

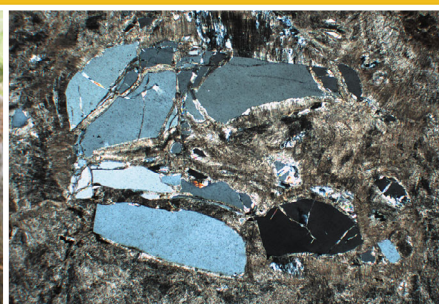


Government of **Western Australia**  
Department of **Mines and Petroleum**

**RECORD 2011/2**

# **GSWA 2011 EXTENDED ABSTRACTS**

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



**Geological Survey of Western Australia**



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

**Record 2011/2**

# **GSWA 2011 EXTENDED ABSTRACTS**

## **Promoting the prosectivity of Western Australia**

**24 February 2011**

**Perth 2011**



**Geological Survey of  
Western Australia**

**MINISTER FOR MINES AND PETROLEUM**  
**Hon. Norman Moore MLC**

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

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

**REFERENCE**

**The recommended reference for this publication is:**

- (a) For reference to an individual contribution:  
Johnson, SP, Sheppard, S, Thorne, AM, Rasmussen, B, Fletcher, IR, Wingate, MTD and Cutten, HN 2011,  
The role of the 1280–1250 Ma Mutherbuckin Tectonic Event in shaping the crustal architecture and mineralization  
history of the Capricorn Orogen: Geological Survey of Western Australia, Record 2011/2, p. 1–3.
- (b) For reference to the publication:  
Geological Survey of Western Australia 2011, GSWA 2011 extended abstracts: promoting the  
prospectivity of Western Australia: Geological Survey of Western Australia, Record 2011/2, 33p.

**National Library of Australia Card Number and ISBN 978-1-74168-361-5 (Print); 978-1-74168-360-8 (PDF)**

**Published 2011 by Geological Survey of Western Australia**

**This Record is published in digital format (PDF) and is available online at [www.dmp.wa.gov.au/GSWApublications](http://www.dmp.wa.gov.au/GSWApublications).**

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## Welcome to GSWA 2011

**GSWA 2011**, the Geological Survey of Western Australia's Open Day, provides an opportunity for geoscientists from the resources industry, researchers, and those involved in land use planning, to get an update on GSWA's latest activities and products through poster displays and technical presentations.

In 2011, the Western Australian Government's Exploration Incentive Scheme (EIS), managed by GSWA, continues to provide funding for airborne magnetic and radiometric surveys covering significant areas of the Eucla and Canning Basins, as well as gravity surveys in the Gascoyne and central Yilgarn regions. Images of surveys released recently will be on display, some of which are quite spectacular.

Other programs being funded through EIS will also feature prominently. Round 3 of the Co-funded Exploration Drilling Program is aimed at financially assisting mineral and energy explorers who are using innovative targeting methodologies in underexplored areas. Images from the Capricorn deep-crustal seismic survey crossing the margins of the Pilbara and Yilgarn Cratons and the Gascoyne Province will also be released.

Our ongoing programs will be highlighted in the extensive poster displays as well as the technical presentations. GSWA geoscientists will be available throughout the day to discuss the details of the geology and mineralization of their project areas and of the State as a whole, as well as other aspects of the Survey's activities, products, and services. GSWA's innovative tool — *GeoMap.WA* — that allows users without GIS software on their computers to view, query, print, and integrate GIS data will be in operation. We have again included poster displays from other geoscience agencies and research groups in Western Australia, including CSIRO, the Centre for Exploration Targeting (CET), and the Centre for 3D Mineral Mapping (C3DMM).

Your feedback on the Survey's work is welcome.

Rick Rogerson  
Executive Director  
February 2011

# GSA 2010 SEMINAR PROGRAM — 24 FEBRUARY 2011

## FREMANTLE

**8.15 – 8.45      REGISTRATION**

**8.45 – 9.00      Welcome and opening remarks**

*Hon Norman Moore, MLC,  
Minister for Mines and Petroleum*

**9.00 – 9.25**      The role of the 1280–1250 Ma Matherbakin Tectonic Event in shaping the crustal architecture and mineralization history of the Capricorn Orogen

*Simon Johnson*

**9.25 – 9.50**      Mineralized basement rocks in the Egerton Inlier and Woodlands Dome: are they correlatives of the Padbury Group?

*Alan Thorne*

### ***Morning tea 9.50 – 11.00***

**11.00 – 11.25**      Lu–Hf isotopes: implications for understanding crustal evolution



*Chris Kirkland*

**11.25 – 11.50**      Coal — new opportunities in the 21st century



*Alan Millar*

**11.50 – 12.15**      A fresh look at the regolith of the central Gascoyne region with implications for mineral exploration



*Carmen Krapf*

### ***Lunch 12.15–1.45***

**1.45 – 2.10**      The geological history and gold prospectivity of the West Arunta Orogen, Western Australia



*Aurore Joly (CET)*

**2.10 – 2.35**      The Hyden–Norseman magnetotelluric survey



*Luis Gallardo and  
Mike Dentiith (CET)*

**2.35 – 3.00**      Fine-fraction gold chemistry of regolith from the East Wongatha area, eastern Yilgarn Craton



*Paul Morris*

### ***Afternoon tea 3.00 – 3.20***

**3.20 – 3.35**      Exploration Incentive Scheme co-funded drilling program



*Margaret Ellis*

**3.35 – 4.00**      Geochemical characteristics of the Alcurra Dolerite (Giles Event) and its extrusive equivalents in the Bentley Supergroup

*Heather Howard*

**4.00 – 4.30**      Crustal evolution of the Murchison Domain and implications for whole-of-Yilgarn tectonic models

*Martin Van Kranendonk*

### ***Sundowner 4.30 – 5.30***

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# The role of the 1280–1250 Ma Mutherbukin Tectonic Event in shaping the crustal architecture and mineralization history of the Capricorn Orogen

by

SP Johnson, S Sheppard, AM Thorne, B Rasmussen\*, IR Fletcher\*,  
MTD Wingate, and HN Cutten

The Capricorn Orogen in central Western Australia records the juxtaposition of the Archean Pilbara and Yilgarn Cratons to form the West Australian Craton over a time period of two hundred million years, followed by one billion years of episodic continental reworking and reactivation. The orogen includes the deformed margins of the Pilbara and Yilgarn Cratons, granitic and medium- to high-grade metamorphic rocks of the Gascoyne Province, and numerous variably deformed Proterozoic sedimentary basins, including the Mesoproterozoic Edmund and Collier Basins that sit unconformably on the province. Much of the orogen is a greenfields region. It is host to a variety of intrusion- or shear zone-related and sedimentary-hosted mineral deposits. However, owing to the long and episodic nature of intracontinental reworking, the controls on mineralization and the structural evolution of these deposits are poorly understood. Elucidating the architecture and timing of reworking events in the orogen with respect to mineralization is a critical step in greatly improving exploration targeting.

Since 2005, a systematic program of SHRIMP U–Pb dating of monazite and xenotime from low- to medium-grade metasedimentary rocks of the Gascoyne Province and sedimentary rocks from the overlying Edmund Basin, has begun to unravel the complex history of reworking in the region. These data, when combined with 1:100 000-scale mapping and the crystallization ages of magmatic zircons from the igneous rocks of the province, demonstrate the distinct, punctuated nature of these tectonomagmatic events as briefly explained below.

Following final suturing of the West Australian Craton during the 2005–1950 Ma Glenburgh Orogeny, the Gascoyne Province was subject to reworking during the 1820–1770 Ma Capricorn Orogeny, the 1680–1620 Ma Mangaroon Orogeny, the 1280–1250 Ma Mutherbukin Tectonic Event, the 1030–955 Ma Edmundian Orogeny, and the c. 570 Ma Mulka Tectonic Event. The overlying Edmund Basin was faulted and/or folded during the

Mutherbukin Tectonic Event, the Edmundian Orogeny, and the Mulka Tectonic Event. In this contribution we focus on the Mutherbukin Tectonic Event because of its potential to form hydrothermal mineral systems.

## Mutherbukin Tectonic Event

### Gascoyne Province

Mineral assemblages and tectonic fabrics related to the Mutherbukin Tectonic Event occur within a 50 km-wide corridor bounded by the Ti Tree and Chalba shear zones directly south of the Minnie Creek batholith. However, discrete narrow shear zones of this age are also present within, and to the north of, the Minnie Creek batholith.

The primary expression of this event is a strong, steeply dipping schistosity in metasedimentary rocks, and a widely developed foliation or gneissic banding within metamorphosed granites. The fabrics trend east-southeast and parallel the main structural elements of the province. Garnet and staurolite-bearing semi-pelitic schists are on the south side of the Minnie Creek batholith. The schists pass into upper amphibolite facies granitic gneisses that locally preserve evidence for in situ melting. Both the metasedimentary rocks and gneissic granites contain a strong, shallow east-plunging mineral lineation that is parallel to the hinges of variable-scale, shear-related folds. Abundant shear-sense indicators in both the schists and granitic gneisses reveal sinistral transtensional shear regimes.

Dating of metamorphic monazite mainly from garnet–staurolite schists at widely spaced localities provides a range of ages between c. 1280 and c. 1210 Ma, interpreted as the age of deformation and metamorphism.

### Edmund Basin

Field evidence for Mutherbukin-age deformation in the Edmund Group sedimentary rocks and underlying Mount Augustus Sandstone is more cryptic, because it is of very low metamorphic grade and restricted to narrow shear zones

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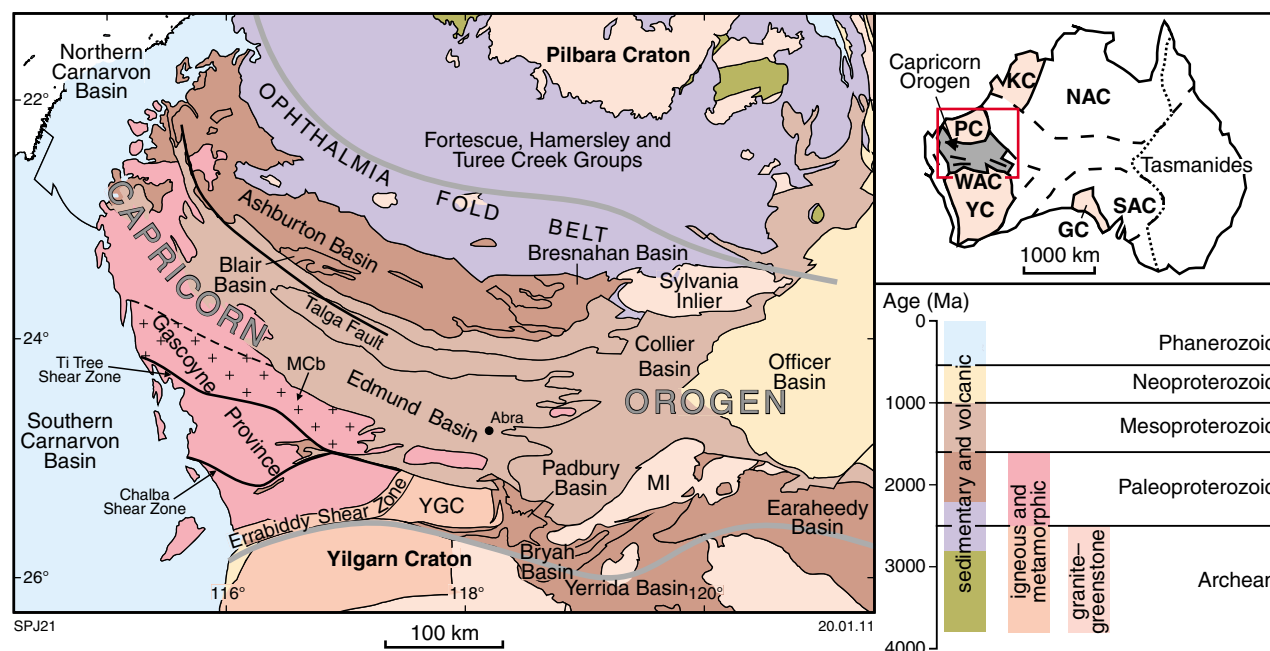


Figure 1. Elements of the Capricorn Orogen and surrounding cratons and basins; modified from Sheppard et al. (2010) and Martin and Thorne (2004). Abbreviations: YGC — Yarlswheel Gneiss Complex; MCb — Minnie Creek batholith; MI — Marymia Inlier; modified from Myers et al. (1996)

and faults that were reactivated during the Edmondian Orogeny and Mulka Tectonic Event. However, abundant Mutherbukin-aged hydrothermal monazite and xenotime within these sedimentary rocks indicates that they were subject to low-grade metamorphism and hydrothermal alteration during this event.

Abra is a major polymetallic Pb–Ag–Cu–Au deposit within the lower Edmund Group. The deposit has been interpreted as part of a hydrothermal breccia-pipe system related to localized magmatism possibly associated with the nearby Tangadee Rhyolite (Pirajno et al., 2009). The geochronology of the deposit and surrounding sedimentary host rocks is complex. Hydrothermal monazite and xenotime suggest that mineralization occurred at c. 1385 Ma (Rasmussen et al., 2010) but this date is about 150 Ma older than the Re–Os date of c. 1280 Ma obtained on pyrite from the deposit itself (Pirajno et al., 2010). The age of the pyrite is similar to that (at c. 1235 Ma) of concentrically zoned, possibly magmatic, xenotime extracted from the Tangadee Rhyolite (Rasmussen et al., 2010). Irrespective of these geochronological complexities, these ages all demonstrate that this part of the Edmund Basin underwent a prolonged period of low-grade metamorphism, hydrothermal activity, and faulting, at a time when low- to medium-grade metamorphism and deformation was also affecting the underlying Gascoyne Province basement.

