



Government of Western Australia  
Department of Mines and Petroleum

RECORD 2014/2

# GSWA 2014 EXTENDED ABSTRACTS

## Promoting the prospectivity of Western Australia



Geological Survey of Western Australia



Government of **Western Australia**  
Department of **Mines and Petroleum**

**Record 2014/2**

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## **Promoting the prospectivity of Western Australia**

**February 2014**

**Perth 2014**



**Geological Survey of  
Western Australia**



**MINISTER FOR MINES AND PETROLEUM**  
**Hon. Bill Marmion MLA**

**DIRECTOR GENERAL, DEPARTMENT OF MINES AND PETROLEUM**  
**Richard Sellers**

**EXECUTIVE DIRECTOR, GEOLOGICAL SURVEY OF WESTERN AUSTRALIA**  
**Rick Rogerson**

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Information Centre  
Department of Mines and Petroleum  
100 Plain Street  
EAST PERTH WESTERN AUSTRALIA 6004  
Telephone: +61 8 9222 3459 Facsimile: +61 8 9222 3444  
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## GSWA Seminar Program — 22 February 2013, Fremantle

8.15 – 8.45 REGISTRATION

8.45 – 9.00 Welcome and opening remarks

*Hon. Bill Marmion MLA,  
Minister for Mines and Petroleum*

### **SESSION 1 Chair – Rick Rogerson**

9.00 – 9.35 The Exploration Incentive Scheme: achievements and future directions  
(no abstract)

*Ian Tyler*

9.35 – 10.00 Collaborative scientific drilling at Hickman Crater



*Peter Haines*

**Morning tea 10.00 – 11.00 in the display area**

### **SESSION 2 Chair – Don Flint**

11.00 – 11.25 GSWA's mineral systems research — helping to discover tomorrow's resources

*Trevor Beardsmore*

11.25 – 11.50 Volcanogenic massive sulfide mineralization at Weld Range: a comparison with Golden Grove

*Joshua Guilliame*

11.50 – 12.15 Crustal architecture of the Youanmi Terrane, Yilgarn Craton: preliminary data and new ideas

*Ivan Zibra*

**Lunch 12.15 – 1.35**

### **SESSION 3 Chair – Ian Tyler**

1.35 – 2.00 Steps towards explaining the heterogeneous distribution of BIF-hosted iron ore deposits in the Yilgarn Craton



*Paul Duuring  
(CET, UWA)*

2.00 – 2.25 Regional applications of low-density geochemical data to mineral exploration — the National Geochemical Survey of Australia

*Andreas Scheib*

2.25 – 2.50 Greenfields exploration in the Albany–Fraser Orogen and on the southeast Yilgarn cratonic margin



*Ignacio González-Álvarez  
(CSIRO)*

**Afternoon tea 2.50 – 3.15 in the display area**

### **SESSION 4 Chair – Margaret Ellis**

3.15 – 3.40 A magnetotelluric survey across the Kimberley Craton, northern Western Australia

*Mike Dentith (CET, UWA)*

3.40 – 4.05 Crustal structure and mineral prospectivity of the west Kimberley



*Mark Lindsay (CET, UWA)*

4.05 – 4.30 Shake, rattle and gold

*Simon Johnson*

**Sundowner 4.30 – 5.30**

## Collaborative scientific drilling at Hickman Crater

by

PW Haines

Hickman Crater lies in the Hamersley Range, about 36 km north-northwest of Newman, on a contact between early Paleoproterozoic Woongarra Rhyolite and overlying Boolgeeda Iron Formation. It has a partially eroded circular rim about 260 m in diameter that rises up to 30 m above a flat circular floor (Fig. 1). The crater was first noticed on Google Earth imagery by Geological Survey of Western Australia (GSWA) geologist Arthur Hickman in 2007. Following preliminary ground observations consistent with an impact origin, the site was named Hickman Crater by Andrew Glikson (Australian National University) in recognition of Hickman's initial discovery, and his achievements in the geological investigation of

the Pilbara Craton over a period of 35 years (Glikson et al., 2008). Despite morphological and structural features typical of simple (i.e. bowl-shaped and lacking central uplift) impact craters, and the presence of surrounding breccia interpreted as impact ejecta, the early studies did not find unequivocal evidence of an impact origin — such as physical or geochemical traces of the projectile or conclusive shock metamorphism (Glikson et al., 2008). This is not surprising because in small simple craters the critical evidence commonly lies within the shattered crater basement and overlying lens of impact breccia (French, 1998; French and Koeberl, 2010). Both are subsequently buried by crater-filling sediments, so that



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**Figure 1.** Diamond drill rig on the central crater floor viewed from the south rim of Hickman Crater



drilling is often the only way to recover samples. For example, after a century of debate the impact origin of the approximately one km-diameter Tswaing Crater (Pretoria Saltpan) in South Africa was only confirmed after drilling to provide petrographic and geochemical samples of the impact breccia and basement (Reimold et al., 1992). In the case of Hickman Crater, a pre-existing creek broke through the northern crater rim at some time after the crater's formation, thereby accelerating the crater-filling process. Preliminary age estimates range from a few tens of thousands up to 100 000 years (Glikson et al., 2008), thus recovery of unoxidized meteoritic material at surface is unlikely.

## Drilling

In late 2012 Hickman Crater was diamond cored from surface in a collaborative project between Atlas Iron Ltd, which holds an exploration licence over the area, and GSWA (Fig. 1). The vertical hole was sited in the centre of the flat crater floor and reached a total depth of 64.7 m. The unconsolidated sediments and breccia, and intensely fractured basement presented challenging drilling conditions, but slow drilling and short core runs using triple-tube methods and large diameter core achieved good recovery for most of the hole. The only comparable drilling of a small suspected impact crater in Australia is that of the roughly 1.2 km-diameter Darwin Crater in Tasmania, which was drilled in 1975 and 1983, but this failed to conclusively demonstrate an impact origin (Howard and Haines, 2007). From a comparison with the new Hickman Crater core the deepest Darwin Crater core may have stopped in a post-impact mass-wasting boulder deposit above potentially impact-diagnostic lithologies.

## Core stratigraphy

The Hickman Crater drillhole intersected the full sequence of units expected for a simple impact crater (Figs 2, 3). The succession from surface to 48.4 m consists of red-brown clay, sand and gravel, representing crater-fill sediment, interspersed with large boulders of rhyolite and banded iron-formation (BIF) near the base. Apart from the gravel interbeds, the sediment is clay-dominated in

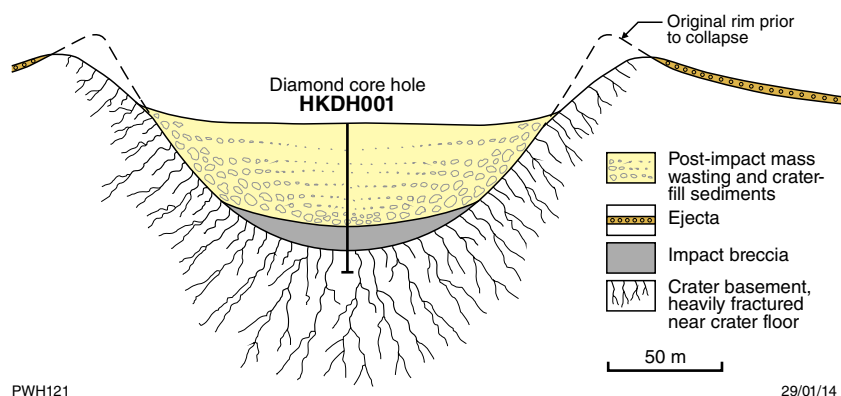
the lower part of the crater-fill succession (from 48.4 m to about 30 m), but comprises fine clayey sand above about 30 m. This change coincides with a significant increase in the magnetic susceptibility of the sediment above 30 m (Fig. 3) and likely marks the transition from an isolated (perhaps ephemeral) crater lake, to a stream-fed lake after stream breakthrough of the northwest crater rim. The higher magnetic susceptibility likely represents the introduction of stream sediment carrying soil-derived maghemite. The magnetic susceptibility of this upper succession is comparable to modern red soils around the crater and on the crater floor, each of which gives much higher susceptibility values than outcropping rhyolite or BIF. Large boulders of rhyolite and BIF near the base of the lower interval probably tumbled down to the topographically lowest centre of the crater from the initially very steep and unstable rim early in the crater's history.

The interval from 48.4 to 55.1 m consists of very poorly sorted angular fragments of altered rhyolite and minor BIF interspersed with small fragments of highly vesicular and commonly clast-rich glassy melt rock typical of a type of proximal impact breccia termed suevite. The remainder of the hole from 55.1 to 64.7 m intersected strongly fractured and altered Woongarra Rhyolite, interpreted as in situ crater basement. The alteration of the rhyolite in the basement and impact breccia, compared to the relatively fresh rhyolite in some unfractured boulders above the impact breccia, is attributed to the weathering action of groundwater penetrating fractures and breccia porosity.

## Geochemistry, petrography and discussion

Samples from the core and surface materials are currently being analysed by GSWA and the Western Australian Museum. Fresh, clast-free glass fragments have been hand-picked from the breccia and submitted for  $^{40}\text{Ar}/^{39}\text{Ar}$  dating at the John De Laeter Centre for Isotope Research.

Geochemical analysis of six samples spaced through the melt-bearing breccia show a pronounced enrichment in Ni, Co, Au and platinum group elements (PGE) compared with samples of rhyolite and BIF from the



**Figure 2.** Interpreted cross section through Hickman Crater and the drillhole (no vertical exaggeration)



## HKDH001 Hickman Crater summary log

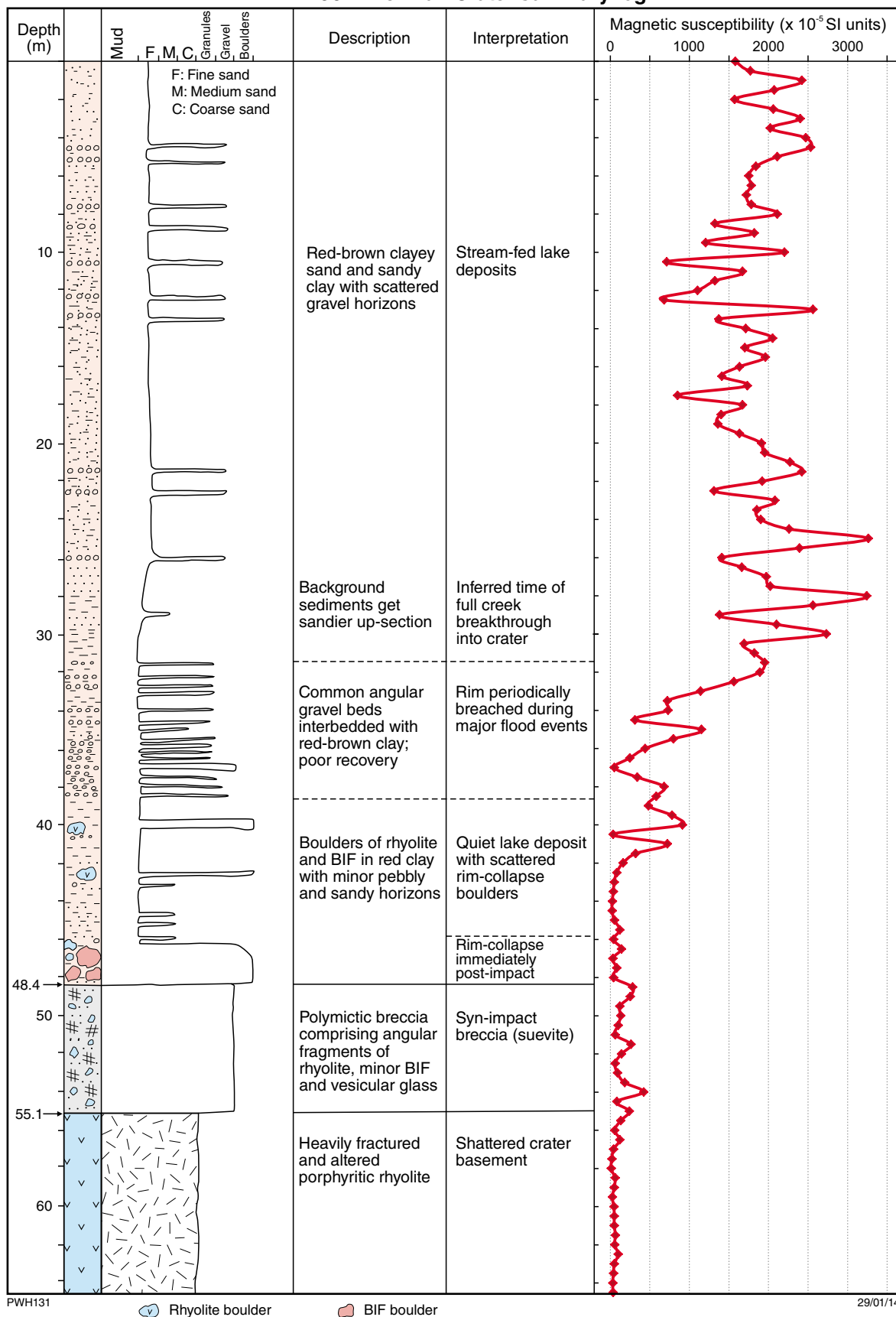


Figure 3. Lithological log of the Hickman Crater drillcore with basic descriptions, interpretations and magnetic susceptibility data (average spacing 0.5 m)

crater basement and boulders above the breccia, and with crater-fill clay and sand. Most notably, the enrichment in Ni, 295–2381 ppm, peaks about three orders of magnitude above background levels in Woongarra Rhyolite (<3 ppm, based on regional geochemical data; Trendall, 1995). Iridium ranges between 9 and 85 ppb in the same samples, but is below the 1 ppb detection limit in all samples outside the melt-bearing breccia (typical continental crust averages about 0.022 ppb Ir; Koeberl, 2007). PGE inter-element ratios are much closer to those in meteorites than to those in continental crust. The enriched elements behave in a coherent way through the impact breccia, with maximum enrichment near the base, proportionally decreasing towards the top, with the exception of one sample. The geochemical results indicate significant contamination of the breccia by disseminated meteoritic material, confirming an impact origin. The Ni abundance is consistent with an iron meteorite projectile (irons average about 8% Ni by weight; Buchwald, 1975). Iron projectiles are the most common type to produce small simple craters, even though chondrites are much more common among meteorite falls; chondrites and other stony projectiles of this size range typically disintegrate in an atmospheric airburst (French, 1998; Collins et al., 2005). Preliminary calculations suggest a meteoritic contribution to the impact breccia of 0.4 – 3 wt%, assuming an iron projectile with an average Ni content and minimal post-impact Ni mobilization. The meteoritic content of the breccia is unusually high; meteoritic contamination in impact breccias is usually well below 1% by weight (Koeberl, 2007). A possible explanation involves significant atmospheric slowing of the relatively small projectile, which Glikson et al. (2008) estimated at about 10 m diameter. In larger and more energetic impacts, where the projectile retains most of its cosmic velocity, the majority of the projectile is vapourized, and only a very small component is retained in the crater rocks.

A sample of shattered rhyolite basement 10 cm beneath the impact breccia shows a weak enrichment in some of the above elements (although some PGE were below detection), using an analysis of the centre of a fresh unfractured (and presumably uncontaminated) rhyolite boulder above the impact breccia as a proxy for unaltered basement. This is consistent with the injection of a small meteoritic component into the basement at the instant of impact, or minor post-impact mobility of enriched elements downward from the impact breccia.

Quartz and other mineral grains in the crater basement and breccia show intense irregular and sub-planar fracturing, but lack the optically distinct planar deformation features (PDFs) that are diagnostic of shock metamorphism in larger, more energetic impact craters. Such planar deformation features in quartz start to form at shock pressures of around 10 GPa (French, 1998). The absence of PDFs may constitute further evidence for significant deceleration of the projectile by atmospheric drag, potentially reducing shock pressures on impact to below this critical level.

## Summary

Hickman Crater drillcore reveals the typical succession expected of a relatively small simple impact crater. Although no definitive shock metamorphism was observed, the melt-bearing breccia shows strong enrichment in Ni, Co, Au and PGE with respect to the basement and infilling sediments. PGE inter-element ratios in the breccia are much more like those in meteorites than average continental crust, confirming a significant meteoritic component and hence an impact origin for the crater. The particularly high Ni content is consistent with an iron meteorite projectile, the most common projectile type in such small craters. The lack of shock metamorphism and unusually high meteoritic component of the breccia may be explained by significant atmospheric deceleration of a relatively small projectile prior to impact. Drilling of the Hickman Crater represents the first scientific drilling of a simple impact crater of this size (<1 km) in Australia, and one of very few worldwide.

## References

- Buchwald, VF 1975, *The handbook of iron meteorites*, volume 1, iron meteorites in general: University of California Press, Berkeley and Los Angeles, 243p.
- Collins, GS, Melosh, HJ and Marcus, RA 2005, *Earth impact effects program: A web-based computer program for calculating the regional environmental consequences of a meteoroid impact on Earth: Meteoritics & Planetary Science*, v 40, p. 817–840.
- French, BM 1998, *Traces of Catastrophe: Lunar and Planetary Institute*, Houston, 120p.
- French, BM and Koeberl, C 2010, The convincing identification of terrestrial meteorite impact structures: what works, what doesn't, and why: *Earth-Science Reviews*, v. 98, p. 123–170.
- Glikson, AY, Hickman, AH and Vickers J 2008, Hickman Crater, Ophthalmia Range, Western Australia: evidence supporting a meteorite impact origin: *Australian Journal of Earth Sciences*, v. 55, p. 1107–1117.
- Howard, KT and Haines, PW 2007, The geology of Darwin Crater, western Tasmania, Australia: *Earth and Planetary Science Letters*, v. 260, p. 328–339.
- Koeberl, C 2007, The geochemistry and cosmochemistry of impacts, in *Treatise of Geochemistry*, online edition, Volume 1: Meteorites, Comets, and Planets *edited by* A Davis: Elsevier, p. 1.28.1–1.28.52.
- Reimold, WU, Koeberl, C, Partridge, TC and Kerr, SJ 1992, Pretoria Saltpan crater: impact origin confirmed: *Geology*, v. 20, p. 1079–1082.
- Trendall, AF 1995, *The Woongarra Rhyolite — a giant lavalike felsic sheet in the Hamersley Basin of Western Australia: Geological Survey of Western Australia, Report 42*, 70p.

## GSWA's mineral systems research — helping to discover tomorrow's resources

by

TJ Beardsmore

### An inconvenient truth

The State Government recognizes that the mineral resources sector is a significant contributor to the Western Australian economy and that to ensure its long-term sustainability requires the continuing discovery and development of new mineral resources.

This is a challenge. Many currently operating mines will close within the next two decades, yet discovery rates for significant ore bodies are declining, development and operating costs are rising, and there are long lead times between discovery and mining (Schodde, 2012). Despite this, two thirds of exploration expenditure in Western Australia in 2012–13 was directed to brownfields regions with long exploration and mining histories, even though new world-class ('company-maker') ore bodies capable of supporting stand-alone mining operations are more likely to be found in greenfields regions, and probably beneath significant cover.

Greater technical and financial risks (reduced likelihood or increased cost of discovery) attend mineral exploration in greenfields regions, because explorers commonly lack the data, knowledge and tools for effective area selection, target generation and testing in such environments. It is up to the Geological Survey of Western Australia (GSWA) to provide fundamental geoscientific information and knowledge that mitigate risk, and thus encourage companies to invest scarce exploration capital in Western Australia.

### Reducing risk — the GSWA tradition

GSWA's contribution to exploration-risk reduction has typically been to improve perceptions of resource prospectivity by providing a better understanding of the State's geology and mineral endowment. Early ad hoc geological mapping and mineral commodity audits yielded to systematic, State-wide geological and mineral endowment mapping in the 1960s — influenced by the vision of then-Director Joe Lord, the newly available systematic stereoscopic aerial photography, the emergence of the plate tectonic paradigm, and the onset of the nickel boom. The first generation of 1:250 000-scale maps and associated products, completed in the 1980s, provided the first coherent overview of the State's geology and mineral

inventory, and the first models for the tectonic evolution of Western Australia's terranes, thereby fundamentally improving the ability of mineral explorers to carry out meaningful prospectivity analyses and generate targets.

This approach continued unchanged into the early 2000s, albeit becoming increasingly sophisticated with more-detailed 1:100 000-scale geological mapping in selected well-exposed or mineralized terranes (eastern Yilgarn Craton, Pilbara Craton, and east Kimberley), supported by satellite imagery, regional airborne magnetic and radiometric data, more accurate and precise geochemical analyses, and IT developments that provided geoscientific data in digital formats.

### Opportunity — with a change of pace

The State Government recognizes that a new generation of geoscience information is required to counter brownfields-dominant exploration spending. Thus was born the Exploration Incentive Scheme (EIS). EIS has provided an additional A\$101 million to GSWA between early 2009 and mid-2014 to encourage mineral explorers to venture into under-explored, higher risk, but potentially higher reward parts of the State. A further \$10 million per year is allocated to EIS initiatives for the next three years. This includes \$5 million per year to continue the co-funded drilling program, which is providing a wealth of new geological information from drillcore and open-file reports. Funding also supports geoscience data acquisition, and development of new techniques for regional prospectivity analysis and target generation.

