Architecture and evolution of the West Musgrave Province, and implications for mineral prospectivity

Aurore Joly, Alan Aitken, Mike Dentith, TC McCuaig
Centre for Exploration Targeting
University of Western Australia,
CRAWLEY WA 6009
aurore.joly@uwa.edu.au

Alok Porwal
Indian Institute of Technology Bombay,
Powai, Mumbai
aporwal@iitb.ac.in

Hugh Smithies, Ian Tyler
Geological Survey of Western Australia,
Department of Mines and Petroleum,
East Perth, Western Australia 6004
Hugh.SMITHIES@dmp.wa.gov.au

Shane Evans
Moombarriga Geoscience
Subiaco WA 6008
shane@moombarriga.com.au

SUMMARY

The West Musgrave Province preserves a geological history spanning much of the Proterozoic, including two major Grenville-aged orogenic events, ca. 1345-1120 Ma. These were followed by the intraplate Giles Event, ca. 1080-1050 Ma, which is characterised by 1- the voluminous mafic intrusions of the Giles Complex and 2- the deposition of a thick sequence of bimodal volcanic rocks and sedimentary rocks (the Bentley Supergroup). The architecture resulting from these events was subsequently overprinted by later events, the ca. 600-520 Ma Petermann Orogeny, and the ca. 450-350 Ma Alice Springs Orogeny. Here we use aeromagnetic, gravity and magnetotelluric data, constrained by geological mapping and petrophysical data, to characterise the 3D architecture of the region, and to unscramble its structural evolution. Early deformation events are well preserved in places, although they do not permit a robust interpretation of the regional architecture at that time. The architecture of the Giles Event is extremely well preserved, and a complex polyphase history is conserved. A series of discrete to semi-continuous deformation events is recorded, with a dominant ESE-WNW trend supplemented by additional NE-SW and N-S trends, each of which was active at several times during the event. Later events are manifested primarily as reactivations of earlier structures. Using this architectural framework along with a variety of other spatial datasets (geology, geochemistry etc) GIS-based prospectivity analysis was applied using a mineral systems approach, targeting Ni, Cu, PGEs and orogenic gold. The conceptual method used compares spatial distributions of various targeting criteria, represented by predictor maps. Each predictor map is then related to metal source, fluid pathways, and chemical and physical trap zones. The output prospectivity maps are used as decision-support tools for exploration and reinforce the idea that the area is highly prospective for magmatic nickel-copper and PGE's deposits.

Key words: Aeromagnetic, gravity, magnetotelluric, 3D architecture, GIS-based prospectivity analysis, West Musgrave Province.

INTRODUCTION

Funded by the Western Australian Government's Exploration Incentives Scheme, exploration targeting products on different unexplored terrains of Western Australia are provided by the Centre for Exploration Targeting at the University of Western Australia. Products to be produced include a study of the architecture of greenfields terrains based on an integration of geological and geophysical data; a mineral system analysis of selected commodities, and the creation of a series of exploration targeting products. One of the studied areas to be analysed in this fashion is the West Musgrave Province (WMP, Fig. 1).

For this study, magnetotelluric, gravity and magnetic potential field data were used to understand the structure of the WMP. These new results allow definition of the geometry of major faults in three dimensions; with a particular focus on deep-penetrating structures which are considered important components of mineralising systems because of their ability to focus the flow of magmas and hydrothermal brines. By unravelling the structural evolution of the WMP, it becomes possible to recognize the most prospective structures for each mineralisation type. From these, prospectivity can be characterised throughout the area.

There is now sufficient understanding of the geology of the WMP to allow a quantitative assessment of its prospectivity. The application of fuzzy logic in a GIS framework is a valuable method to assist in mineral prospectivity assessments. The multi-commodity study in this document uses various integrated datasets: geological, structural, geophysical, geochemical. Together they function as a "spatial attribute relational data model" that provides evidence, in the form of predictor maps, to estimate mineral potential according to the mineral system approach. This knowledge-based fuzzy method is shown to be valuable to minimize some aspects of how explorers determine mineral potential for a region using various integrated datasets. Prospectivity analysis has been undertaken for the WMP for the seven following types of mineral deposit: magmatic nickel-copper-PGE, orogenic and intrusive gold, iron oxide copper gold (IOCG), granite-hosted tin-tungsten and surficial uranium. For brevity, only the magmatic nickel-copper-PGE mineral system is presented here.