## Architecture and mineralization

The Mutherbukin Tectonic Event may have been a relatively protracted intracontinental oblique strike-slip event, or series of events (c. 1385–1210 Ma), the driver of which is currently

unknown. During the event, episodic magmatism and near-continuous shearing and faulting were accompanied by regional-scale hydrothermal fluid flow. The geological, geochronological, and geophysical data demonstrate that the major Mutherbukin-aged structures in the Gascoyne Province basement extend into the overlying Edmund Basin, albeit at much lower metamorphic and structural grade. Although the structures themselves may not be mineralized, they are essential for ore formation because they provided pathways for mineralizing fluids from the middle (and possibly lower) to upper crust. Magmatism, faulting, and the transport of hydrothermal fluids, appear to have played a critical role in the formation of the Abra polymetallic deposit. The regional-scale distribution of Mutherbukin-age structures and associated hydrothermal fluid flow, potentially makes this one of the most important primary mineralization events in the Capricorn Orogen, and targeted exploration in this region may lead to significant discoveries.

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# Mineralized basement rocks in the Egerton Inlier and Woodlands Dome: are they correlatives of the Padbury Group?

by

AM Thorne, S Sheppard, SP Johnson, MTD Wingate, and HN Cutten

Low-grade, mostly metasedimentary rocks underlie the 1620–1465 Ma Edmund Group in the Egerton Inlier and Woodlands Dome, in the central Capricorn Orogen (Fig. 1). Rocks of the Egerton Inlier have a history of gold production dating back to the early part of the twentieth century, whereas those of the Woodlands Dome are associated with nearby Fe–Pb–Cu–Ba mineralization (Cooper et al., 1998).

Historically, these metasedimentary rocks have been correlated with the Paleoproterozoic Padbury Group, based on their lithologies and broad stratigraphic relationships (Muhling et al., 1978; Muhling and Brakel, 1985; Sheppard and Swager, 1999). Until now, there have been limited geochronological data to support these correlations, a situation worsened by the fact that the age of the Padbury Group is itself very poorly constrained. It has a maximum age of between 2000 and 1900 Ma (Windh, 1992; Nelson, 1997), based on the youngest detrital zircons from the Wilthorpe and Labouchere Formations in the lower to middle Padbury Group. The younger age limit is fixed at c. 1620 Ma, the maximum age of the unconformably overlying Edmund Group (Martin et al., 2005).

## Egerton Inlier

Rocks of the Egerton Inlier comprise low-grade metasiltstone and metasandstone, interlayered with lesser amounts of metadolerite, mafic schist, metaconglomerate and metadolostone. A sample of metasandstone (GSWA 156814) yielded detrital zircons as young as c. 1983 Ma and significant older components with c. 2725, 2297, 2171, and 2034 Ma (Wingate et al., written comm.). These rocks are intruded by non-foliated, biotite tonalite (GSWA 190685) that has yielded a SHRIMP U–Pb date of  $1811 \pm 5$  Ma (Wingate et al., written comm.).

Although structural complexity prevents a detailed stratigraphy being established for the Egerton Inlier, a broad three-fold lithological subdivision can be recognized. The lower stratigraphic unit (LSU), exposed in the central and northern parts of the inlier, comprises thin- to very thick-bedded, deep marine turbidite metasandstone and metasiltstone, interlayered with subordinate schistose metadolerite and recrystallized dolostone. Metasandstones

preserve graded bedding and ripple cross-lamination. Metasiltstones dominate the upper part of the lower unit and are sharply overlain by the middle stratigraphic unit (MSU), composed of about 150 m of upward-fining, shallow-marine, silicified cross-stratified and ripple cross-laminated meta-quartz sandstone and minor metaconglomerate. The MSU has a gradational contact with the overlying upper stratigraphic unit (USU), which outcrops in the southern part of the inlier and is made up of deeper marine metasiltstone and minor thin-bedded metasandstone and schistose metadolerite.

Low-grade metamorphic rocks of the Egerton Inlier record a complex history of polyphase deformation that pre-dates Edmund Group deposition. Northern parts of the inlier are characterized by west-southwesterly striking, steep to overturned bedding that shows younging to the north-northwest or south-southeast, although no  $F_1$  fold hinges were observed. Two cleavages,  $S_1$  and  $S_2$ , and thin mylonitic shear zones are broadly sub-parallel to bedding. Medium- to large-scale, very steeply plunging  $F_2$  fold hinges are observed locally in central parts of the inlier. These preserve a steeply west-southwesterly dipping, crenulated  $S_1$  cleavage, cut by a steep west-southwesterly striking  $S_2$  fabric. Younging directions in the hinge zones are to the west and the east-southeast. In southern parts of the inlier silicified rocks of the MSU are overturned and folded about a tight, northwest-trending  $F_2$  hinge. These structural relationships are interpreted as the result of the refolding of upright, tight to isoclinal, north-northwesterly trending  $F_1$  fold hinges about a tight, upright, south-southwesterly trending  $F_2$  fold.

Most gold production from the Egerton Inlier has come from quartz veins near the west-southwesterly trending contact between a thick, foliated metagabbro or metadolerite, and quartz–muscovite pelitic schist (Muhling et al., 1978; Dahl, 1997). Other workings are focused on lenticular, pyritic quartz veins, aligned parallel to the  $S_2$  cleavage in the metasedimentary host rocks.

## Woodlands Dome

In the Jillawarra Sub-basin (Fig. 1) most of the schistose rocks, originally thought to be Padbury Group equivalents,

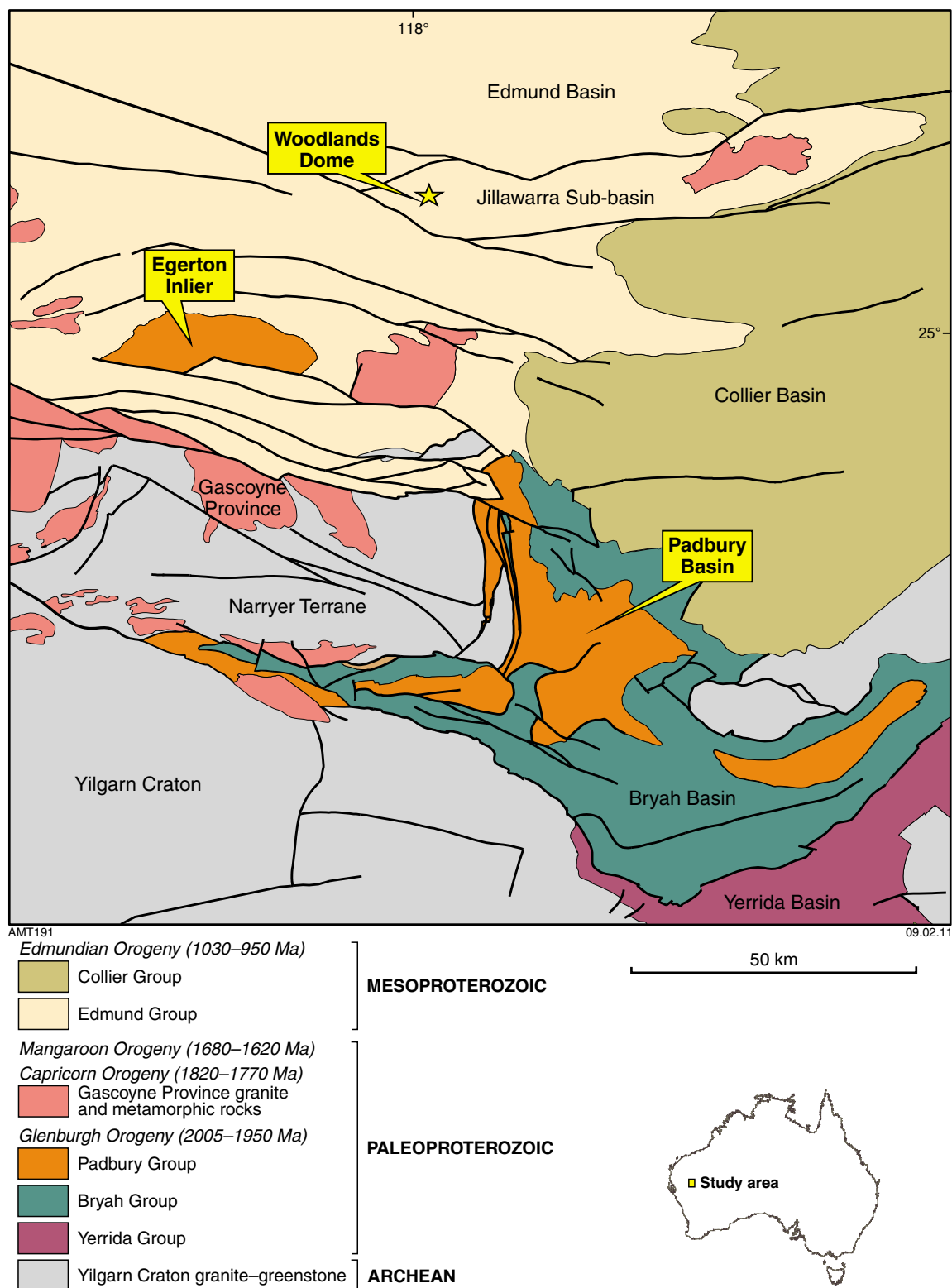


Figure 1. Simplified geological map of the central Capricorn Orogen showing the location of the Padbury Basin, Egerton Inlier, and Woodlands Dome

were later assigned to the Bangemall Supergroup (Vogt, 1995). However, one area that still remains problematic is the Woodlands Dome, in the west of the sub-basin, where low-grade, schistose metasandstone and metaconglomerate unconformably overlie a muscovite–biotite granite.

The granite and the metasedimentary rocks are cut by a shallowly dipping muscovite-grade foliation that is mostly sub-parallel with, or shallowly inclined to, the gently domically folded sedimentary bedding. This foliation is not pervasive throughout the immediately overlying metasedimentary succession, but instead appears to have a large-scale, anastomosing distribution. Small-scale kink folds are also observed within finer grained beds. The schistosity becomes weaker and finally disappears, when traced upwards for about 50 to 100 m through the overlying shallow-marine sedimentary succession and into the conformably overlying and lithologically similar lower Edmund Group.

Samples (GSA 169811, 169812) from schistose metasedimentary rocks and the immediately overlying Edmund Group at Woodlands have almost identical detrital zircon age components (Wingate et al., written comm.). Both have a youngest component dated at c. 1755 Ma and also a significant age component dated at between c. 1790 and 1800 Ma.

## Correlation with the Padbury Group

Based on the available data, it is possible that basement rocks of the Egerton Inlier are Padbury Group correlatives, although this cannot be proven. Pre-Edmund Group rocks of the Egerton Inlier were deposited and deformed in the interval between c. 1983 Ma and c. 1811 Ma (Wingate et al., in prep.) and therefore fall within the current broad age range for the Padbury Basin. The mostly deep-marine turbidite succession of the inlier is similar to the Labouchere Formation (lower Padbury Group) and the meta-quartz sandstone and metaconglomerate unit (MSU) of the Egerton area may equate to one of the meta-quartz sandstone marker horizons described by Martin (1998). The Egerton Inlier and northern Padbury Basin have a similar deformation history, although it is unclear if the north-northwest, south-southeast shortening in the latter area is the result of post-Edmund Group deformation. The presence of auriferous quartz veins in both the Egerton Inlier basement rocks and the Padbury Group (Cooper et al., 1998) provides further evidence for a possible correlation.

Field relationships and detrital zircon age spectra from the Woodlands Dome metasedimentary rocks indicate that these are unlikely to be Padbury Group equivalents, but instead belong to the lower Edmund Group. Here, the localized development of a low-grade schistosity may have occurred during one or more tectonic events between 1385 Ma and 1210 Ma (Johnson et al., 2011, this volume) or during the 1030–950 Ma Edmundian Orogeny (Sheppard et al., 2010).

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# Lu–Hf isotopes: implications for understanding crustal evolution

by

CL Kirkland, MTD Wingate, SP Johnson, CV Spaggiari, E Belousova\*, and R Murphy\*

Knowledge of crustal evolution is important for understanding mineralization, because juvenile addition of material from the mantle into the crust is commonly associated with significant heat and fluid flow and element mobility. Geological Survey of Western Australia (GSWA) routinely determines the ages of rocks by measuring the ratios of uranium, thorium, and lead isotopes in crystals of zircon and other minerals using the Sensitive High Resolution Ion MicroProbe (SHRIMP). GSWA has added significant value to its regional geochronological U–Pb datasets by acquisition of complementary Lu–Hf data from previously dated crystals. The Lu–Hf analyses are conducted by the Centre for Geochemical Evolution and Metallogeny of Continents (GEMOC) at Macquarie University. The project is funded through the Western Australian Government's Exploration Incentive Scheme (EIS) and aims to analyse up to 2000 crystals each year for four years. Lu–Hf analyses incorporate both detrital zircons in sedimentary rocks, as well as zircons from magmatic rocks, including those with multiple growth stages. This allows the reconstruction of crustal history at several points in time — all recovered from a single rock sample or, in some cases, from a single crystal.

The isotope  $^{176}\text{Lu}$  is unstable and undergoes spontaneous  $\beta$  decay to stable  $^{176}\text{Hf}$ , with a half-life of approximately 37 billion years. During melting, the daughter element hafnium (Hf) partitions into melts to a higher degree than the parent element Lutetium (Lu). This leads to significant variation in  $^{176}\text{Hf}/^{177}\text{Hf}$  over time. Crystals with higher  $^{176}\text{Hf}$  have evolved from a source with elevated Lu and **depleted** Hf (typically the radiogenic mafic residuum), whereas lower  $^{176}\text{Hf}$  is a result of lower Lu and **enriched** Hf (typically the unradiogenic felsic melt). Juvenile addition from the mantle results in **depleted** Hf values at the time of zircon crystallization, whereas reworking of older crust produces **enriched** Hf values. Hence the Lu–Hf system can be used as a geochemical tracer, providing information on both the timing of material input into the crust as well as the process by which this material was added.