EIS has funded the following projects:

- Completion of State-wide airborne magnetic and radiometric coverage to better than 400 m-line spacing
- Collection of regional, high-resolution (2.5 km-station spacing) ground-based gravity data for 25% of the State
- Purchase of State-wide ASTER imagery
- Execution of seismic-reflection and magnetotelluric surveys across significant crustal terrane boundaries
- Targeted stratigraphic drilling into basement under the Eucla Basin

- One of the world's largest airborne EM surveys (over the Capricorn Orogen).

EIS also supports whole-rock, mineral, major and trace element, stable and radiogenic isotope geochemistry for constituent country rocks and mineralization. Such information is now informing realistic interpretations of whole-of-crust architecture, is delineating important, mantle-tapping structures that may have influenced mineral deposit formation, and is constraining time-integrated petrogenetic, metallogenic, and geodynamic models for the northern Yilgarn Craton and the Capricorn, west Musgrave and Albany–Fraser Orogens.

## Embracing mineral systems

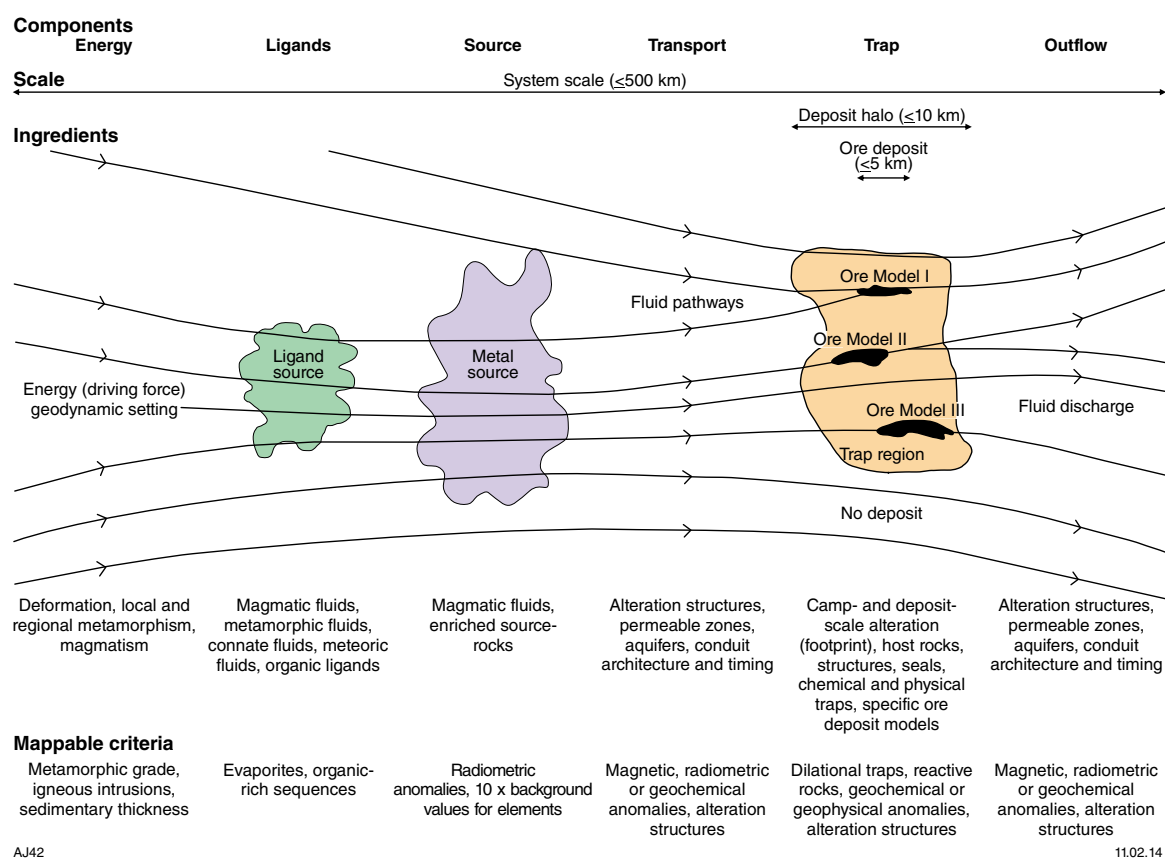
Exploring for minerals in regions of cover requires a sound understanding of mineral systems, or 'all geological factors that control the generation and preservation of mineral deposits' (Wyborn et al., 1994; Fig. 1). GSWA has traditionally left to others the task of deducing and applying metallogenic factors, but now recognizes that considerable value and utility can be added to its products by integrating 'mineral systems' knowledge. It is therefore contributing to empirical and conceptual studies to define critical factors and geological elements to locate mineralization. Such studies include:

- Cu–Zn VMS systems in the Archean Yilgarn Craton (Yuinmery, Austin–Quinns, Wheatley, Golden Grove, Glenview) and Proterozoic Capricorn Orogen (Abra)

- REE in the Yilgarn Craton (Mount Weld), Capricorn Orogen (Yangibana), and east Kimberley (Cummins Range, John Galt, Browns Range)
- Gold systems in the Proterozoic Ashburton and Glenburgh Terranes (Paulsens, Glenburgh)
- Iron ore systems in the Yilgarn (Mount Richardson) and Pilbara Cratons (Corunna Downs).

There is also research on fertility and metallogenic epochs for VMS mineralization in greenstone successions of the Yilgarn Craton; the potential for pyrite and magnetite chemistry as indicators of, and vectors to, gold and base metals systems in the northern Yilgarn Craton and southern Capricorn Orogen; and the distribution and chemistry of diamonds and diamond indicator minerals throughout the State.

Conceptual studies include numerical modelling of the migration of deformation, energy (heat) and mass (fluids, magmas, metals) in the lithosphere for a range of tectonic scenarios to provide insights into upper lithospheric processes controlling metallogenesis, and test the models proposed for the geodynamic and metallogenic evolution of the eastern Yilgarn Craton. Another strand of this work seeks to apply multi-scale wavelet analysis to different types of exploration data (e.g. multi-element assays, distribution and intensity of alteration) to determine whether it is possible to distinguish 'economic' from 'failed' systems, and to vector within such systems.



**Figure 1.** Schematic representation of the mineral systems approach, after Joly et al. (2013), modified from Wyborn et al. (1994)

## Joining the hunt

GSWA is also applying accumulated knowledge of terrane geology and mineralizing processes to prospectivity analysis and targeting. The intent is not to replicate or supplant the efforts of mineral explorers, but to assist with developing new, better techniques for greenfields exploration.

One project has sought to validate empirical geological criteria commonly used to target Archean greenstone-hosted gold systems, by analysing the spatial relationships between each criterion and known gold endowment in the Eastern Goldfields (Witt et al., 2013). Outcomes include a suite of 'valid' criteria used to re-evaluate gold prospectivity in the Eastern Goldfields (Fig. 2), and which might be used to assess the prospectivity of other terranes.

A second project adopts a 'mineral systems' approach, using known geological characteristics as proxies for processes critical for forming and preserving particular mineral systems (deposit types) expected to be present (McCuaig et al., 2010). Each 'mineral systems analysis' mathematically combines a suite of suitably buffered and weighted geological proxies, to produce a map in which strong spatial correlations denote domains that are interpreted to be more prospective. Analyses are complete for the west Arunta (Joly et al., 2013) and west Musgrave (Joly et al., in prep.). Assessments of the west Kimberley and Gascoyne regions have commenced, and are planned for the eastern Capricorn Orogen.

## Help needed!

Most of the geoscientific programs with which GSWA is involved require access to talent, analytical facilities and funding beyond the capacity of any single institution to provide. Collaboration is therefore the norm, and for any particular project, GSWA is commonly in partnership with local and interstate universities, state and federal government-funded research bodies, and resource companies, outsourcing research with funding through EIS.

## A wise investment?

First results from GSWA mineral systems studies are only now being released, so it is premature to assess their impact on exploration investment and discovery in Western Australia. There can be little doubt, however, that provision of precompetitive data and financial incentives are contributing to exploration success. To cite just a few examples:

- EIS has to date offered co-funded drilling subsidies to nearly 400 greenfields projects
- Discovery in 2012 of the Nova–Bollinger massive Ni–Cu sulfide deposit (within a new nickel province) in the Mesoproterozoic Albany–Fraser Orogen was supported by a nickel anomaly in a GSWA regolith geochemical survey from 1998; interesting features in GSWA regional aeromagnetic data (the 'Eye'); recent GSWA 1:100 000-scale mapping that suggested

geological similarities with terranes hosting giant Canadian Ni deposits; and encouraging results from EIS co-funded drilling

- The Theseus paleochannel sand-hosted uranium deposit was discovered south of Lake Mackay in 2011 during drilling co-funded by EIS that targeted a domain of anomalous  $U_3O_8$  evident in GSWA regional airborne radiometric data
- Recent precompetitive regolith mapping and radiometric data for the Murchison Province were used to define the Byro, Peranbye and Yalgoo paleochannel calcrete-hosted uranium prospects
- The DeGrussa (Doolgunna) copper–gold VMS deposit, discovered in 2009, followed up GSWA work that recognized the Proterozoic mafic volcanic and sedimentary rocks of the Bryah Basin as a rift-related succession. This enhanced perceptions of the mineral potential of the Bryah Basin and of Western Australia's potential for significant new VMS and sediment-hosted copper deposits.

## Into the future ...

GSWA will continue to collect pre-competitive data and maintain ventures at rates determined by future funding levels. However, GSWA is also looking to expand and develop new regional-scale, minerals-oriented products, such as:

- a prospectivity analysis of the Capricorn Orogen incorporating regional airborne electromagnetic survey data
- an enhanced Western Australian mineral deposit database (MINEDEX)
- a mineral systems atlas that would inform GIS-based prospectivity and targeting studies, and highlight significant gaps in our understanding of particular metallogenic epochs, thereby guiding future GSWA programs
- digital 3D crustal architecture models of particular parts of Western Australia, leading ultimately to a model for the entire State
- a petrophysical database to constrain modelling of geophysical potential field data
- an 'indicator mineral' chemistry database incorporating data for accessory phases from fresh host rock and regolith that could be used to characterize mineral system type, size and proximity.

GSWA is seeking to deliver products to very large, collaborative 'geosystems' programs that integrate all available data and knowledge into 3D and 4D crustal architectural and metallogenic models for particular terranes. These programs are seen as one possible expression of the nationwide 'Uncover' initiative (Australian Academy of Science, 2010), and hence will initially focus on relatively less-explored or buried, seemingly poorly endowed terranes such as the Capricorn and 'sub-Eucla' Albany–Fraser Orogens.



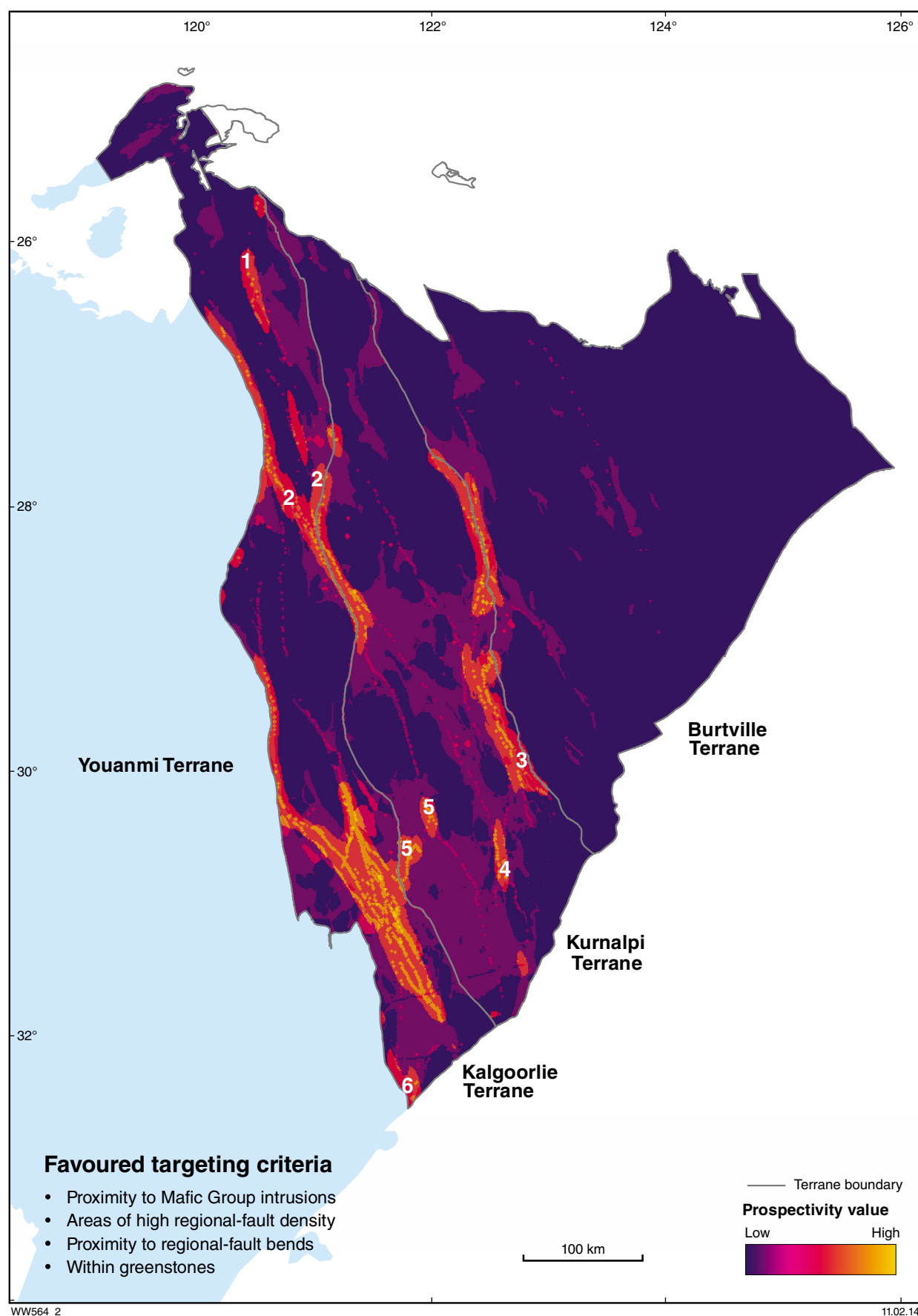


Figure 2. Gold prospectivity map for the Eastern Goldfields Superterrane created using fuzzy logic and four favoured targeting criteria. Numbers indicate areas that may warrant further exploration, modified after Witt et al. (2013)

## ... and the verdict?

GSWA continues to deliver products that reduce technical and financial risk for mineral explorers in Western Australia. With significant support via the State Government's EIS, these include enhanced pre-competitive regional geoscience information, including new 'value-adding' initiatives such as mineral systems studies, and techniques to assess prospectivity and generate targets in under-explored, commonly buried terranes having unknown mineral endowment.

These EIS products and drilling subsidies for greenfields exploration, collectively appear to be encouraging earlier definition and drill testing of targets in under-explored parts of the State, and in some conspicuous instances have contributed to the discovery of significant mineral deposits in emerging mineral provinces.

Such successes might (optimistically) be early indications of a new era of discovery of the next generation of large to world-class ore bodies in Western Australia.

## References

- Australian Academy of Science 2012, Searching the Deep Earth: a vision for exploration geoscience in Australia, 42p, viewed January 2014, <[www.science.org.au/policy/uncover.html](http://www.science.org.au/policy/uncover.html)>.
- Joly, A, Aitken, ARA, Dentith, MC, Porwal, AK and Smithies, RH in prep., Mineral prospectivity analysis of the west Musgrave Province: Geological Survey of Western Australia, Report 117.
- Joly, A, Dentith, MC, Porwal, A, Spaggiari, CV, Tyler, IM and McCuaig, TC 2013, An integrated geological and geophysical study of the west Arunta Orogen and its mineral prospectivity: Geological Survey of Western Australia, Perth, Western Australia, Report 113, 89p.
- McCuaig, TC, Beresford, S and Hronsky, J 2010, Translating the mineral systems approach into an effective exploration targeting system: Ore Geology Reviews, v. 38, p. 128–138.
- Schodde, R 2012, What's the future for mineral exploration in Australia? ...and why we need smart geoscientists now!: Geological Society of Australia, Victoria Division, presentation, 25 October 2012, viewed 10 January 2014, <[www.minexconsulting.com/publications.html](http://www.minexconsulting.com/publications.html)>.
- Witt, WK, Ford, A, Hanrahan, B and Mamuse, A 2013, Regional-scale targeting for gold in the Yilgarn Craton: Part 1 of the Yilgarn Gold Exploration Targeting Atlas: Geological Survey of Western Australia, Perth, Western Australia, Report 125, digital data package.
- Wyborn, LAI, Heinrich, CA and Jaques, AL 1994, Australian Proterozoic mineral systems: essential ingredients and mappable criteria: Australasian Institute of Mining and Metallurgy, Annual Conference, Darwin, 1994, Proceedings, p. 109–115.

# Volcanogenic massive sulfide mineralization at Weld Range: a comparison with Golden Grove

by

J Guilliamse

The Archean Yilgarn Craton of Western Australia appears to be poorly endowed with volcanogenic massive sulfide (VMS) deposits when compared to the Archean cratons of Canada. Balancing this rather pessimistic perception, the presence of at least a few economic VMS deposits in the Yilgarn Craton suggests that rather than poor endowment there may be other factors such as weathering or lack of outcrop hindering the discovery of VMS, resulting in reduced exploration success.

## Geology and geochemistry

Base metal mineralization was discovered at the Glenview prospect, by Hampton Hill Mining NL, in a felsic volcanic succession on the northern side of the Weld Range in the northern Murchison Domain of the Youanmi Terrane, Yilgarn Craton. The company considered the geology in this prospect to be similar to that at Golden Grove (Fig. 1), which is Western Australia's largest VMS deposit. The prospectivity of the Glenview area was evaluated by comparing it with Golden Grove, focusing particularly on some of the features that are deemed necessary for VMS formation and preservation, as well as some that are considered favourable for VMS mineralization in the Murchison Domain, i.e. characteristics that are similar to Golden Grove (Guilliamse, 2013; in prep.).

Golden Grove is situated within a felsic volcano-sedimentary sequence that shows good lateral continuity and has evidence for deep subaqueous emplacement of both host rocks and mineralization (Clifford, 1992). The sequence is dominated by felsic volcanic, volcanoclastic, and sedimentary rocks, with evidence of hydrothermal activity from chemical sediments interspersed with fine-grained, laminated volcanoclastic and sedimentary units. Sericite and chlorite alteration are associated with the massive sulfide and stringer mineralization.

