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

RECORD 2015/2

GSWA 2015 EXTENDED ABSTRACTS
Promoting the prospectivity of Western Australia




Geological Survey of Western Australia

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February 2015

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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
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Abracadabra — dating hydrothermal mineralization and fluid flow in a long-lived crustal structure

by

SP Johnson, J Zi[1], B Rasmussen[1], JR Muhling[1,2], IR Fletcher[1], DJ Dunkley[1], AM Thorne, HN Cutten, and FJ Korhonen

The Proterozoic Capricorn Orogen (Fig. 1a) is a major tectonic zone that records the assembly of the West Australian Craton from the Archean Pilbara and Yilgarn Cratons and the Glenburgh Terrane. Assembly was followed by a long history of tectonic reworking and reactivation focused along a series of major crustal structures, some of which are spatially associated with hydrothermal mineral deposits (Johnson et al., 2013), implying a link between hydrothermal fluid flow and the generation or reactivation of these structures. The Abra polymetallic deposit (Fe, Pb, Zn, Ba, Cu, Au, Ag, Bi, and W) is the largest base metal accumulation in the Capricorn Orogen, and is located close to the crust-cutting Lyons River – Quartzite Well fault zone (Fig. 1a). Despite being discovered in the early 1980s, the tectonic setting, age, and style of mineralization are still not precisely known. Robust radiometric dates for the timing of sediment deposition and hydrothermal mineralization are essential for understanding the geological history of this long-lived orogen and the processes that formed the ore deposits.

The Abra deposit

The Abra polymetallic deposit is a blind, stratabound, hydrothermal deposit that is hosted in sedimentary rocks of the Mesoproterozoic Edmund Group (Fig. 1; Pirajno et al., 2009; Rasmussen et al., 2010a; Thorne et al., 2009; Vogt and Stumpfl, 1987). Mineralization occurs within a structural corridor at the eastern end of the Jillawarra Sub-basin (Vogt, 1995), close to the junction of two major faults, the northeast-trending Bujundunna Fault and the easterly trending Quartzite Well Fault (Fig. 1b). The latter is interpreted to be an extension of the Lyons River Fault (Fig. 1a), which is a major crustal suture between the Pilbara Craton and the Glenburgh Terrane of the Gascoyne Province (Johnson et al., 2013). The southern margin of the structural corridor is delineated by the Coodardoo South Fault (Fig. 1b).

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The main mineralization is hosted within both the Irregully Formation and the lower alluvial-fan deposits of the Kiangi Creek Formation (Fig. 2a), but not in the unconformably overlying deltaic to deep-marine facies of the Kiangi Creek Formation (Thorne et al., 2009). This relationship suggests that the timing of the Abra mineralization broadly coincided with a period of active growth faulting, alluvial-fan sedimentation, and minor felsic volcanism during deposition of the lower part of the Kiangi Creek Formation. However, isolated barite–chalcopyrite–dolomite–galena veins, up to 10 mm wide, are present in the overlying deltaic to deep-marine facies, implying a second generation of mineralization and hydrothermal activity after the deposition of the upper part of the Kiangi Creek Formation.

U–Th–Pb phosphate dating

In situ U–Th–Pb SHRIMP geochronology of xenotime intergrown with magnetite–hematite–galena from the ore zone yields a weighted mean $^{207}Pb/^{206}Pb$ age of 1594 ± 10 Ma (n = 14, MSWD = 2.6), although individual analyses provide a range of concordant dates from as old as c. 1610 Ma to as young as c. 1590 Ma (Fig. 3a). These ages indicate a prolonged period of hydrothermal activity, with the main phase of mineralization occurring at c. 1595 Ma. Hydrothermal monazite from the ore zone gives $^{207}Pb/^{206}Pb$ ages of 1375 ± 14 Ma (n = 16, MSWD = 0.99), interpreted to represent a hydrothermal event post-dating the main phase of mineralization (Fig. 3b). Monazite in samples distal to mineralization yield weighted mean $^{207}Pb/^{206}Pb$ ages of 1221 ± 14 Ma (n = 5, MSWD = 1.04) and 995 ± 18 Ma (n = 6, MSWD = 1.3), interpreted as records of discrete episodes of hydrothermal fluid flow, tentatively dating the development of regional barite–chalcopyrite–dolomite–galena veins (Fig. 3b).

Depositional age of the Edmund Group

The new ages obtained from the ore zone at Abra also provide critical constraints for the timing of deposition of the host Edmund Group sedimentary rocks. The oldest

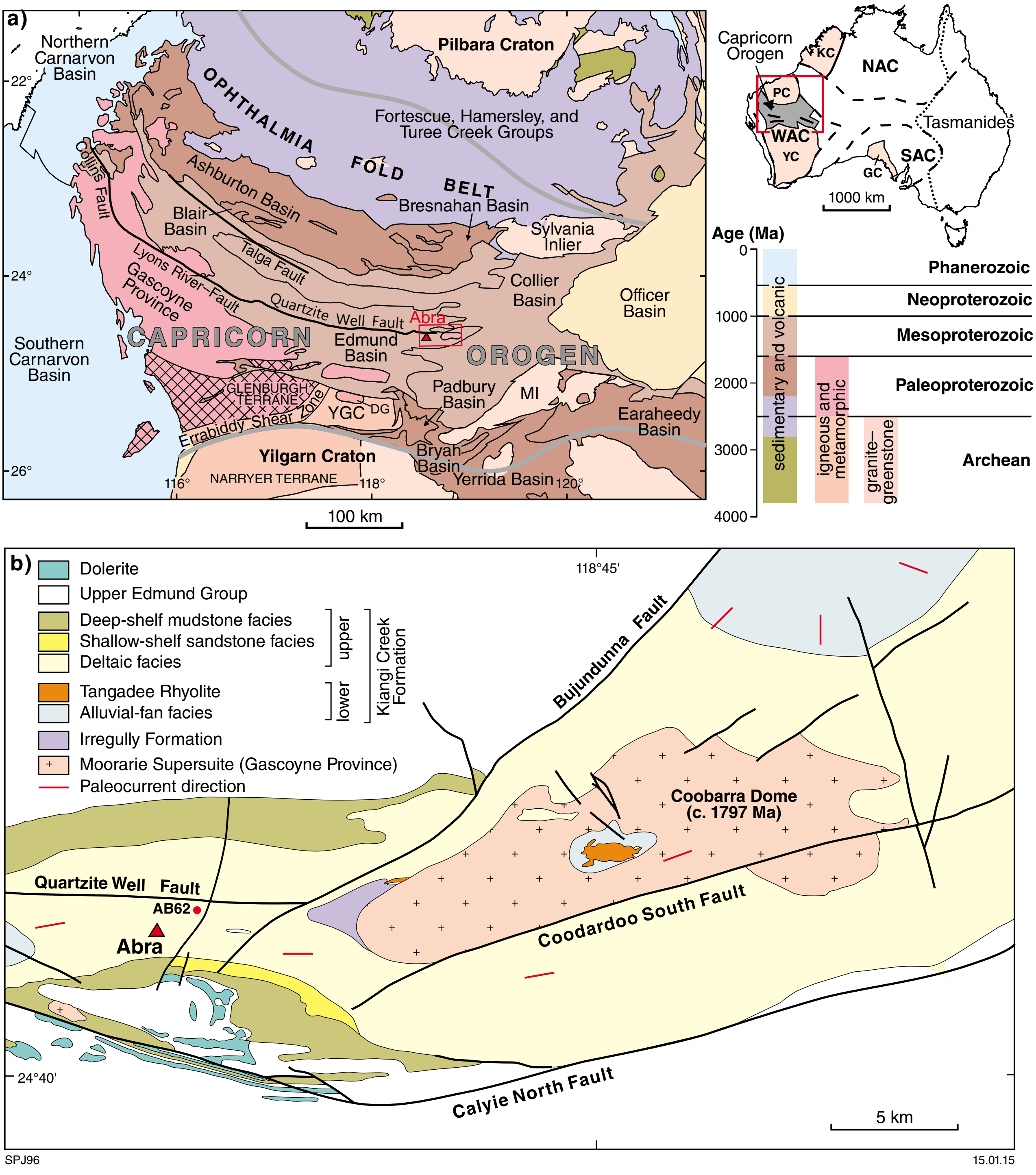

Figure 1. a) Regional geological setting of the Mesoproterozoic Edmund Group within the Capricorn Orogen, showing the location of the Abra polymetallic deposit. Abbreviations: DG, Discretion Granite; GC, Gawler Craton; KC, Kimberley Craton; MI, Marymia Inlier; NAC, North Australian Craton; PC, Pilbara Craton; SAC, South Australian Craton; WAC, West Australian Craton; YC, Yilgarn Craton; YGC, Yarlarweelor Gneiss Complex; b) interpreted bedrock geology of the area showing the location of Abra in relation to the major structures and depositional facies of the Kiangi Creek Formation