OVERVIEW OF THE WMP GEOLOGY

The WMP (Fig. 1) consists of Mesoproterozoic high-grade basement lithologic units with protolith SHRIMP U-Pb zircon ages between ca. 1400 and ca. 1150 Ma (Camacho and Fanning, 1995; Smithies et al., 2010) which host the latest Mesoproterozoic Giles Complex mafic intrusions, and associated granitic intrusions and supracrustal volcanic/sedimentary sequences (The Warakurna Supersuite).

The Province has a long and complex tectonic history involving multiple tectonic and magmatic events. The most important event being the 1080-1050 Ma Giles event during which Nebo-Babel Ni-Cu-PGE deposit emplaced. The Giles Event (Daniels, 1974; Ballhaus and Glikson, 1989, 1995) began with deposition of the Kurnmarnara Group (Fig. 1b), consisting of basalts and conglomerates, onto the basement rocks. This was followed by the emplacement of layered Giles Complex intrusions (Giles 1, e.g. Jameson Intrusion, Fig. 2b) into the Kurnmarnara Group, before Giles 2 intrusions (e.g. Hinckley Gabbro, Fig. 2b) were intruded shortly after (Evins et al., 2010). Following the emplacement of these plutons, a period of erosion saw them brought to the surface, before the deposition of the upper parts of the Bentley Supergroup (e.g. Tollu Group,), a ~10km thick sequence of bimodal volcanics and associated sedimentary units. Alcurra dykes were emplaced throughout the later stages of the Giles event.

The Petermann Orogeny, ca. 600-520 Ma affected the Musgrave province, and is characterised by two distinct styles of deformation. The northern Musgrave Province was widely affected by the development of major low-angle thrust faults, and nappe-style folding, which involved both the granitic basement and overlying sedimentary rocks of the Tjauwata Group and Amadeus Basin (Edgoose et al., 2004). To the south, deformation was characterised by the development of an anastomosing network of transpressional shear zones, several of which penetrate the Moho (Aitken et al., 2009).

The Alice Springs Orogeny took place between 450-300 Ma and, in the Musgrave province, is characterised by S-directed thrusting at the southern margin, as indicated by a monoclinal upturn of Ordovician sedimentary strata within the Officer basin (Lindsay and Leven, 1996).

AEROMAGNETIC INTERPRETATION OF THE WMP

Domain definition and characterisation

The method used calls for structurally distinct domains to be identified, within which a common evolution is likely. The interpreted region was divided into 18 domains, each with different magnetic character from its neighbours. Most are bound by major shear zones, which typically show activity late in the Province's evolution, but often with a likely earlier history. These domains are essentially subdivisions of the major tectonic zones identified in previous work (Smithies et al., 2008)

These domains were then structurally interpreted on an individual basis, using a method akin to form-surface mapping in structural geology. A key aim was to define magnetic form-lines for early structures. Later generations of structure could then be inferred from the deformation of these. Additional indications of structure included increased or reduced magnetisation associated with shear zones, and also intrusive and sedimentary contacts and dykes.

From this mapping, a local sequence of deformation events was identified within each domain. These were linked into the stratigraphy on the basis of local overprinting relationships with mapped geology.

Results

The structural analysis shows that the structural architecture of the West Musgrave Province is dominated by the ca. 1080-1050 Ma Giles Event; although earlier events are well preserved in places and later events have exerted a substantial influence on the present architecture. Early deformation events relate to the ca. 1345-1293 Ma Mt West Orogeny, and the ca. 1220 -1150 Ma Musgravian Orogeny. Preserved structures of the subduction-related Mt West Orogeny are of variable orientation and uncertain kinematics. Structures from the Musgravian Orogeny are dominantly contractional and commonly NE-trending, and are interpreted to represent continued deformation in an intraplate setting. Together, these orogens likely record the convergence of the South Australian Craton with the West Australian and North Australian Craton, as part of a broader orogenic belt encompassing much of central Australia (e.g. Aitken and Betts, 2008).

The Giles Event records intraplate deformation and magmatism. This event is divided into a number of sub-events on the basis of relative chronology, although these events occurred over a short period of time, and represent a near-continuous deformational evolution. Thus, overlap between events is commonly observed, nevertheless, the general progression of this event is captured:

1. Early Giles Event (EGE) deformation is synchronous with the emplacement of the Giles Complex mafic plutons. This deformation is characterised by the development of a metamorphic foliation and folding in the Kunmarnara Group and the generation of syn-magmatic deformation within and surrounding Giles Complex plutons. These are followed by the development of a fairly localised event characterised by NNW trending shear zones in the Hinckley and Murray Ranges (Fig. 1). Existing vanadium-titanium mineral occurences within the upper parts of the Jameson intrusion show a clear link to EGE structures.