Owing to its close chemical affinity with zirconium, the element Hf is a significant component of zircon grains. Zircon has very low Lu/Hf ratios, which means that the

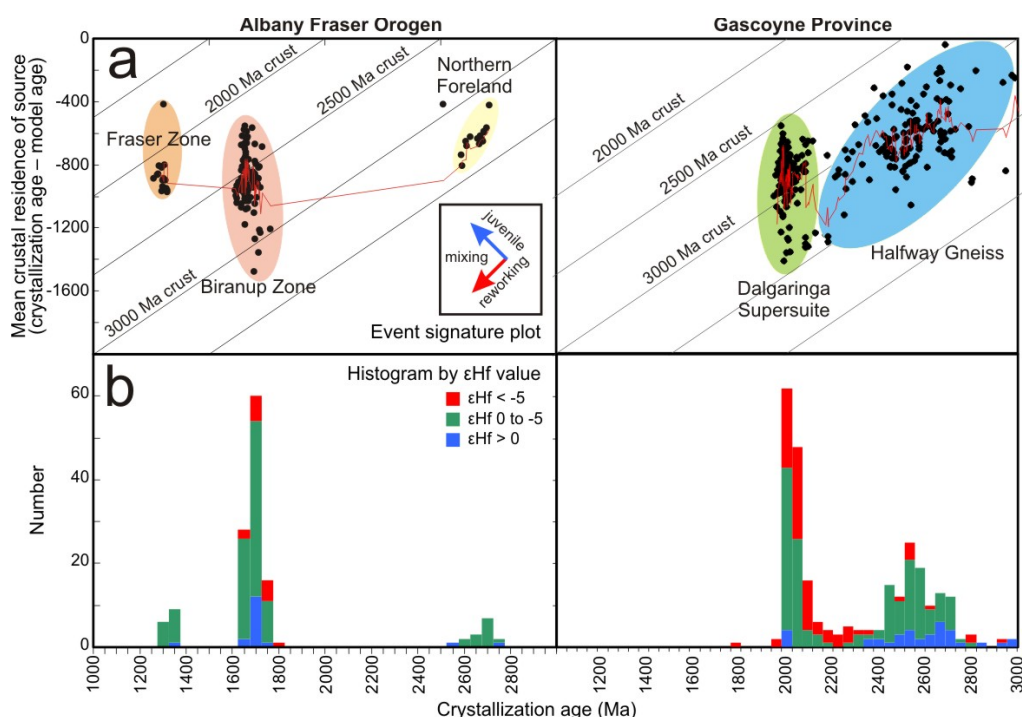
Hf isotope composition measured today requires only a minor time-correction to derive the initial value at the time of crystallization. Moreover, zircon is physically and chemically robust and Lu–Hf isotopes are highly resistant to later disturbance (even more so than the U–Pb system), thus Lu–Hf in zircon has the potential to decipher the geological evolution of highly metamorphosed and overprinted terranes. When coupled with U–Pb geochronology, Hf isotope measurements in zircon provides unique, time-integrated information about the relative roles of juvenile mantle input versus reworking of older continental crust.

## Lu–Hf results from the Albany–Fraser Orogen

The Albany–Fraser Orogen, along the southeastern margin of the Yilgarn Craton, represents the Mesoproterozoic continent–continent collision between the combined North and West Australian Cratons and the combined East Antarctic and South Australian Cratons (Bodorkos and Clark, 2004). However, recent geochronology, together with structural and geophysical data, reveals that the fault-bounded Paleoproterozoic Biranup Zone makes up a large component of the orogen, and includes rocks that were deformed during the c. 1680 Ma Zanthus event (Kirkland et al., in prep.). There has been considerable uncertainty regarding the origin of the Biranup Zone, with most work favoring an exotic source. However, Lu–Hf results indicate an indigenous origin on the Yilgarn margin. The oldest magmatic rocks in the Biranup Zone (c. 1700 Ma) have Hf isotope values similar to those of the Yilgarn Craton (Fig. 1). However, over about the next 50 million years, Hf isotopic values become increasingly dominated by more radiogenic (depleted) values (Fig. 1). This Hf evolution is compatible with melt production from mixed sources: a juvenile component, and an evolved component with crustal residence ages of more than about 3100 Ma. This juvenile material progressively and thoroughly diluted the isotope signal from the basement through time and reflects the influence of radiogenic Paleoproterozoic input into non-radiogenic Archean sources.

This temporal trend can also be recognized within individual intrusions. For example, magmatic zircon rims indicate higher  $\epsilon\text{Hf}$  values than their cores, implying increasing juvenile input at a timescale below the age resolution of the geochronology. These results directly link the Biranup Zone

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**Figure 1.** a) Event signature diagram showing the general trend of reworking (downwards), mixing (horizontal), or juvenile input (upwards); b) stacked histograms for juvenile ( $> 0$ ), intermediate (0 to  $-5$ ) and evolved ( $< -5$ )  $\epsilon_{\text{Hf}}$  values. The data on the left are from three lithostratigraphic domains in the Albany–Fraser Orogen: the Biranup Zone, Fraser Zone, and Northern Foreland. The data on the right are from the Gascoyne Province, Glenburgh Terrane

of the Albany–Fraser Orogen to the Yilgarn Craton margin, and suggest that the Paleoproterozoic evolution of the region is best explained by back-arc development and rifting on the craton margin between about 1700 and 1650 Ma. This process resulted in Archean remnants becoming isolated from their ancestral home on the Yilgarn Craton by additions of predominantly juvenile crust. This is important for clarifying the geodynamic setting of gold mineralization (such as the Tropicana deposit) on the southeastern Yilgarn Craton margin.

## Lu–Hf results from the Gascoyne Province

The Capricorn Orogen records the Paleoproterozoic juxtaposition of the Archean Yilgarn and Pilbara Cratons to form the West Australian Craton (Johnson et al., 2010). The orogen consists of the deformed craton margins and a wedge of exotic rocks named the Glenburgh Terrane. The Glenburgh Terrane comprises a basement of heterogeneous granitic gneisses (the Halfway Gneiss), overlain by a package of continent-derived siliciclastic metasedimentary rocks (Moogie Metamorphics). These rocks were intruded at c. 2000 Ma by a suite of igneous rocks (Dalgaringa Supersuite), interpreted to have formed in a volcanic arc on the southern margin of the terrane prior to collision with the Yilgarn Craton (Sheppard et al., 2004). Hf isotopes from the Glenburgh Terrane imply a component of the terrane was resident in the crust since c. 3750 Ma, with additional

crustal growth events at c. 2800–2600, 2600–2430, and 2005–1970 Ma (Fig. 1).

The oldest and youngest events appear to have tapped juvenile, mantle-derived material, whereas magmas generated in the 2600–2430 Ma episode were derived by the reworking of pre-existing crust. This crustal history is dissimilar to that of either the Pilbara and Yilgarn Cratons, confirming the exotic heritage of the Glenburgh Terrane prior to final suturing of the West Australian Craton during the Glenburgh Orogeny, between 2005 and 1950 Ma. Results for younger intrusions of the 1820–1775 Ma Moorarie Supersuite indicate mainly reworking of Glenburgh Terrane basement. However, some intermediate to felsic plutonic rocks of the Minnie Creek batholith are less evolved, suggesting mixing between mantle-derived material and pre-existing felsic crust. The evolution of the Gascoyne Province demonstrates the cyclic nature of crustal evolution, with episodic juvenile mantle additions into the crust, followed by major, prolonged reworking–homogenizing events.

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# Coal — new opportunities in the 21st century

by

A Millar

## The World scene

Despite a poor public image and a common perception it is a fuel from the last century, coal has numerous uses critically important to economic development and poverty alleviation worldwide. The most significant of these are electricity generation, and the production of steel, aluminium, cement, and liquid fuels (World Energy Council, 2010).

Approximately 5800 Mt of hard coal and 953 Mt of brown coal were used worldwide in 2008. From 2000, the global consumption grew faster than any other fuel at 4.9% per annum (World Energy Council, 2010). In 2008, coal generated approximately 41% of the world's electricity and almost 70% of the world's steel production was dependent on coal (World Coal Association, 2009, 2011). In 2009 coal's share of world energy consumption was 29.4%, the highest since 1970 (BP, 2010).

The International Energy Agency (IEA), using its New Policies Scenario predicts that world primary energy demand will increase by 36% between 2008 and 2035. Fossil fuels — oil, coal, and natural gas — will remain the dominant energy sources in 2035 in all of IEA's three scenarios, though their share of the primary fuel mix varies (International Energy Agency, 2010). Non-OECD (Organisation for Economic Co-operation and Development) countries account for 93% of the projected increase in world primary energy demand, with China contributing 36% to the projected growth in energy use. Predicted demand for coal rises to around 2020 and starts to decline toward 2035.

World electricity demand will continue to grow more than other final forms of energy, with a predicted growth of 2.2% per annum between 2008 and 2035, with more than 80% of the increase in non-OECD countries. China is projected to add generating capacity over the next 15 years equivalent to the current installed capacity of the United States. Despite this significant increase in electricity generation, IEA predicts that 1.2 billion people will still lack access to electricity in 2030 compared with the current estimate of 1.4 billion (over 20% of the present world population).

Globally, under the New Policies Scenario, coal will remain the main source of electricity generation in 2035, although its share is predicted to decline from 41% to 32%. A large increase in non-OECD coal-fired generation will be partially

offset by a fall in coal-fired generation in OECD countries (International Energy Agency, 2010).

In recent ABARE (now ABARES, Australian Bureau of Agriculture and Resource Economics and Sciences) energy projections that include the Renewable Energy Target and a 5% emissions reduction target, Australia's coal production increases at an average annual rate of 1.8% up to 2029–30, although its share of total energy production is expected to fall (Syed et al., 2010; Geoscience Australia and ABARE, 2010). A recent study from the University of Queensland concluded that coal would be a principal energy source for the world for the foreseeable future (Knights and Hood, 2009).

In addition to rising global energy demands, new and developing technologies will allow exploitation of coal resources that are uneconomic using current technologies. These new technologies include both mining or alternative extraction methods and coal conversion technologies, to either gas or liquids. The modernisation of electricity generation technologies along with carbon capture and storage will also add to the acceptance of coal as a fuel for the future. The application of these new and/or alternative technologies could allow the development of a number of Western Australia's known, but undeveloped, coal resources and potentially lead to new discoveries.

## Western Australian opportunities

Although coal was first discovered in 1846 in Western Australia on the Irwin River, the first commercial discovery was at Collie in 1883. Mining commenced with the extension of the railway to the town in 1898 (Le Blanc Smith, 1990). Despite ongoing exploration and a number of discoveries from the 1960s to the 1980s, Collie is the only producing area in the State. The combined output from the two producing companies is approximately 6.5 Mtpa, of which the majority is for electricity generation, with lesser amounts for industrial uses and a small but expanding export component.

The hiatus in coal exploration activities during the 1990s reflected a combination of the ability of the then available resources to meet local requirements, low coal prices, and a lack of export potential. Increasing world energy demands

— and therefore coal prices — and the development of alternative technologies have led to a substantial increase in activity, particularly in the last two to three years, to the extent that exploration licences now cover most prospective areas. Current activities include both greenfields exploration and the economic evaluation of more-advanced projects. Several companies are currently targeting relatively under-explored but prospective Permian strata in the Canning Basin. Renewed exploration is also taking place in areas containing known coal deposits, including the northern Perth Basin, Vasse Shelf, Boyup and Wilga Sub-basins, and the Eucla Basin.

Advanced projects targeting traditional coal extraction methods are being considered at Osmington (underground, Vasse Shelf), Eneabba (opencut with an associated power station, northern Perth Basin), and a potential trench highwall mining operation near Camballin in the Canning Basin for the export market. A proposed coal-to-urea plant near Collie has recently received conditional environmental approvals with construction likely to commence this year. This operation will use approximately 2.5 Mtpa of opencut mined coal to produce 2.1 Mtpa of urea, largely for export through the Bunbury port.

Non-conventional coal uses are also being evaluated. East of Dongara, in the northern Perth Basin, a resource with an estimated 194 Mt (74 Mt Indicated, 119 Mt Inferred) of sub-bituminous Jurassic coal is being assessed as an underground coal gasification (UCG) project. Two separate coal-to-liquids (CTL) projects are under evaluation north of Esperance in the Eucla Basin. These two projects are based on large Eocene lignite deposits that were discovered during the 1980s. Current evaluation is concentrating on upgrading data on the resource and the application of conversion technologies.

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# A fresh look at the regolith of the central Gascoyne region with implications for mineral exploration

by

CBE Krapf

A major challenge facing mineral exploration in many parts of Western Australia is exploring effectively and efficiently through commonly thick and extensive regolith cover. Mapping regolith and understanding its genesis is crucial in terms of developing a landscape evolution model, which is critical for mineral exploration in regolith-dominated terrains.

The Gascoyne region has an extensive regolith cover including regolith that is genetically related to the underlying bedrock or transported. There are few actual age determinations for regolith, so the age of regolith units is invariably based on their position in the landscape, degree of induration, extent to which they have been dissected by more-recent processes, or the extent of overlying material. This study is the first attempt to gain a more-detailed insight into the regolith and therefore the landscape evolution of the central Gascoyne region, and has a strong emphasis on identifying both residual and relict regolith units, some of which represent remnants of previous landforms. A variety of regolith exposures in the central Gascoyne were investigated and several stratigraphic sections were measured, providing detailed information about different regolith types and successions.

## Regional setting

The study area comprises most of the MOUNT PHILLIPS 1:250 000 map sheet, located in the central Gascoyne region. It encompasses rocks of the Paleoproterozoic Gascoyne Province, the Mesoproterozoic Edmund Basin (Bangemall Supergroup), and the Phanerozoic Southern Carnarvon Basin, all of which are overlain by various regolith units of variable thickness up to 150 m.

## Regolith distribution and occurrence

A wide variety of regolith types is present in the study area, some of which are closely related to the underlying bedrock. Most of the transported relict regolith units and some of the older alluvial and colluvial regolith units were cemented and lithified under alternating wet and dry conditions. They are now preserved as elevated erosional remnants within

paleovalleys, or as topographically inverted paleochannels. Differential erosion rates and weathering during the Cenozoic formed a variety of regolith profiles over Archean to Phanerozoic bedrock. Ferruginization, calcretization, and silicification of these regolith successions led to the formation of resistant rises, hills, and mesas. Relief inversion is found in many places over partly silicified paleochannel deposits. In situ regolith profiles are retained where the rate of weathering is greater than the rate of erosion especially along old drainage systems, resulting in their preservation.