coherent age component of hydrothermal xenotime in the ore zone, dated at c. 1610 Ma, provides a minimum age for deposition of the Irregully Formation and alluvial-fan facies of the Kiangi Creek Formation. The youngest detrital zircons from the stratigraphic sequence are dated at c. 1679 Ma (from the underlying Mount Augustus Sandstone; Martin et al., 2008), indicating that the basal part of the Edmund Group must have been deposited sometime between c. 1679 and 1610 Ma. As the upper part of the Kiangi Creek Formation and overlying Edmund Group rocks are unmineralized, they must have been deposited after the main phase of hydrothermal mineralization — the youngest phosphate date is c. 1590 Ma. This indicates that the lower and upper parts of the Edmund Group are separated by a major unconformity that represents a time break of at least 20 Ma. In the Jillawarra Sub-basin this unconformity is interpreted to be within the Kiangi Creek Formation, but this break is not recognized elsewhere in the Edmund Basin. It is possible that the identity of the lower alluvial-fan sequence at Abra has been misidentified and could instead represent part of the Gooragoora Formation (Fig. 2b). Thus, the major unconformity would coincide with the regional unconformity at the base of the Kiangi Creek Formation, which is recognized throughout much of the Edmund Basin.

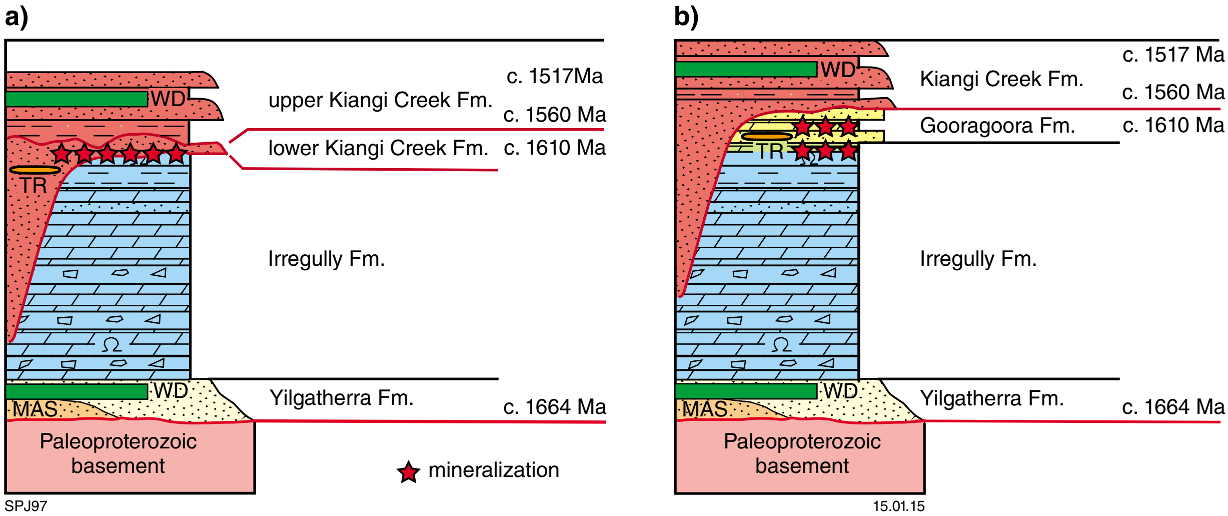

Figure 2. Alternative interpretations of the stratigraphy of sedimentary rocks at Abra, showing the location of unconformities (red lines) and new age constraints for deposition: a) shows the traditional interpretation where the lower alluvial-fan facies belongs to the lower part of the Kiangi Creek Formation; whereas b) shows a new interpretation with the lower alluvial-fan facies forming part of the Gooragoora Formation. Abbreviations: MAS, Mount Augustus Sandstone; TR, Tangadee Rhyolite; WD, Waldburg Dolerite

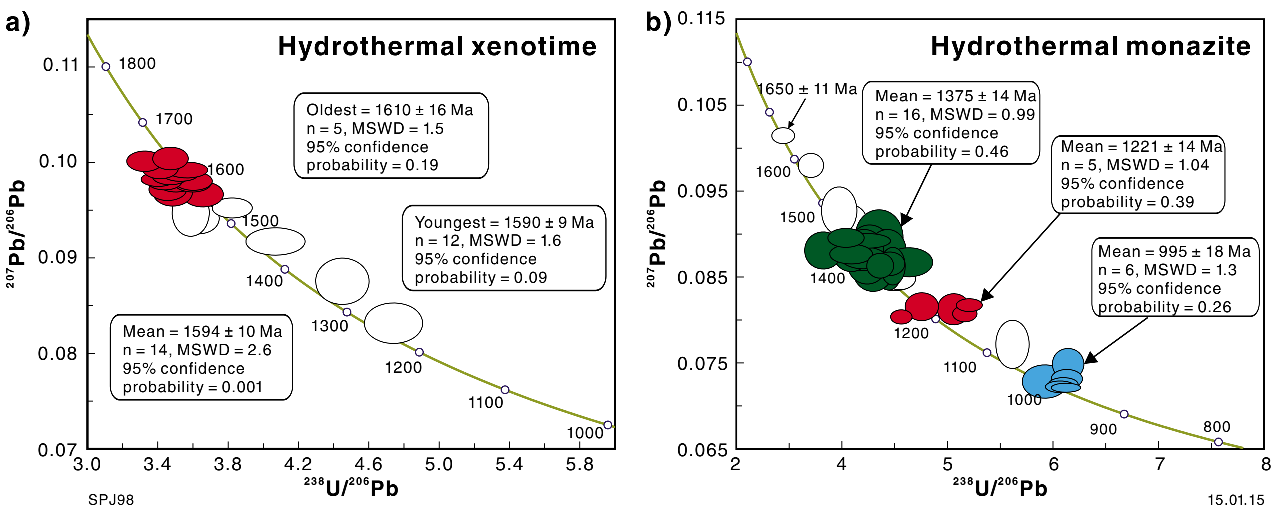

Figure 3. Tera-Wasserburg concordia plots of the U–Pb data for: a) hydrothermal xenotime from the ore zone of the Abra deposit; b) hydrothermal monazite from the ore zone and distal to mineralization

Summary

Mineralization at Abra was synchronous with the deposition of sediments into the lower part of the Edmund Basin between c. 1610 and 1590 Ma. Crustal extension, basin formation (including the formation of the Jillawarra Sub-basin) and sedimentation was controlled by the reactivation of major, pre-existing crustal structures including the Lyons River – Quartzite Well, Talga, Mount Vernon, and Bujundunna Faults (Cutten et al., 2011; Johnson et al., 2013). These major structures, particularly the Lyons River – Quartzite Well Fault, appear to have played an important role in a mineral systems setting, acting as deep-plumbing systems that focused fluid flow from the mantle, or mid- to lower crust, into the upper crust (Wyborn et al., 1994). The episodic growth of hydrothermal monazite and xenotime demonstrates that this fault system was reactivated numerous times over at least a 600 Ma period (from c. 1610 to 995 Ma), with the fault system being the locus for hydrothermal fluid flow during these reworking events.

Monazite and xenotime represent ideal chronometers for investigating the complex histories of hydrothermal mineralization and fluid flow in major crustal structures, and can be used to help to unravel the geological evolution of complex intracratonic orogens.