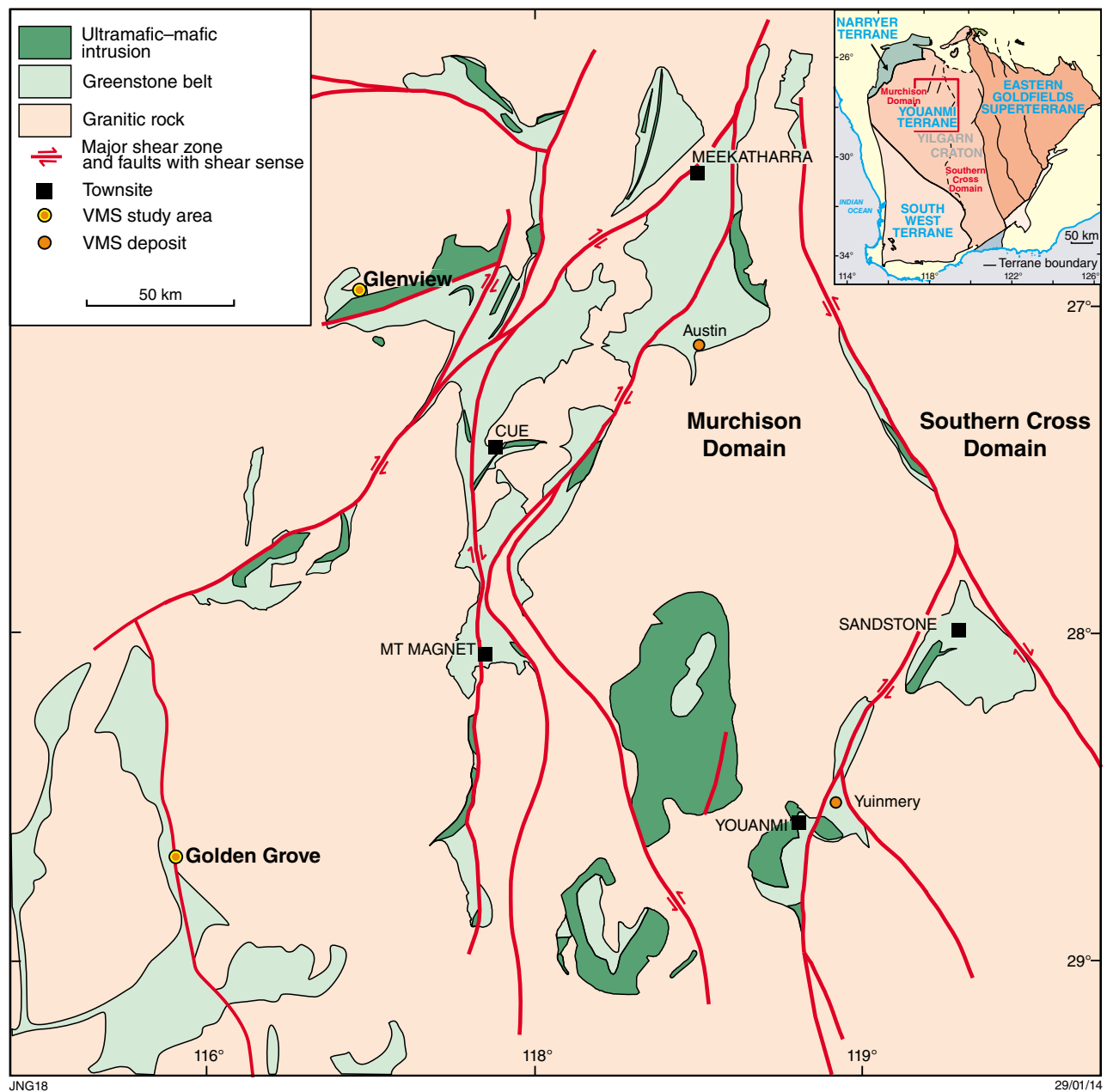
Petrologic studies indicate that Glenview is also developed in a felsic volcano-sedimentary sequence, consisting of volcanoclastic rocks, hyaloclastites, coherent felsic lavas, clastic sedimentary rocks, chert, and banded iron-formation. There is extensive sericite and chlorite alteration, and the presence of sulfide veins and minor massive sulfide mineralization indicates percolation of metal-laden hydrothermal fluids. Although the sedimentary and volcanic units at Glenview show evidence for subaqueous emplacement, definitive evidence for depth of emplacement is lacking. However, the absence of

welding in pyroclastic-rich volcanoclastic units suggests a minimum depth of 500 m, defined by Cas (1992) as the minimum depth needed to produce the confining pressures required to prevent boiling and facilitate massive sulfide formation on the sea floor.

In the fertility diagram of Lesher et al. (1986), felsic volcanic rocks from Golden Grove and Glenview both plot in the highly prospective FII and FIIIa fields (Fig. 2). The lithologic and geochemical similarities between Glenview and Golden Grove suggest that they formed in similar tectonic settings. Geochemical signatures for both areas are consistent with an active continental-margin setting based on Th and Ta ratios defined by Schandl and Gorton (2002) as shown on Figure 3. Although active continental margins are common settings for post-Archean deposits, most of the Archean deposits in Canada were noted by Schandl and Gordon (2002) to plot in the within-plate volcanic zone.

## Isotopic dating and spectral scanning

Felsic volcanic rocks on the northern side of Weld Range, which host the Glenview prospect, were previously mapped as part of the c. 2752 Ma Wilgie Mia Formation on the MADOONGA 1:100 000 geological sheet (Ivanic, 2009). However, a SHRIMP U–Pb zircon age of  $2977 \pm 3$  Ma for crystallization of rhyolite at Glenview (GSWA 155569, Wingate et al., 2013a) indicates that these rocks are significantly older. This age is consistent with results for other rocks east of Glenview on the northern side of the range, including  $2979 \pm 3$  Ma for a metarhyolite clast in volcanoclastic breccia (GSWA 193972, Wingate et al., 2012), and a unimodal age component of  $2969 \pm 3$  Ma for detrital zircons in a metasandstone (GSWA 184112, Wingate et al., 2008). A felsic metavolcanoclastic rock near the middle of the Weld Range yielded a maximum depositional age of  $2752 \pm 9$  Ma (Wang, 1998). On the southern side of the Weld Range, felsic volcanoclastic metasandstone is dominated by a  $2747 \pm 3$  Ma zircon age component (GSWA 155572, Wingate et al., 2013b). The age difference of about 230 Ma across the Weld Range indicates the presence of an unconformity, the exact location of which is not known but could be where a boulder conglomerate outcrops.



**Figure 1.** Simplified geology of the northern Murchison Domain showing the location of Golden Grove and Glenview. Modified from Van Kranendonk et al. (2010)

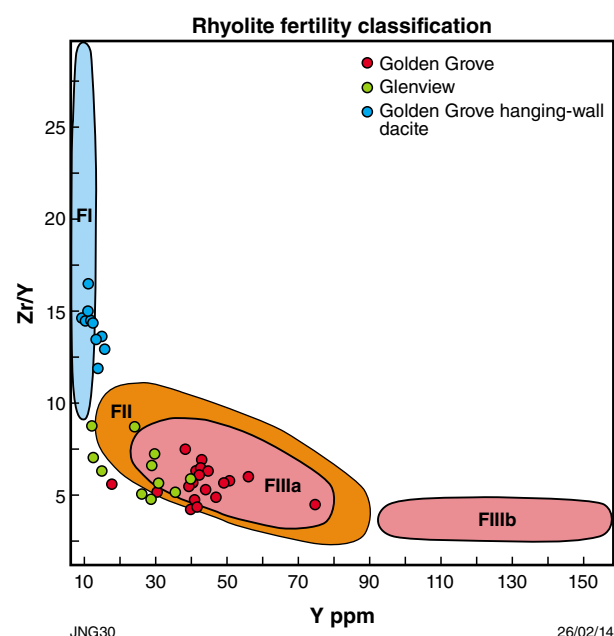
Crystallization ages of c. 2977 Ma for rhyolite at the base of the Weld Range are only slightly older than those of c. 2960 Ma for the entire dacitic succession at Golden Grove (GSWA, unpublished data). Also, galena samples from Glenview dated by CSIRO for MIM Exploration Pty Ltd indicated Pb-isotope dates of c. 3180 Ma, broadly similar to a Pb-isotope date of c. 3145 Ma for Golden Grove (Martin et al., 1997).

HyLogger spectral scanning of drillcore from Golden Grove indicated changes in the species of chlorite and white mica that provide measurable vectors towards sulfide mineralization. In relation to distance from sulfide mineralization, chlorite becomes Fe-rich over a metre scale, whereas paragonite becomes the dominant white mica over a decametre scale. Changes in the variability of specific absorption features related to white mica are also found to be effective vectors at indicating mineralization.

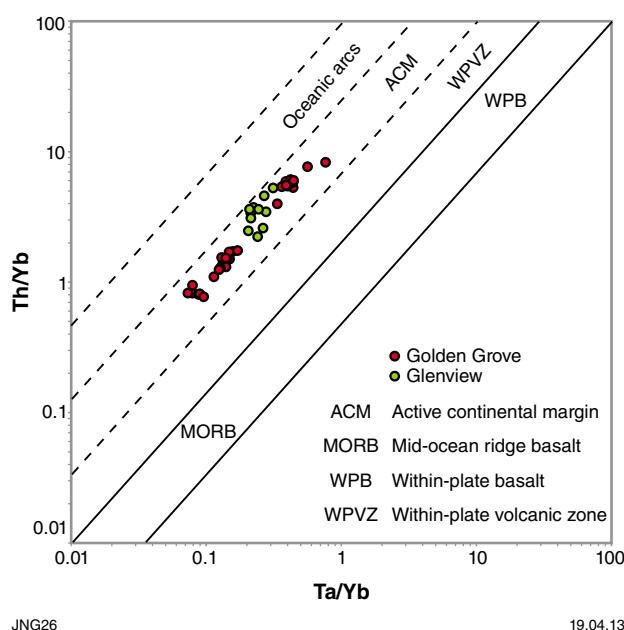
The wavelength at which the diagnostic AlOH absorption feature occurs is less variable in mineralized drillcore. Applied to Glenview, these vectors indicate favourable conditions for mineralization in the eastern portion of the Glenview prospect, where drillholes contain abundant paragonite and display markedly less variation in the wavelength of the AlOH absorption feature related to white mica (Fig. 4).

## Conclusion

The present study indicates that the tectonic setting, environment of formation, and age of felsic volcanism at Glenview are similar to those at Golden Grove, and that the Weld Range is prospective for VMS deposits. Alteration patterns suggest that the most prospective area may be in the eastern part of the Glenview prospect.

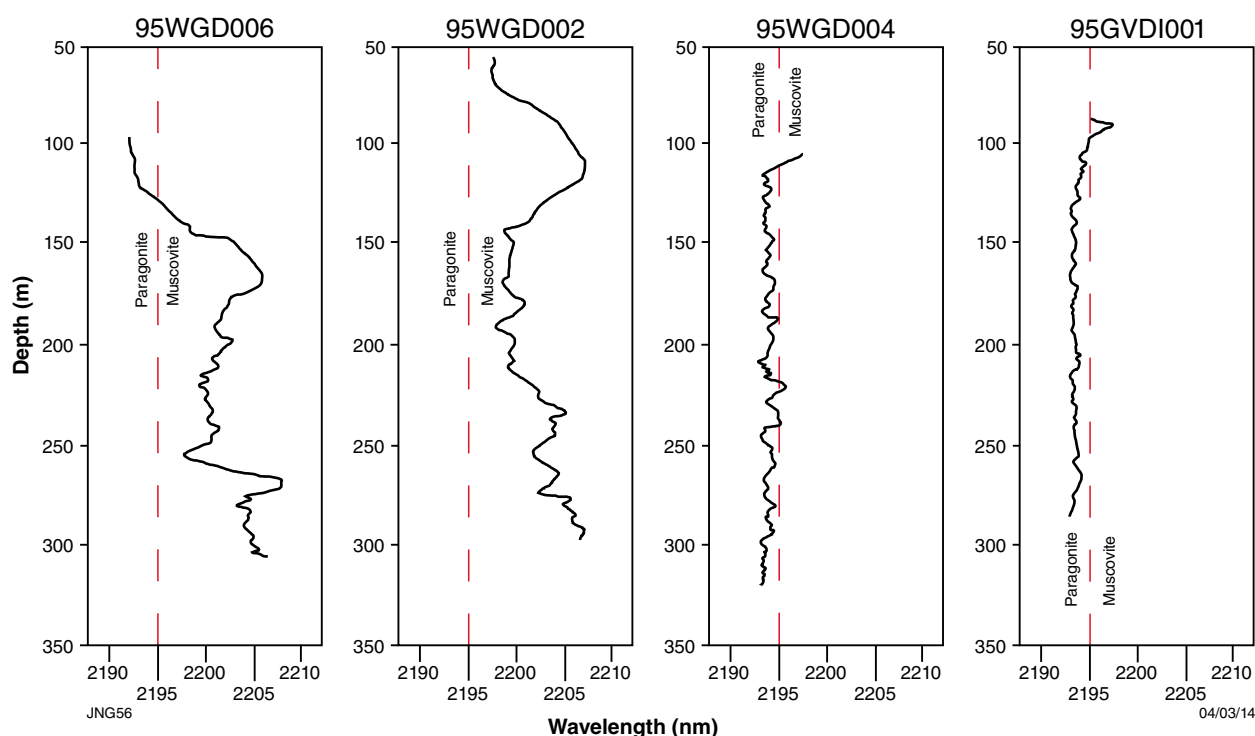


**Figure 2.** Felsic fertility plot of Leshner et al. (1986). Felsic volcanic rocks from Glenview and Golden Grove plot mainly in the FII and FIIIa fields, indicating that both are prospective for VMS mineralization



**Figure 3.** Tectonic setting discrimination diagram (modified from Schandl and Gorton, 2002), suggesting that felsic metavolcanic rocks from the Weld Range and Golden Grove both formed in an active continental margin setting





**Figure 4.** Downhole variation in the wavelength intersection of the AIOH absorption feature related to white mica in drillholes from Glenview, illustrating the difference between western (95WGD006 and 95WGD002) and eastern (95WGD004 and 96GVDI001) drillholes

## References

- Cas, RAF 1992, Submarine volcanism; eruption styles, products, and relevance to understanding the host-rock successions to volcanic-hosted massive sulfide deposits: *Economic Geology*, v. 87, no. 3, p. 511–541.
- Clifford, BA 1992, Facies and palaeoenvironment analysis of the Archaean volcanic–sedimentary succession hosting the Golden Grove Cu–Zn massive sulphide deposits, Western Australia: Monash University, Melbourne, PhD thesis (unpublished).
- Guilliamse, JN 2013, Investigation into the potential for volcanic-associated massive sulphide mineralisation at Weld Range by using Golden Grove as a comparative model: Centre for Exploration Targeting, The University of Western Australia, Perth, MSc thesis (unpublished).
- Guilliamse, JN in prep, Assessing the potential for volcanogenic massive sulfide mineralization at Weld Range, using Golden Grove for comparison: Geological Survey of Western Australia, Report.
- Ivanic, TJ 2009, Madoonga, WA Sheet 2444: Geological Survey of Western Australia, 1:100 000 Geological Series.
- Leshner, CM, Goodwin, AM, Campbell, IH and Gorton, MP 1986, Trace-element geochemistry of ore-associated and barren, felsic metavolcanic rocks in the Superior Province, Canada: *Canadian Journal of Earth Sciences*, v. 23, no. 2, p. 222–237.
- Martin, NK, Kneeshaw, AD and Andrews, P 1997, Annual report for the period ending 28 February 1997 on E20/163, E20/168, E20/208, E20/220, E20/229–230, E20/258, E20/280, E20/284–288, E51/525, E51/527–528, M20–311, P20/1674–1681, P20/1686–1687, P51/2162; M.I.M. Exploration Pty Ltd: Geological Survey of Western Australia, Statutory mineral exploration report, A51364 (unpublished).
- Schandl, ES and Gorton, MP 2002, Application of high field strength elements to discriminate tectonic settings in VHMS environments: *Economic Geology*, v. 97, no. 3, p. 629–642.
- Wang, Q 1998, Geochronology of the granite–greenstone terranes in the Murchison and Southern Cross Provinces of the Yilgarn Craton, Western Australia: Australian National University, Canberra, PhD thesis (unpublished).
- Wingate, MTD, Bodorkos, S and Kirkland, CL 2008, 184112: metasandstone, Ram Well; Geochronology Record 736: Geological Survey of Western Australia, 6p.
- Wingate, MTD, Kirkland, CL and Ivanic, TJ 2012, 193972: metarhyolite clast in volcanoclastic breccia, Weld Range; Geochronology Record 1011: Geological Survey of Western Australia, 4p.
- Wingate, MTD, Kirkland, CL, Guilliamse, JN, Van Kranendonk, MJ and Wyche, S 2013a, 155569: metarhyolite, Weld Range; Geochronology Record 1096: Geological Survey of Western Australia, 4p.
- Wingate, MTD, Kirkland, CL, Guilliamse, JN, Ivanic, TJ, Wyche, S and Van Kranendonk, MJ 2013b, 155572: felsic volcanoclastic metasandstone, Weld Range; Geochronology Record 1097: Geological Survey of Western Australia, 5p.

# Crustal architecture of the Youanmi Terrane, Yilgarn Craton: preliminary data and new ideas

by

I Zibra

The understanding of Archean geodynamics largely hinges around the long-standing debate on what tectonic styles were active on early Earth (Condie and Benn, 2006). The two end-member processes that have been proposed for Archean tectonics can be summarized as ‘horizontal tectonism’ and ‘vertical tectonism’, reflecting the view that Archean geodynamics was dominated by uniformitarian or non-uniformitarian processes, respectively (Van Kranendonk, 2004, for a review). In Western Australia, the Archean Pilbara and Yilgarn Cratons show some contrasting first-order geometric and structural features that are only partly understood, offering the opportunity for this contribution to the long-standing debate.

## Geodynamic models

The Paleo- to Mesoarchean East Pilbara Terrane represents a well-documented example of crustal evolution dominated by vertical tectonics (Van Kranendonk et al., 2004), and includes a well-preserved dome-and-keel architecture, with map-view geometries characterized by circular granite–migmatite domes wrapped by greenstone envelopes displaying a well-preserved stratigraphy and lateral continuity. In contrast, the Yilgarn Craton, which is mostly Neoarchean, is dominated by craton-scale, approximately north-trending high-strain zones (Fig. 1), mostly associated with highly deformed elongate granite bodies and dismembered greenstone packages, superficially resembling Phanerozoic orogenic belts. The Yilgarn Craton is a wide hot orogen (Chardon et al., 2009) where syn-orogenic shortening was distributed over several hundreds of kilometres across strike, and deformation was assisted by long-lived magmatism (in part of juvenile nature) and HT–LP metamorphism.

Contrasting geodynamic models have been proposed to account for the structural, magmatic and metamorphic evolution of the Yilgarn Craton. Modern-style subduction–accretion models seem to adequately explain the large-scale linear structures and crustal-penetrating shear zones associated with consistently east-dipping first-order geometry (Goleby et al., 2004). In contrast, plume-dominated models may explain some features, such as a comparable craton-scale magmatic evolution throughout a large part of the Neoarchean and the apparent lack of important metamorphic gradients across the craton (Van Kranendonk et al., 2013).

The Neoarchean has been described as a period of ‘global crisis’ (Rey et al., 2003), as the intense and protracted magmatic activity led to a nearly complete reworking of the felsic continental crust. This is consistent with the observation that, across the whole craton, the base of the c. 2900–2720 Ma greenstone sequences is invariably represented by a younger intrusive contact. This observation implies that the felsic basement to the greenstones, which may be Eoarchean in places (Wyche et al., 2012), has been completely remelted and assimilated by the voluminous c. 2720–2600 Ma-old granitic plutons. However, spatial, temporal and genetic relationships between such voluminous and protracted crustal reworking and the development of the craton-scale shear zone network are mostly unclear. Given that at least some of the exposed Yilgarn shear zones are likely rooted within the lower crust (Goleby et al., 2004), relations between structures and magmatism also have significant implications for the understanding of mineral systems.

This contribution provides an overview of some case studies in progress from the Youanmi Terrane of the Yilgarn Craton. New meso- and microstructural observations, supported by recently acquired geophysical and geochemical data, are used to understand the relationships between magmatism, shearing and polyphase deformation in mineralized Neoarchean granite–greenstone systems.

## Geological setting and crustal architecture of the Youanmi Terrane

The Yilgarn Craton comprises several terranes (Fig. 2), each defined as having distinct sedimentary and magmatic associations, geochemistry and ages of volcanism (Cassidy et al., 2006). The Youanmi Terrane is isotopically distinct because Sm–Nd and Lu–Hf data show several events of crustal formation and reworking between 4000 and 2600 Ma (Wyche et al., 2012). The terrane is cut by a network of late-orogenic, large-scale anastomosing shear zones more than 100 km long and about 2 to 10 km wide (Fig. 1). Several field studies indicate that most of these shear zones have a transpressional character (Zibra et al., in press).





Figure 1. Geophysical image (gravity draped over aeromagnetics) showing the trace of the terrane-scale network of late-orogenic shear zones (white) that likely controlled the rheology of the whole crustal section. The c. 2620 Ma post-kinematic plutons Garden Rock Granite (GR) and Taincrow Granite (TG), postdating the development of the shear-zone network, are marked in yellow



The dataset used for this study includes about 2000 structural observation points throughout the northern portion of the Youanmi Terrane. The points are mainly clustered along, or in the vicinity of, the recently acquired seismic traverses (Wyche et al., 2013), marked as YU1, 2, 3 on Figures 1 and 2. About 600 thin sections were studied from oriented samples, and 200 samples were also selected for quartz crystallographic preferred orientation (CPO) analysis, which is currently in progress. Structural data are combined with about 230 geochemical analyses of both granite and greenstone units and with geochronology data produced by GSWA during the routine activity of regional mapping.

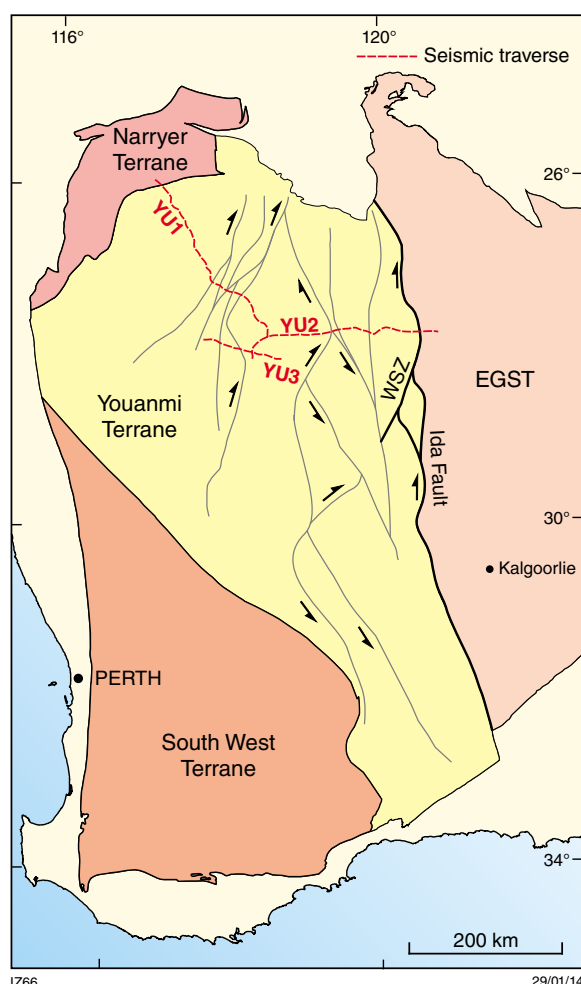
For the Youanmi Terrane, the data available so far provide a structural picture that differs from the typical architecture of most Archean hot orogens (Chardon et al., 2009). One of the main peculiarities of the Youanmi Terrane (and possibly of the whole Yilgarn Craton) is represented by a marked three-dimensional asymmetry of the crustal-scale structural grain, which strikingly contrasts with the map-view apparent orthorhombic structural symmetry (Figs 1, 2). The work in progress

highlights the close relationships between transpressional deformation and magmatic processes, such as the extraction of granitic magma from its lower crustal source and the syndeformational pluton assembly in upper crustal sink regions. The geochemical evolution of some studied syntectonic plutons shows that early components of TTG affinity were followed by younger magma batches characterized by a more evolved composition (i.e. transitional to low-Ca granites).

