval shaped magnetic anomalies in the south-west corner of the magnetic images reflect anomalous magnetisation within the Zamu Dolerite and magnetite in contact metamorphic zones surrounding the intrusion.

A prominent 10 km long oval shaped, relatively long wavelength feature oriented along a north-east axis and centred approximately at 320000mE 8640000mN is associated with the Nabarlek Granite.

A large number of magnetic features in the central and eastern portions of the project area are interpreted to be sourced within the Oenpelli Dolerite. Measurements on samples of this unit (Table 3) indicate the presence of significant induced and remanent magnetisation, with the latter dominating the total magnetisation. Areas of uniform negative response bounded by large amplitude curvilinear anomalies are indicative of subhorizontal sheets of Oenpelli Dolerite. Other areas surrounding these sheets have complex anomaly patterns including many short strike length features that are interpreted to reflect the presence of partially preserved, faulted outcrops of Oenpelli Dolerite sills.

Low amplitude short wavelength ‘speckled’ anomalies across the south-east third of the project area are interpreted to be associated with the gently dipping Nungbalgarri Volcanics. This is supported by variable weakly elevated induced susceptibility measurements on drill core samples (Table 3). It is unclear whether the highs in the extreme south-east corner of the TMI RTP image reflect an increase in the magnetisation-thickness product of the Nungbalgarri Volcanics or a broad magnetic source in the Pine Creek Orogen sequence, possibly a magnetic granite pluton.

A large number of narrow linear north-east trending long strike length anomalies are interpreted to be sourced by sub-vertical dykes intruding the Katherine River Group. A smaller number of magnetic dykes with north-west orientation appear to intrude both the Katherine River Group and Pine Creek

Orogen sequences. A distinctive pair of north-west trending linear anomalies approximately 15 km apart are present in the central south-west part of the project area. They are distinguished by the absence of a short wavelength contribution, and hence must be sourced by buried features. Although the north-east feature correlates with the position of the Bulman Fault Zone, there is no evidence of any significant vertical or horizontal offset in the geological mapping shown by Lally and Doyle (2005). This would suggest that the features are a pair of buried magnetic dykes rather than being the magnetic field expression of faults with significant displacement.

The attenuation of short wavelength features observed in the north-east corner of the project area is interpreted to signify the presence of an increasing thickness of non-magnetic Arafura Basin sediments.

Qualitative assessment of the vertical gravity data

The vertical gravity image in Figure 2 is dominated by a north trending positive anomaly approximately 100 km in length. The property measurements in Table 2 and the horizontal position of this feature suggest that it is related to a thick trough of Nourlangie Schist. It is unknown whether this trough represents structural thickening through folding and faulting, a primary depositional feature or a preservation feature. The north trending gravity low to the west is associated with the Nanambu Complex and Cahill Formation. An elevated response near the south-west corner coincides with outcrops of Mundogie Sandstone and Wildman Siltstone, Central Domain correlatives of the Nourlangie Schist.

The gravity low centred around 330000mE 8625000mN is interpreted to be sourced by the Tin Camp Granite pluton and to a lesser extent the Nabarlek Granite. The presence of a second pluton of Tin Camp Granite is inferred from the gravity low at approximately 360000mE 8590000mN.

Second order gravity lows around (a) 300000mE 8660000mN, (b) 310000mE 8615000mN and (c) 315000mE 8580000mN are interpreted to reflect domal structures within the Pine Creek Orogen sequence surrounded by mantles of Nourlangie Schist. Cahill Formation meta-sedimentary rocks outcrop at the centre of (a), whilst Kakadu Group quartzites are present at the centre of (b). Cahill Formation rocks are interpreted subcrop beneath the Katherine River Group at the centre of (c). The surrounding gravity highs are interpreted to be partially reinforced by contributions from the Oenpelli Dolerite, which appears to occur in horizontal locations above Nourlangie Schist more often that above Cahill Formation. Forward modelling indicated that an extensive horizontal dolerite unit with +0.3 t/m^3 density contrast, thickness up to 300 m, and top surface at 0 mAHD could contribute up to 3 mGal to the total response measured at 1300 mAHD.