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The Glenburgh Au deposit, Gascoyne Province — evidence of metamorphosed gold?

by

LK Roche

Gold deposits are rare in upper amphibolite to granulite facies environments, and known examples commonly attract debate about whether they formed at these high temperatures, or instead represent metamorphosed or superimposed (retrograde) mineralization. The one million-ounce Glenburgh gold deposit (Gascoyne Resources Ltd) lies in the Paleoproterozoic upper amphibolite to granulite facies gneisses of the Glenburgh Terrane, in the southern Gascoyne Province of Western Australia (Fig. 1).

The ‘continuum model’ indicates that ‘orogenic’ gold deposits formed during peak metamorphism, anywhere from the prehnite to granulite facies (Groves, 1993). This model has been challenged by a re-examination of ‘high metamorphic grade’ examples, such as Griffins Find and Big Bell, previously used to support the continuum model (Phillips and Powell, 2009; Tomkins and Grundy, 2009), and of partially melted metamorphic rocks associated with gold mineralization (Tomkins and Mavrogenes, 2002). It has been argued that it is difficult to transmit hydrothermal fluids in a major gold-forming event through rocks at temperatures above 600–650 °C, because the addition of any (aqueous) hydrothermal fluid under these conditions would cause partial melting of the rocks, and consumption of the fluid, thereby inhibiting its transfer (Tomkins and Grundy, 2009). Partial melting is indicated by the presence of pegmatite dykes or migmatites in many high-metamorphic-grade gold deposits, such as Big Bell, Hemlo, Griffins Find, Challenger, Renco, and including Glenburgh (Phillips and Powell, 2009).

The Capricorn Orogen records the two-stage collision between the Archean Pilbara and Yilgarn Cratons with the exotic Glenburgh Terrane to form the West Australian Craton, followed by over one billion years of intraplate reworking (Occhipinti et al., 2004; Johnson et al., 2010). The Glenburgh gold deposit is located close to the suture zone between the Glenburgh Terrane and the Yilgarn Craton in voluminous calc-alkaline tonalite–trondhjemite–granodiorite (TTG) magmatic arc rocks of the 2005–1970 Ma Dalgaringa Supersuite. These rocks formed in a continental magmatic arc over a north- or northwest-directed subduction zone with magmatism occurring within the Glenburgh Terrane (Occhipinti et al., 2004). High-grade metamorphism (D_{1g}), dated at c. 1997 Ma in sample GSWA 185942 (Wingate et al., 2010), accompanied the intrusion of the magmatic-arc rocks. D_{1g} metamorphism is interpreted to have peaked at ~800–1000 °C at 7–10 kbar (Johnson et al., 2010). This was followed by the collision of the combined Pilbara–Glenburgh Craton with the Yilgarn Craton, which took place during the 1965–1950 Ma collisional phase (D_{2g}) of the Glenburgh Orogeny.

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Gold mineralization

Gold in the Glenburgh deposit is disseminated within discontinuous, east-northeasterly trending steeply north-dipping packages of tightly folded quartz–biotite–garnet gneisses (subdivided into quartz–feldspar ± garnet leucosomes and biotite-rich melanosomes), amphibolites and (post-gold) quartz–chlorite veins that are offset by faulting. There appears to be no clear association of gold with any specific lithology (appearing in each unit), nor any obvious associated alteration.

Sample GSWA 214909 contains several disseminated, generally sub-rounded gold grains up to ~100 µm in size that are not associated with any sulfides (Fig. 2a). Smaller grains lie along the edges of larger grains. The main minerals associated with gold in this sample are a calcium amphibole (which semi-quantitative SEM analysis suggests is tschermakite) and ilmenite.

The gold grains were etched to provide insight into their internal structure and to help understand the growth history of the gold (Nikolaeva et al., 2004). In one case an intergranular high-purity gold veinlet was observed between two sub-grains (Fig. 2b), which formed due to leaching of silver from internal grain boundaries through post-depositional processes such as deformation, metamorphism, or weathering (Nikolaeva et al., 2004). This is supported by the lack of silver measured within all gold grains under Scanning Electron Microscope (between 0.5 and 2% Ag). In contrast, primary hypogene Au–Ag alloys commonly contain 5 to 20% Ag. Within the same grain there is evidence of incoherent twins (Fig. 2c), which suggests this gold has been thermally annealed at elevated temperatures (Hough et al., 2007).

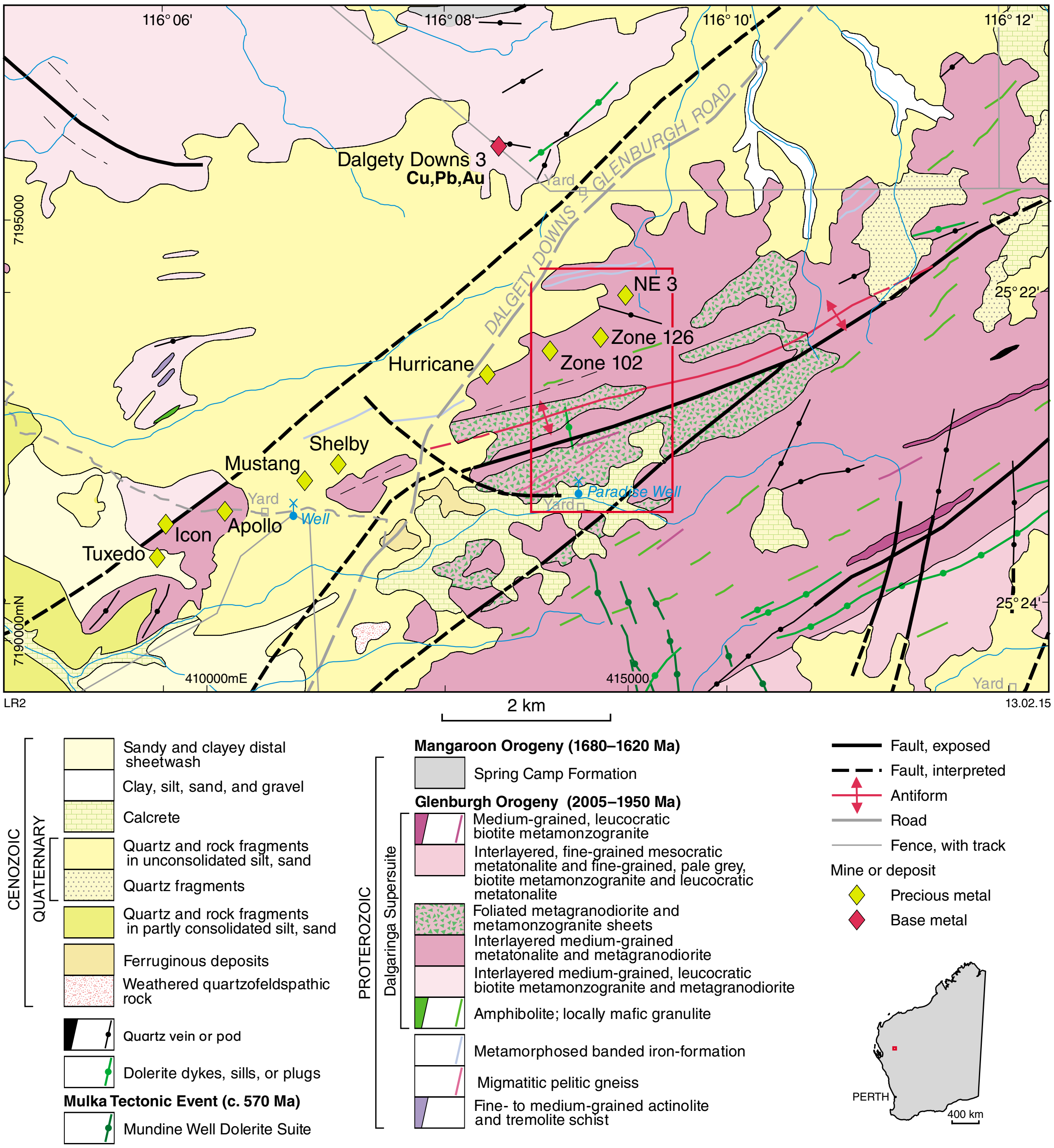

Figure 1. Regional geological map around the Glenburgh gold deposit (after Occhipinti et al., 2011); the field mapping area is outlined by red box