These new data, and in particular the combined structural, geochronology and geochemical observations, suggest that geochemistry trends of Archean granites are not only a response to secular changes of Earth conditions (Martin and Moyen, 2002). Rather, at pluton to regional scale, such chemical changes within the same pluton reflect the thermal evolution of syn-magmatic, oblique-slip shear zones. In other words, such chemical trends are the result of the complex interaction between magmatism and localization of deformation within shear zones.

## References

- Cassidy, KF, Champion, DC, Krapež, B, Barley, ME, Brown, SJA, Blewett, RS, Groenewald, PB and Tyler, IM, 2006, A revised geological framework for the Yilgarn Craton, Western Australia: Geological Survey of Western Australia, Record 2006/8, 8p.
- Chardon, D, Gapais, D and Cagnard, F, 2009, Flow of ultra-hot orogens: a view from the Precambrian, clues for the Phanerozoic: *Tectonophysics*, v. 477, p. 105–118.
- Condie, KC and Benn, K 2006, Archean geodynamics: similar to or different from modern geodynamics?: *American Geophysical Union, Monograph* 164, p. 47–59.
- Goleby BR, Blewett, RS, Korsch, RJ, Champion, DC, Cassidy, KF, Jones, LEA, Groenewald, PB and Henson, P 2004, Deep seismic reflection profiling in the Archean northeastern Yilgarn Craton, Western Australia: implications for crustal architecture and mineral potential: *Tectonophysics*, v. 388, p. 119–133.
- Martin, H and Moyen, J-P 2002, Secular changes in tonalite–trondhjemite–granodiorite composition as markers of the progressive cooling of Earth: *Geology*, v. 30, p. 319–322.
- Rey, PF, Philippot, P and Thébaud, N 2003, Contribution of mantle plumes, crustal thickening and greenstone blanketing to the 2.75–2.65 Ga global crisis: *Precambrian Research*, v. 127, p. 43–60.
- Van Kranendonk, MJ 2004, Archean tectonics 2004: a review: *Precambrian Research*, v. 131, p. 143–151.
- Van Kranendonk, MJ, Collins, WJ, Hickman, AH and Pawley, MJ 2004, Critical tests of vertical vs. horizontal tectonic models for the Achaean East Pilbara Granite–Greenstone Terrane, Pilbara Craton, Western Australia: *Precambrian Research*, v. 131, p. 173–211.
- Van Kranendonk, MJ, Ivanic, TJ, Wingate, MTD, Kirkland, CL and Wyche, S 2013, Long-lived, autochthonous development of the Archean Murchison Domain, and implications for Yilgarn Craton tectonics: *Precambrian Research*, v. 229, p. 49–92.
- Wyche, S, Kirkland, CL, Riganti, A, Pawley, MJ, Belousova, E and Wingate, MTD 2012, Isotopic constraints on stratigraphy in the central and eastern Yilgarn Craton, Western Australia: *Australian Journal of Earth Sciences*, v. 59, p. 657–670.
- Wyche, S, Ivanic, TJ and Zibra, I 2013, Youanmi and southern Carnarvon seismic and magnetotelluric (MT) workshop: Geological Survey of Western Australia, Record 2013/6, 171p.
- Zibra, I, Gessner, K, Smithies, RH and Peternell, M in press, On shearing, magmatism and regional deformation in Neoproterozoic granite–greenstone systems: insights from the Yilgarn Craton: *Journal of Structural Geology*, doi:10.1016/j.jsg.2013.11.010.



**Figure 2.** Geological sketch of the western portion of the Yilgarn Craton showing the location of the major terranes and the terrane-scale shear-zone network that typifies the Youanmi Terrane. Modified after Zibra et al. (in press). Abbreviations: ESGT, Eastern Goldfields Superterrane; WSZ, Waroonga Shear Zone

## Steps towards explaining the heterogeneous distribution of BIF-hosted iron ore deposits in the Yilgarn Craton

by

Paul Duuring<sup>1\*</sup>, Thomas Angerer<sup>1</sup> and Steffen Hagemann<sup>1</sup>

Banded iron-formations (BIF) are the dominant host rocks for higher grade (>55 wt%) iron ore deposits throughout the world, including the major occurrences in the Hamersley Province of Western Australia, the Quadrilátero Ferrífero district of Brazil, and the Transvaal Supergroup in South Africa. Although the BIF-hosted iron deposits in the Yilgarn Craton are generally smaller than their counterparts in the major provinces, the deposits of the Yilgarn show similar diversity in the range of iron ore styles, structural controls, and relative timing with respect to regional deformation events (Angerer et al., in press). Accordingly, the development of an holistic understanding about the processes controlling iron ore genesis in BIF in the Yilgarn Craton has direct relevance to other granite–greenstone terranes, such as the Pilbara Craton. As well, it provides the basis for a comparison with sedimentary basin-hosted BIF iron ore deposits in the Hamersley Province (Superior-type BIF-hosted deposits). This present study has wider implications; in relating the genesis of iron orebodies to craton-scale geological events affecting the Yilgarn, including other mineral systems such as gold and nickel (Wyche et al., 2012; Mole et al., 2013). This study is an ongoing joint project between the Centre for Exploration Targeting at The University of Western Australia and the Geological Survey of Western Australia (GSWA), with funding from the Royalties for Regions' Exploration Incentive Scheme. The aim of the project is to provide a synthesis of deposit- to district-scale studies on higher grade iron ore deposits in the Yilgarn Craton to better constrain an holistic 'Mineral Systems' (Wyborn et al., 1994) understanding for the genesis of these deposits, and to translate these insights into improved exploration targeting criteria for BIF-hosted iron ore. This two-year project began in 2013 and is presently operating at two scales: (i) processing collected sample materials from completed research projects (e.g. from Weld Range, Jack Hills, Koolyanobbing and Windarling); and (ii) investigating new iron ore occurrences located in different parts of the Yilgarn Craton (Murchison and Southern Cross Domains, Eastern Goldfields Superterrane). This abstract gives a brief review of some of the likely geological controls on the present distribution of iron ore deposits in the Yilgarn Craton.

### Iron ore deposit types and size in the Yilgarn Craton

Iron ore deposits in the Yilgarn Craton (Fig. 1) are divided by GSWA into primary BIF (including metamorphosed quartz–magnetite-bearing BIF), enriched BIF, granular iron-formation, layered mafic igneous rocks (orthomagmatic Fe–V–Ti), those associated with pisolite/Channel Iron Deposits, and minor detrital iron ores (Cooper, 2013). BIF-hosted occurrences account for about 90% of the reported total contained iron resource for the Yilgarn Craton (i.e. some 6115 of 6876 Mt contained Fe).

Primary or metamorphosed quartz–magnetite-bearing BIF occurrences have the largest reported resource values of contained iron (e.g. up to 882 Mt for the Jack Hills camp), but are generally lower grade (25 to 37% Fe) and high-contaminant ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ) ore bodies, with low cutoff values of <20% Fe used in their resource calculation. The economic value of these deposits and prospects is strongly determined by the costs associated with the shipping and beneficiation of the ores. In comparison, the enriched BIF occurrences are generally higher value ores — with higher average iron grades of between 53 and 62% (calculated using cutoff grades of more than 45% Fe). Just a few camps account for the majority (67%) of reported resources of contained iron, with the largest being Weld Range (145 Mt), Koolyanobbing/Windarling (93 Mt), Wiluna West (78 Mt), and Jack Hills (78 Mt). Thus, the size versus number of deposits approximates a power law distribution in the Southern Cross Domain, Murchison Domain, and Narryer Terrane (Fig. 2).

### Distribution of BIF and iron ore in the Yilgarn Craton

The craton-scale distribution of BIF in the Yilgarn Craton is a product of the present configuration of Archean greenstone belts. That is, greenstone-hosted BIF macrobands (>10 m thick) are exposed in each major subdivision of the Yilgarn Craton, including the Youanmi, Narryer and South West Terranes and the Eastern Goldfields Superterrane. However, iron ore occurrences (including deposits and prospects) are mainly concentrated in the Youanmi and Narryer Terranes, with notable under-representation in the Eastern Goldfields Superterrane and the South West Terrane (Figs 1, 2).

<sup>1</sup> Centre for Exploration Targeting, The University of Western Australia, 35 Stirling Highway, Crawley WA 6009

\* Corresponding author: pduuring@hotmail.com



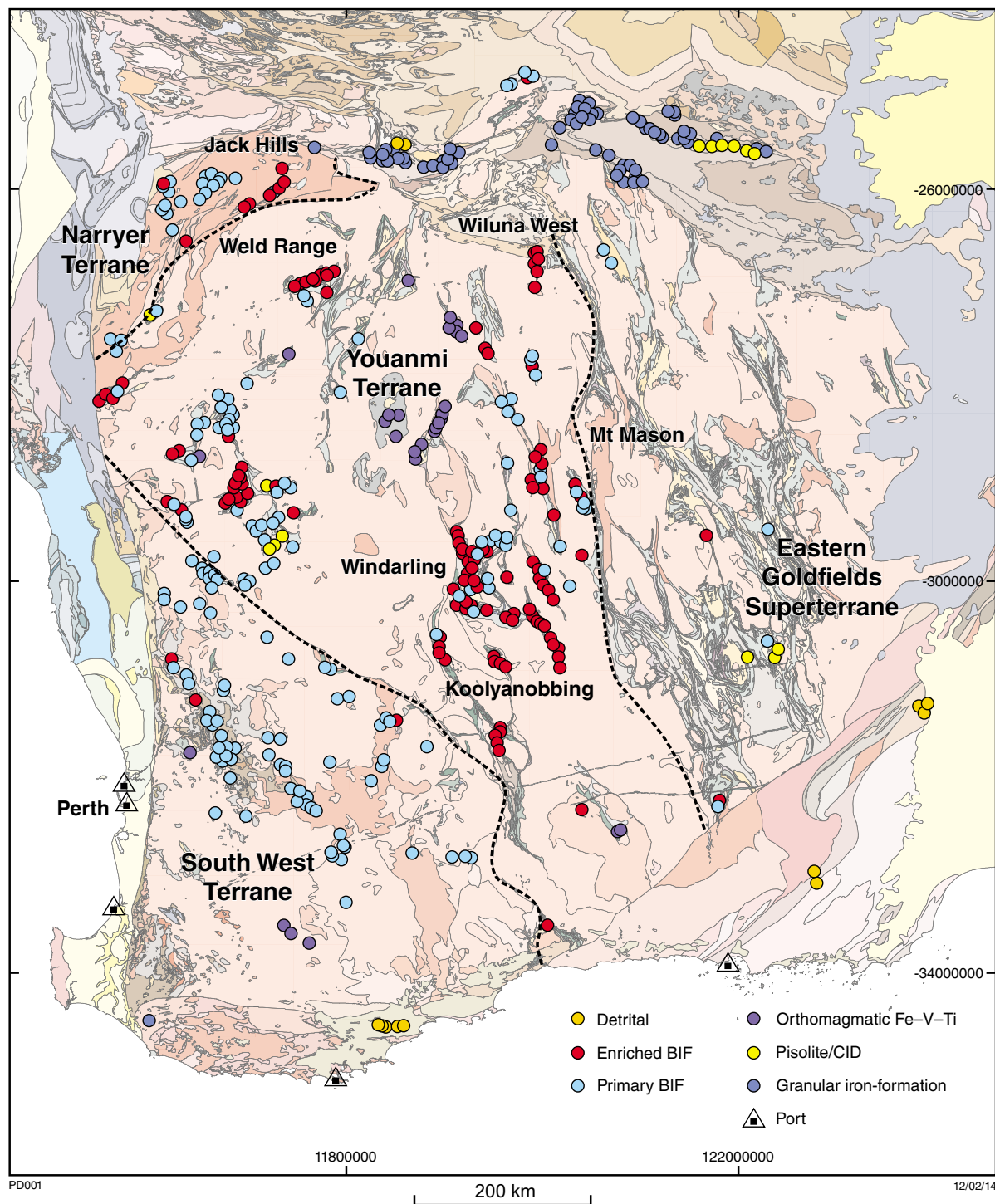
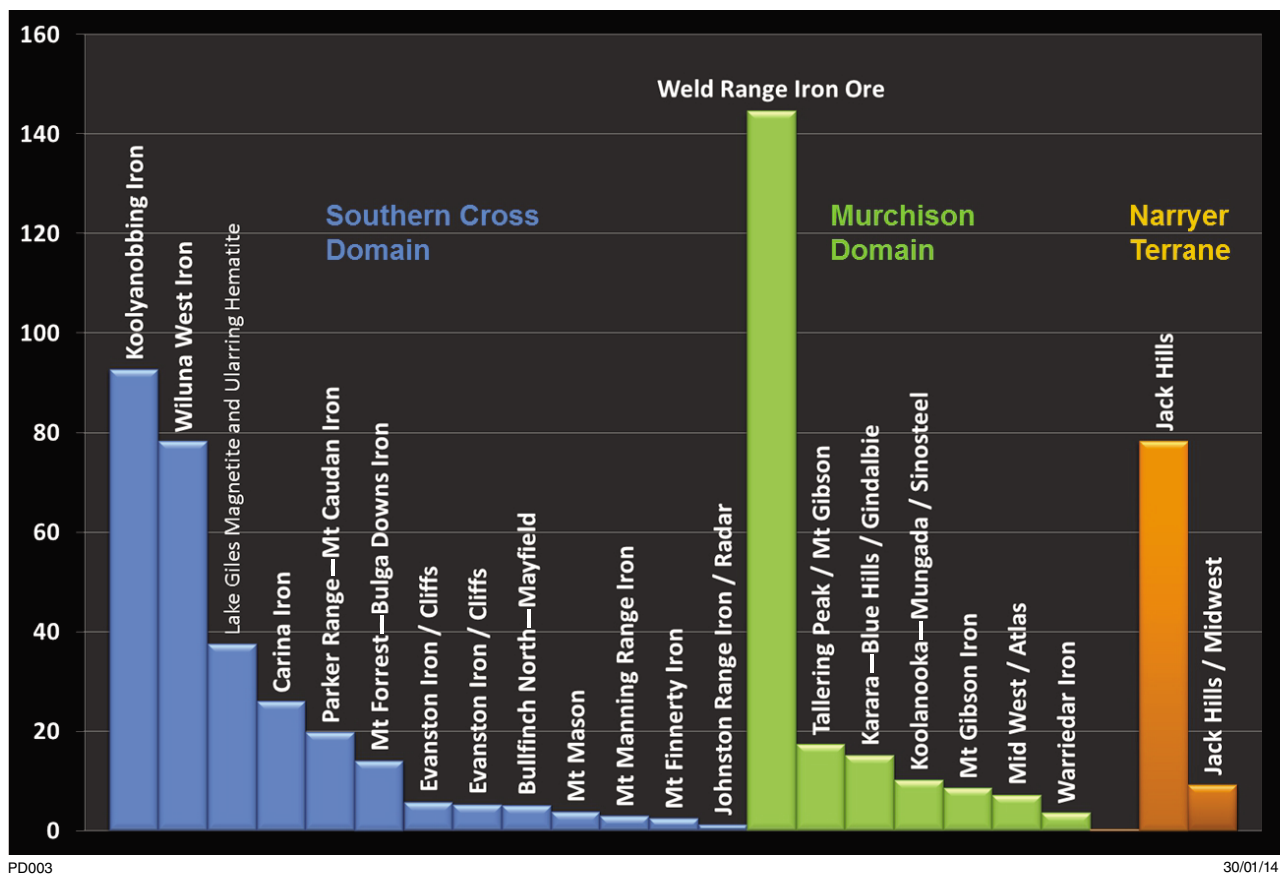


Figure 1. The location of iron ore occurrences in the Yilgarn Craton (data sourced from the Department of Mines and Petroleum's MINEDEX database, November 2013)



**Figure 2.** Examples of enriched BIF iron deposits in the Yilgarn Craton, grouped by their location and amount of contained Fe in Mt (data sourced from the MINEDEX database, November 2013). The Southern Cross and Murchison Domains are in the Youanmi Terrane

The Youanmi Terrane hosts 85% of all reported resources of contained iron, with the remaining 15% hosted by the Narryer Terrane (based on the reported combined resource and reserve estimates for enriched BIF in the Yilgarn Craton, from Department of Mines and Petroleum's MINEDEX database, November 2013). Within the Youanmi Terrane, the Southern Cross Domain is moderately more endowed relative to the Murchison Domain (the former hosts about 58% of total resources of contained iron).

The rarity of enriched BIF occurrences in the Eastern Goldfields Superterrane is remarkable considering that BIF macrobands at least 20 m thick are mapped there; notable examples include BIF macrobands that define the Mount Margaret anticline in the Leonora to Laverton district, BIF exposed in the Granny Smith gold deposit, and outcrop located in the Leinster nickel camp. BIF macrobands are also reported in the South West Terrane (Fig. 1).

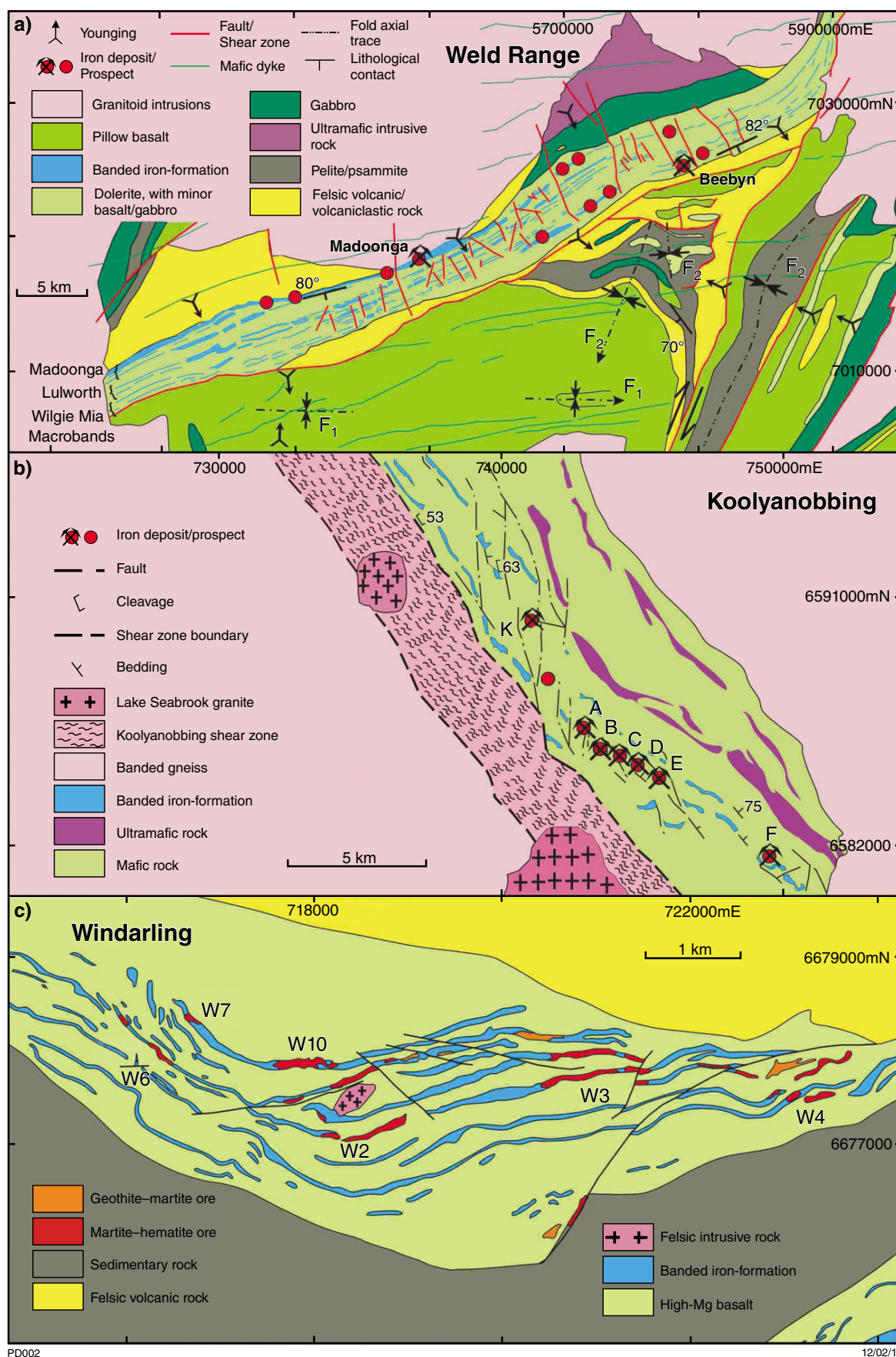
## Camp-scale heterogeneity in the distribution of iron ores

Iron ore occurrences are heterogeneously distributed within iron camps, with prospects and deposits developed

in specific macrobands. For example, in the Weld Range greenstone belt, iron ore occurrences are distributed within the two BIF macrobands located along the northern and southern borders of the greenstone belt (i.e. the Madoonga and Wilgie Mia BIF macrobands), with the central Lulworth macroband being notably devoid of known occurrences (Fig. 3a). At Koolyanobbing, iron ore deposits are distributed within the macroband positioned closest to the southern border of the greenstone belt, proximal to the Koolyanobbing Shear Zone and Ghooli dome felsic pluton (Fig. 3b). At Windarling, the known iron ore deposits define a more regularly dispersed pattern, with iron ore located across several neighbouring BIF macrobands (Fig. 3c).