2. Middle Giles Event deformation is characterised by ~E-W oriented close folding and reverse faulting of the Giles Complex plutons and Tollu Group volcanics. This event represents shortening under N-S compression. Other areas record events of similar age, but different orientation and style, and it is unclear if these are related.

3. Late Giles Event (LGE, Fig. 2a) deformation is characterised by three major events. The first involves an array of NE oriented normal shear zones, the second involves another array of shear zones, this time oriented ESE and typically with dextral-normal shear sense. The third is characterised by N-S trending shear zones, often associated with co-located Alcurra dykes. These N-S shear zones commonly show limited apparent offsets with sinistral shear sense, and may be transtensional (Seat et al., 2007). The kinematics of these Late Giles shear zones may indicate a stress field initially characterised by NW-SE tension during LGE1, with a subsequent switch to NE-SW tension during

LGE2 and LGE3. Late Giles-Event structures are associated with many mineral occurrences, including the Nebo-Babel deposit, and the Halleys and Tollu Prospects (Fig. 2b).

Later, several deformation events resulted from the Petermann Orogeny, characterised by North-South shortening, resulting in east-trending folds and thrusts (e.g. Woodroffe Thrust, Fig. 1a), and transpressional shear zones of a variety of orientations, although an anastomosing network of east-south-east trending shear zones dominate for which dextral shear sense is dominant. Thrusting at the southern province margin and north-trending structures within the province are interpreted to represent the Alice-Springs Orogeny.

NICKEL- COPPER PROSPECTIVITY ANALYSIS

Methods

GIS-based prospectivity analysis was used to identify the most prospective ground for Nickel-Copper deposits in WMP. A knowledge-driven fuzzy model (Porwal et al., 2003) was implemented. This approach is essentially based on empirical mathematical models which compare the spatial distributions of various targeting criteria (represented by predictor maps). The targeting criteria are based on a mineral systems model for deposit formation and the approach used involves creation of a series of predictor maps based on the occurrence of geological features associated with the relevant model for deposit formation (Wyborn et al., 1994).

The WMP contains all the ingredients required to form magmatic nickel-copper deposits, as is confirmed by the presence of Nebo-Babel deposit which highlights the potential for Noril'sk-style mineralization associated with the Warakurna Large Igneous Province. Factors favourable for the formation of such deposits are: 1) Primitive, mantle-derived, differentiated, Mg rich rocks (such as ultramafic and mafic rocks) as a main source; 2) Magma flow focused and locally enhanced by shifting compressive–extensional tectonic regimes that permit fluid migration; 3) Nickel physical traps into which the mineralising fluids are focused. Dilatational zones of high, fracture-related permeability constitute potential trap sites; 4) Nickel and copper content indicative of chemical traps as well as abundant S-rich crustal rocks that can provide an external S source that is required for the majority of deposit's sulphur.

Results

The final GIS model map (Fig. 3) infers 16 clusters, marked by [α], [β], [χ], [δ], [ε], [ϕ], [γ], [η], [ι], [φ], [κ], [λ], [μ], [ν], [o] and [π]. These 16 areas have a high fuzzy PRODUCT value varying from 0.239 to 0.264. Interestingly, most of the 16 clusters do not correspond to the nickel deposits. Most of the known nickel deposits (Fig. 3) are located in areas of high to middle fuzzy PRODUCT value (0.238-0.16).

Figures

Figure 1. a. Regional geological sketch of the Musgrave Complex (Modified by Smithies et al., 2008 from Glikson et al., 1996 and Edgoose et al., 2004). b. Interpreted bedrock geology map of the eastern portion of the WMP (Smithies et al., 2008).