## Landscape evolution model

Several episodes of weathering, ferruginization, calcretization, silicification, and erosion occurred in the central Gascoyne region leading to the complex regolith distribution of the current landscape (Fig. 1). With the exception of the rocks of the Southern Carnarvon Basin, most of the bedrock on MOUNT PHILLIPS has been periodically subaerially exposed since at least the Precambrian (Pillans, 2005). This resulted in continuous weathering and the formation of extensive in situ regolith profiles over Gascoyne Province and Edmund Basin rocks. In the southwestern part of the study area, where Upper Carboniferous and Lower Permian sedimentary rocks of the Southern Carnarvon Basin are exposed, land surface exposure started during the Permian (Pillans, 2005).

Ferruginization and development of deep-weathering profiles over bedrock was common in Australia during the Early Cretaceous to early Paleogene (McGowran, 1979). Williams et al. (1983) and Elias and Williams (1980) reported a 'Tertiary' land surface, which, due to active erosion, is only preserved as 'laterite' remnants along watersheds. Williams et al. (1983) also included calcrete and silcrete as part of this 'old duricrust surface'. The current study has shown that two distinct types of ferruginous duricrust (in situ and transported) are found on MOUNT PHILLIPS. In situ ferruginous duricrust is part of the in situ regolith profiles developed over bedrock mainly within the Gascoyne Province, whereas transported ferruginous duricrust is the result of widespread ferruginization of alluvial sediments in ancestral river valleys and alluvial plains. There is no conclusive evidence that they are either relative age equivalents or genetically related.

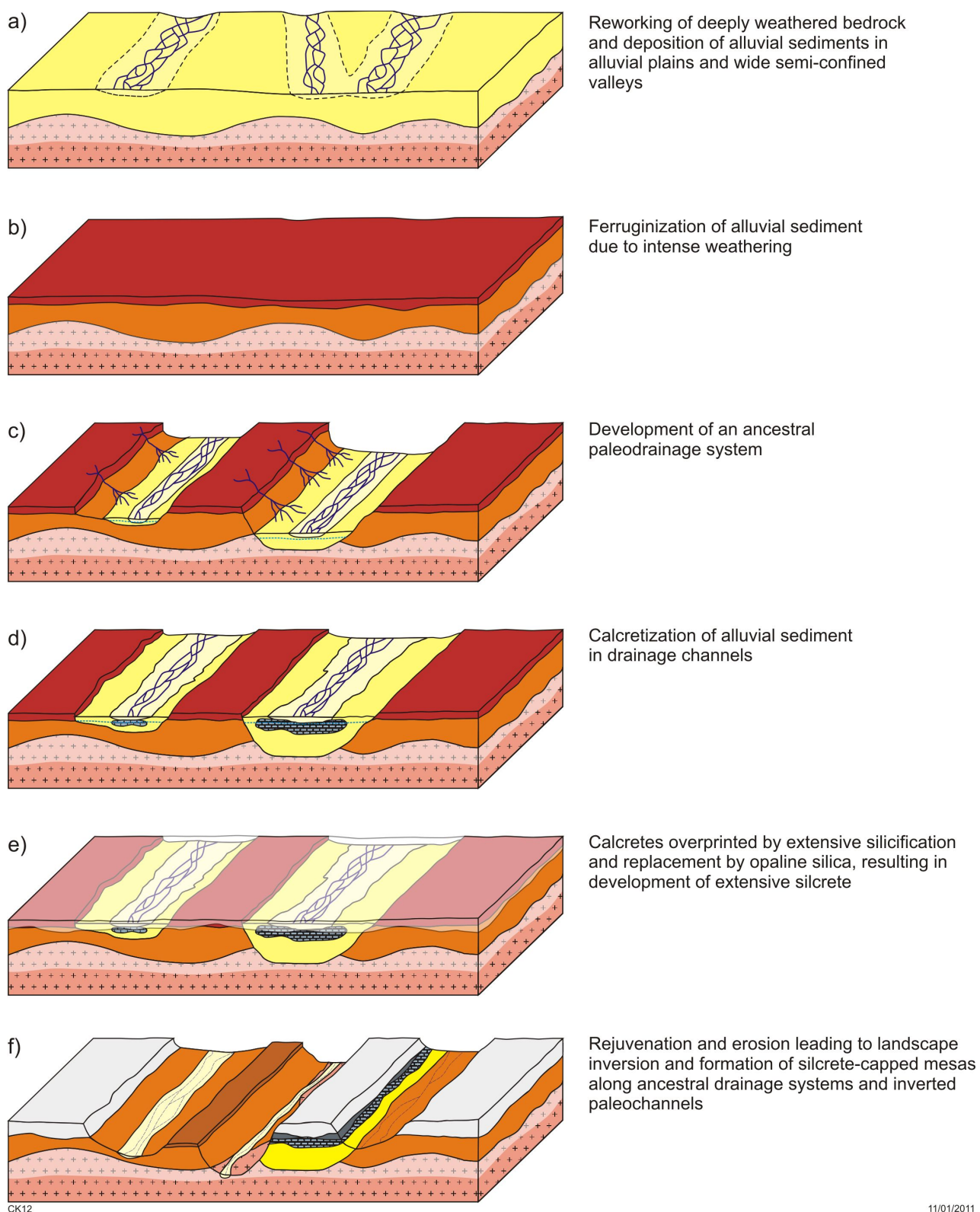


Figure 1. Landscape evolution model on MOUNT PHILLIPS

The transported ferruginous duricrust, overlain in many areas by calcrete and silcrete, is the result of intense post-depositional ferruginization and reworking of sediments that were originally deposited on alluvial plains and in wide semi-confined valleys (Fig. 1a). After deposition these sediments were intensely bioturbated and overprinted by soil development, cementation, weathering and erosion.

These alluvial deposits underwent extensive ferruginization and resulting in a more subdued landscape (Fig. 1b). Erosion of this landscape led to the development of an ancestral paleodrainage system followed by the development of calcrete mainly within and along the ancestral river courses (Fig. 1c). Calcretization partly continued into the underlying transported ferruginous duricrust (Fig. 1d). The calcretes in turn were overprinted by extensive silicification and replacement by opaline silica, resulting in development of an extensive siliceous duricrust (Fig. 1e).

Following development of the silcrete, the landscape experienced rejuvenation and erosion leading to landscape inversion and the formation of silcrete-capped mesas mainly along the valleys of the ancestral drainage systems and inverted paleochannels that are unrelated to any present drainage pattern (Fig. 1f).

In areas adjacent to the Gascoyne River, silicified calcretes are exposed up to 35 m above the present river level. Therefore, uplift must have rejuvenated the river systems after extensive calcrete development and subsequent silicification, a process that has also been discussed by Butt et al. (1977). As a result of rejuvenation, the sediments have been eroded and elevated in the form of mesas or inverted paleochannels.

## Implications for mineral exploration

Understanding the landscape evolution of a region can assist in finding new exploration targets and in developing efficient exploration strategies. In the case of the central Gascoyne region, a new paleochannel 15 km long, up to 2 km wide, and elevated 10 to 15 m, has been identified in the northwestern part of MOUNT PHILLIPS during this study. Here, transported ferruginous duricrust is overlain by groundwater calcrete. The calcrete is partly silicified or replaced by opaline silica and overlain by silcrete to form the elevated and inverted areas of the paleochannel. The calcrete areas of the paleochannel show an elevated response in the uranium band of the Ternary Radiometric Image (TRI) and two surface calcrete samples from the paleochannel have increased uranium values compared to other regolith samples from MOUNT PHILLIPS (Sanders et al., 1997).

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# The geological history and gold prospectivity of the West Arunta Orogen, Western Australia

by

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Located in remote east-central Western Australia, the West Arunta Orogen (WAO) is one of the least-studied and least-understood areas in the State. Using regional geophysical, geological, and geochemical datasets acquired by GSWA, the interpreted bedrock geology map in Geological Survey of Western Australia (2009) has been modified to create a new geological map of the WAO to use as the basis for prospectivity analysis of the terrain. Here we concentrate on prospectivity for gold, although other commodities have also been studied. This work was funded by the Western Australian Government's Exploration Incentive Scheme (EIS) with the WAO the first of several terrains to be analysed in this fashion by the Centre for Exploration Targeting (CET) at The University of Western Australia.

## Geological setting

The WAO is the westward continuation of the Arunta Orogen, which outcrops predominantly in the Northern Territory. It comprises two distinct provinces with different protolith ages and histories (Scrimgeour, 2004; Scrimgeour et al., 2005): the 1870–1710 Ma Aileron Province to the north, and the exotic 1690–1600 Ma Warumpi Province to the south. Both provinces are separated by the north-dipping crustal-scale Central Australian Suture (Shaw and Black, 1991; Close et al., 2004; Scrimgeour et al., 2005). The WAO is unconformably overlain by the Neoproterozoic Murraba Basin in the north and by the stratigraphically equivalent Neoproterozoic to Devonian Amadeus Basin to the south (Zhao et al., 1992; Maidment et al., 2007). The Early Ordovician to Early Cretaceous Canning Basin overlies the Amadeus Basin. Based on data from the Northern Territory, the WAO is interpreted to record multiple Proterozoic crustal processes over a 1500 million-year period from before 1800 Ma through to the Paleozoic (Collins and Shaw, 1995; Scrimgeour et al., 2005).

## Datasets

Two regional government geophysical datasets were used as the principal basis for the geological interpretation of the

WAO: aeromagnetic and gravity data. The aeromagnetic data were acquired with a 400-m flight-line spacing and 60- to 80-m flight height. The average station spacing for the gravity data is about 2.5 km.

## Interpreted geology from potential field data

A series of interpretation products were created, primarily from the potential field data, but with reference to the known geology and the small amount of petrophysical data that are available (Schroder and Gorter, 1984; Lambeck et al., 1988). The resulting geological map is shown in Figure 1.

Areas of shallow or exposed WAO have short wavelength magnetic anomalies due to changes in magnetism within the basement rocks. The oldest known basement in the region, the Lander Rock Formation, has a characteristic magnetic response comprising a modest level of total magnetic intensity (TMI), but linear anomalies are evident.

Areas of basin-fill are generally magnetically subdued, although basement-sourced variations are sometimes evident and clear linear anomalies due to mafic rocks within the Amadeus Basin sequence occur locally. Subtle anomalies allow bedding within basin-fill to be mapped in places. There is commonly a lack of correspondence between gravity and magnetic responses. In areas of basin-fill, the major causes of gravity variations are basement depth and the presence of salt within the Amadeus Basin sequence. Surprisingly, significant variations in gravity also occur in areas of outcropping basement, specifically regions with distinct negative anomalies.

Linear features, mostly defined by magnetic data, are interpreted as: (i) two sets of faults (based primarily on differences in orientation) identified from offsets and truncations of adjacent anomalies; (ii) trend lines — probably representing stratigraphic and metamorphic layering; (iii) banded iron-formation (BIF) — a special case of the trend lines identified from their high amplitude TMI response; (iv) fold axes — based on closures and veing of the trend lines; (v) mafic dykes — identified from cross-cutting relationships with trend lines representing lithological layering.

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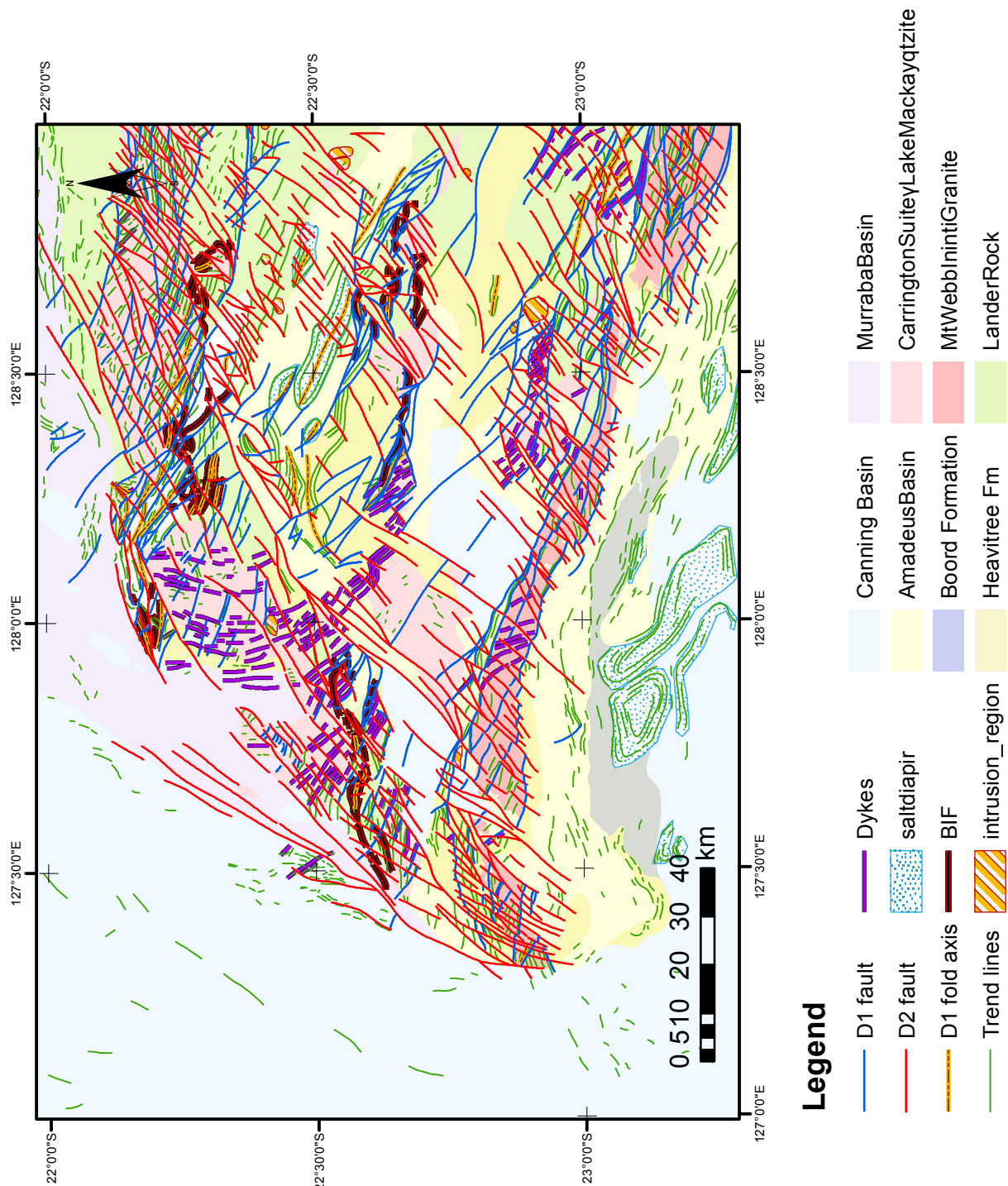