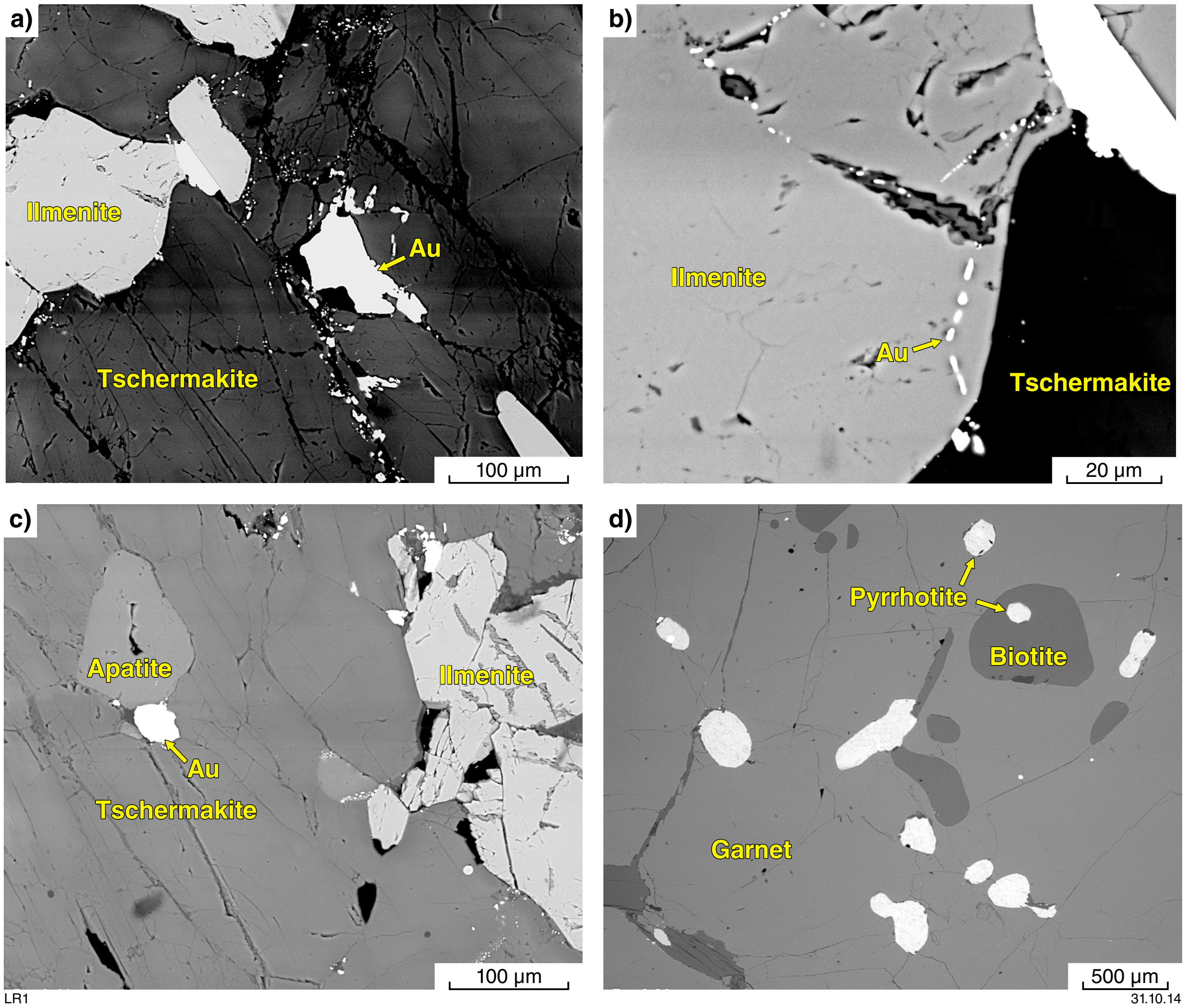

Figure 2. a) Gold grains in reflected light with tschermakite (main groundmass) and ilmenite (grey), GSWA 214909; b) etched gold grain under SEM: internal grain boundaries highlighted as well as an intergranular high-purity gold veinlet, likely to have been caused by silver leaching on grain boundaries, GSWA 214909; c) etched gold grain under SEM: incoherent twinning broken off at the edges of an internal gold grain, characteristic of thermal annealing at elevated temperatures, GSWA 214909; d) well-rounded pyrrhotite grains (light grey) with one strip of chalcopyrite (lighter shade) and biotite (darkest) within garnet porphyroblasts, GSWA 214901

Pyrrhotite is the main sulfide in the deposit (between 0.1 and 5%) and is interstitial to silicates. The pyrrhotite contains minor chalcopyrite inclusions. Pyrite is also present and often rims or replaces pyrrhotite, suggesting it formed later. Peak metamorphic garnet porphyroblasts contain well-rounded pyrrhotite and biotite inclusions (Fig. 2d), implying the presence of a pre-peak metamorphic sulfide phase that is likely to have been associated with the gold mineralizing event.

U–Pb dating of both detrital and metamorphic zircons was completed on three migmatite samples from Gascoyne Resources' Zone 126 deposit (Wingate et al., 2015a,b,c). The youngest detrital zircons indicate a conservative maximum depositional age of 2035 ± 12 Ma (GSWA 208325; Wingate et al., 2015a). The metamorphic zircons in three samples provide an age for peak D_{1g} metamorphism of 1991 ± 2 Ma (Wingate et al., 2015a,b,c).

Conclusion

Evidence from field mapping, visual logging of drill core, thin section petrography, and gold microstructure analysis of gold-bearing rocks at Glenburgh demonstrates that gold mineralization occurred after sediment deposition and prior to high-grade D_{1g} metamorphism.

U–Pb zircon geochronology indicates that sediment deposition was younger than 2035 ± 12 Ma, and that high-grade metamorphism occurred at 1991 ± 2 Ma (Wingate et al., 2015a,b,c). Therefore, gold mineralization took place over a maximum ~44 Ma interval between c. 2035 and 1991 Ma. Given the presence of a calcium amphibole associated with gold, its formation could be an indication of carbonate alteration associated with gold mineralization. This research further supports the argument that orogenic gold deposits may not form at high temperatures and pressures.

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Distal footprints of giant ore systems: Capricorn case study

by

R Hough* and the Capricorn Distal Footprints Research Team

Australia is an old continent with much of its remaining mineral endowment obscured by a thick cover of weathered rock, sediment, and soil materials. This presents a critical challenge for mineral exploration now and into the future, as the industry currently lacks the fundamental data, scientific knowledge, and technological tools needed to discover new, world-class ore deposits buried deep under this cover.

Aligning with the Australian Academy of Sciences UNCOVER initiative to boost exploration geoscience research in Australia, and the Federal Government's National Exploration Strategy, the distal footprints of giant ore systems project was launched in August 2013. This collaboration between CSIRO, UWA (through the Centre for Exploration Targeting), Curtin University, the Geological Survey of Western Australia (GSWA), and in partnership with approximately ten junior and one major exploration company, aims to begin to address the key technical risks impeding future greenfields exploration.

The key to discovering new resources under cover is the ability to detect and recognize the distal footprints (faint mineral signatures) of deep giant ore systems. This Science and Industry Endowment Fund (SIEF) and Minerals Research Institute of Western Australia-supported four-year collaborative project is working to create a distal footprints 'toolkit' — an inter-related suite of tools (know-how, methodologies, new field and laboratory analysis techniques) — useful for practical exploration in areas of cover. The toolkit will create an exploration workflow that assists industry with the process of exploration targeting and the application of field campaigns.

The Capricorn Project area

The Capricorn Orogen, spanning an area of ~200 000 km^2 in Western Australia is a complex zone, comprising a range of variably deformed and metamorphosed igneous and sedimentary rocks. In the west, the Gascoyne Province, which forms the core of the Orogen, is dominated by medium- to high-grade metamorphic rocks, including granitic and metasedimentary gneisses. In the east, the province is overlain by numerous low- to medium-grade metasedimentary basins. The orogen records a complex tectonic history including more than one billion years of episodic reworking between two ancient cratons: the Pilbara Craton to the north and the Yilgarn Craton to the south (Johnson et al., 2013). Although the western and central parts of the Orogen are particularly well exposed, the northwest and eastern regions are characterized by a variably thick and complex regolith, much of it transported cover.