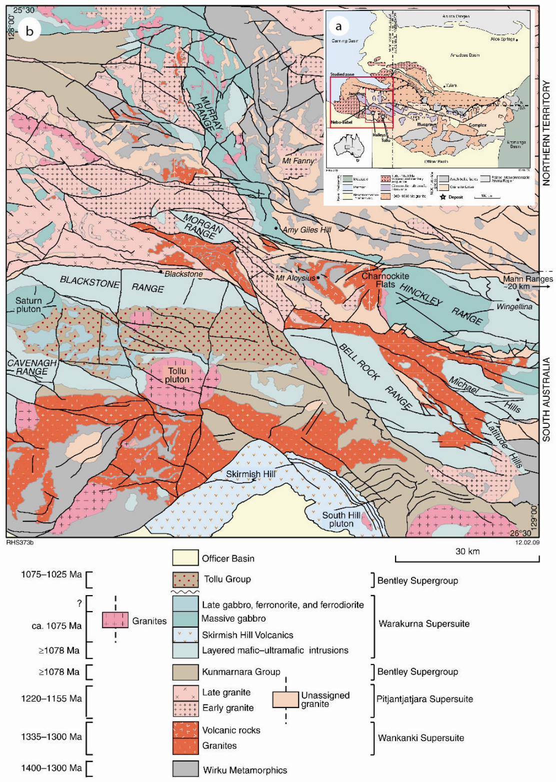
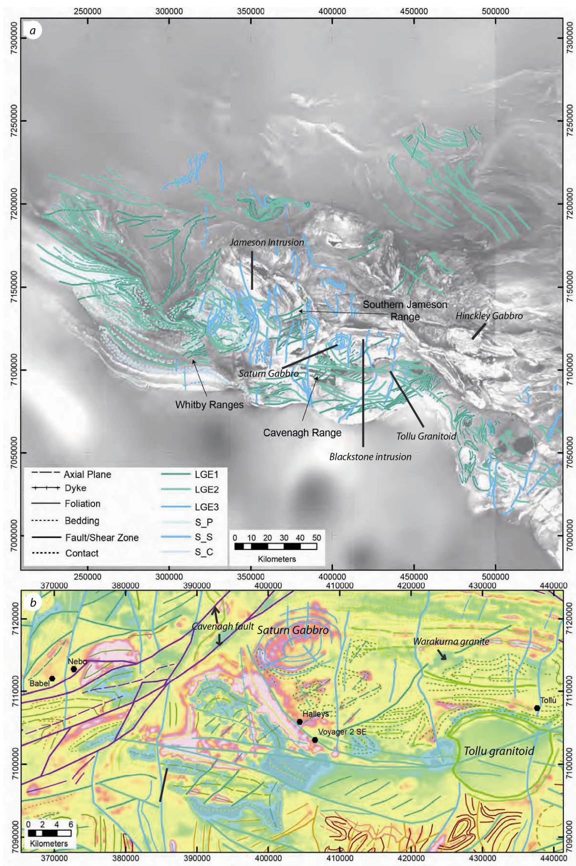


Figure 2. Magnetic interpretation maps with a) Structures of the Late Giles Event. This figure shows the distribution of structures attributed to the Late Giles Event, and its key locality – the Cavenagh-Blackstone region and b) This Cavenagh-Blackstone region show in more detail the many structures of the late Giles Event, including the Cavenagh



Fault, and smaller NE trending LGE1 structures, one cut by a Warakurna granite. The ESE trending LGE2 shear zones cut the LGE1 fabrics, and the conjugate dykes in the Cavenagh Intrusion may provide a key constraint on the stress field during this deformation event. Several N-trending LGE3 shear zones cross the area. Each of these events is likely associated with mineralisation, i.e. LGE1 – Nebo-Babel, LGE2 – Halleys, Voyager, LGE3-Tollu.

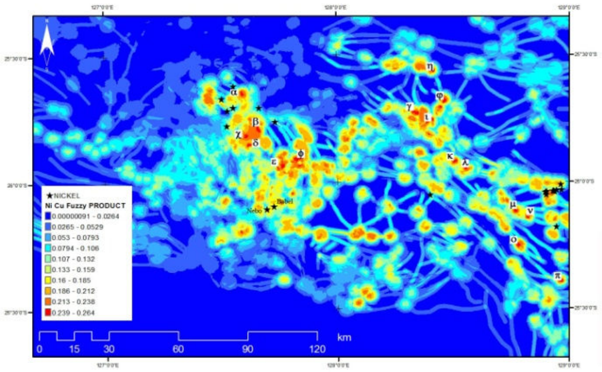


Figure 3. Fuzzy prospectivity model for magmatic Ni-Cu mineral system.

CONCLUSIONS

The WMP is an area with a highly complex architecture. However, high quality geophysical and geological interpretation allows geological and structural entities that are significant for exploration to be identified, and by placing the entire analysis in a mineral systems framework, it is possible to identify and demarcate areas that have the greatest prospectivity. The GIS-based fuzzy prospectivity products are not expected to show the locations of the deposits themselves. Rather, they are intended to be tools to assist in exploration strategy development and decision making by illustrating the spatial variation in geological favourability for each type of deposit, within the constraints of the assumptions about the local geology and the way these deposits form.