Figure 1. Interpretative structural map highlighting the Proterozoic architecture of the West Arunta Orogen

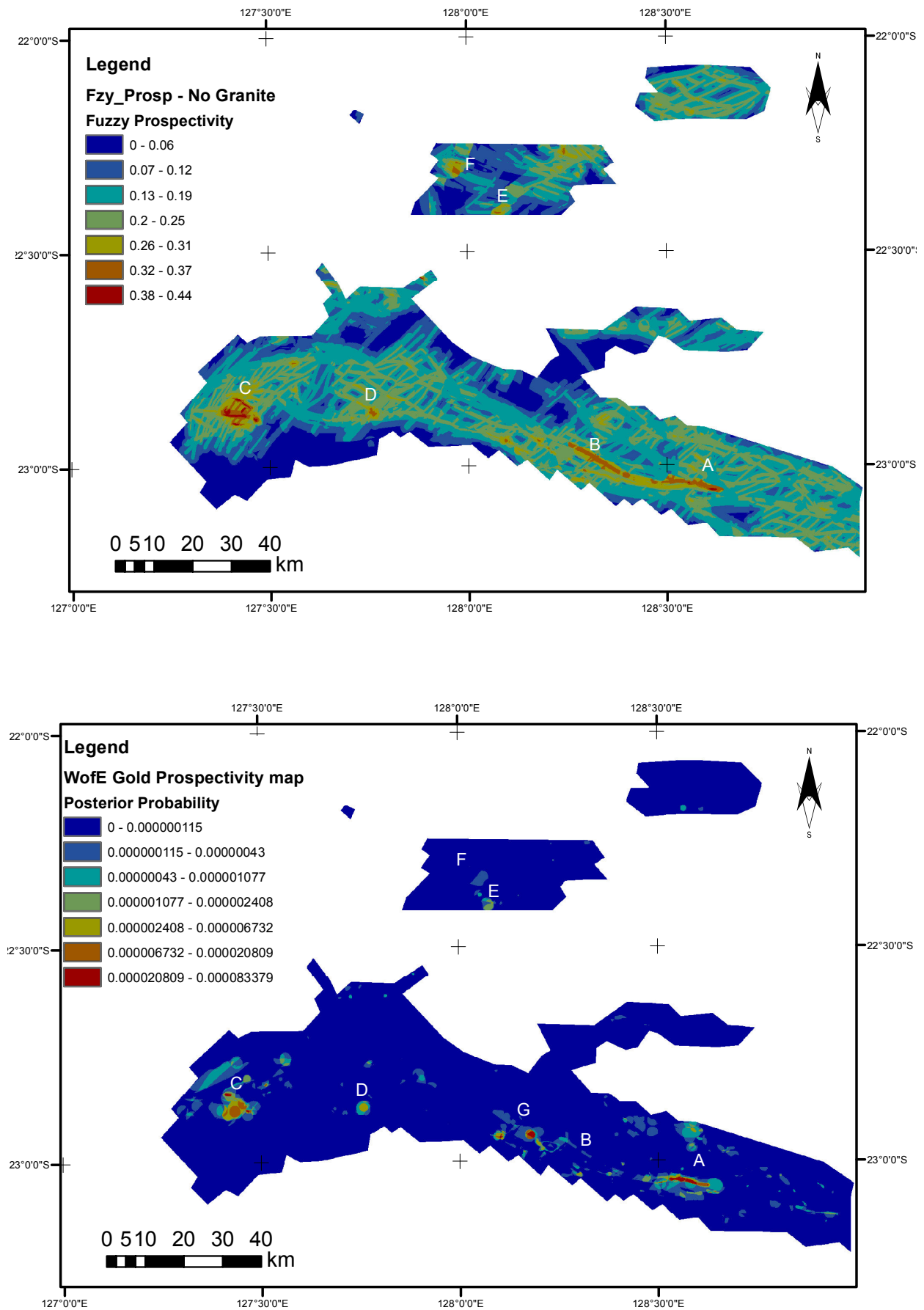


Figure 2. Fuzzy (top) vs WofE (bottom) prospectivity models for gold in the West Arunta Orogen

## Inferred geological history of the West Arunta Orogen

Two major deformation events control the current architecture of the WAO, which overprint and reactivate structures produced during earlier Proterozoic events (including the 1810–1800 Ma Stafford Event, 1780–1770 Ma Yambah Event, 1640–1630 Ma Leibig Orogeny, c. 550 Ma Petermann Orogeny). The first is a set of structures that trend west-northwest. Seismic data acquired along strike to the east show that major structures with a similar orientation are north-dipping and extend to the base of the crust (Goleby et al., 1988; Wright et al., 1990). Inconsistent responses in gravity and magnetic data, in particular negative Bouguer anomalies in areas where the magnetic data show that basement is at the surface, are interpreted as indicating that basement outcrops are 'slivers' structurally emplaced within a succession comprising predominantly sedimentary rocks of the Amadeus Basin, with deformation mostly likely associated with the 400–300 Ma Alice Springs Orogeny (Devonian–Carboniferous). This interpretation is consistent with structural studies in the Arunta Orogen outside Western Australia (Flottmann et al., 2004).

To test the idea that the WAO consists of a basement-involved, thick-skinned, thrust terrain, 2D gravity forward modelling was completed on a profile drawn perpendicular to the Central Australian Suture. As with any potential-field modelling, the model is not unique, but it demonstrates that the thick-skinned structural style is consistent with the gravity data.

The second major structural trend is northeast–southwest. Major examples of these  $D_2$  structures comprise basin-bound structures of the Canning and Murraba Basins. These structures were probably much older faults that were reactivated as normal faults during the late Triassic Fitzroy Movement in the Canning Basin, and represent the main control on the thickness of preserved sedimentary rocks.

Older tectonic fabrics created during the long and complex tectonic history of the region are interpreted as having been reactivated during tectonic episodes recorded in the fill in adjacent sedimentary basins. However, the current outcrop pattern in the WAO is probably mostly controlled by the faulting associated with the Alice Springs Orogeny and the Fitzroy Movement.

## Gold prospectivity modelling of the West Arunta Orogen

GIS-based prospectivity analysis was used to identify the most prospective ground for gold deposits in the WAO. A knowledge-driven fuzzy model (Porwal et al., 2003) and a data-driven weights-of-evidence (WofE) model (Agterberg et al., 1990) were implemented. These approaches are essentially based on empirical mathematical models which compare the spatial distributions of various targeting criteria (represented by predictor maps). The targeting criteria are based on a mineral systems model for deposit formation and

the approach used involves creation of a series of predictor maps based on geological features associated with the relevant model for deposit formation. Both intrusion-related gold systems and the orogenic gold systems were considered in the WAO study, the essential difference being the presence of granitoids.

The fluid-pathway component of the gold mineral system in the WAO was associated with the two main sets of faults, these being potential fluid conduits. Physical traps are locales into which the mineralizing fluids are focused. Fault intersections, closure folds, and unconformities constitute potential trap sites. The final component of the WAO gold mineral model is a chemical scrubber; the presence of a favourable geochemical environment for deposition of metal. The role of iron oxide minerals in desulfidation of fluids makes, for example, the presence of BIF a potential indicator of a chemical trap. Finally, geochemical data were also used to create predictor maps.

Results indicate that the most prospective areas for gold in the WAO are located in the A, C, D, and E regions (Fig. 2). Region C contains known mineralization. This study indicates that regions B, F, and G are also potentially prospective.

## Conclusion

The WAO is an area with complex and poorly understood geology. However, high-quality geophysical datasets allow geological entities with significant exploration potential to be identified, and by placing the entire analysis in the mineral systems framework, it is possible to identify and demarcate areas that have the greatest prospectivity.

The WAO study is the first of a series where the integration of multiple geological and geophysical datasets from various terrains in Western Australia, in a mineral systems context, will be used as a basis for regional-scale prospectivity analysis.

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# The Hyden–Norseman magnetotelluric survey

by

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Funded by the Western Australian Government's Exploration Incentive Scheme, a magnetotelluric (MT) traverse has been completed across the southern Yilgarn Craton from east of Hyden to Norseman (Fig. 1). The survey comprises a single traverse and crosses the boundaries between the South West Terrane, Youanmi Terrane (Southern Cross Domain), and Kalgoorlie Terrane (Eastern Goldfields Superterrane). These data allow variations in electrical conductivity in the crust and upper mantle to be mapped to a depth of about 120 km.

## Magnetotelluric data

Magnetotelluric data were acquired in two campaigns, in late 2009 and in 2010, in a cooperative venture between the Centre for Exploration Targeting and Moombarriga Geoscience. The second component of the survey was to collect 'infill' data in areas highlighted as significant from the initial phase, and also to determine whether a large dyke south of the traverse was affecting the data (see below). During the second campaign, shallow EM data were collected at all of the sites in an effort to correct for static shift.

The final dataset consists of 40 stations varying in spacing between 10 and 5 km. In addition, two sites were collected to the south of the main traverse to determine if off-line responses were present. Each station comprised approximately 36 hours of recording using Phoenix MTU-5A instruments. The electric field was recorded by north–south and east–west dipoles approximately 100 m in length. The magnetic field was recorded by MTC-50 induction coils, with all three components being recorded if possible, although in some cases it was not possible to record vertical component data. Electromagnetic soundings of the near-surface were made in the time-domain using a Terratem instrument with a 100 m square loop. The MT data processing was done using robust remote-reference algorithms supplied by Phoenix Limited and based on the coherence-sorted cascade decimation method of Wight and Bostick (1981) and the heuristic robust approach of Jones and Jödicke (1984).

The MT impedance response can provide information on whether the causative electrical resistivity structure is 1-D (flat-layered), 2-D (possessing a geoelectric strike direction in which the resistivity is invariant), or a more complex 3-D structure, and whether the response has been distorted by near-surface resistivity structures. Analysis of geoelectric strike directions showed these to be northeasterly, but with different directions in crust and mantle. The MT data are in the process of being inverted using a range of included data and a range of inversion parameters in order to obtain both a 2-D resistivity model and information on the degree of resolution of features in the model. The inversions used the 2-D non-linear conjugate gradient algorithm of Rodi and Mackie (2001) as implemented in the WinGLink® MT Workstation (Geosystem SRL, 2008). Modelling of the data is ongoing. The latest result is shown in Figure 2.

## Geological implications of the MT data

The MT traverse links areas with significantly different geochemical characteristics, and these areas host significant mineral deposits, notably nickel-sulfide deposits in greenstone belt rocks. The traverse crosses three greenstone belts: the Southern Cross greenstone belt, the Lake Johnstone greenstone belt, and the Norseman–Wiluna greenstone belt. The greenstone rocks in the Southern Cross and Lake Johnston belts are typically older than those in the Norseman belt with ages back to 2.9 Ga. Rocks in the Norseman area have been dated at 2.7 Ga, with evidence of local older components. Also, a map of variations in granite Nd<sub>TM</sub> produced by Cassidy and Champion (2004) shows significantly different values in the Eastern Goldfields Superterrane compared to the other terranes crossed by the MT traverse. The location of the implied intervening structures between these different areas is poorly defined, and it is uncertain whether known structures represent the terrane boundaries or there are major structures yet to be identified. Moreover, the geometry at depth of the known major structures in the study area is unknown. The locating and mapping of crustal-scale structures was the primary motivation for the MT survey.

A key issue identified during the planning of the survey and the early stage of data modelling was the presence of apparently east-dipping structures coming to surface near the Lake Johnston greenstone belt. Referring to Figure 1,

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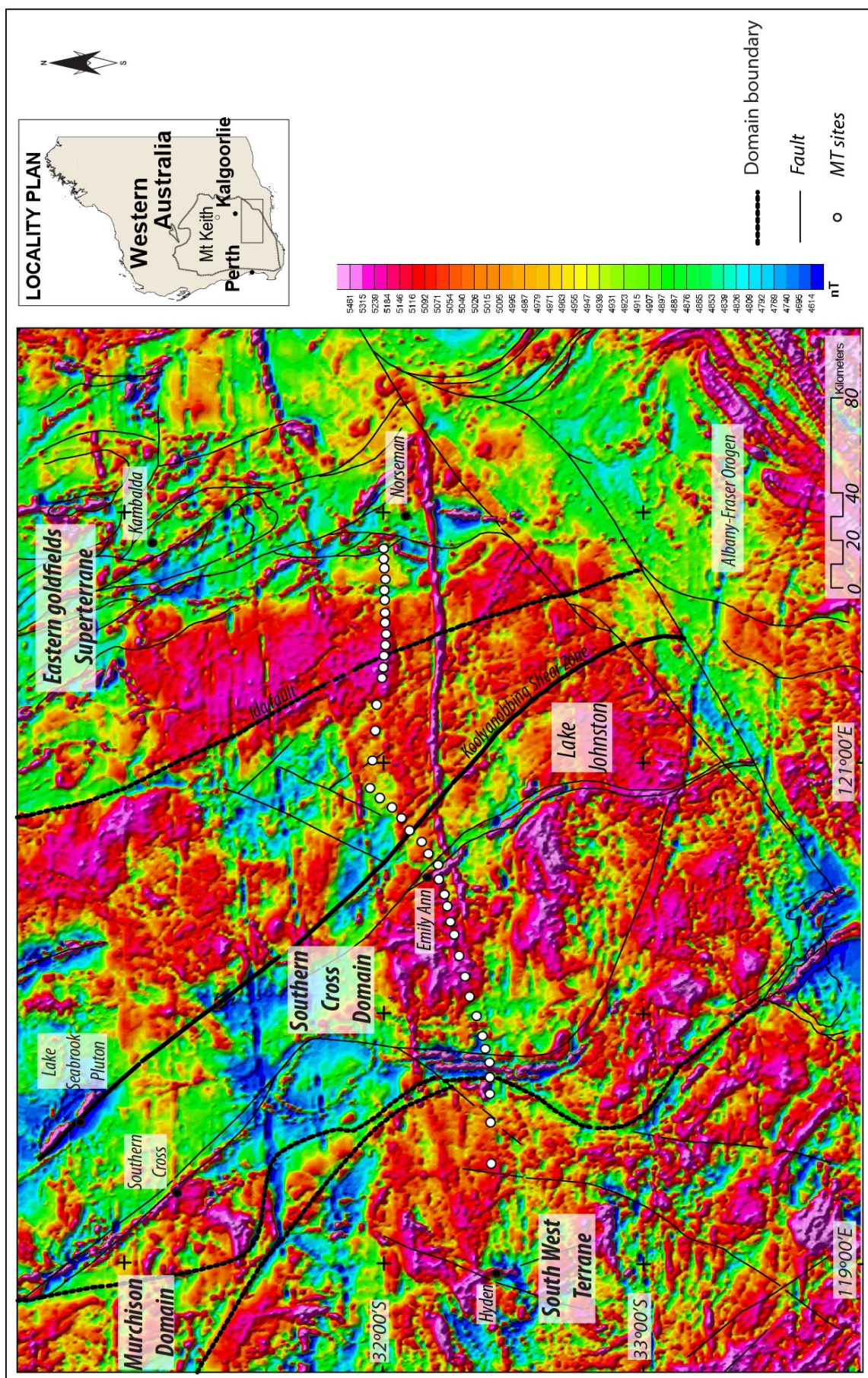