The reduced amplitude of the positive vertical gravity anomalies interpreted to be associated with the Nourlangie Schist within the Nimbuwah Domain relative to the corresponding north trending anomaly in the Nanambu Domain is thought to reflect partial migmatisation of the Nourlangie Schist as granitic material is introduced, a reduced thickness of Nourlangie Schist, and a sub-horizontal orientation for this unit when viewed at the broadest scale.

The Katherine River Group and Oenpelli Dolerite are interpreted to have had relatively little impact on the vertical gravity data at this regional scale, particularly having upward continued the data to approximately 1 km above the surface.

The presence of the Arafura Basin in the north-east of the project area is thought to be responsible for the gravity low at this location.

3D GEOLOGICAL MAPPING

Several important interpretive decisions were required to supplement the available geological data en route to production of a 3D geological map.

Needham (1988) subdivided the Pine Creek sequence for the present map region into the Nanambu Domain in the west and Nimbuwah Domain in the east. The distinction was principally based on differences in metamorphic grade (upper greenschist and lower amphibolite grades versus upper amphibolite and lower granulite grades) and structural expression (steep folds facing both east and west versus flat west-verging folds). There is general consensus that the Kakadu Group, Cahill Formation and Nourlangie Schist of the Nanambu Domain are also present in the Nimbuwah Domain, but recognition of the stratigraphic boundaries in the latter domain is made difficult by the elevated metamorphic grade and poor outcrop. Critical continuity in surface expression is also lost through a combination of weathering, faulting and the presence of younger cover. Some outcrops in the Nimbuwah domain have been assigned to the Kakadu Group and Cahill Formation, but the bulk of the Pine Creek Orogen basement has generally been classified as Myra Fall Metamorphics or Nimbuwah Complex.

To present a scenario in this mapping project depicting the maximum permissible continuity of primary geological units, areas mapped by Lally and Doyle (2005) as Myra Falls Metamorphics were reassigned to the Cahill Formation or to the Nourlangie Schist. The migmatites and granites of the Nimbuwah Complex were retained as a distinct unit.

The Zamu Dolerite, outcropping in the vicinity of an oval shaped TMI anomaly in the south-west corner of Figure 3 and Figure 4, was omitted from the initial 3D geological map.

A second pluton of Tin Camp Granite was included in the south-east of the map region based on a qualitative interpretation of the vertical gravity low around 360000mE 8590000mN (Figure 2).

Within the Katherine River Group, the Gumarrirnbang Sandstone and Gilruth Volcanic Member were combined into a single unit, as were the Marlgowa Sandstone and McKay Sandstone. Software predictions of the thickness of units within the Katherine River Group based on outcrop boundary traces, surface topography and structural orientation measurements were supplemented by open file information from drillholes within the project area (KUN_01, KUN_03, KUN_04, KUN_07, KUN_09, KBW006, KBW008, KLD003, KLD017, and KLD21) and from 2 deep holes to the south of the project area (DAD_0006 and DAD_0008).

The 3D mapping software can use orientation measurements for planar surfaces on or sub-parallel to mapping unit boundary surfaces to assist in the interpolation of the boundaries. A limited number of bedding-related orientation measurements were available as part of the digital package compiled by Lally and Doyle (2005) and from Cameco sources. Given an incomplete sampling of orientation information and the very real potential for aliasing, the available samples were subjected to careful individual review before being included in the 3D map computations. The measurements for Pine Creek Orogen units generally reflected observations made on local structures that were not representative at the broad scale of the present mapping, and hence these measurements were almost completely discarded. The observations for the gently dipping McArthur Basin sequence were far more representative at the scale of the present mapping. A small number of these measurements were excluded where it was felt that they were affected by drag folding near faults.

There are strong interdependencies between the orientation of shallow dipping units such as the Katherine River Group, the presence of faults that exhibit vertical offset (however small), the outcrop pattern, and the representation of surface topography used in the mapping. Considerable time was spent resolving minor inconsistencies between the outcrop boundaries, orientation data and SRTM topography to prevent unintended geometries being introduced into the 3D geological map.