Apart from the high-grade iron ore in the Hamersley Ranges, the area contains the Paulsens and Plutonic Gold Mines (Northern Star Resources) and the DeGrussa copper–gold deposit in Sandfire Resources NL’s Doolgunna Project area. There are also numerous small-scale deposits that comprise a wide range of commodities and the area remains a prospective greenfields exploration region.

The Project

The overall project is split into six themes: 1. Mineral systems; 2. Cover — depth and character; 3. Mineral footprints; 4. Deep geological sensing using hydrogeochemistry; 5. Metal reservoirs — sulfur sources and sinks; 6. Data management and digital models (Fig. 1).

Mineral systems: Collection and integration of large-scale geological and geophysical datasets will provide constraints on present-day crustal architecture to better target major new economic mineral deposits within the crust and under cover, perhaps linked to deep structures that tap geochemical fertile regions of the lithosphere and act as conduits for metallogenic endowment through fluid and melt migration. Integration of present-day architecture with structural analysis, geochemical studies, and targeted geochronology will provide valuable constraints on the tectonic and architectural evolution of the region that will provide the framework for understanding temporal variations in mineral endowment and remobilization. This will provide a better understanding of how changing crustal architecture over time focuses magmas and fluids to produce large deposits or deposit clusters and will allow the targeting of appropriate-age rocks for footprint analysis.

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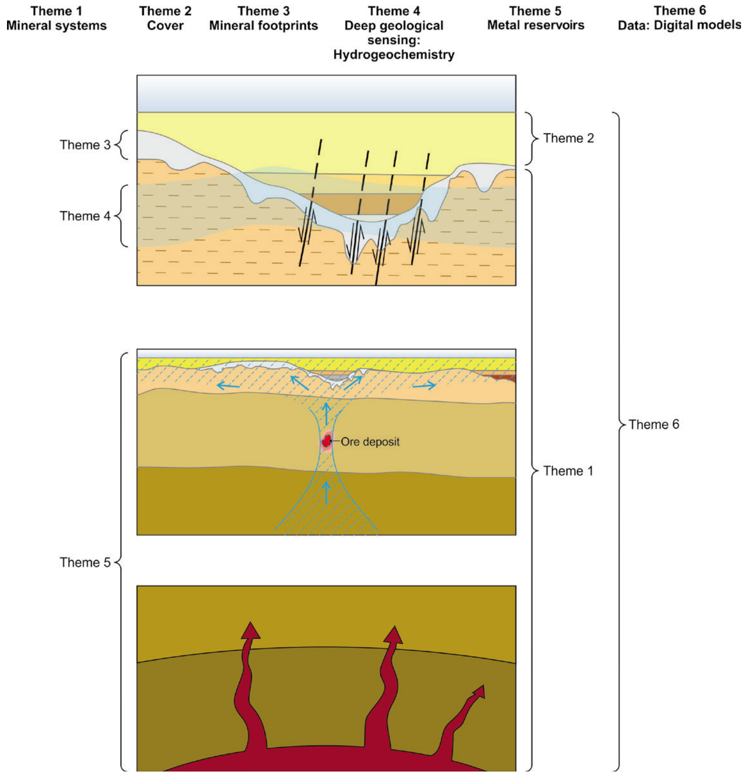

Figure 1. Cartoon illustration of the six themes of the project: 1. Mineral systems; 2. Cover — depth and character; 3. Mineral footprints; 4. Deep geological sensing using hydrogeochemistry; 5. Metal reservoirs — sulfur sources and sinks; 6. Data management and digital models

Cover: Given the paucity of outcrop in the eastern Capricorn region, and the extent of a variable and complex regolith cover across the whole region, the characterization of the regolith cover, its depth and complexity, and its 3D geometry needs to be better understood to define exploration strategies across the Capricorn Orogen. Regolith depth and nature requires the use of geophysical (aeromagnetic, electromagnetic, and gravity) techniques. A major, regional scale, near-surface geophysical survey, employing airborne electromagnetic techniques, combined with regolith characterization and regional landscape evolution modelling will therefore provide one of the basic building blocks for the project.

Mineral footprints: Mineralogical and geochemical signatures in the regolith and fresh rock from focused study areas, around known mineralization in the region, provide the opportunity to test for potentially subtle but far-field signatures as footprints that are manifested in individual mineral phases as an anomaly as compared to geological background. For example, rutile has been shown to contain anomalous W in porphyry or lode gold hydrothermal systems. Using isotopic and trace element composition, at regional scales on bulk samples and at microscale in individual minerals, within the context of a well-characterized architectural and tectonic evolution, we will be able to constrain signatures of the fluid flux; both fluid pregnant with metals and the spent fluid discharge thought to reach tens of kilometres away. These distal patterns and the minerals that host them will form a new armory for the exploration toolkit. These phases can also be preserved in regolith cover and provide a sampling and analysis opportunity at detrital interfaces in the cover. It is these phases that provide the undercover prospecting tool similar to surface exploration that makes use of lateritic nodules and pisoliths or stream sediment sampling.

Deep geological sensing: We propose to create a hydrogeochemical map of the Capricorn Orogen and surrounds, in order to obtain under-cover lithological and structural information, rank areas of interest, understand baseline chemistry for environmental management, and to suggest prospective zones for mineral exploration in a region that is significantly underexplored. Our previous research has demonstrated the capacity of this media to 'see through' tens of metres of barren cover. This database will also have the capability to test the effectiveness of surface-based sampling technologies such as soil-sampling, radiometrics, and ASTER mapping. The study will be primarily based on windmill sampling of 1000+ samples.

Metal reservoirs: The development of ore bodies can be considered within the context of a lithospheric-scale mineral system that comprises several critical steps. One of these critical stages is the transport of ore-bearing fluids from likely source regions to sites of ore deposition.

One potentially important fluid is melt, as it has been shown that periods of extraction of magmas from the Earth's mantle to form new, juvenile crust coincides with periods of enhanced base metal deposition. In order to form large-scale mineralizing systems, it is essential that these magmas incorporate significant volumes of crustal material on their paths to emplacement. Elements such as sulfur are incorporated in this way. Hence an orogen's mineral potential is critically linked to the timing, distribution, and processes of its magmatic systems and mantle–crust interactions.

An effective way to determine the timing of juvenile magmatic additions to the crust, and the degree of crustal assimilation by the magmas within an orogenic system, is to analyse the multiple isotope systems contained within the mineral zircon. Zircon contains three key isotopic systems that independently record (i) the timing of emplacement of magmatic rocks (U–Pb); (ii) whether the magmas were derived directly from the mantle or from older crustal sources (Lu–Hf); and (iii) the degree to which the magmas have interacted with crustal material during their path through the crust ($\delta^{18}O$). The robust nature of zircon, arising from its low intracrystalline diffusion rates and chemical inertness during thermal perturbations, means that zircon effectively retains its original isotopic signatures through subsequent crustal metamorphic and tectonic events. This is an essential quality given the multiple reworking events that have been experienced by the rocks of the Capricorn Orogen. Zircon is far superior to whole-rock and other mineral-isotopic systems in this respect.

Sulfides play a key role in the formation of numerous world-class mineral systems, including gold, nickel, copper, and the platinum group elements. It is known that S is a ligand that complexes, transports, and concentrates gold in hydrothermal fluids. Similarly, base metals such as nickel, cobalt, copper, zinc, arsenic, and lead — due to their high chalcophile nature in S-saturated magmatic and hydrothermal systems — may be concentrated in sulfides, particularly pyrite.

Although the genetic association between S and metal enrichment is well established, it is generally difficult to fingerprint and spatially localize the sulfur and metal sources that play a role in ore genesis within terranes. In fact, in any given setting S and other trace metals may occur in a wide range of stratigraphic intervals and/or geological units. However, the specific reservoir implicated in the ore-forming process may be very localized. Therefore, the ability to quickly and reliably map different S and trace-metal reservoirs in terms of their metal ratios and isotopic signatures within specific zones of terranes would impact on targeting criteria at the deposit, camp, and regional scale, in brownfields and greenfields terranes.