Figure 1. Location of MT stations overlain on TMI image with major geological entities also shown

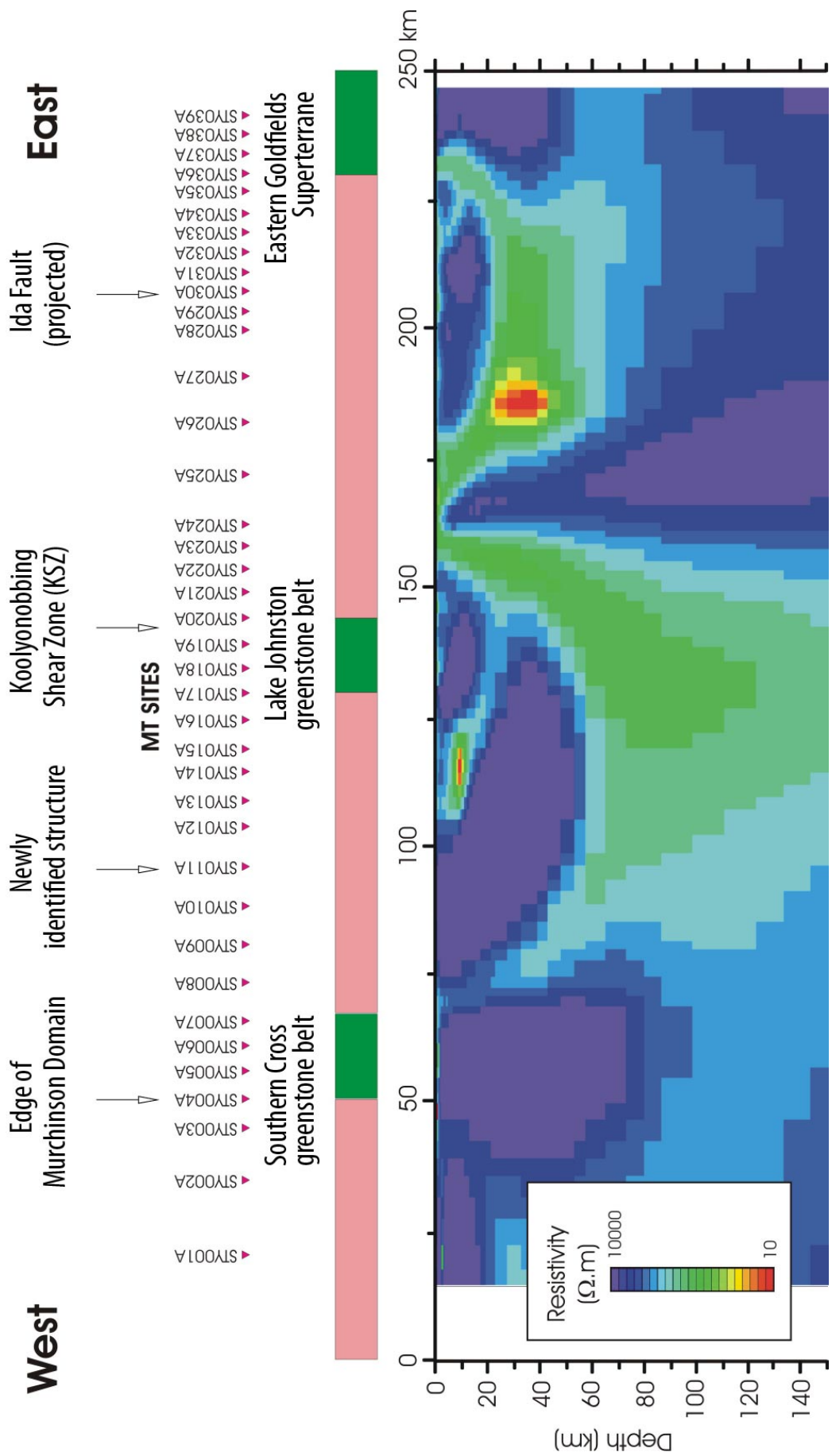


Figure 2. Provisional electrical conductivity cross section and surface geology

the magnetic response from the west-southwesterly trending Jimberlana Dyke is clearly seen south of the traverse and east of the Lake Johnston area. A response from this dyke could have been the source of the observed variations in conductivity. However, the collection of two datasets on the dyke itself showed that it was not a conductive feature and hence not affecting the conductivity model. It was to avoid any effects from the dyke that the data were acquired further north, thus requiring a less linear traverse and more difficult access.

The major causes of electrical conductivity variations at mid-crustal and greater depths are conductive mineral species — very likely graphite and metal sulfides. Major structures are often associated with more-conductive regions — see for example Spratt et al. (2009) — and are probably due to such minerals in the fault zone. The more-conductive regions in Figure 2 are interpreted in this fashion. In several cases these features correlate with known structures. For example, the Koolyanobbing Shear Zone appears as a near-vertical feature extending through the entire crust. The Ida Fault is also evident as an east-dipping zone of greater conductivity, although interestingly, from an electrical prospectivity point of view, a structure further to the east is more significant. An apparently previously unrecognized structure lies approximately half way between the Southern Cross and Lake Johnston greenstone belts.

Seismic studies suggest the Moho in the study area is at a depth of about 30 km (Clitheroe, 1999; Dentith et al., 2000). The electrical structure in Figure 2 suggests it is deeper but this may be a function of the resolution of the MT data. A conductive region in the mantle occurs in the central part of the profile. Modelling to date suggests this is a robust feature although its cause is uncertain. One possibility is a difference in mantle mineralogy suggestive of juxtaposition of different lithospheric blocks.

## Summary

The results of as-yet-unfinished modelling of MT from the southern Yilgarn Craton show that the method can map major structures/lithospheric blocks. Several known major structures correspond with areas of increased conductivity and the data suggest the presence of previously unknown structures.

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# Fine-fraction gold chemistry of regolith from the East Wongatha area, eastern Yilgarn Craton

by

PA Morris

Regional-scale regolith geochemical data can be used to identify both bedrock-hosted mineralization and the extent of different bedrock lithologies, if regolith and bedrock are genetically linked. In areas of thick and transported cover, this link can be missing or overprinted, yet in parts of Chile, the USA, and Canada regolith geochemistry has been successfully used to detect buried mineralization through tens of metres of transported cover, usually by partial digestion of the fine fraction of each sample. This suggests that, in some cases, the geochemical signature of buried mineralization has successfully migrated to the surface and is preserved in the overlying transported cover. Partial digestion and analysis of the silt and clay fraction of regolith from the East Wongatha area (a part of the eastern Yilgarn Craton dominated by thick cover) shows that the extent of bedrock and areas of potential mineralization can be detected through thick and exotic cover, supporting the viability of using regolith geochemistry to detect mineralization even in areas of transported cover.

## Regional setting

The East Wongatha project area, some 250 km east of Kalgoorlie, covers an area of approximately 13 000 km<sup>2</sup>. The project spans the eastern part of the Yilgarn Craton and parts of the Gunbarrel Basin, Albany–Fraser Orogen, and Eucla Basin (Fig. 1). The area is characterized by about 3% outcrop and extensive sandplain cover (approximately 70%), which has a strong eolian component (McGuinness, 2010). Open-file drilling data indicate that in the western part of the project area, post-Archean cover can be up to 400 m thick, with a regolith thickness of more than 55 m in some areas.

## Regolith sampling and analysis

Regolith from 835 sites was collected from a depth of approximately 80 cm using a power auger. The majority of regolith contains a high proportion of windblown quartz sand, which could act as a dilutant to both elements of economic interest and pathfinder elements. In order to minimize this quartz-dominated eolian component, the <50 µm (silt and clay) fraction was dry sieved from each sample and digested with aqua regia, a 3:1 mixture of

hydrochloric and nitric acids. This is a partial digest that preferentially attacks sulfides, oxides, and carbonates but is largely unreactive to silicates (Chao, 1984). The digest aims to liberate the exogenic component of the sample (i.e. material loosely bonded or bound to the sample medium) while minimizing the input of the endogenic component — the sample medium itself, which may be primarily transported (Cameron et al., 2004).

The fine-fraction chemistry illustrates the effectiveness of a partial-digestion approach to detecting buried gold mineralization.

## Fine-fraction gold chemistry

Aqua regia digestion and inductively-coupled plasma mass spectrometric (ICP-MS) analysis can provide a lower limit of detection for Au of one part per billion (1 ppb). Samples have an Au concentration range of <1 ppb to 29 ppb, with 36% of samples returning concentrations of less than the lower limit of detection (LLD). Statistical analysis of Au data where censored values are replaced by half the LLD show that outlier and extreme (i.e. anomalous, >9 ppb) values are largely found in the western part of the project area over areas of greenstone indicated by regional geophysical data and minimal outcrop. However, samples with anomalous gold concentrations are also found on strike extensions and adjacent to areas of greenstone, and extending from greenstones underlying parts of the Gunbarrel Basin. Other anomalous samples are found close to the Yilgarn Craton – Gunbarrel Basin margin in the south of the project area, and over isolated areas of more-magnetized bedrock associated with the Albany–Fraser Orogen.

The strong spatial association of anomalous Au in fine-fraction regolith and the geophysical expression of greenstones suggests that anomalous Au in regolith is sourced from greenstones. Open-file company data show that cover sequences in the areas of anomalous fine-fraction regolith Au over Yilgarn Craton greenstones are between 60 m and 80 m thick. Data for cover thickness (i.e. combined regolith and post-Archean sedimentary rock) in the Gunbarrel Basin southeast of the Stella Range greenstone belt indicate thicknesses of up to 120 m (averaging 55 m) near samples with anomalous Au concentrations.