Numerous sub-horizontal sills of Oenpelli Dolerite are present in both the Pine Creek Orogen and McArthur Basin sequences. They are associated with prominent TMI anomalies due to the presence of strong remanent magnetisation (Table 3). Each individual sill must be very carefully constructed and this task proved insurmountable, at least for the present.

None of the faults shown by Lally and Doyle (2005) have inferred offsets that are significant at the scale of the 3D mapping (e.g., +1 km), and hence it was not necessary to include any faults in the regional 3D geological map.

The results of the initial 3D geological mapping are shown in Figure 5.

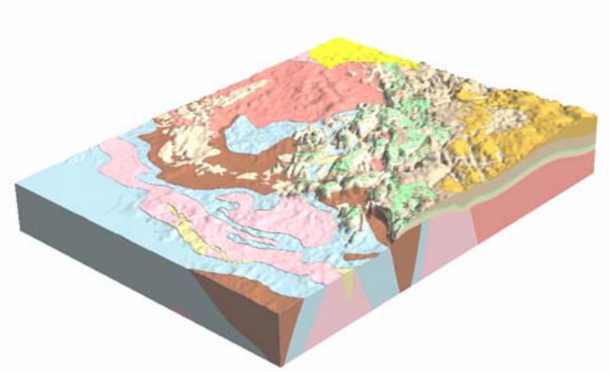

Figure 5. Perspective view of the 3D geological map from above the southwest corner, looking towards the northeast. A vertical exaggeration of 1:20 has been applied.

QUANTITATIVE MODELLING OF POTENTIAL FIELD DATA

Fixed-geometry, bounded least squares property inversion

To evaluate the mass density implications of the geometries in the initial 3D geological map in combination with the observed vertical gravity data, an inversion to recover estimates of the mass density properties was carried out. The vertical gravity response of each of the geological units as represented in the initial 3D geological map was calculated using a density contrast of +1 t/m^3. A bounded least squares procedure was then used to derive the optimal weighted linear combination of these contributions, plus terms representing an unknown sloping regional trend, to match the observed vertical gravity data. This method of solving for the optimal property contrast given the geometry for a number of regions is described by Blakely (1995, pp 223-225, Equation 10.9).

The density contrasts derived with this approach were reviewed together with estimates obtained from hand specimen samples. Where the two estimates were in reasonable agreement, the original value from samples was retained. Where there was a significant discrepancy, revised values were distilled from the two estimates for subsequent use (Table 2). Such adjustments can be justified given the limited, and probably biased, sampling that has been carried out.

Full geometry and property evaluation

The mapping package not only includes facilities to produce 3D geological maps that honour various supplied geological constraints, but also includes tools to simulate the gravity and magnetic response of these maps given supplied rock property information. Procedures are available to explore different geological configurations to discover those that have suitable consistency with the combination of geological constraints, rock property distributions and geophysical observations. An outline of this stochastic variable-geometry litho-inversion procedure is given in Lane et al. (2007). This part of the project is presently in progress with the goal of reporting initial outcomes at the ASEG Conference in Perth, November 2007.

DISCUSSION AND CONCLUSIONS

The construction and evaluation of a 3D geological map of the West Arnhem Land region is being used as a regional-scale trial of the mapping and potential field modelling functions available in the GeoModeller software package. After determining the geological units that could be feasibly represented at the desired mapping scale, the available geological, rock property and geophysical data were gathered and assessed. A mental picture of a general 3D configuration of these units was derived. Geological data were imported from GIS and drillhole data files into the mapping software, 'filtered' according to an assessment of the required detail and the degree to which the observations were representative at the mapping scale, and supplemented by manually inserted interpreted boundary and orientation points to produce an initial 3D geological map. This map was refined by modifying the interpreted data points, re-computing the 3D geological map coefficients, visualising the map on sections and as 3D surfaces, and analysing the resultant 3D architecture. This procedure was applied in iterative fashion until the result was deemed to conform to the conceptual understanding of the 3D geological architecture.