Numerous studies have looked at the sulfur isotopic composition of sulfide-bearing units in a wide range of country rocks and gold-mineralized environments in a wide range of Precambrian terranes worldwide. However, most of these studies have only characterized the $\delta^{34}S$ signature of these S reservoirs, which in itself is not a robust discriminating isotopic system, open to resetting during alteration and metamorphic processes. Conversely, this study aims at characterizing the multiple S isotopic signature ($\Delta^{33}S$ and $\Delta^{36}S$) and the trace element signature (Se, Te, Co, Ni, As, Sb, Au, Ag) of S reservoirs and mineralized occurrences in selected sites along the Capricorn Orogen of Western Australia.

Data: The datasets collected in the themes above are already becoming very large and multi-scale in nature. A key challenge in such a project is enabling visualization and integration of that data and to develop tools for virtual interrogation of the data and in the production of digital 3D models that can be used in exploration targeting and planning.

AEM — mapping the cover, an early highlight

In complex geological settings with a variable cover, regional-scale geophysical surveys provide a relatively rapid method for greatly increasing our understanding of these settings. A regional AEM survey covering the Capricorn Orogen undertaken by GSWA through Geoscience Australia (GA) is aimed at characterizing the nature of the cover in the region and provides an early highlight from the project team. The Capricorn 2013 AEM survey is the largest AEM survey by area flown in Australia to date, covering over 146 300 km^2 (Costelloe, 2014). In particular, we review the spatial character of the Capricorn's geo-electrical variability, to better define the causes of the modelled conductivity structure and its links to the regolith. Previous work (Munday et al., 2013) and current reprocessing of existing, public domain AEM data from across the Capricorn, suggest that some of the more dominant features identified in AEM data are linked to sediment-filled valleys associated with paleodrainage systems that at some point were prevalent in the region. The survey acquired over 190 flight lines, composed of more than 2 155 000 data points (or soundings), for a total of 30 119 line km of data (Costelloe, 2014). With separation between lines at 5 km, this meant coverage of the near full extent of the orogen (Fig. 2).

Work on this dataset is now focused on inversions and reinterpretation in light of regional basement geology, regolith geology, and contemporary drainage.

Acknowledgements

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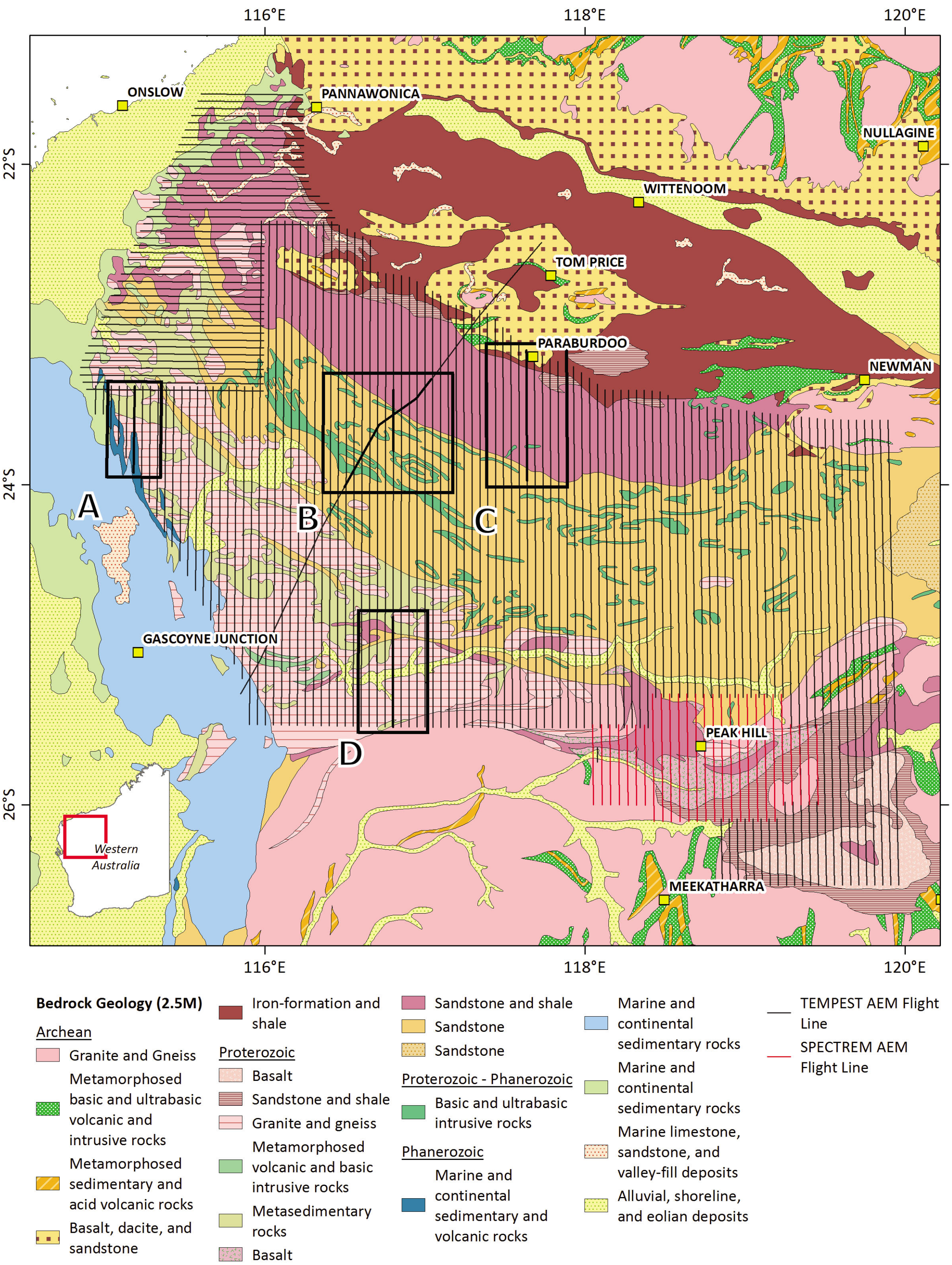

Figure 2. **Map of the TEMPEST and SPECTREM flightline coverage of the Capricorn Orogen over a map of the regional geology of the region**

3D Geoscience at GSWA

by

K Gessner

The aim of the 3D Geoscience Section at the Geological Survey of Western Australia (GSWA) is to increase the knowledge of Western Australia's subsurface through the integration of geophysical, geological, and geochemical data in 3D structural models.

3D models are generated by the integration of depth data with high-quality surface data from the Survey's geological mapping program. Active and passive seismic surveys and magnetotelluric models add the third dimension to geological and geochemical mapping. It is crucial that models are tested against potential field data, gravity, and magnetics, to verify the validity of the model and to reduce uncertainties.

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

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

Although 3D geological models can be generated at all scales, the focus is on regional structural models at the scale of the Earth's crust. For example, passive seismic studies are looking at whole crustal-scale structures using a variety of methods such as receiver-function analysis and ambient-noise studies. Current projects are based in the Albany–Fraser Orogen (with the Australian National University) and Capricorn Orogen (with CET and Macquarie University) regions. A review of existing passive seismic data has indicated the differences in crustal thickness and composition between the Yilgarn and Pilbara Cratons. The Pilbara Craton has a thin crust of felsic composition, whereas the Murchison Domain of the Yilgarn Craton shows a slightly thicker crust with a more felsic composition. In contrast, the South West Terrane of the Yilgarn Craton has a thicker crust with a much more mafic composition. The southeast edge of the Yilgarn Craton in the Fraser Zone of the Albany–Fraser Orogen comprises the thickest crust at more than 45 km, but further to the east the crust thins again slightly under the Eucla Basin. There is even an indication that a double Moho has been preserved where the Capricorn Orogen was thrust under the Narryer Terrane at the northwest margin of the Yilgarn Craton during the formation of the West Australian Craton (Fig. 1). The current Albany–Fraser passive seismic network registered the Kalgoorlie earthquake of 14 February 2014, which interestingly showed an east–west extension and its waveforms indicate a two-layered crust with a felsic upper crust and mafic lower crust.