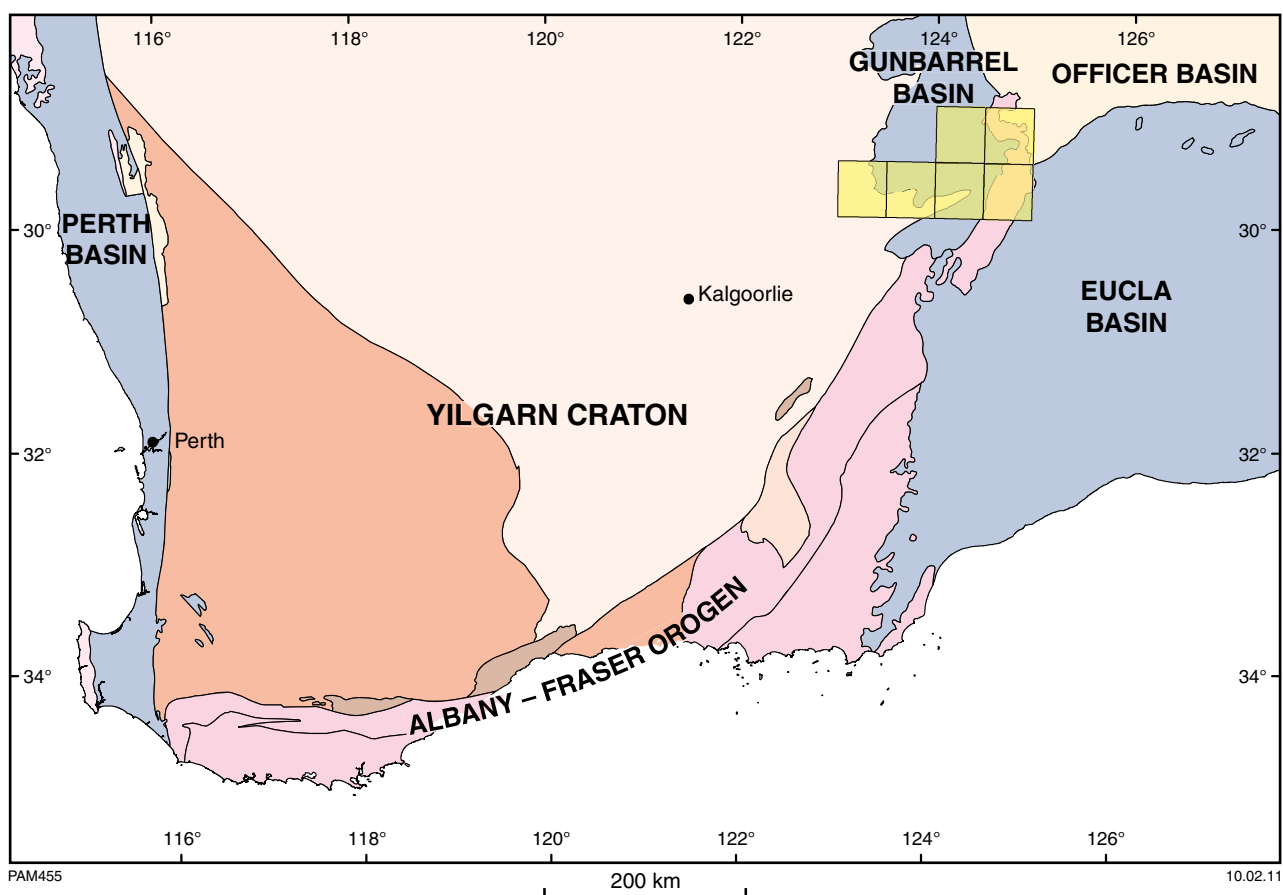


Figure 1. Location of the East Wongatha project area

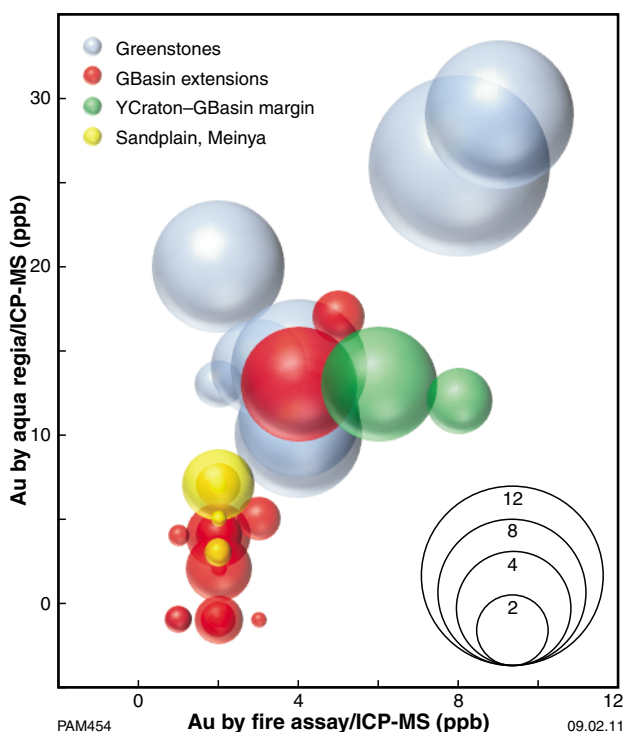


Figure 2. Scatterplot showing Au by fire assay/ICP-MS on the <2 - >0.475 mm fraction versus Au by aqua regia/ICP-MS on the <50 µm fraction (both in ppb), with symbols scaled according to gold concentration following deionized water digestion of the <50 µm fraction followed by ICP-MS analysis. Greenstones = samples on or close to Yilgarn Craton greenstones; GBasin extensions = samples over NW-SE magnetized rocks extending from greenstones under the Gunbarrel Basin; YCraton-GBasin margin = samples near the Yilgarn Craton — Gunbarrel Basin margin; Sandplain, Meinya = samples from sandplain-dominated regolith on MEINYA 1:100 000 sheet

Fifty samples with varying Au concentrations have been further analysed by fire assay–ICP-MS (<2 mm – >0.475 mm fraction) and deionized water digestion–ICP-MS (<50 µm fraction). The plot of fire assay Au versus aqua regia Au (Fig. 2) has symbols scaled according to Au following deionized water–ICP-MS analysis. The overall positive correlation is accentuated by a number of samples over Yilgarn Craton greenstones and parts of the Gunbarrel Basin having elevated Au concentrations when digested by deionized water and subsequently analysed. These data show that gold is present in both the coarse- and fine-grained fraction of regolith samples, and can be released from the latter by even benign digests such as deionized water as well as more aggressive digests such as aqua regia. This indicates that some gold is present as extremely weakly bonded or bound micron-scale particles (c.f. Hough et al., 2008). If this is the case, then the strong spatial association of anomalous gold and greenstones implies that some gold has migrated vertically, possibly as small particles, through processes such as seismic pumping (Cameron et al., 2004), soil gas movement (Wang et al., 2007), redox chimneys (Cameron et al., 2004), along fractures or faults or in solution, and has then been deposited close to the surface (e.g. Lintern et al., 2009). These results endorse the potential for using fine-fraction chemistry of regolith to detect buried mineralization through thick transported cover.

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# Geochemical characteristics of the Alcurra Dolerite (Giles Event) and its extrusive equivalents in the Bentley Supergroup

by

HM Howard, RH Smithies, M Werner, CL Kirkland, and MTD Wingate

The c. 1067 Ma Alcurra Dolerite is geographically widespread throughout the Musgrave Province of Australia. This geochemically distinct suite was emplaced during the complex series of intrusive (Warakurna Supersuite) and extrusive (Bentley Supergroup) mafic to felsic magmatic episodes that form the c. 1085–1030 Ma Giles Event. The suite postdates the major mafic intrusive components of the Warakurna Supersuite (the c. 1078–1075 Ma layered mafic–ultramafic intrusions and c. 1075 Ma massive gabbros), which form the west-northwest spine (Fig. 1) of the west Musgrave Province.

The Alcurra suite is of particular importance because of its potential direct genetic links with mineralization — for example with contemporaneous and geochemically similar gabbros hosting orthomagmatic Cu–Ni–PGE mineralization at Nebo–Babel as well as Cu(–Ni–PGE–Au) mineralization at the Halleys Prospect. The Alcurra suite may also have links with orthomagmatic to hydrothermal Cu mineralization found at the Tollu Prospect and in dykes to the north of the Jameson Community. In view of these potential links, our ongoing investigation into the stratigraphy and geochemical relationships of the Warakurna Supersuite and Bentley Supergroup seeks to understand petrogenetic links between the Alcurra Dolerite and voluminous extrusive units of the Bentley Supergroup and to explain any petrogenetic differences using new geochronological and geochemical data.

## Geochemistry of the Alcurra Dolerite

The Alcurra Dolerite is an evolved, strongly Fe-enriched and incompatible trace element-rich suite of tholeiitic to mildly alkalic intrusions that extends across all lithotectonic zones of the west Musgrave Province (Fig. 1). These rocks are geochemically distinct from other mafic intrusive rocks of the Giles Event and from rocks of other dyke suites in the region (e.g. the Kullal Dyke Suite; Fig. 2). Major- and trace-element trends suggest that the evolution of the suite is mainly controlled by fractionation of olivine and plagioclase, with later magnetite fractionation. Bulk compositions ( $\text{SiO}_2$  ~47.5 wt% and MgO ~6 wt%) are consistent with crystallization at high T, and low P,  $f_{\text{H}_2\text{O}}$  and  $f_{\text{O}_2}$ . Minimum La/Nb (~1.5) and La/Sm (~2.6) ratios (Fig. 3) are regionally

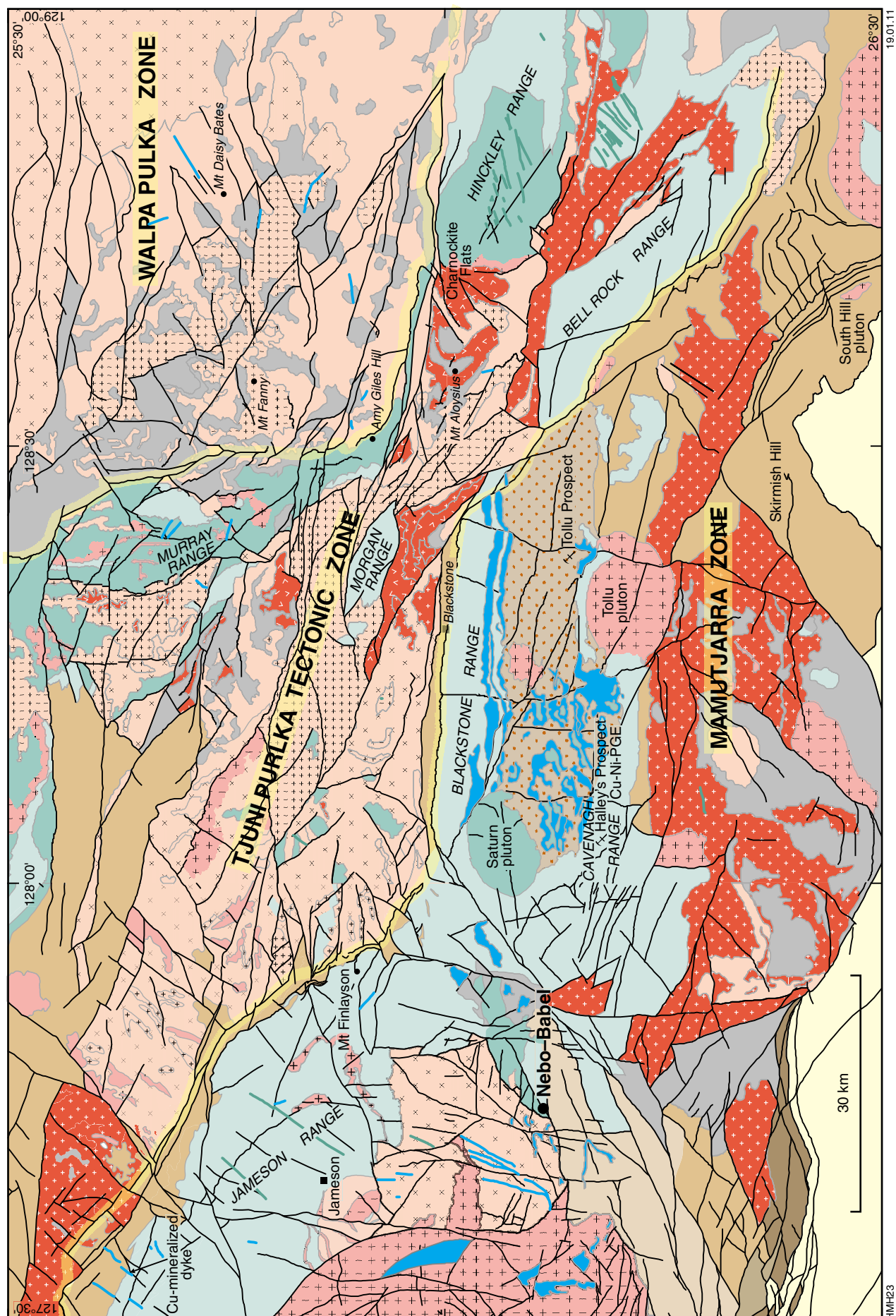
constant and reflect incorporation of an enriched (ultimately crustal) component into the melt that was compositionally homogeneous. Neodymium isotopic data indicate that this enriched component was ancient (>1600 Ma) and likely either reflects a compositionally homogeneous lower crustal contaminant or a previously enriched mantle source. Divergences from these minimum La/Nb and La/Sm ratios likely reflect upper crustal contamination (see arrows in Fig. 3) and, interestingly, are most pronounced in areas where the Alcurra Dolerite is known to be mineralized.

## Comparisons with the Bentley Supergroup

The Bentley Supergroup is composed mainly of voluminous bimodal mafic and felsic volcanic rocks. The oldest component — found in the Blackstone region — is the c. 1078 Ma Kunmarnara Group, and includes the amygdaloidal basaltic lavas of the Mummawarrawarra Basalt. This basalt is a very distinct geochemical group (Fig. 3) that can be correlated, over several 100 km, with the Mount Harris Basalt in the Northern Territory (Close et al., 2003). Evidence for significant contamination by a discrete crustal component clearly distinguishes it from the younger Alcurra Dolerite.

The Tollu Group is composed of the felsic lavas of the c. 1072 Ma Smoke Hill Volcanics and these are overlain by the basic to intermediate lavas of the Hogarth Formation. Deposition of the Hogarth Formation possibly overlapped with emplacement of the Alcurra Dolerite, and the two groups show strong compositional similarities.

The Bentley Supergroup is best exposed in the Mount Eveline – Warburton Range area where its oldest outcrop component is the Pussy Cat Group. This group includes the amygdaloidal basaltic lavas of the Glyde Formation, some of which might be as young as c. 1065 Ma, although the rhyolitic 1071 ± 5 Ma Kathleen Ignimbrite (GSWA sample 195723) also forms a component of the group. Although basalts of the Glyde Formation show evidence of significant upper crustal contamination (Fig. 3), their least-contaminated rocks are compositionally very similar to the Alcurra Dolerite.