## Critical controls for the distribution of iron ores

According to the available mineral systems model for BIF-hosted iron deposits in Western Australia (Angerer et al., in press), critical factors that determine the presence and distribution of iron include: (i) the presence of thick BIF; (ii) a broad, inter-connected deformation zone that acts as a fluid pathway; (iii) a large volume of silica-under-saturated fluid; (iv) exhumation and surficial modification of BIF; and (v) the preservation of ore bodies.



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**Figure 3.** Examples of camp-scale distribution of reported iron deposits and prospects: a) Weld Range; b) Koolyanobbing; c) Windarling camps. Solid geology maps are modified from Duuring and Hagemann (2012); Angerer and Hagemann (2010); and Angerer et al. (2012), respectively



By definition, the major iron ore camps in Western Australia have each of these critical factors, whereas BIF in the Eastern Goldfields Superterrane and the South West Terrane are likely to be missing one or more of these critical geological prerequisites. Preliminary observations are that BIF is present in primary or secondary thicknesses of at least 20 m in the under-represented areas. Further detailed investigations are required to examine the presence or absence of other important features, including the proximity of thickened BIF to first- or second-order deformation zones, or the presence of nearby late-stage felsic plutons as a potential source of energy or fluid. This study aims to better constrain the timing and source of hypogene fluids responsible for higher grade iron ore bodies relative to major geological events (deformation, plutonism, metamorphism) in the well-endowed areas for comparison with the remaining areas of the Yilgarn Craton.

## References

- Angerer, T, Duuring, P, Hagemann, SG, Thorne, W and McCuaig, TC in press, A mineral systems approach to iron ore in Archaean and Palaeoproterozoic BIF of Western Australia, *in* Ore deposits in an evolving Earth, Special Publication 393, *edited by* GRT Jenkin, PAJ Lusty, I McDonald, MP Smith, AJ Boyce and JJ Wilkinson: Geological Society of London, London.
- Angerer, T and Hagemann, SG 2010, The BIF-hosted high-grade iron ore deposits in the Archean Koolyanobbing greenstone belt, Western Australia: structural control on synorogenic- and weathering-related magnetite-, hematite-, and goethite-rich iron ore: *Economic Geology*, v. 105, p. 917–945.
- Angerer, T, Hagemann, SG and Danyushevsky, L 2012, High-grade iron ore at Windarling, Yilgarn Craton: a product of syn-orogenic deformation, hydrothermal alteration and supergene modification in an Archean BIF-basalt lithostratigraphy: *Mineralium Deposita*, v. 48, p. 697–728.
- Cooper, RW 2013, Iron ore deposits of the Yilgarn Craton — 2013 (1:1 500 000 scale): Geological Survey of Western Australia.
- Duuring, P and Hagemann, SG 2012, Leaching of silica bands and concentration of magnetite in Archean BIF by hypogene fluids: Beebyn Fe ore deposit, Yilgarn Craton, Western Australia: *Mineralium Deposita*, v. 48, p. 341–370.
- Mole, DR, Fiorentini, ML, Cassidy, KF, Kirkland, CL, Thebaud, N, McCuaig, TC, Doublier, MP, Duuring, P, Romano, SS, Maas, R, Belousova, EA, Barnes, SJ and Miller, J 2013, Crustal evolution, intra-cratonic architecture and the metallogeny of an Archaean craton, *in* Ore deposits in an evolving Earth, Special Publication 393, *edited by* GRT Jenkin, PAJ Lusty, I McDonald, MP Smith, AJ Boyce and JJ Wilkinson: Geological Society of London, London, doi: 10.1144/SP393.8.
- Wyborn, LAI, Heinrich, CA and Jaques, AL 1994, Australian Proterozoic mineral systems: essential ingredients and mappable criteria: Australasian Institute of Mining and Metallurgy, The AusIMM Annual Conference, Darwin, 1994, Proceedings, p. 109–115.
- Wyche, S, Fiorentini, ML, Miller, JL and McCuaig, TC 2012, Geology and controls on mineralisation in the Eastern Goldfields region, Yilgarn Craton, Western Australia: *Episodes*, v. 35, p. 273–282.

# Regional applications of low-density geochemical data to mineral exploration — the National Geochemical Survey of Australia

by

AJ Scheib

The National Geochemical Survey of Australia (NGSA) involved the collection and analysis of 1315 catchment-outlet sediments covering approximately 81% of Australia at an average density of one site per 5200 km<sup>2</sup>, for a total of 276 samples from Western Australia. These multi-element data from Western Australia were examined, and a selection of the results is presented — with particular focus on their regional application to mineral exploration.

The survey was coordinated by Geoscience Australia and samples from Western Australia were collected by the Geological Survey of Western Australia. At each site, outlet-sediment samples were collected from the top at 0 to 10 cm and from the bottom of the hole at 60 to 80 cm. Three subsamples were prepared for analysis from each depth: one bulk sample, one coarse sample of <2 mm and one fine sample of <75 µm. The fine and coarse subsamples were analysed by three analytical methods including XRF and ICP-MS following a total digest, and partial digestion using aqua regia (AR) and Mobile Metal Ion (MMI, for coarse top subsamples only; Mann et al., 2012). In addition to these analyses, sample grain size, pH and electrical conductivity were determined on the bulk samples. More-detailed information on the NGSA and results are presented in De Caritat and Cooper (2011) and data specifically relevant to Western Australia are presented in Scheib (2013).

## Predictable relationships between geochemistry and geology

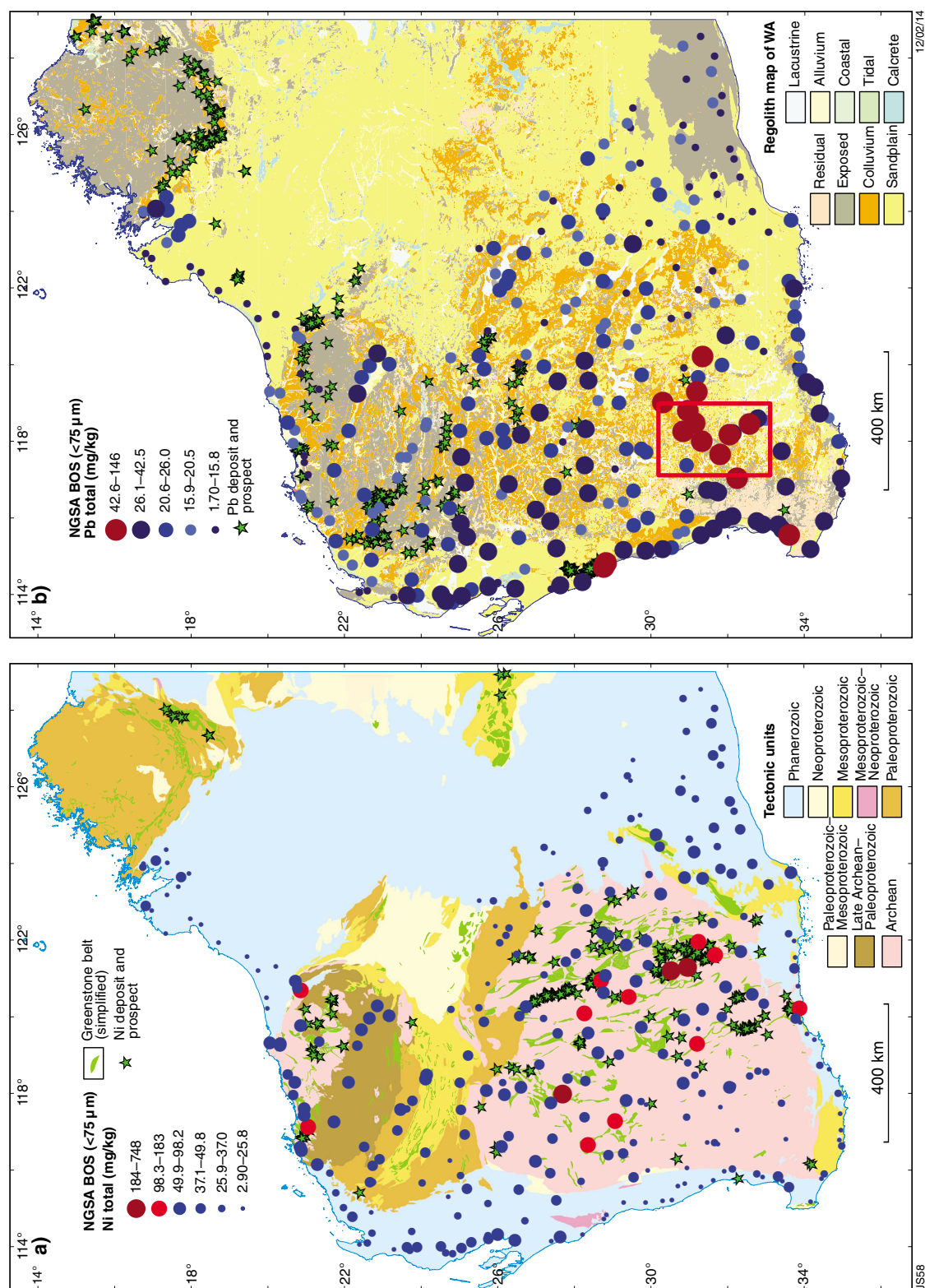
In Western Australia, sediment samples from older cratonic and orogenic areas comprise weathered, silicate-rich material, whereas samples from Cenozoic sedimentary basins, for example the Eucla Basin, generally correspond to finer grained material with high carbonate content and elevated pH. The distribution of samples with elevated concentrations of base metals, such as nickel (Fig. 1a), clearly highlights a close relationship to greenstone belts and known mineral prospects. Although this may be a predictable relationship, it is remarkable that this distribution can be observed at such a low sampling density. Similarly predictable is the distribution of high-field strength elements (HFSE) such as zirconium, hafnium and tantalum. Here, elevated total concentrations are predominantly found in samples from coastal areas of the State and closely relate to known

heavy mineral sand deposits that are enriched in zircon. These deposits relate to paleostrand lines, recent eolian deposits and enrichment through in-situ weathering of Cenozoic sediments. The latter is typical of the north and northwestern coastal areas. The source of heavy mineral sands in the southwest is possibly the South West Terrane of the Yilgarn Craton, which is further confirmed by results from the terrane-scale data analysis described below. The AR digest predictably yields only very low extractable concentrations of HFSE (<10%), which is due to the resistate nature of their host minerals, such as zircon. However, the distribution of the AR-extractable concentrations shows almost a reverse relationship to the total data, where coastal areas are associated with the lowest AR concentrations and inland areas show the highest concentrations, possibly as a result of longer exposure and weathering processes.

## Anomalous lead and rare earth element concentrations in lacustrine sediments of the Wheatbelt

The NGSA data also highlight several unexpected anomalies. One of them is a cluster of samples with anomalous lead (>42.5 mg/kg) and rare earth element (REE; e.g. Ce >176 mg/kg) concentrations in lacustrine sediments of the central Wheatbelt, an area that has no documented economic mineralization. This is emphasized by the distribution of anomalous lead (Fig. 1b). The highest concentrations within the NGSA data relate to lacustrine deposits of the Wheatbelt that correspond to salt lake systems. Possible sources of lead are Archean monzogranites of the area, which, through long-term weathering, may have contributed to the increased levels in the sediments and groundwater (Mann, 1983). Lead concentrations are highest in the fine fraction and at the bottom part of the sediments. The sediments also tend to be enriched in clay and gypsum and, therefore, lead may either be sorbed to clay minerals or present in the lead sulfate, anglesite. Apart from elevated concentrations in sediments along the coastal areas, which reflect resistate minerals accumulated in heavy mineral sands, most anomalous REE concentrations are found in sediments from the same sample locations in the Wheatbelt that are associated with anomalous lead. An additional two sites





**Figure 1.** Maps of total a) nickel and b) lead concentrations in the fine fraction (<75 µm) of bottom outlet sediments (BOS); both show locations of known nickel and lead deposits and prospects as green stars (Department of Mines and Petroleum MINEDEX data, May 2012; Cooper et al., 2011). Base maps are derived from a) the State 1:2 500 000 tectonic units map (Tyler and Hocking, 2008) and include the generalized extent of Precambrian greenstone belts, and b) the State 1:500 000 regolith map (Marnham and Morris, 2003; Marnham et al., 2002). Red rectangle indicates sites in the central Wheatbelt

with anomalous REE concentrations lie further west at the edge of the Yilgarn Craton, near Northam. Similar to lead, the highest REE concentrations relate to the fine fraction and the lower part of the sediment profile. For sites in the Wheatbelt, REE concentrations are more extractable and may relate to evaporites, such as gypsum, or clay minerals. Data for the two sites near Northam, however, indicate a much lower extractability, which indicates a more resistate mineral source for the REE and possibly relates to garnets derived from the local garnet-rich gneiss (Scheib, 2013).

## Terrane-scale characterization of the Yilgarn Craton

The Yilgarn Craton is one of the dominant building blocks of Western Australia and the host for various commodities and mineralization styles. The craton is divided into seven terranes (Cassidy et al., 2006; Pawley et al., 2012; and Fig. 2a). Low-density data for 96 NGSA outlet sediments were used to geochemically characterize five of the terranes (Fig. 2a), with the Narryer and Yamarna Terranes excluded because of lack of data. Figure 2a also shows the distribution of more than 2000 rock samples, for which Cassidy et al. (2002) provided geochemical data. Comparisons of both datasets showed that concentrations of cerium (Fig. 2b) and the remaining REE, lead, and the HFSE are particularly elevated in NGSA and rock samples from the gneiss-dominated South West Terrane (Scheib, 2013). The South West Terrane seems to be geochemically distinct from the other granite–greenstone dominated terranes, which have a more mafic signature shown by strong chalcophile and ferro-alloy element associations. The distribution of elevated chromium in Figure 2c, particularly for data from the Kalgoorlie Terrane, highlights this. The difference between the NGSA and rock data and their actual concentration ranges are possibly a result of supergene enrichment or an accumulation effect in the outlet sediments (Scheib, 2013). Furthermore, all investigated elements from both datasets display the same trend across the five terranes.

## Summary

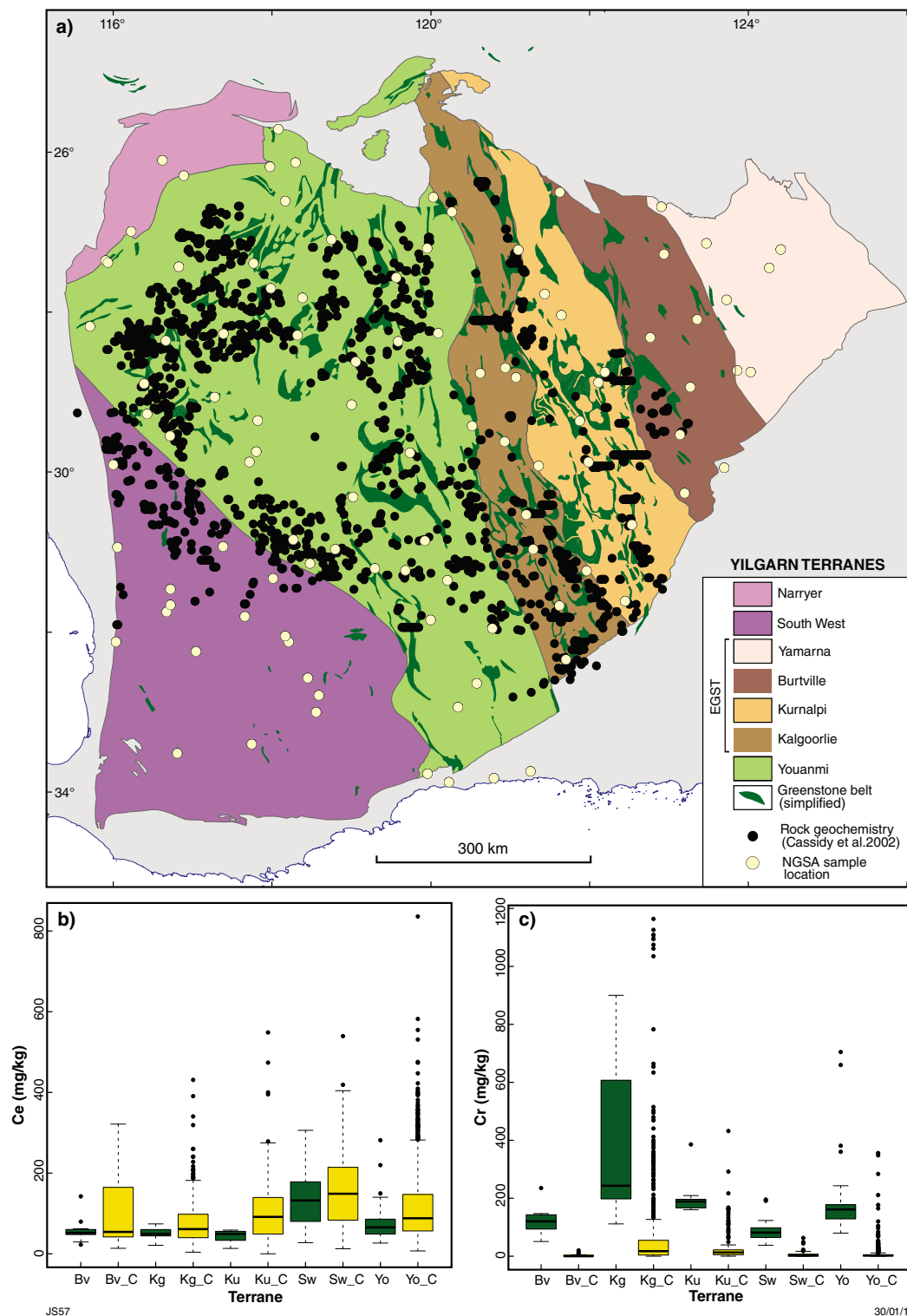
Assessment of the NGSA multi-element dataset shows that almost all anomalous concentrations of both total and AR data are associated with samples from the lower part of the sediment profile; the result of higher clay and silt contents. The exceptions are HFSE, which are enriched in the fine fraction at the top of the sediment profile. These results have implications for geochemical surveys in mineral exploration, because the success of them depends on choosing not only the right sampling medium, but also the sampling depth, analytical method and grain size.

The results for the selected elements presented here are further evidence that data from low-density surveys can define regional patterns that correspond to well-known areas of mineralization and to the underlying geology. The data also provide new insights on the distribution of lead and REE that are strongly associated with salt lake systems of the Wheatbelt instead of areas of known

mineralization. The usefulness of this dataset is further highlighted by results of terrane-scale characterization. Here, data from only 96 sediment samples achieve the same broad, geochemical division of the five terranes as a whole-rock geochemical dataset of >2000 samples. However, it should be mentioned that only the latter dataset would allow a detailed analysis of, for example, the petrogenesis or crustal evolution of these terranes. These few examples show that the NGSA data can be used to define the regional to continental distribution of elements and their natural baseline, indicate regions of preferential accumulation of element associations, and point to regional mineralization.