The fabric of the Yilgan Craton can be imaged by surface-mapping techniques, but also from GSWA-acquired seismic reflection surveys. On the surface, the synthesis of geological mapping with gravity and magnetic fields shows ductile shear zones that have accommodated shortening by oblique slip. This late orogenic shear network is overprinting older shallow-dipping structures having a northeasterly trend. The existence of this persistent trend, also shown in the seismic reflection surveys, is consistent with observations such as the structural grain in the Narryer Terrane (where some of the oldest rocks in the State are found), isotopic maps of crustal evolution, and the orientation of the 1.8–1.6 Ga Barren Basin rifting, which came to define the southeast margin of the Yilgarn Craton.

On a more regional scale, areas such as the Windimurra Igneous Complex and the Sandstone greenstone belt have been modelled and then inverted against potential field data to produce 3D volumes (Fig. 2). These, with other models that have been submitted to GSWA, will be made available in our first 3D digital data package.

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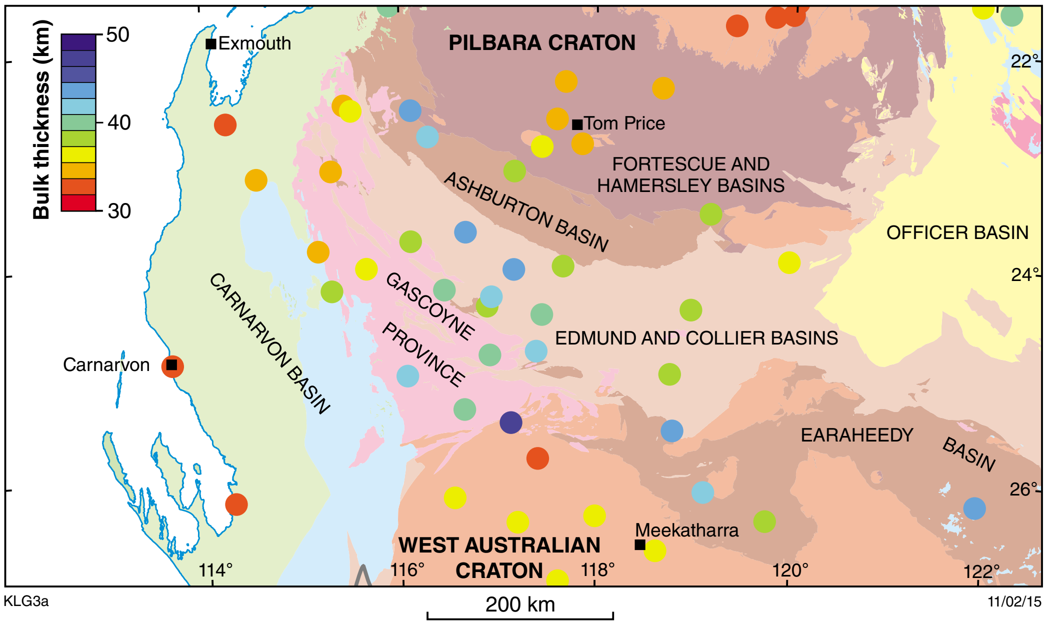

Figure 1. Crustal thickness based on passive seismic deployments in the Pilbara Craton, the Capricorn Orogen, and the northern Yilgarn Craton; imaging of very deep and very shallow points next to each other suggests a possible 'double Moho' implying that the Glenburgh Terrane is thrust under the Narryer Terrane

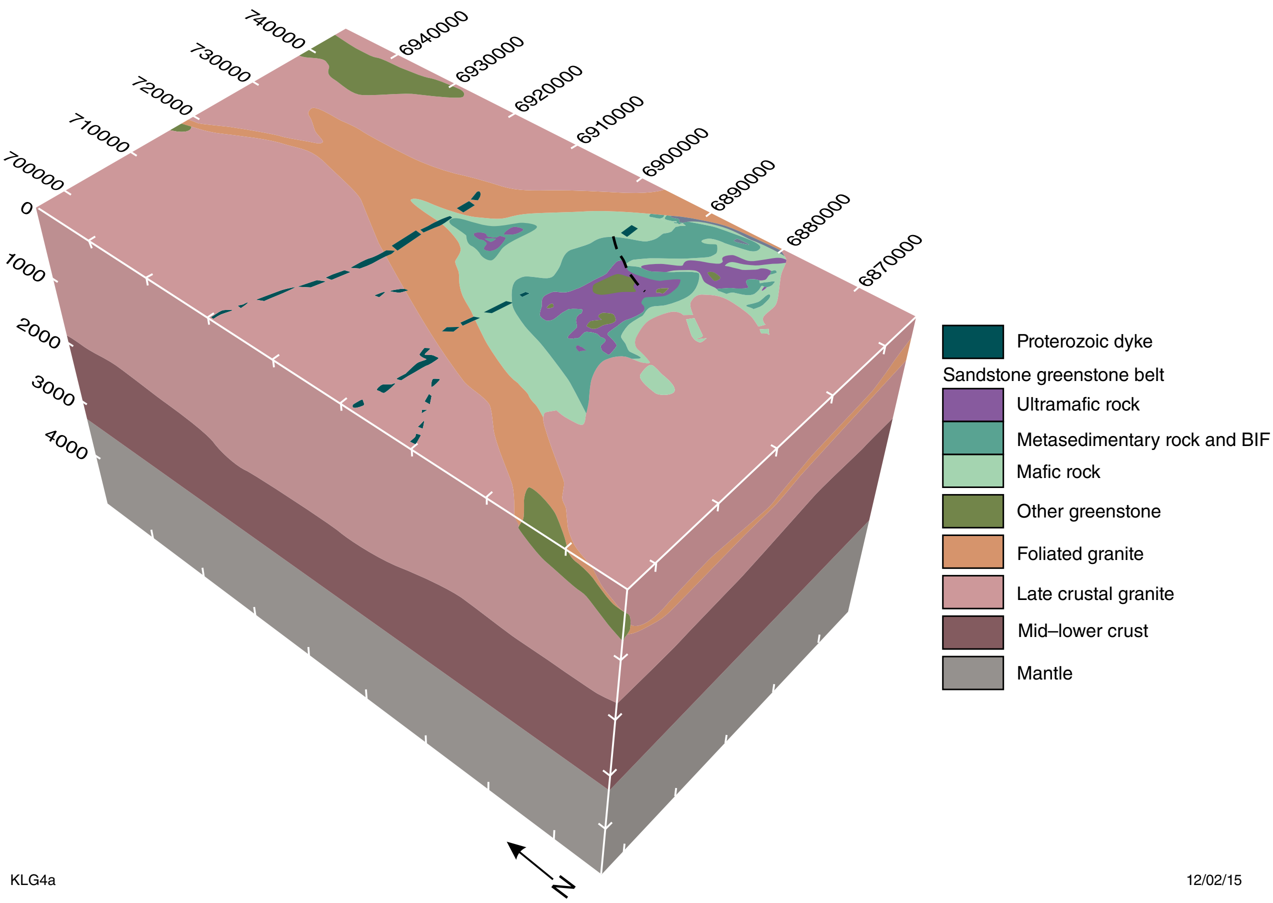

Figure 2. Block model of the Sandstone greenstone belt

On a smaller scale, 3D imaging of outcrops, and even of individual hand specimens, can tell us a lot about large-scale tectonics. Modern photo techniques can produce 3D images of field outcrops so that structural information and relationships can be combined into a single image. Large datasets can now be montaged with the appropriate distortion corrections to image outcrops so that the 'bigger picture' can be viewed and interrogated. Images of bedrock pavements in the Yilgarn Craton have been montaged so that cross-cutting relationships of intrusive veins can be viewed across a whole outcrop (Fig. 3). On the micrometre scale, the physical properties of sheared and fractured rocks of the Moyagee fault in the Murchison Domain of the Youami Terrane were analysed using X-ray tomography and acoustic-property measurements to better understand the structural control on gold mineralization.

GSWA's 3D Geoscience Section collaborates with other Australian and international institutions to provide better imaging and interpretation methods for 3D models. The Integrated Exploration Platform, in conjunction with CET, is a GIS plugin that will assist in the visualization and interpretation of geological and geophysical datasets in Western Australia. This platform uses filtering and blending techniques to visualize more than one dataset at once and to find features that are common to or independent of each dataset. Future work will look at how to best display volumetric datasets in 3D.