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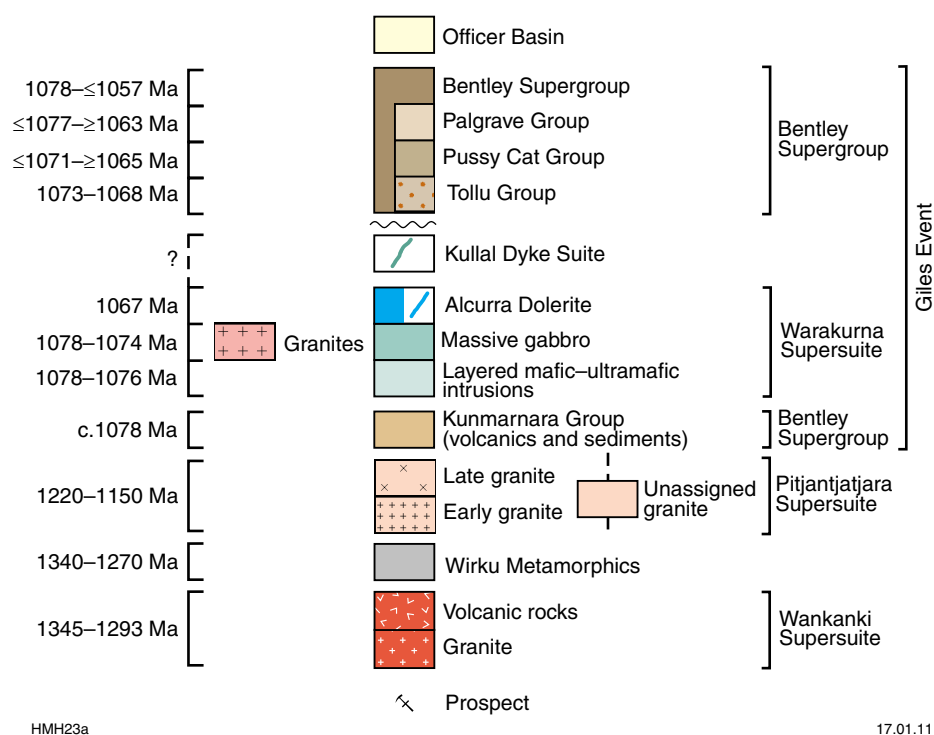


Figure 1. Solid geology interpretation of the eastern portion of the west Musgrave Province showing the distribution of major Alcurra Dolerite intrusions, extending through the Jameson, Blackstone and Bell Rock Ranges

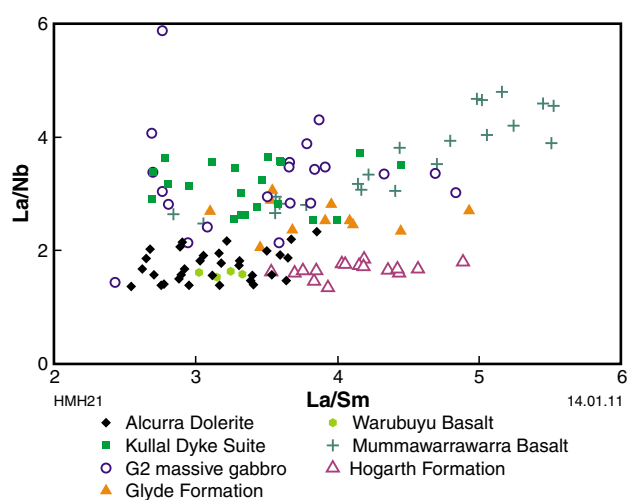


Figure 2. La/Nb vs La/Sm showing the Alcurra Dolerite, massive gabbro (Warakurna Supersuite), Kullal Dyke Suite, Mummawarrawarra Basalt, Glyde and Hogarth Formations, and Warubuyu Basalt

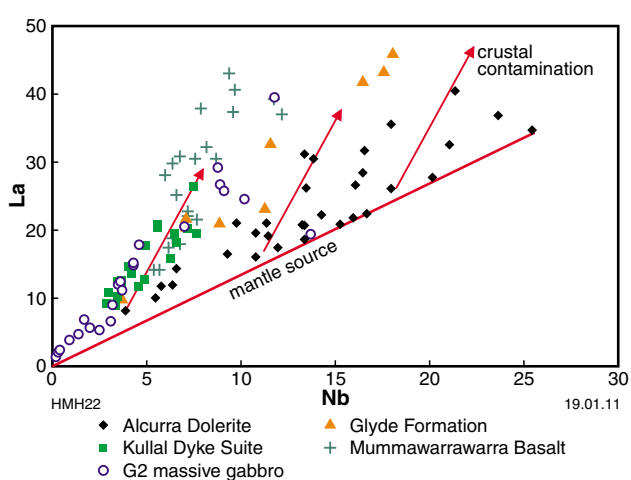


Figure 3. La vs Nb showing regionally constant minimum La/Nb and the effect of upper crustal contamination on all magma batches

The c. 1064 Ma Palgrave Group consists of a generally south-striking sequence that dips and youngs to the west. The succession is folded on a large scale and consists of felsic volcanic and pyroclastic rocks with minor lenses of mafic volcanic rocks. Regionally extensive, formerly vitric, units show remarkable geochemical homogeneity. Geochemically similar rhyolite forms a major component of the Scamp Volcanics and a new age of  $1064 \pm 5$  Ma from the Scamp Volcanics (GSWA sample 195678) potentially links them with the Palgrave Group. Mafic lenses within the lower Palgrave Group and dolerite intrusions within the Scamp Volcanics are both geochemically very similar to the Alcurra Dolerite.

The Cassidy Group consists of a sequence of alternating and variably amygdaloidal mafic lavas and flow-banded rhyolitic lavas, such as the  $1065 \pm 5$  Ma Wururu Rhyolite (GSWA sample 174690) and the  $1057 \pm 6$  Ma Thomas Rhyolite (GSWA sample 174691). Several microgranite intrusions in the Mount Eveline area are geochemically similar to the Wururu Rhyolite and are most likely their synvolcanic equivalents. Basalts such as the Warubuyu Basalt show strong compositional similarities with the Alcurra Dolerite. The Thomas Rhyolite shows geochemical similarities with evolved rocks of the Hogarth Formation and with  $1055 \pm 10$  Ma quartz diorite intrusions (GSWA sample 187054), which were emplaced into the Palgrave Group, and all of these show trace-element similarities with the Alcurra Dolerite.

The geochemical composition of the Alcurra Dolerite differs from most other mafic intrusive units of the Warakurna Supersuite (Figs 2, 3). However, several volcanic units of the Bentley Supergroup show remarkable compositional similarities and were most likely derived from the same source. Although the uncertainties on geochronological constraints allow the possibility that dolerite intrusions in the Scamp area, the Warubuyu Basalt, and quartz diorite intrusions into the Palgrave Group, are the same age as the Alcurra Dolerite, they are more likely to be younger intrusions derived from the same mantle source. Furthermore, the geochemical trends discussed show that basalts of the Glyde Formation and mafic lenses in the lower Palgrave Group could be genetically linked to the Alcurra Dolerite (suite).

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# Crustal evolution of the Murchison Domain and implications for whole-of-Yilgarn tectonic models

by

MJ Van Kranendonk, TJ Ivanic, MTD Wingate, CL Kirkland, JB Cliff\*, and S Wyche

Outcrop, geochemical, and isotopic data from the north-eastern Murchison Domain of the Yilgarn Craton have been compiled to develop a model of autochthonous crustal growth between 2.96 and 2.60 Ga (Fig. 1; Van Kranendonk and Ivanic, 2009). Greenstones are assigned to the Murchison Supergroup, which is divided into four autochthonous groups, separated by unconformities: 1) the 2960–2930 Ma Mount Gibson Group of mafic and felsic volcanic and volcanoclastic rocks; 2) the widespread 2825–2805 Ma Norie Group of mafic volcanic rocks, felsic volcanoclastic sandstones, and banded iron-formation; 3) the 2800–2735 Ma Polelle Group of mafic–ultramafic volcanic rocks, intermediate to felsic volcanic and volcanoclastic sedimentary rocks, and banded iron-formation; and 4) the 2735–2700 Ma Glen Group of coarse clastic sedimentary rocks, komatiitic basalt, and minor rhyolite. Very large, layered mafic–ultramafic complexes of the Meeline and Boodanoo suites (e.g. Windimurra Igneous Complex) accompanied eruption of the Norie Group during crustal extension at 2825–2805 Ma. Less voluminous mafic–ultramafic intrusive suites accompanied eruption of the Polelle and Glen Groups.

Deposition of the Mount Gibson, Polelle, and Glen Groups was accompanied by widespread intrusion of syn-volcanic plutons, and followed by 120 Ma of widespread and voluminous granitic magmatism from 2720 to 2600 Ma. The similarity of c. 2950 Ma inherited zircons within these granites to detrital zircon age populations in 2820 to 2720 Ma greenstones, together with Hf isotope data on zircons from dated granites, indicate autochthonous granite generation within an older crust that was extracted from a mantle source around 3 Ga.

In the Polelle Group, initial mafic–ultramafic volcanism, which was derived from deep mantle (plume) melting, changes to andesitic and then dacitic–rhyolitic volcanism between 2760 and 2740 Ma, coeval with sodic granitic plutons (tonalite–trondhjemite–granodiorite (TTG), or high-Ca granites, Champion and Cassidy, 2002). Geochemical data indicate the intermediate to felsic volcanic rocks derive from a variety of sources. Hf isotopic data ( $\epsilon\text{Hf}_{2750\text{ Ma}} = -1$  to  $-10$ ) indicate that some of these magmas derive from, or include components of, a much older evolved (unradiogenic)

crustal source, with residence in the crust since 3.8 Ga. A subduction origin for the andesites is possible, and may have included a component of entrained sediment derived from a much older source than is currently exposed in the Murchison Domain. In order to test this hypothesis, oxygen isotope data were obtained from zircons from the same dated granites that returned unradiogenic  $\epsilon\text{Hf}$  values. However, the oxygen isotope results indicate values within uncertainty of mantle (e.g.  $\delta^{18}\text{O} \approx 5.6\text{‰}$ ). Thus, an allochthonous input of older sedimentary material is not supported. Rather, geochemical modelling shows that c. 2760 Ma andesites can be explained by mixing of mantle-derived basaltic and crust-derived granitic magmas, a suggestion bolstered by field observations of magma mixing within sodic granitic rocks of this age (Fig. 2). Furthermore, the c. 2760 Ma age of onset of intermediate–felsic magmatism corresponds well with the calculated time lag of conductive heating of the crust following the onset of plume-derived magmatism (e.g. 30 Ma; Sandiford et al., 2004). Thus, we interpret the 2760 Ma calc-alkaline volcanic and contemporaneous TTG granitic event in the Murchison Domain as the result of widespread partial melting of a horizontally layered, stagnant older crust in response to a major mantle-plume event at 2820 Ma, including an older, lower crustal component isolated from near-surface processes. This lower crustal component was sampled only during extreme melting events.

Much of the late Archean history of the Murchison Domain, from 2720 to 2630 Ma, is similar to, and broadly contemporaneous with, events within the Eastern Goldfields Superterrane. Specifically, we note coeval komatiite–basaltic volcanism at c. 2720 Ma, followed by widespread felsic magmatism (2690–2660 Ma), early deformation at 2675 Ma, shear-hosted gold mineralization at 2660–2630 Ma, and post-tectonic granites at c. 2630 Ma. These findings, together with the overall low metamorphic grade of the crust (prehnite–pumpellyite to upper greenschist facies), and a lack of evidence for significant thrusting and for passive margin/foreland basin/accretionary prism successions, suggest that a re-evaluation of popular subduction–accretion tectonic models for craton development (e.g. Barley et al., 1989, 2008), is warranted.

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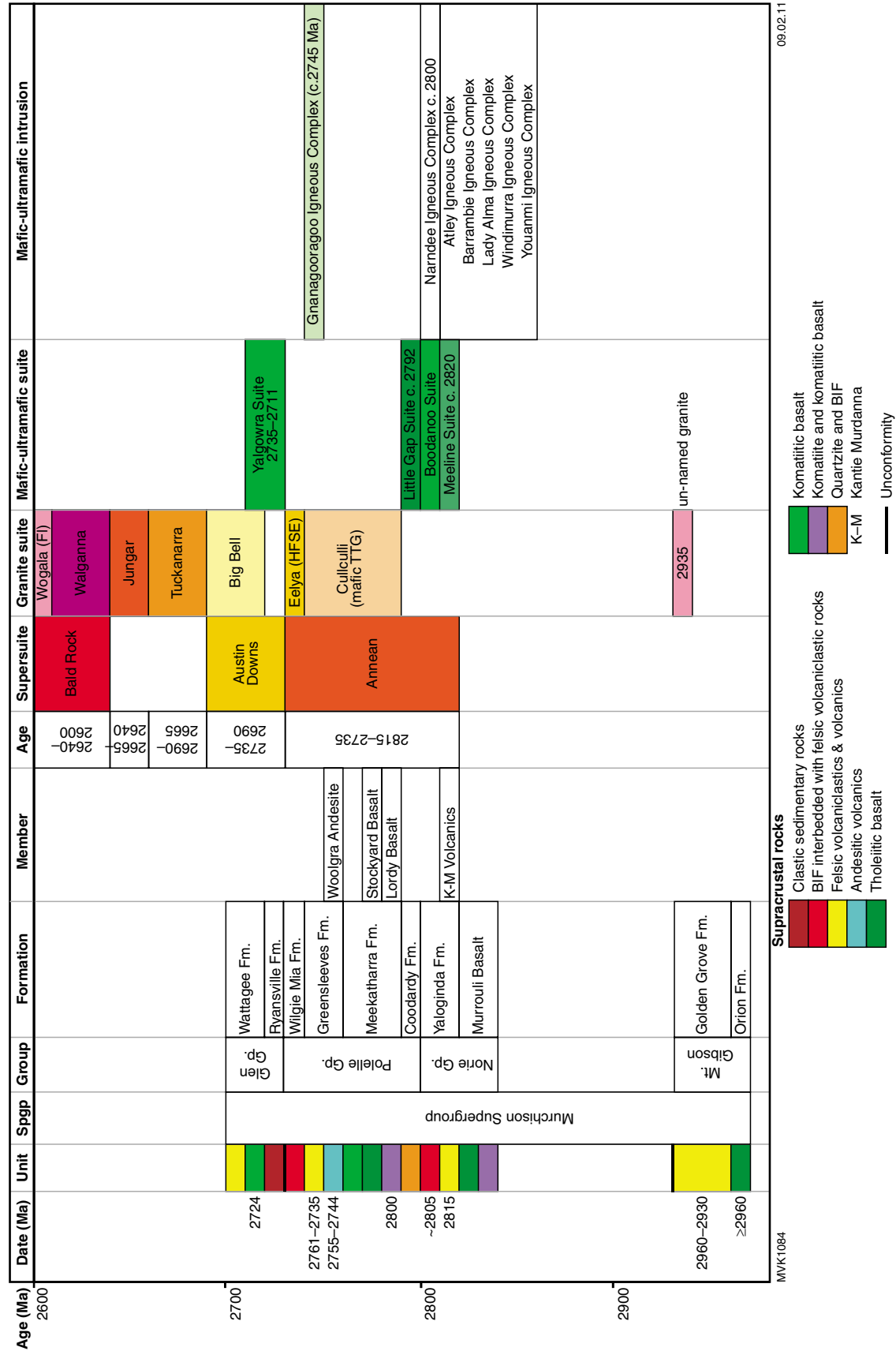


Figure 1. Stratigraphic scheme for the Murchison Domain, divided into three main columns for supracrustal rocks, granitic rocks, and mafic-ultramafic intrusive rocks (updated from Van Kranendonk and Ivanic, 2009)



**Figure 2.** *Outcrop view of scattered, tectonically strained mafic inclusions in a c. 2750 Ma sodic granite of the northeastern Murchison Domain, which is considered to indicate magma mingling*

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