## References

- Cassidy, KF, Champion, D, McNaughton, N, Fletcher, I, Whitaker, A, Bastrakova, I and Budd, A 2002, Characterisation and metallogenic significance of Archean granitoids of the Yilgarn Craton, Western Australia: Minerals and Energy Research Institute of Western Australia (MERIWA), Perth, Western Australia, Report 222 (Project M281).
- Cassidy, KF, Champion, DF, Krapež, B, Barley, ME, Brown, SJA, Blewett, RS, Groenewald, PB and Tyler, IM 2006, A revised geological framework for the Yilgarn Craton, Western Australia: Geological Survey of Western Australia, Record 2006/8, 8p.
- Cooper, RW, Abeyesinghe, PB, Flint, DJ, Strong, CA and Haworth, JH 2011, Western Australia atlas of mineral deposits and petroleum fields 2011: Geological Survey of Western Australia, 50p.
- De Caritat, P and Cooper, M 2011, National Geochemical Survey of Australia: The Geochemical Atlas of Australia: Geoscience Australia, Record 2011/020 (2 volumes).
- Mann, A, de Caritat, P and Prince, P 2012, Bioavailability of nutrients in Australia from Mobile Metal Ion® analysis of catchment outlet sediment samples: continental-scale patterns and processes: Geochemistry: Exploration, Environment, Analysis, v. 12, p. 277–292.
- Mann A, 1983, Hydrogeochemistry and weathering of the Yilgarn Block, Western Australia — ferrolysis and heavy metals in continental brines: *Geochimica et Cosmochimica*, v. 47, p. 181–190.
- Marnham, J and Morris, PA 2003, State regolith north of 26th parallel (1:500 000 scale): Geological Survey of Western Australia, GeoVIEW.WA, digital data layer, viewed 13 December 2012, <[www.dmp.wa.gov.au/geoview](http://www.dmp.wa.gov.au/geoview)>.
- Marnham, J, Sanders, AJ and Morris, PA 2002, State regolith south of 26th parallel (1:500 000 scale): Geological Survey of Western Australia, GeoVIEW.WA, digital data layer, viewed 13 December 2012, <[www.dmp.wa.gov.au/geoview](http://www.dmp.wa.gov.au/geoview)>.
- Pawley MJ, Wingate, MTD, Kirkland CL, Wyche S, Hall, CE, Romano, SS and Doublier, MP 2012, Adding pieces to the puzzle: episodic crustal growth and a new terrane in the northeast Yilgarn Craton, Western Australia: *Australian Journal of Earth Sciences*, v. 59, p. 603–623.
- Scheib AJ 2013, The National Geochemical Survey of Australia — selected interpretations for Western Australia: Geological Survey of Western Australia, Record 2013/4, 48p.
- Tyler, IM and Hocking, RM 2008, 1:500 000 interpreted bedrock geology of Western Australia, 2008 update: Geological Survey of Western Australia, GeoVIEW.WA, digital data layer, viewed 13 December 2012, <[www.dmp.wa.gov.au/geoview](http://www.dmp.wa.gov.au/geoview)>.



**Figure 2.** a) Map of the main tectonic terranes and greenstone belts of the Yilgarn Craton based on Cassidy et al. (2006) and Pawley et al. (2012), showing locations of 96 NGSA samples (pale yellow circles) and 2049 rock samples (black circles; from Cassidy et al., 2002); b) and c) show box-and-whisker plots for total cerium and chromium concentrations in the fine (<75  $\mu$ m) fraction of bottom outlet sediments (BOS, green boxes) and granitic rocks from Cassidy et al. (2002, yellow boxes; Cassidy data labelled \_C), respectively; data are grouped by the five main terranes: Burtville Terrane (Bv, n = 14 NGSA / 27 rock samples), Kalgoorlie Terrane (Kg, n = 11/466), Kurnalpi Terrane (Ku, n = 9/209), South West Terrane (Sw, n = 17/173), and Youanmi Terrane (Yo, n = 45/1174). One chromium outlier (7824 mg/kg) was excluded from the NGSA dataset (Youanmi Terrane), as were four cerium outliers (1800 to 2000 mg/kg) from the Cassidy data (Kurnalpi Terrane). Box-and-whisker plots show interquartile range (IQR, boxes), and median (bold horizontal lines); whiskers represent  $IQR \pm (1.5 \times IQR)$  and outliers (black circles) are values greater or less than  $IQR \pm (1.5 \times IQR)$

# Greenfields exploration in the Albany–Fraser Orogen and on the southeast Yilgarn cratonic margin

by

I González-Álvarez<sup>1\*</sup>, RR Anand<sup>1</sup>, R Hough<sup>1</sup>, W Salama<sup>1</sup>, C Laukamp<sup>1</sup>, Y Ley-Cooper<sup>1</sup>, MT Sweetapple<sup>1</sup>, I Sonntag<sup>2</sup>, M Lintern<sup>1</sup>, T Abdat<sup>1</sup>, M leGras<sup>1</sup> and J Walshe<sup>1</sup>

The Albany–Fraser Orogen (AFO) is a regolith-dominated terrain with some significant differences in regolith evolution compared with its neighbouring Yilgarn Craton. These unknowns in the regolith framework pose significant challenges for greenfields exploration in the region. Two major discoveries — the Tropicana–Havana Au system (with a gold resource of 6.41 M oz) in 2005, and the Nova Ni–Cu deposit in the Fraser Range in 2012 — have sparked mineral exploration interest in the AFO.

In this region, regolith covers about 85% of the total surface area and can reach thicknesses of up to 150 m (Anand and Paine, 2002). The paleoclimatic evolution of the exposed AFO ranged from humid and sub-tropical from the Mesozoic to the Pliocene, shifting during the Quaternary to arid and semi-arid (Anand and Butt, 2010). Consequently, weathering profiles in the AFO are the result of successive climatic overprinting. In this terrain, weathering profiles obscure the surface expression of the basement geochemistry, and therefore blur or obliterate the geochemical footprint of mineral systems at depth.

## Regolith framework of the Albany–Fraser Orogen and southeast Yilgarn Craton margin

A conceptual model of the AFO as a paleocoast with numerous islands and estuarine zones driven by transgression–regression events is proposed. ‘On inland’ and ‘on island’ weathering profiles vary in maturity and saprolite development, with or without transported cover derived from exotic marine sedimentary rocks and limestones, and clastic detritus from the Yilgarn Craton. These areas are more reliable for understanding geochemical anomaly – basement relationships, whereas the ‘marine inundated’ areas would require a more-detailed investigation, due to the role of marine reworking of weathering profiles (Fig. 1).

Within the above framework, the following four different regolith settings have been identified: (i) Albany; (ii) Kalgoorlie–Norseman margin; (iii) Esperance; and (iv) Neale. The landscape changes from a topographically high, dissected Yilgarn surface geomorphology with thick saprolite and inverted paleochannels, to a nearly flat terrain dominated by sand dunes and thin saprolite towards the coast.

Mapping the paleocoasts, islands and estuarine zones, as well as the region of influence of marine limestones and sedimentary rocks, significantly improves the planning and implementation of exploration campaigns in the region, as these features have been shown to have a severe impact on conventional regolith development and vertical trace element mobility (Worrall and Clarke, 2004).

## Gold anomaly in calcrete: the displaced anomaly at Woodline

The Woodline Au Project (Sipa Resources Ltd), about 110 km northeast of Norseman, is within the Kalgoorlie–Norseman margin setting. This site was selected to study and understand the formation of gold anomalies in calcrete displaced from mineralization in the region. This anomaly was previously described as *in situ*. Results from our study indicated a transported anomaly in younger colluvium overlying Pliocene marine sediments, with no gold mineralization beneath.

## Neale area: regolith stratigraphy and trace element mobility

The main study site was the Neale area (Hercules and Atlantis Au prospects; 60 km northeast of the Tropicana–Havana Au system), to improve understanding of trace element mobility from the basement through the regolith profile.

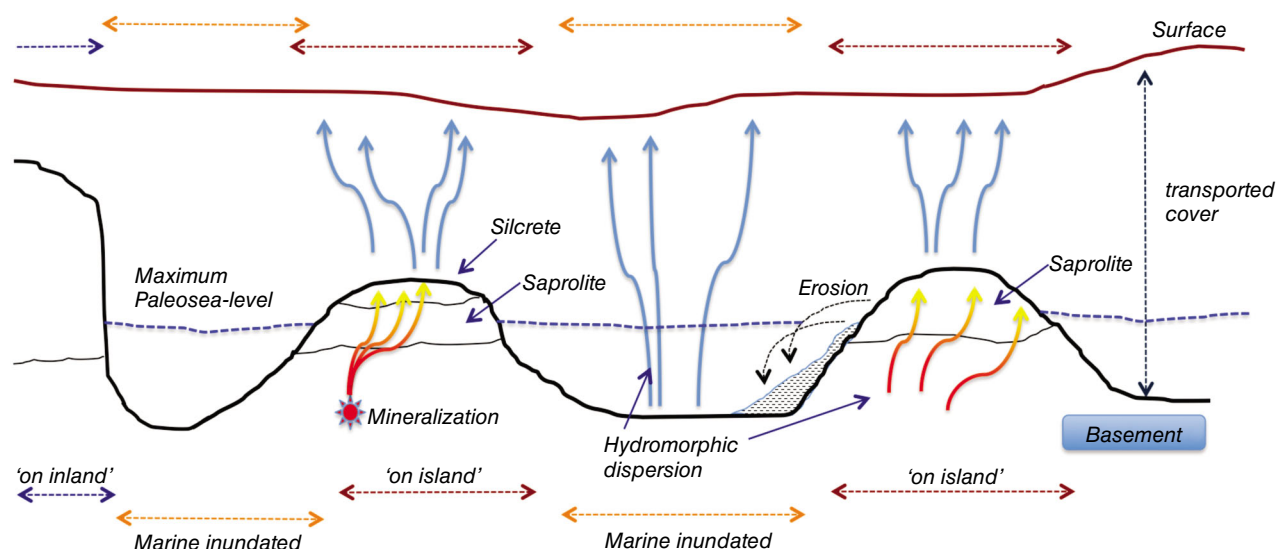
Basement lithologies at Neale contain two styles of gold mineralization: a disseminated style related to altered felsic to intermediate intrusive rocks, and a dilational quartz vein-hosted style associated with mylonite zones. Gold is associated with copper, mostly chalcopyrite. Gold and sulfide species are interpreted to have a relatively late paragenesis.

1 CSIRO, Earth Science and Resource Engineering, Minerals Down Under Flagship, Perth WA

\* Corresponding author: i.gonzalez.alvarez@gmail.com

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





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**Figure 1.** Sketch of the effect of sea transgressions and regressions generating 'on inland' and 'on island' areas together with 'marine inundated' zones, and the implications for vertical trace element dispersion for the basement geochemical signature

Silver-rich gold at the Hercules Au prospect is found as fine inclusions in pyrite, and is hosted in mica-altered felsic to intermediate granites, granofels, and discrete quartz veins. At the Atlantis Au prospect, gold is identified in single crystalline grains of about 10  $\mu\text{m}$  size with no silver content, within chlorite-sericite-altered granite, and typically hosted in mylonites, with subordinate mica-altered felsic to intermediate granites.

Regolith developed above the Neale mineralized area presents a total thickness of about 75 m, including about 25 m of transported cover that overlies a silcrete unit (Fig. 2). The silcrete unit (from 4 to 20 m thick) is widely distributed, capping the kaolinitic upper saprolite. Cementation of the unit varies, with more permeable areas, resulting from more intense vertical weathering. Surface geochemical sampling above these permeable areas should deliver more-reliable geochemical basement signatures (Fig. 2).

The regolith is divided into: ferruginized lower saprolite and sandy kaolinitic upper saprolite. The weathering overprint at Neale developed in oxidizing, acidic conditions within a low-salinity groundwater environment, displaying low vertical hydromorphic dispersion of REE (from La to Lu), HFSE (Zr, Hf, Nb, Ta and Th) and transition metals (V, Cr, Co, Cu, Ni and Sc) within the upper saprolite and through the transported cover, but with no detectable expression in the eolian sand cover. Drillcore and RC samples from the lower saprolite preserve the main geochemical features (REE and transition element patterns, LREE/HREE, Zr/Hf, Nb/Ta, Th/Sc ratios) of the basement, and therefore can be used in geochemical exploration targeting (Fig. 2).

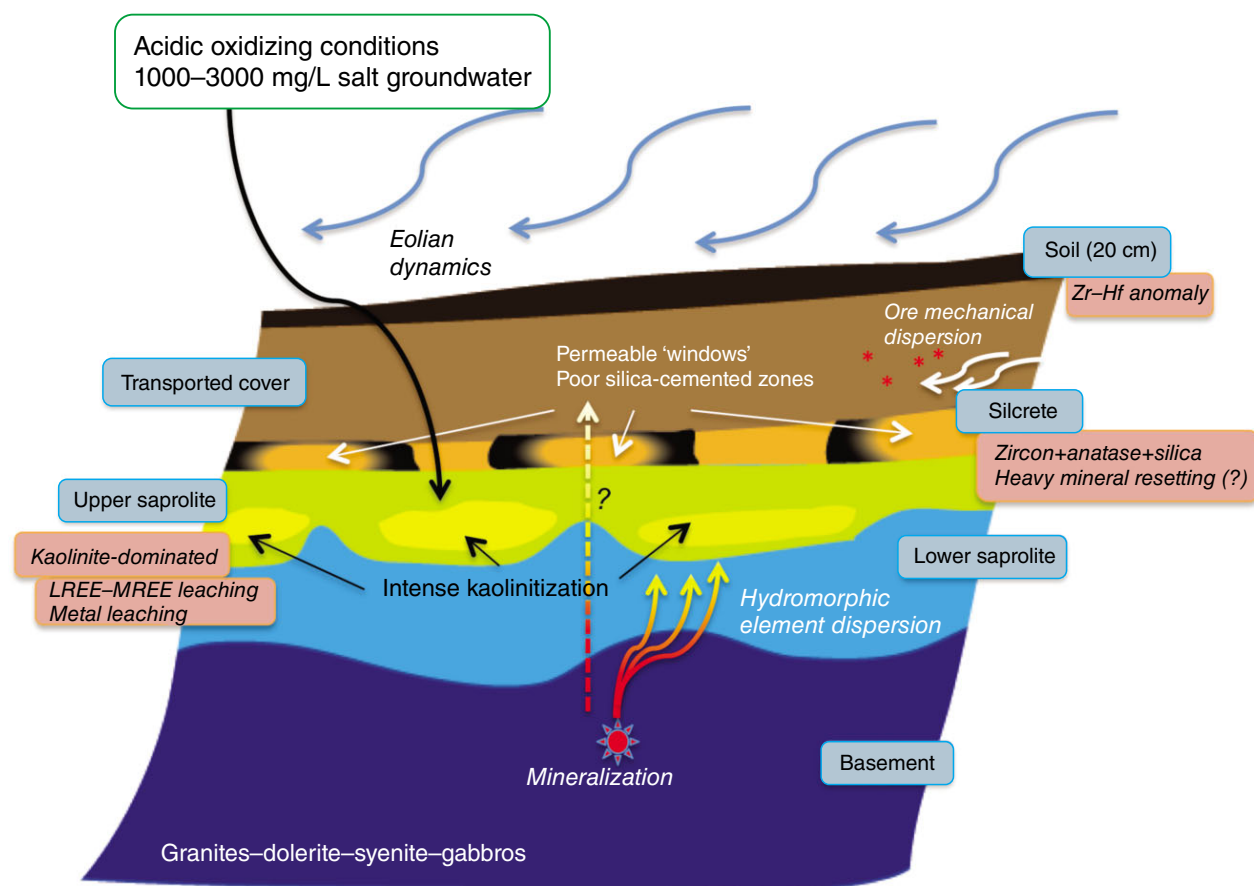
## New exploration technologies in the AFO: ASTER, HyLogger spectral scanning and AEM

ASTER geoscience products were used for geological mapping at district and camp scales, where patterns in single regolith units enable differentiation between regolith domains. Using kaolinite crystallinity, Hylogger spectral scanning was able to accurately segregate in situ versus transported material in regolith profiles at Salmon Gums and Neale. This was confirmed by manual logging. Spatially dense HyLogger spectral data (1 cm steps) from seven drillholes from the Hercules and Atlantis prospects successfully interpreted primary lithologies, alteration and regolith mineralogy, enabling mapping of narrow (cm-wide) carbonate-altered or cherty layers.

Airborne electromagnetic (AEM) datasets from the Tropicana gold system were examined to determine their potential for assisting exploration through cover. The historical AEM data collected using a fixed-wing airborne time-domain EM system (TEMPEST) were reinterpreted based on the regolith context and groundwater salinity constraints. The fully inverted dataset permitted better definition of basement topography and regolith architecture (saprolite and transported cover). This result highlights the usefulness of revisiting historical AEM surveys and their transforms, by subjecting them to a full inversion, which permits a better understanding of the weathered landscape and regolith in the AFO.

New exploration techniques such as ASTER appear promising for tenement-scale regolith mapping; and





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**Figure 2.** Geochemical dispersion model, based on study of the Neale area

the Hylogger spectral scanning data for segregation of in situ versus transported cover from drillhole samples; whereas AEM could be largely used as a tool to assist in characterizing regolith architecture, depending on groundwater salinity and the local geomorphological and sedimentary environment.

## References

- Anand, RR and Butt, CRM 2010, A guide for mineral exploration through the regolith in the Yilgarn Craton, Western Australia: Australian Journal of Earth Sciences, v. 57, p. 1015–1114.
- Anand, RR and Paine, M 2002., Regolith geology of the Yilgarn Craton, Western Australia: implications for exploration: Australian Journal of Earth Sciences, v. 49, p. 3–162.
- Worrall, L and Clarke, JDA 2004, The formation of geochemical anomalies in the eastern goldfields: the role of an Eocene acid weathering event, in Minerals exploration seminar: Cooperative Research Centre for Landscape Evolution and Mineral Exploration (CRC LEME) and Association of Mining and Exploration Companies (AMEC), Abstracts, June 2004, Perth, 23p.

## A magnetotelluric survey across the Kimberley Craton, northern Western Australia

by

J Spratt<sup>1</sup>, M Dentith<sup>2</sup>, S Evans<sup>3</sup>, A Aitken<sup>2</sup>, M Lindsay<sup>2</sup>, JA Hollis,  
IM Tyler, A Joly<sup>2</sup> and J Shragge<sup>4</sup>

A magnetotelluric (MT) survey, funded by the Kimberley Science and Conservation Strategy, completed in the Kimberley region in northern Western Australia, had two primary goals: addressing the nature of the concealed basement comprising the Kimberley Craton; and mapping major lithospheric structures within the craton and adjacent orogenic belts.

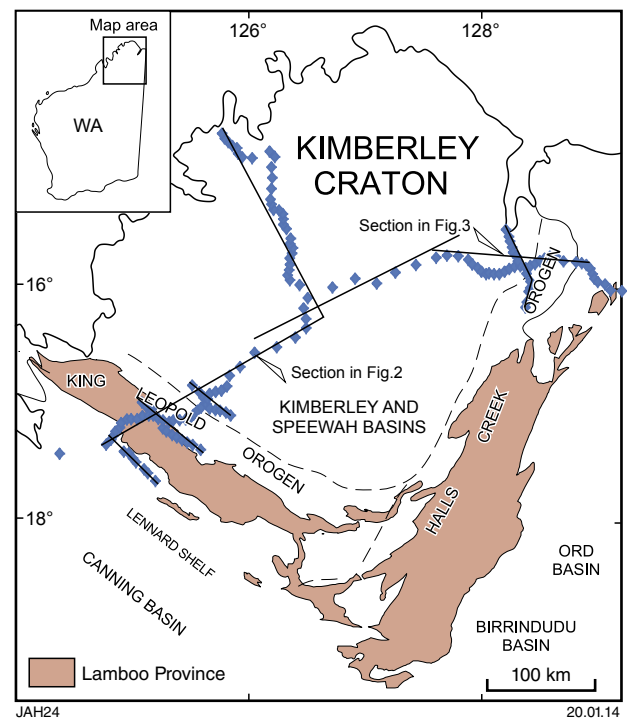
The MT method is a deep-penetrating, natural source, electromagnetic technique that provides information on the electrical conductivity structure of the Earth's crust and upper mantle. Data were acquired at 155 sites and electrical conductivity variations have been derived along eight 2D profiles that cross the craton and the adjacent King Leopold Orogen and Halls Creek Orogen (Fig. 1).

This was followed by west-dipping subduction, collision, and suturing of the Kimberley Craton with the North Australian Craton (represented in the HCO by the eastern zone of the Lamboo Province) during the 1835–1810 Ma Halls Creek Orogeny (Sheppard et al., 2001). During the course of orogenesis, at c. 1835 Ma, sediments derived from the tectonically active HCO were deposited into a retro-arc foreland basin, the Speewah Basin, followed by deposition of sand-dominated sediments and basaltic magmatism in the shallow-marine Kimberley Basin. These were intruded by the 1797 Ma Hart Dolerite. The Kimberley Basin and Lamboo Province are overlain by siliciclastic rocks of the c. 1200 Ma Carr Boyd Group in the northeast HCO. The c. 560–530 Ma King Leopold Orogeny marks dextral transpression along northwest-striking shear zones (Tyler and Griffin, 1990).

### Regional geology

The Kimberley Craton in Western Australia is one of several crustal blocks that together form the Archean to Proterozoic North Australian Craton (NAC, Cawood and Korsch, 2008). The Kimberley Craton underlies the Paleoproterozoic Speewah and Kimberley Basins. It has been proposed that an Archean Kimberley Craton was a stable root against which the adjacent Proterozoic Halls Creek Orogen (HCO) and King Leopold Orogen (KLO) were deformed or, alternatively, that these orogens extend beneath the Kimberley Basin (Gunn and Meixner, 1998; Downes et al., 2007).