Use of the regional airborne magnetic data was largely restricted to qualitative interpretation during the process of creating the initial 3D geological map. The majority of the features present in these data are associated with relatively narrow units, representing a small proportion of any of the volume of any of the map units in this regional-scale 3D geological map. It was felt that the effort and time required to represent a large number of local sources at the sub-map unit level was not warranted. If quantitative utilisation of the magnetic data was desired, a more effective approach would be to selectively analyse critical subsets of the data to determine parameters such as depth-to-top and orientation for tabular sources, and to utilise this information to refine the 3D geological proposition.

Forward gravity modelling of the 3D geological map was carried out, confirming first order qualitative agreement between the proposed architecture, estimates of the mass density properties derived from limited sampling and the observed vertical gravity data. Quantitative evaluation of the architecture and property values will be carried out using two different inversion methods: (1) a deterministic least squares fixed-geometry inversion method to determine the optimal density values implied by the architecture in the 3D geological map, and (2) a stochastic variable-geometry litho-inversion method to determine the geometrical arrangements for the each of the geological units that would have higher likelihood given the vertical gravity observations and the supplied constraints (i.e., the geometry in the reference 3D geological map, the estimates of the properties, etc.).

ACKNOWLEDGMENTS

The generous support of Cameco Australia Pty Ltd, the Northern Territory Geological Survey (NTGS) and Geoscience Australia (GA) is gratefully acknowledged by the authors. The initial development and commercialisation of GeoModeller mapping and inversion software was a collaborative project between Intrepid Geophysics and BRGM, with support from the Commonwealth, State and Territory geological agencies of Australia, Geological Survey of Namibia, Geological Survey of Canada, Barrick Gold Corporation, and Shell Exploration and Production. The commercialisation project was also supported by International Science Linkages established under the Australian Government's innovation statement, Backing Australia's Ability. Peter Milligan (Geoscience Australia) carried out the processing of the SRTM data used in this work. Lane publishes with the permission of the CEO, Geoscience Australia.

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	"Series"	"Formation"	Relationship	Comment
	Arafura Basin	Wessel Group	Erode	
	Oenpelli Dolerite	Oenpelli Dolerite	Erode	
	Katherine River Group	Marlgowa Sandstone / McKay Sandstone	(Conformable)	
		Gumarrirnbang Sandstone / Gilruth Volcanic Member	(Conformable)	
		Nungbalgarri Volcanics	(Conformable)	
		Mamadawerre Sandstone	Erode	
	Nabarlek Granite	Nabarlek Granite	Erode	
	Tin Camp Granite (1)	Tin Camp Granite (1)	Erode	Mapped Tin Camp Granite pluton.
	Tin Camp Granite (2)	Tin Camp Granite (2)	Erode	Inferred subsurface granite pluton in the southeast of the region.
	Nimbuwah Complex	Nimbuwah Complex	Erode	Excludes ghost vestiges of Cahill Formation and Nourlangie Schist.
	Nourlangie Schist	Nourlangie Schist	Onlap	Includes Mundogie Sandstone, Wildman Siltstone and Koolpin Formation from the Central Domain of the Pine Creek Orogen. Although the Nourlangie Schist was assigned to a separate series that onlaps the Cahill Formation, conformance between the two series was enforced.
	Cahill Formation	Cahill Formation	Erode	Includes interpreted Cahill Formation remnants within mapped Nimbuwah Complex, and Masson Formation from the Central Domain of the Pine Creek Orogen.
	Kakadu Group	Kudjumarndi Quartzite / Mount Howship Gneiss	Onlap	Includes Munmarlarly Quartzite and Mount Basedow Gneiss from the Central Domain of the Pine Creek Orogen.
	Nanambu Complex	Nanambu Complex	N/A	

Table 1. Stratigraphic column listing the 3D geological mapping units. The third column shows the geological relationship assigned for the base of each "series" (i.e., with respect to older units). Functionally, an "erode" relationship is treated the same as an "intrusive" relationship.