ACKNOWLEDGMENTS

This study described here was funded by the Geological survey of Western Australia as part of the Western Australian Governments Exploration Incentives Scheme. Our work on the West Musgrave Province has benefited from the open discussions with GSWA and the CET team.

REFERENCES

Aitken A. R. A., Betts P. G., 2008. High-resolution aeromagnetic data over central Australia assist Grenville-era (1300–1100 Ma) Rodinia reconstructions. Geophysical Research Letters 2008;35:L01306. doi:10.1029/2007GL031563.

Aitken, A.R.A., Betts, P.G. and Ailleres, L., 2009. The architecture, kinematics, and lithospheric processes of a compressional intraplate orogen occurring under Gondwana assembly: The Petermann orogeny, central Australia. Lithosphere, 1, 6, 343-357.

Ballhaus, C. and Glikson, A.Y., 1989, Magma mixing and intraplutonic quenching in the Wingellina Hills intrusion, Giles Complex, Central Australia: Journal of Petrology, 30, 1443–1469.

Ballhaus, C. and Glikson, A.Y., 1995, The petrology of layered mafic-ultramafic intrusions of the Giles Complex, western Musgrave block, central Australia: Australian Geological Survey Organisation, 16, 69–89.

Camacho, A. and Fanning, C.M., 1995, Some isotopic constraints on the evolution of the granulite and amphibolite terranes in the eastern Musgrave block, central Australia: Precambrian Research, 71, 155–181.

Edgoose, C.J., Scrimgeour, I.R. and Close, D.F., 2004, Geology of the Musgrave Block, Northern Territory, NTGS.

Evins, P.M., Smithies, R.H., Howard, H.M., Kirkland, C.L., Wingate, M.T.D. and Bodorkos, S., 2010, Devil in the detail: The 1150-1000 Ma magmatic and structural evolution of the Ngaanyatjarra rift, west Musgrave province, Central Australia: Precambrian Research.

Glikson, A.Y., Stewart, A.T., Ballhaus, G.L., Clarke, G.L., Feeken, E.H.T., Leven, J.H., Sheraton, J.W., Sun, S.-S., 1996, Geology of the western Musgrave Block, central Australia, with reference to the mafic–ultramafic Giles Complex. AGSO Bull 239:206.

Lambeck, K. and Burgess, G., 1992, Deep crustal structure of the Musgrave Block, central Australia: results from teleseismic travel time anomalies. AJES, 39, 1, 1-19.

Lindsay, J.F. and Leven, J.H., 1996, Evolution of a Neoproterozoic to Palaeozoic intracratonic setting, Officer Basin, South Australia. Basin Research, 8, 403-424.

Seat Z., Beresford S.W., Grguric B.A., Waugh R.S., Hronsky J.M.A., Gee M.A., Groves D.I. and Mathison, C.I. 2007, Architecture and emplacement of the world-class Nebo-Babel gabbronorite-hosted magmatic Ni–Cu–PGE system, West Musgrave, WA. Mineral. Dept.,42, 551–582.

Smithies, H.R., Evins, P. and Howard, H.M., 2008, Myths and mylonites: Some new perpectives on the Proterozoic evolution of the West Musgrave Complex [abs.]: GSWA, Record 2008/2, p. 3.

Smithies, R. H., Howard, H. M., Evins, P. M., Kirkland, C. L., Kelsey, D. E., Hand, M., Wingate, M. T. D., Collins, A. S., Belousova E., Allchurch S., 2010, Geochemistry, geochronology and petrogenesis of Mesoproterozoic felsic rocks in the western Musgrave Province of central Australia, and implication for the Mesoproterozoic tectonic evolution of the region; GSWA, Report. 106, p. 73.

Porwal, A., Carranza, E.J.M. and Hale, M., 2003, Artificial neural networks for mineral potential mapping: a case study from Aravalli Province, western India. Natural Resources Research, 12, 3, 155-177, ISSN 15207439.

Wyborn, L.A.I., Heinrich, C.A., and Jaques, A.L., 1994, Australian Proterozoic mineral systems: essential ingredients and mappable criteria [abs.], in Hallenstein, P.C., ed., Australian Mining Looks North – the Challenges and Choices: Australian Institute of Mining and Metallurgy Publication Series, 5, 109-115.