The Paleoproterozoic tectonic history of the Kimberley is largely preserved in the HCO (east Kimberley) and KLO (west Kimberley), which are together known as the Lamboo Province (Fig. 1). The evolution of the Lamboo Province involved a series of collision and accretion events in the period between 1870 and 1840 Ma, culminating in the c. 1835 Ma Halls Creek Orogeny, marking collision of the Kimberley and North Australian Cratons.



**Figure 1.** Location map showing the positions of MT stations (blue symbols), modelled cross sections (black lines) and the major geological entities in the Kimberley area

- 1 Consultant, Wakefield, Quebec, Canada
- 2 Centre for Exploration Targeting, The University of Western Australia, 35 Stirling Highway, Crawley WA 6009
- 3 Moombarriga Geoscience, 32 Townshend Road, Subiaco WA 6008
- 4 Centre for Petroleum Geoscience and CO<sub>2</sub> Sequestration, The University of Western Australia, 35 Stirling Highway, Crawley WA 6009

The Precambrian rocks of the Kimberley are unconformably overlain by Phanerozoic sedimentary rocks that in the east comprise the Bonaparte, Ord and Canning Basins.

## Data processing

The MT data were processed using modern, robust, remote-referencing techniques. Prior to 2D modelling the data were analysed for static shift, dimensionality, and geoelectric strike direction. Electrical conductivity variations in the crust and upper mantle were derived using 2D inverse modelling. As the region is structurally complex, models were generated at different strike angles to observe how variations in the preferred geoelectric strike direction influence the inversion and to determine the most accurate 2D representation of the subsurface beneath the profile.

## Interpretation and discussion

The 2D images of electrical conductivity variations along two profiles are shown in Figures 2 and 3. Important results are:

- the Kimberley Basin sedimentary and volcanic succession is a thin conductive unit with a maximum thickness of 5 km. Phanerozoic rocks are also conductive
- the upper crust is predominantly highly resistive (greater than 10 000 ohm-m), consistent with laboratory measurements for crystalline rocks and with values observed in stable Archean cratons worldwide

- the upper crust is cut by several less resistive, steeply dipping structures. These structures extend to lower crust depths, and may extend deeper; however, the presence of a lower crustal conductor (described below) masks their response
- at the southwestern margin of the Kimberley Basin, there appear to be important along-profile conductivity signatures that define boundaries between different structural blocks. Notable examples are the deformed boundary between the Kimberley Basin and KLO and the northeastern boundary of the Canning Basin
- the most significant variations observed in the electrical resistivity models are across the eastern margin of the Kimberley Basin, where a robust northwestward dipping resistive feature is interpreted as ancient subducted lithosphere
- the lower crust is conductive, and the depth to its base is in reasonable agreement with Moho depth estimates from seismic data of between 38 and 45 km. Where it is resistive this correlates closely with the crustal block boundaries identified based on potential field data (Gunn and Meixner, 1998).

## Acknowledgements

We thank Ray Addenbrooke for his assistance in the field; pastoralists at Kimberley Downs, Napier Downs and Mount House Stations; Department of Parks and Wildlife rangers at Silent Grove, Windjana Gorge and Mitchell Falls; and the field crew: Nick Mann, Cody Graco, Dean Clinknick and Christian Anzenhofer.

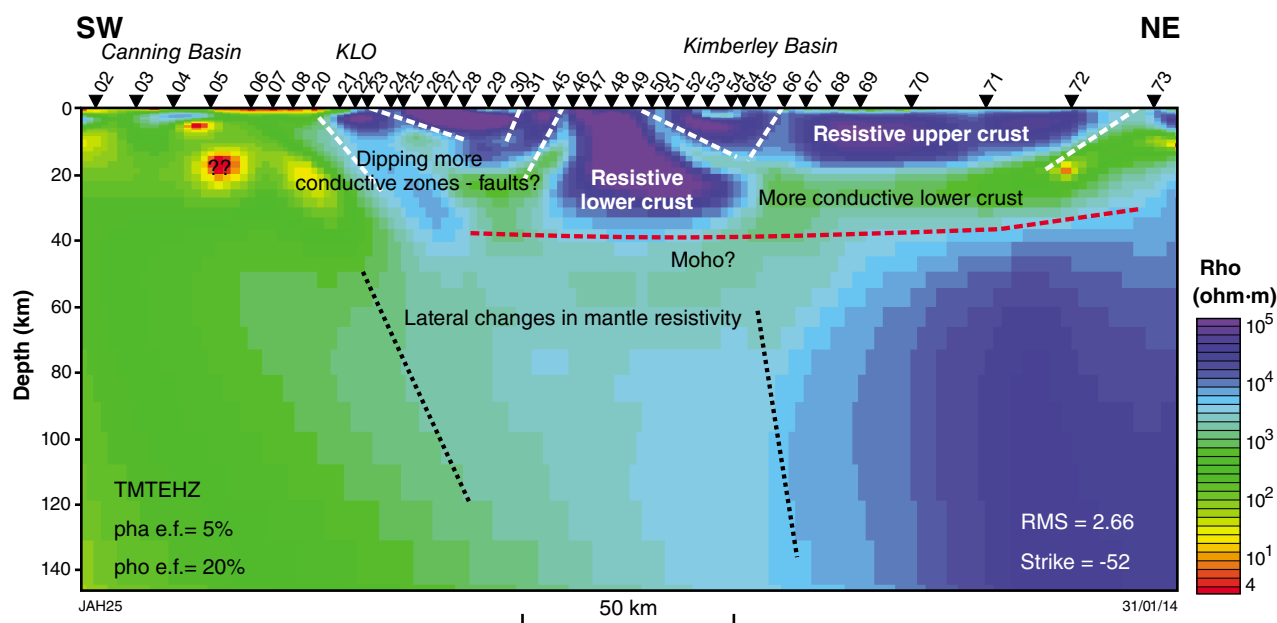
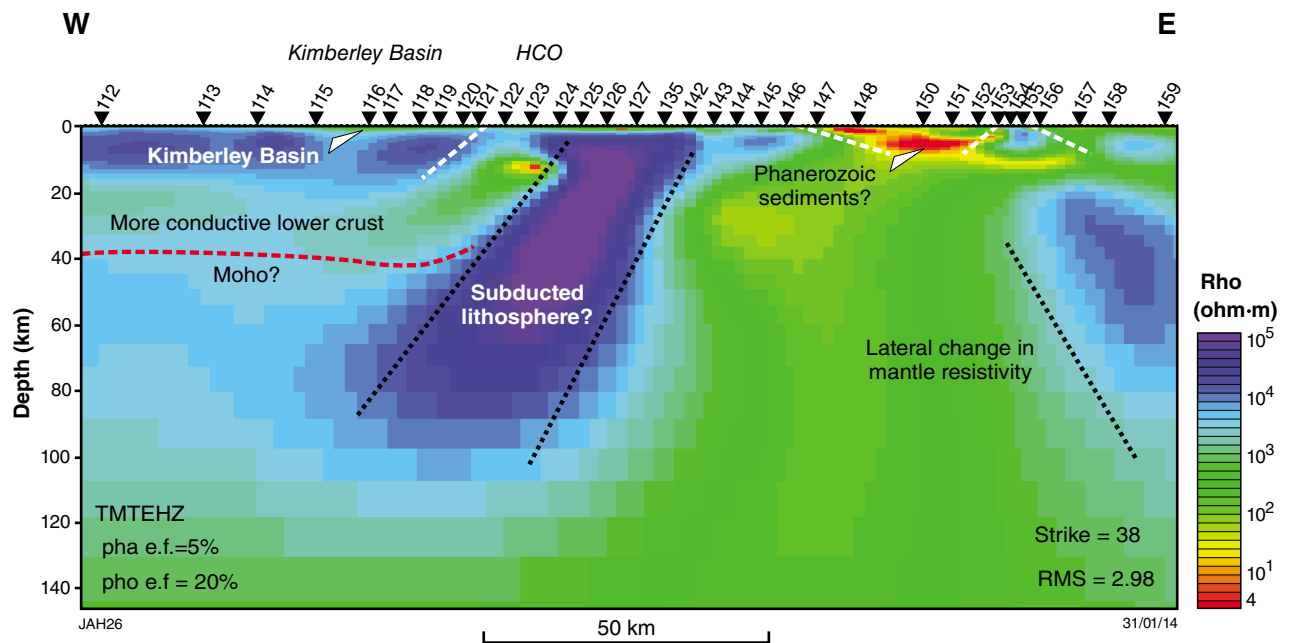


Figure 2. The preferred 2D model across the southern and western margin of the Kimberley Craton and the RMS values for each site along the profile



**Figure 3.** The preferred 2D model along the central and northeastern margin of the Kimberley Craton and the RMS values for each site along the profile

## References

- Cawood, PA and Korsch, RJ 2008, Assembling Australia: Proterozoic building of a continent: *Precambrian Research*, v. 166, p. 1–38.
- Downes, PJ, Griffin, BJ and Griffin, WL 2007, Mineral chemistry and zircon geochronology of xenocrysts and altered mantle and crustal xenoliths from the Aries micaceous kimberlite: constraints on the composition and age of the central Kimberley Craton, Western Australia: *Lithos*, v. 93, p. 175–198.
- Gunn, PJ and Meixner AJ 1998, The nature of the basement to the Kimberley Block, Northwestern Australia: *Exploration Geophysics*, v. 29, no. 4, p. 506–511.
- Sheppard, S, Griffin, TJ, Tyler, IM and Page, RW 2001, High- and low-K granites and adakites at a Palaeoproterozoic plate boundary in northwestern Australia: *Journal of the Geological Society, London*, v. 158, p. 547–560.
- Tyler, IM and Griffin, TJ 1990, Structural development of the King Leopold Orogen, Kimberley region, Western Australia: *Journal of Structural Geology*, v. 12, p. 703–714.

# Crustal structure and mineral prospectivity of the west Kimberley

by

MD Lindsay<sup>1\*</sup>, ARA Aitken<sup>1</sup>, MC Dentith<sup>1</sup>, JA Hollis and IM Tyler

The King Leopold Orogen and Lennard Shelf together make up the west Kimberley region, located in the north of Western Australia (Fig. 1a). The crustal architecture and geodynamic history of this region is investigated via interpretation of regional gravity and magnetic data. Three forward modelled sections detail the subsurface structures, including those that potentially reach the Moho. Crustal-scale structures separate regions of different geophysical and geological character and may provide controls on the formation of the oldest geological units. Rock units and structures important for mineral prospectivity are identified, including mantle-tapping fluid pathways, dilational fault jogs, fault intersections and areas of structural complexity, and are used in prospectivity analysis based on the ‘mineral systems approach’.

The King Leopold Orogen and Lennard Shelf form a roughly 360 by 180 km region striking east-southeast that separates the northern margin of the Canning Basin from the southern margin of the Kimberley Basin (Fig. 1a). The King Leopold Orogen records a series of Proterozoic tectonic events, including the 1870–1850 Ma Hooper Orogeny, c. 1835 Ma Halls Creek Orogeny, the <1400–1000 Ma Yampi Orogeny and the c. 560 Ma King Leopold Orogeny (Tyler and Griffin, 1990; Sheppard et al., 2012). The Paleoproterozoic King Leopold Orogen consists of two distinct tectonic regions: (i) deformed sedimentary and mafic volcanic rocks of the Paleoproterozoic Kimberley Basin; and (ii) layered mafic and ultramafic sills, I-type granites, metasedimentary rocks, felsic volcanic rocks and migmatites of the Lamboo Province (Fig. 1b). To the south of the King Leopold Orogen the Lennard Shelf strikes parallel and comprises Frasnian to Famennian (Late Devonian) reef complexes (Playford et al., 2009) overlain by Carboniferous to Permian glaciogene rocks.

## Geophysical interpretation

Structural interpretation of aeromagnetic data was used to better understand the tectonic evolution and large-scale structural architecture of the King Leopold Orogen

and Lennard Shelf (Fig. 1c). Gravity data were useful in delineating large-scale domains and structure, although, with lower resolution, they were used more sparingly than the magnetic data. Crustal-scale architecture was analysed and constrained via 2.5D magnetic and gravity forward modelling of profiles 1, 2 and 3 (Figs 1c, d). This work suggests: (i) the Paperbark Supersuite batholith is between about 6 and 12 km thick; and (ii) the Carson Volcanics occupies a widespread layer up to 1.5 km thick, significantly more than the 720 m previously suggested by Griffin et al. (1993).

Basement-penetrating faults are identified, including east-trending south-up reverse faults beneath the Phillips Range anticline. These faults indicate an influence on the magmatic system as they show a clear association with Hart Dolerite sills. Crustal-scale northeast-trending discontinuities likely representing fundamental crustal-to lithospheric-scale boundaries are also interpreted. The northeast-trending structures coincide with the approximate style and location of major boundaries identified by Gunn and Meixner (1998). Differences in crustal character along strike point to the influence of these faults in providing regional-scale structural control within the study area, and have implications for mineral prospectivity.

## Mineral systems analysis

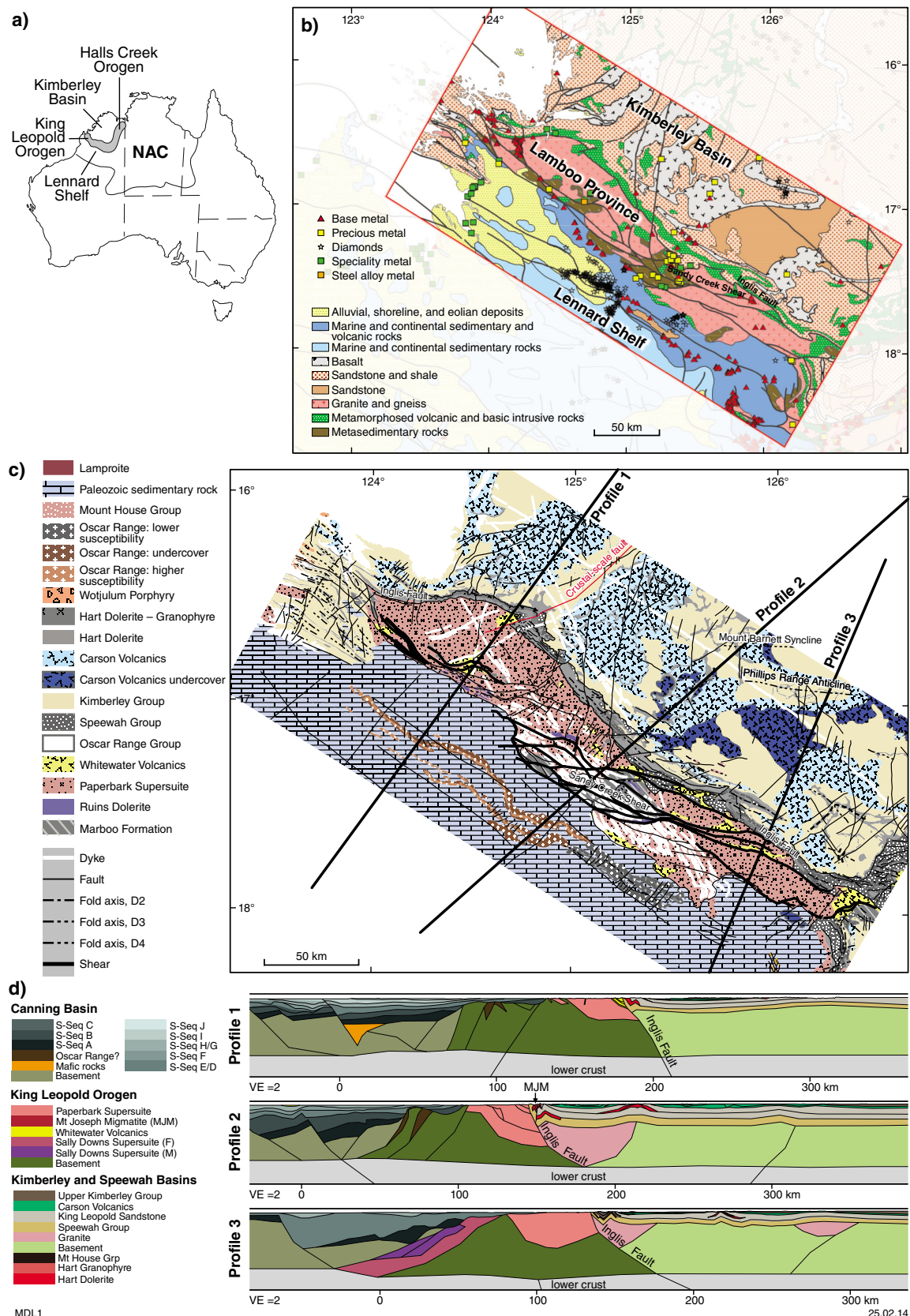
The mineral systems approach is used to guide prospectivity mapping by recognizing that ore deposits are small expressions of much larger Earth processes and systems that focus mass and energy flux at multiple scales (Wyborn et al., 1994). Fundamental to the mineral systems approach is the identification and representation of metal sources, fluid transport mechanisms, and traps. Predictor maps act as proxies for the source/transport/trap mineral system components and include parameters such as distance to a particular geological feature, locations of rheological and chemical contrast, structural complexity and locations of mantle-tapping structures. Predictor maps are combined using a knowledge-driven inference framework to produce prospectivity maps and incorporate expert knowledge of ore deposit formation through assigned weightings and confidence values (Porwal et al., 2003).

Regional prospectivity analysis of the west Kimberley (Fig. 2) has been undertaken using the results of

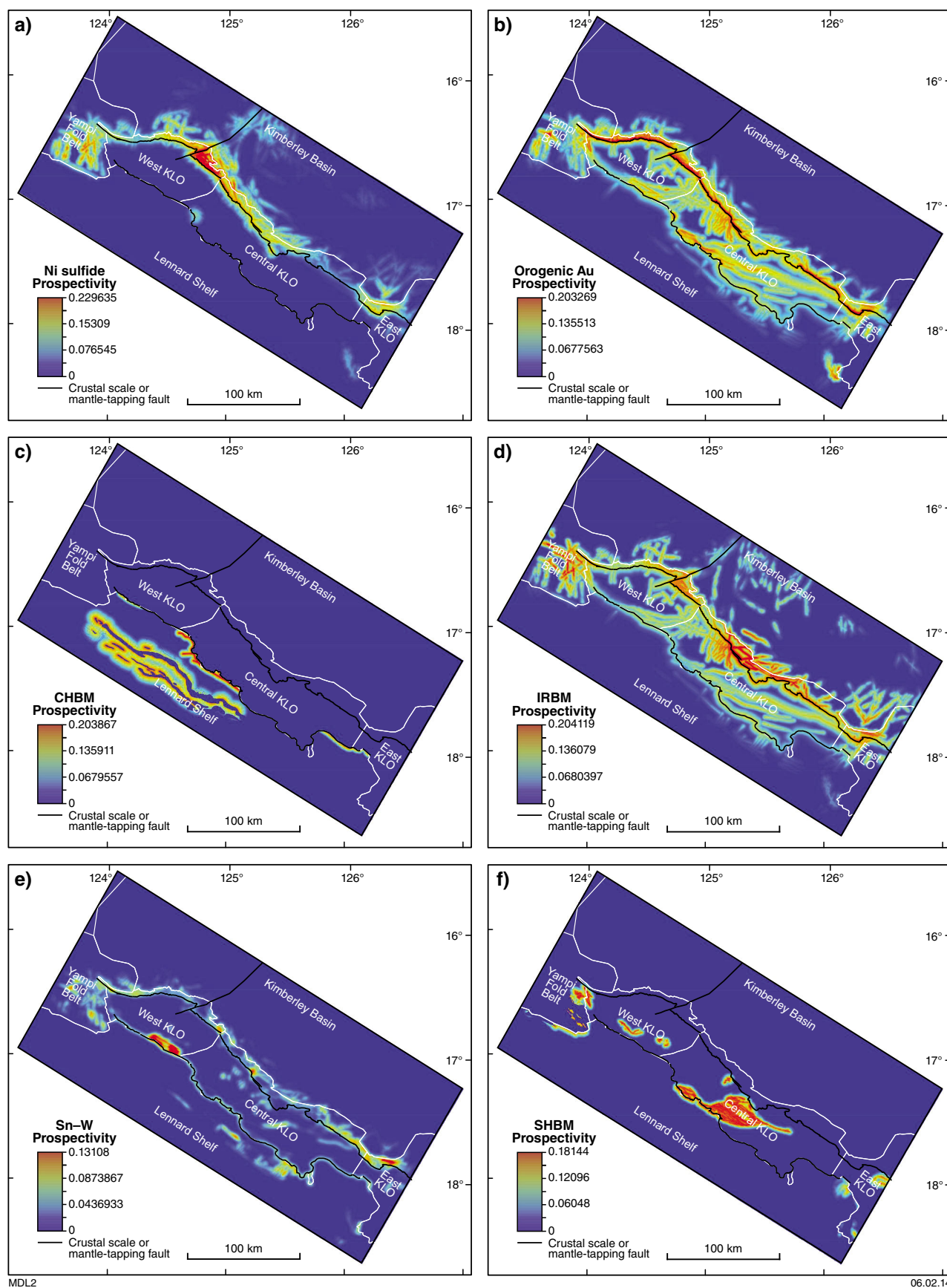
<sup>1</sup> Centre for Exploration Targeting, The University of Western Australia, 35 Stirling Highway, Crawley WA 6009

\* Corresponding author: mark.lindsay@uwa.edu.au





**Figure 1.** a) Location of the King Leopold Orogen and Lennard Shelf in Australia (after Tyler et al., 2012); b) Simplified geological map showing location of mineral occurrences; c) Structural interpretation of the west Kimberley showing different stratigraphic units and geological structures. Note the location of a newly identified crustal-scale fault (highlighted in red). Also shown are the locations of the forward modelled profiles, the interpretation of which are shown in d); d) Geological interpretation of sections jointly forward modelled from magnetic and gravity data. Sally Downs Supersuite (F) and (M) units represent felsic and mafic components respectively



**Figure 2.** Final prospectivity maps for: a) nickel sulfide; b) orogenic gold; c) carbonate-hosted base metals (CHBM); d) intrusion-related base metals (IRBM); e) tin-tungsten (Sn-W); and f) stratiform-hosted base metals (SHBM). The Inglis Fault and the newly identified crustal-scale fault (refer Fig. 1c) are shown to be associated with higher levels of mineral prospectivity across the nickel sulfide, orogenic gold, IRBM and tin-tungsten mineral systems

geophysical structural interpretation and mineral systems-based prospectivity modelling. Predictor maps were generated from the magnetic and gravity interpretations, forward modelling and existing geological data. The mineral systems analysed are: nickel sulfide (Fig. 2a); orogenic gold (Fig. 2b); carbonate-hosted base metals (CHBM; Fig. 2c); intrusion-related base metals (IRBM) including iron-oxide-copper-gold or porphyry deposits (Fig. 2d); tin-tungsten (Fig. 2e); and stratiform-hosted base metals (SHBM; Fig. 2f).