	Initial estimates			Revised values		Source	Comments
	Mode 1 %	Mean (t/m^3)	StdDev (t/m^3)	Mean (t/m^3)	StdDev (t/m^3)		
	100	2.55	0.100	2.55	0.100	4	
	100	2.95	0.010	2.95	0.010	3	Some weathered samples excluded.
	100	2.55	0.008	2.55	0.008	3	Only a small number of samples.
	100	2.55	0.008	2.55	0.008	3	Only a small number of samples.
	100	2.68	0.010	2.68	0.010	3	
	100	2.55	0.008	2.55	0.008	3	(1) have Kombolgie Sandstone (now Kombolgie Sub-Group) as 2.63 t/m^3 (StdDev 0.03 t/m^3).
	100	2.63	0.005	2.63	0.005	2	2 Cameco samples have a mean of 2.645 t/m^3. (1) have Cullen Granite as 2.65 t/m^3 (StdDev 0.06 t/m^3).
	100	2.63	0.050	2.58	0.050	3	(1) have Cullen Granite as 2.65 t/m^3 (StdDev 0.06 t/m^3).
	100	2.63	0.050	2.58	0.050	3	(1) have Cullen Granite as 2.65 t/m^3 (StdDev 0.06 t/m^3).
	100	2.67	0.005	2.63	0.005	3	Only 2 samples, and likely to have wide compositional range.
	100	2.73	0.010	2.82	0.010	3	13 Cameco samples have a mean of 2.73 t/m^3 (StdDev 0.06 t/m^3).
	100	2.73	0.006	2.74	0.006	3	(1) have quartz-chlorite schist (Mean 2.75 t/m^3, StdDev 0.12 t/m^3), quartz-muscovite schist (Mean 2.81 t/m^3, StdDev 0.11 t/m^3), and amphibolite (Mean 3.00 t/m^3, StdDev 0.05 t/m^3)
	100	2.73	0.013	2.73	0.013	2	10 Cameco samples have a mean of 2.63 t/m^3 (StdDev 0.02 t/m^3).
	100	2.64	0.005	2.64	0.005	1	1 Cameco sample 2.65 t/m^3.

Table 2. Mass density property values. The rows in this table are in the same order as those of Table 1. Modifications following initial modelling were referenced to the Nanambu Complex value of 2.64 t/m^3 (i.e., the unit with the largest volume in the model). Histogram plots suggested that all distributions were uni-modal normal distributions. Sources: (1) Tucker et al. (1980), (2) Emerson et al. (1993), (3) laboratory measurements on Cameco samples, and (4) estimate from composition.

	Initial estimates						Source
	Mode 1 %	**Mean** (SI x 1e5)	**StdDev** (SI x 1e5)	**Mode 2** %	**Mean** (SI x 1e5)	**StdDev** (SI x 1e5)	
	100	10	3	N/A	N/A	N/A	3
	60	3000	1000	40	100	30	1,2
	100	3	3	N/A	N/A	N/A	1,2
	100	3	3	N/A	N/A	N/A	1,2
	80	100	30	20	3000	1000	1,2
	100	3	3	N/A	N/A	N/A	1,2
	100	300	100	N/A	N/A	N/A	3
	100	10	3	N/A	N/A	N/A	1
	100	10	3	N/A	N/A	N/A	1
	80	30	10	20	3000	1000	2
	100	30	10	N/A	N/A	N/A	2
	95	20	7	5	10000	3000	1,2
	100	10	5	0	N/A	N/A	2
	100	10	3	0	N/A	N/A	3

Table 3. Induced and remanent magnetisation property values. The rows in this table are in the same order as those of Table 1. The ambient magnetic field has amplitude 46210 nT, inclination -39.7 degrees (down positive), and declination 3.9 degrees (east of north). Based on laboratory measurements on 18 Cameco samples, the Oenpelli Dolerite has remanence of 0.6 A/m (StdDev 0.3 A/m), inclination -26 degrees (down positive), and declination 182 degrees (east of north). Histogram plots of susceptibility distributions suggested that several units had bi-modal induced susceptibility distributions, and the proportions and properties of the 2 modes have been separated in the table. Sources: (1) laboratory measurements on Cameco samples, (2) field measurements on Cameco samples, and (3) estimate from composition.