Analysis of nickel sulfide mineral systems indicates that the Inglis Fault and Yampi Fold Belt present higher nickel sulfide prospectivity. Carbonate-hosted base metal prospectivity is restricted to regions overlying basement highs in the Lennard Shelf. A buried northwest extension of the Oscar Range interpreted from geophysical data is also identified as a region of high carbonate-hosted base metal prospectivity. High gold prospectivity is mostly associated with the Inglis Fault, the Yampi Fold Belt and the central portion of the King Leopold Orogen. The centre, west and east of the King Leopold Orogen and parts of the Yampi Fold Belt show small regions of high stratiform-hosted base metal prospectivity. The northwest and east parts of the King Leopold Orogen show small regions of high tin-tungsten prospectivity. Prospectivity for intrusion-related base metal mineralization is widespread, though highest in the Yampi Fold Belt (due to the Wotjulum Porphyry), and in the northern central part of the King Leopold Orogen.

## References

- Aitken, ARA, Dentith, MC, Evans, SF, Gallardo, LA, Joly, A, Thiel, S, Smithies, RH and Tyler, IM 2013, Imaging crustal structure in the west Musgrave Province from magnetotelluric and potential field data: Geological Survey of Western Australia, Report 114, 81p.
- Geological Survey of Western Australia, 2010, MINEDEX Database: Department of Mines and Petroleum, Western Australia, <www.dmp.wa.gov.au/datacentre>, viewed 2010.
- Griffin, TJ, Tyler, IM and Playford, PE 1993, Lennard River, Western Australia: Geological Survey of Western Australia, 1:250 000 Geological Series Explanatory Notes (3rd ed.), 56p.
- Gunn, PJ and Meixner, AJ 1998, The nature of the basement to the Kimberley Block, Northwestern Australia: Exploration Geophysics, v. 29, no. 4, p. 506–511.
- Playford, PE, Hocking, RM and Cockbain, AE 2009, Devonian reef complexes of the Canning Basin, Western Australia: Geological Survey of Western Australia, Bulletin 145, 444p.
- Porwal, A, Carranza, EJM and Hale, M 2003, Knowledge-driven and data-driven fuzzy models for predictive mineral potential mapping: Natural Resources Research, v. 12, no. 1, p. 1–25.
- Sheppard, S, Page, RW, Griffin, TJ, Rasmussen, B, Fletcher, IR, Tyler, IM, Kirkland, CL, Wingate, MTD, Hollis, JA and Thorne, AM 2012, Geochronological and isotopic constraints on the tectonic setting of the c. 1800 Ma Hart Dolerite and the Kimberley and Speewah Basins, northern Western Australia: Geological Survey of Western Australia, Record 2012/7, 28p.
- Tyler, IM and Griffin, TJ, 1990, Structural development of the King Leopold Orogen, Kimberley region, Western Australia: Journal of Structural Geology, v. 12, no. 5–6, p. 703–714.
- Tyler, IM, Hocking, RM and Haines, PW 2012, Geological evolution of the Kimberley region of Western Australia: Episodes, v. 35, no. 1, p. 298–306.
- Wyborn, LAI, Heinrich, CA and Jaques, AL 1994, Australian Proterozoic mineral systems: essential ingredients and mappable criteria: Australasian Institute of Mining and Metallurgy, Annual Conference, Darwin, 1994, Proceedings, p. 109–115.



# Shake, rattle and gold

by

SP Johnson and FJ Korhonen

The Capricorn Orogen is a 1000 km-long, 500 km-wide region of variably deformed meta-igneous and metasedimentary rocks located between the Pilbara and Yilgarn Cratons (Fig. 1). The orogen records the punctuated Paleoproterozoic assembly of the West Australian Craton during the 2215–2145 Ma Ophthalmian and 2005–1950 Ma Glenburgh Orogenies, as well as nearly two billion years of subsequent intraplate reworking (Sheppard et al., 2010). A recent deep-crustal seismic-reflection survey across the orogen has revealed the deep-crustal structure of the orogen, providing insights into the timing and style of both the collisional and subsequent continental reworking events (Johnson et al., 2011; 2013).

The orogen hosts a variety of mineral deposit types — including orogenic lode-gold (e.g. Paulsens, Mount Olympus, Glenburgh and Star of Mangaroon) and base metals (e.g. Ashburton Downs, Abra and Glen Florrie) — the majority of which are located on, or close to, major lithospheric-scale structures (Johnson et al., 2013). However, the timing and geological setting of the mineralizing events are poorly constrained, as is their relation to multiple movements on the major lithospheric structures and their splays. To increase the prospectivity of the region and provide explorers with a more focused set of exploration parameters, a better understanding of the structural evolution of the major lithospheric fault zones is required.

## The Collins Fault

The Collins Fault is a major brittle–ductile structure that outcrops in the northern part of the Gascoyne Province (Fig. 1). The main fault zone is ~1 km wide, although associated brittle–ductile structures are developed at various scales up to ~30 km away from the main fault.

At the outcrop-scale the main fault zone, as well as the ancillary structures, are defined by thin, subparallel ‘faults’ 1–5 mm wide, which show millimetre- to centimetre- (and locally metre) scale offsets (Fig. 2a). Away from the main fault zone, different generations of ancillary faults are developed in various orientations, each set with opposing sinistral and dextral offsets (Fig. 2a). At some localities up to five different generations of faults are recorded. Most generations show evidence of early ductile deformation with a variably developed S–C fabric (Fig. 2a), which is overprinted by brittle deformation. Many of the faults are

associated with en echelon quartz veins (Fig. 2b), some of which have been overprinted by successive periods of ductile and brittle deformation.

## Microstructural evolution

The effects of deformation are best observed in faults that deform fine- to medium-grained, equigranular, leucocratic granites and medium-grained, porphyritic granites of the 1680–1620 Ma Durlacher Supersuite. Fault zones of different generations show a similar microstructural evolution. Both quartz and feldspar grains show undulatory extinction and extensive subgrain development. In the porphyritic granites, originally tabular K-feldspar grains now appear with rounded edges (Fig. 2c) as the margins of feldspar porphyroclasts are recrystallized to smaller grains. Muscovite also shows extensive subgrain development. It is commonly bent and reoriented, and along with the recrystallized K-feldspar porphyroclasts in the porphyritic granites, forms a new fabric (S fabric) commonly at 45° to fault margins (Fig. 2a). This early ductile deformation is characterized by low- to medium-grade protomylonitic fabrics.

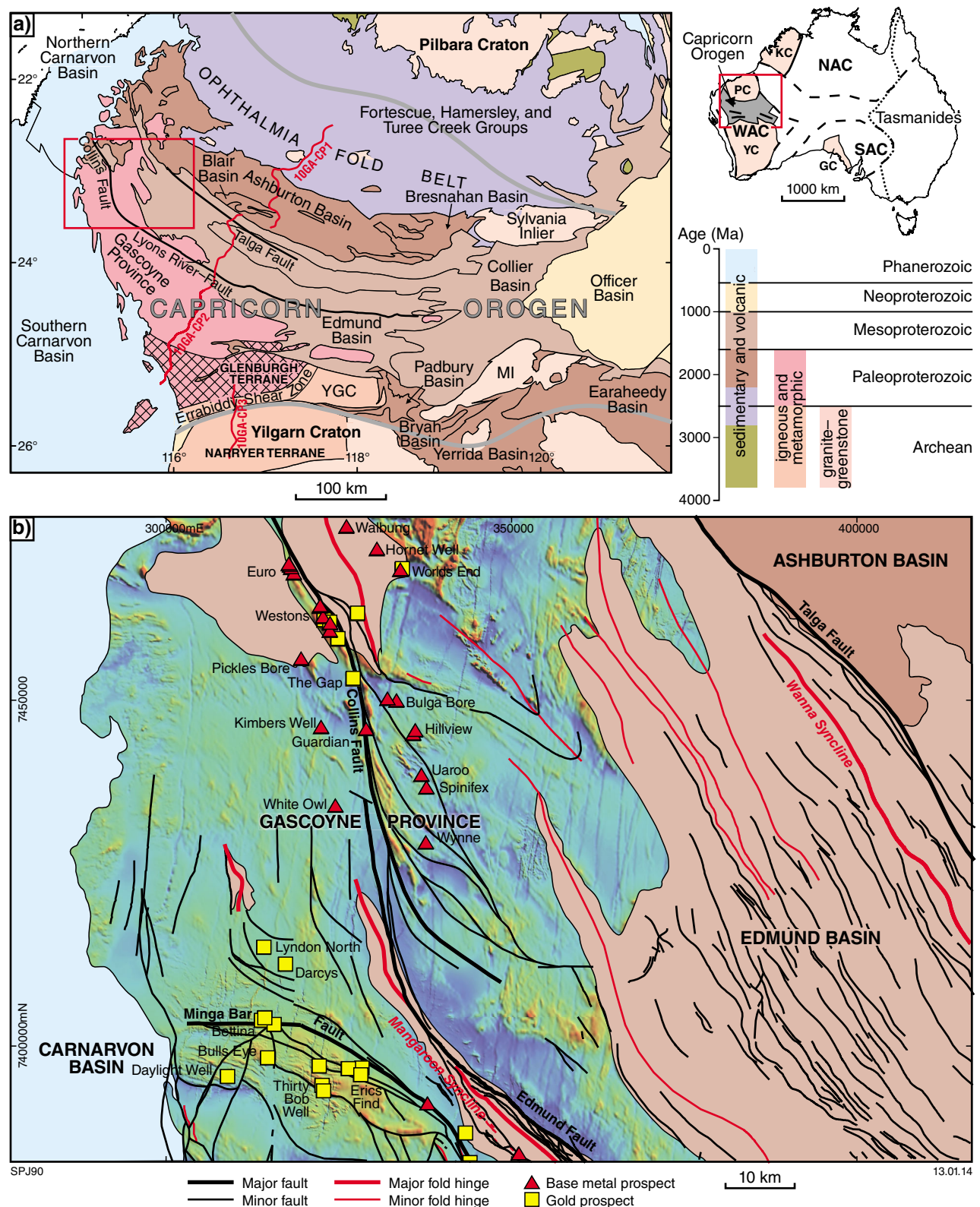
These deformation features are overprinted by an intense, very fine grained quartz–sericite-rich cataclasite that forms seams and bands parallel to the fault margins (C fabric). There is little variation in grain size and the margins of the cataclasite are diffuse with the host, commonly leaving isolated lenses of protomylonite surrounded by very fine grained cataclasite (Area A in Fig. 2c).

The textural evolution of these faults implies a rapid switch from a ductile to a brittle regime, most likely during an increase in strain rate and accompanying rock failure. The transition to a brittle regime would have been accompanied by massive energy release in the form of an earthquake.

## Earthquakes, faults and gold mineralization

Recent experiments have shown that significant amounts of gold can be precipitated during earthquakes (Weatherly and Henley, 2013). The rapid decrease in pressure within fault jogs during faulting and earthquake activity causes

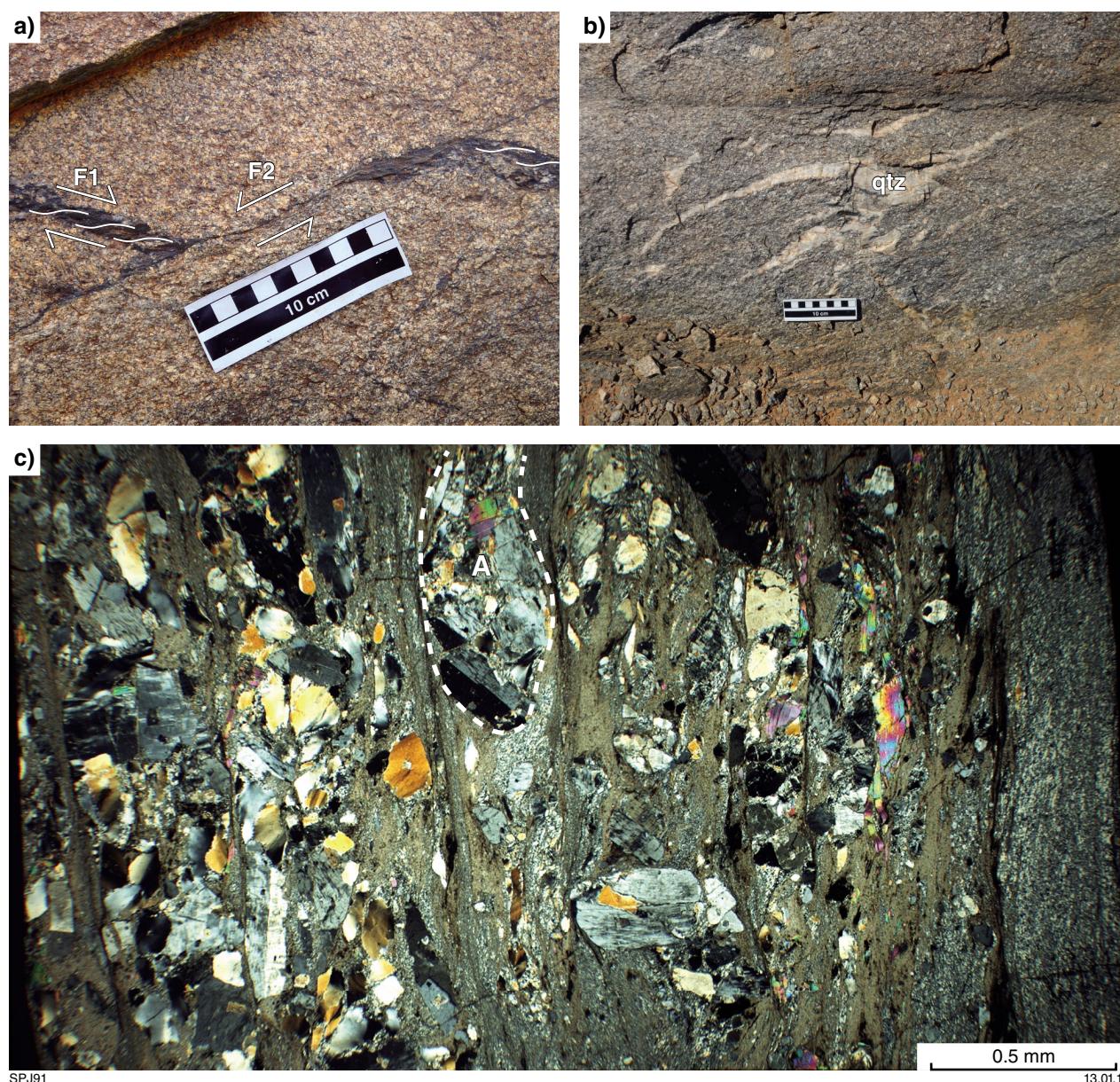




**Figure 1.** a) Elements of the Capricorn Orogen and surrounding cratons and basins, showing the seismic-reflection profiles. The thick grey lines delimit the northern and southern boundaries of the Capricorn Orogen. Red box shows location of Figure 1b. Abbreviations: GC — Gawler Craton; KC — Kimberley Craton; MI — Marymia Inlier; NAC — North Australian Craton; PC — Pilbara Craton; SAC — South Australian Craton; WAC — West Australian Craton; YC — Yilgarn Craton; YGC — Yarlalweelor Gneiss Complex

b) Total magnetic intensity aeromagnetic image of the northern Gascoyne Province showing the location of the major faults and folds, and gold and base metal deposits





**Figure 2.** a) Outcrop photograph of two fault sets. The earliest set (F1) shows a well-developed S–C fabric with a dextral offset of unknown magnitude. The later set (F2) are much thinner and sinistrally offset the F1 faults by about 10 cm

b) En echelon quartz veins within a fine-grained, equigranular and leucocratic monzogranite of the 1680–1620 Ma Durlacher Supersuite

c) Photomicrograph (under crossed-polarized light) across part of a brittle–ductile fault zone within fine- to medium-grained porphyritic monzogranite of the 1680–1620 Ma Durlacher Supersuite. Note the isolated lenses (e.g. Area A) and discontinuous layers (left side of image) of protomylonite surrounded by very fine grained cataclasite

flash vapourization of fluid, and minerals (including gold) are rapidly precipitated, commonly as gold-bearing quartz veins. Weatherley and Henley (2013) also demonstrated that thousands of small earthquakes in a fault zone are more likely to form a large gold deposit than a single large earthquake.

The Collins Fault zone has great potential for gold and base metal mineralization as it shows evidence for cyclical faulting and earthquake activity, including the precipitation of fault-related quartz veins. Although no recent detailed geochemical investigations have been conducted on rocks within this zone, numerous gold and base metal prospects (e.g. Kimbers Well, Guardian, White Owl and Wynne) lie on, or close to, the Collins Fault zone (Fig. 1). Reconnaissance rock chip assaying by Resolute Ltd in the late 1990s (Keillor, 1996) returned anomalous gold and base metal results with up to 1090 ppb Au and 4% Cu at the Kimbers Well main prospect, 0.35 g/t Au and 2.5% Cu at the Guardian Prospect, and 0.15 g/t Au and 14.9% Cu at the White Owl prospect. At the time of assaying, the cause of these anomalies was not known and the tenements were subsequently surrendered.

The petrographic and tectonic observations presented here provide a cause for the gold and base metal anomalies, which may be associated with the flash precipitation of gold-bearing quartz veins during multiple movements on the Collins Fault and ancillary structures. Understanding the tectonic setting of gold and base metal mineralization in this region therefore provides a focused exploration strategy that should concentrate on the assaying of fault-related quartz veins, as well as detailed stream sediment sampling across the fault zone and ancillary structures.

## References

- Johnson, SP, Thorne, AM and Tyler, IM (editors) 2011, Capricorn Orogen seismic and magnetotelluric (MT) workshop 2011: extended abstracts: Geological Survey of Western Australia, Record 2011/25, 120p.
- Johnson, SP, Thorne, AM, Tyler, IM, Korsch, RJ, Kennett, BLN, Cutten, HN, Goodwin, J, Blay, OA, Blewett, RS, Joly, A, Dentith, MC, Aitken, ARA, Holzschuh, J, Salmon, M, Reading, A, Heinson, G, Boren, G, Ross, J, Costelloe, RD and Fomin, T 2013, Crustal architecture of the Capricorn Orogen, Western Australia and associated metallogeny: Australian Journal of Earth Sciences, v. 60, no. 6–7, p. 681–705.
- Keillor, B 1996, Kimbers Well Project (E08/846, E08/847, E08/862, E08/863, E08/864); Annual Report; Resolute Ltd: Geological Survey of Western Australia, Statutory mineral exploration report, A49993 (unpublished).
- Sheppard, S, Johnson, SP, Wingate, MTD, Kirkland, CL and Pirajno, F 2010, Explanatory Notes for the Gascoyne Province: Geological Survey of Western Australia, Perth, Western Australia, 336p.
- Weatherly, DK and Henley, RW 2013, Flash vaporization during earthquakes evidenced by gold deposits: Nature Geoscience, v. 6, no. 4, p. 294–298.



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