With a focus on integrating geoscience data in regional geological models at the scale of the Earth's crust, the 3D Geoscience Section aims to contribute to better understanding how the Western Australian lithosphere formed, and what controls the spatial distribution of Western Australia's mineral and energy resources.

KLG5 29/01/15

Figure 3. Megapixel image of an approximately 10 m-wide pavement of granitic bedrock in the Yilgarn Craton showing cross-cutting relationships of intrusive veins

VHMS mineralization in the Yilgarn Craton: greenstone prospectivity and new results from the Eastern Goldfields

by

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Despite isolated successes in the 1970s, such as the discovery of significant orebodies at Golden Grove and Teutonic Bore, exploration for volcanic hosted massive sulfide (VHMS) mineralization waned in Western Australia through most of the 1980s and 1990s (Yeats, 2007). Although renewed exploration during the past decade has identified a number of new resources in the Yilgarn Craton (e.g. Bentley, Austin, Just Desserts, Kundip, Hollandaire; Hollis et al., 2014), only a handful of deposits have been brought into production. Exploration challenges associated with regolith and deep cover exacerbate the already difficult task of exploring for small, deformed deposits in stratigraphically complex volcanic terranes. However, understanding the tectono-stratigraphic relationships of VHMS deposits in greenstone sequences (Hollis et al., 2014; Belford et al., 2014; Hayman et al., in press.), and the prospectivity of different units in those sequences, greatly improves the effectiveness of greenfields exploration.

Archean paleo-rift zones

Economic VHMS mineralization in the Yilgarn Craton is largely restricted to two main zones of juvenile crust (the Kurnalpi and Cue zones), as revealed through regional (Nd, Pb, Hf) isotope variations (Ivanic et al., 2012; Huston et al., 2014; Mole et al., 2014; Fig. 1). Interpreted as an Archean paleo-rift zone (see Huston et al., 2014), the Cue zone of the northern Youanmi Terrane is associated with at least three episodes of VHMS mineralization (Hollis et al., 2014):

- An initial stage, dated from c. 2980 Ma to c. 2930 Ma, of bimodal to dominantly felsic greenstone belts (e.g. Golden Grove, Mount Gibson, Weld Range). These sequences likely resulted from an extensional regime as evident isotopically in the Cue rift zone (3.0–2.9 Ga; Fig. 1a). The linear occurrence of these units over about 300 km is also testament to a possible rift.
- At c. 2815 Ma, during eruption of the plume-related Norie Group, the emplacement of at least five large igneous complexes at shallow levels in the crust resulted in several isolated VHMS deposits (e.g. Austin–Quinns, Youanmi – Just Desserts). These occur dominantly to the east of the Cue rift zone and their distribution may have been controlled by pre-existing structures.
- Throughout the Cue rift zone, from c. 2760 to c. 2745 Ma, during the deposition of the Greensleeves Formation, the Murchison Domain hosts widespread VHMS deposits (e.g. Hollandaire, Dalgaranga, Mount Mulcahy; Hayman et al., in press.).

An additional VHMS event in the northeastern Youanmi Terrane at c. 2725 Ma is restricted to the southeastern Gum Creek greenstone belt (e.g. The Cup, Bevan). This age is coincident with the Yalgowra Suite mafic magmatic event and may be related to rift development as noted further west in the Glen Group (Van Kranendonk et al., 2013).

A second paleo-rift zone c. 2690–2670 Ma in the Yilgarn Craton runs north–south through the Kurnalpi Terrane (Huston et al., 2014). The spatial relationship between this area of juvenile crust and Cu–Zn mineralization is clear (Fig. 1), with significant resources mined around Teutonic Bore, and sub-economic VHMS mineralization to the northeast (e.g. Tuff Hill, Mason Hill) and further south (e.g. Jungle Pool and Anaconda). VHMS-prospective tholeiitic FII- to FIII-affinity felsic rocks, indicative of high heat flow and melting at shallow crustal depths, have been identified in the Kurnalpi Terrane, for example around the Teutonic Bore camp, and in sequences of similar age in the Yamarna Terrane.

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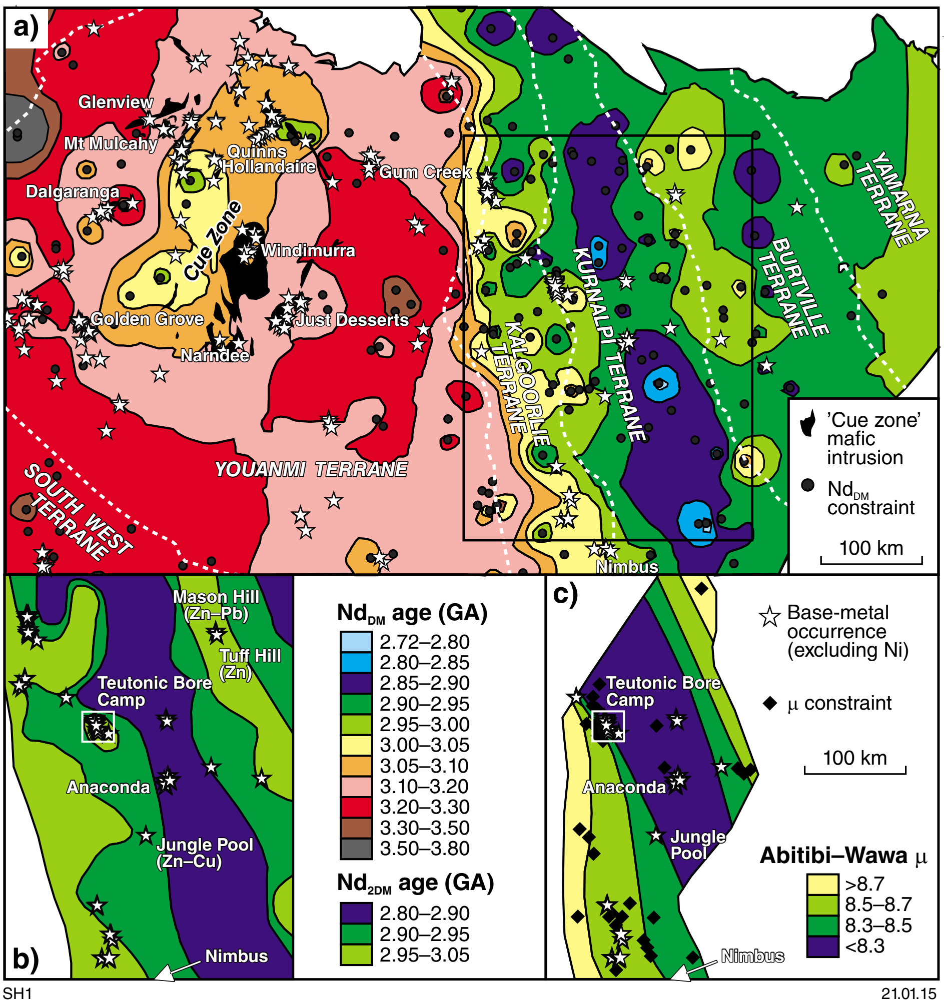

Figure 1. **Regional Nd and Pb isotope variations of the Yilgarn Craton: a) Nd-depleted mantle model (Nd_{DM}) age map of Champion and Cassidy (2007; colour legend in 1b); b) and c) Nd_{2DM} and µ maps of Huston et al. (2014) for the central Kalgoorlie and Kurnalpi Terranes**

Copper–zinc VHMS mineralization in the Kurnalpi Terrane

Since the 1970s, the Teutonic Bore area has been known to host significant VHMS mineralization. Economic deposits are at Teutonic Bore (1.68 Mt mined at 10.7% Zn, 3.5% Cu, 140 g/t Ag), Jaguar (1.60 Mt pre-mining reserve at 11.3% Zn, 3.1% Cu, 115 g/t Ag) and Bentley (3.05 Mt pre-mining resource at 9.8% Zn, 2.0% Cu, 139 g/t Ag, 0.7 g/t Au), with numerous other prospects along strike (references in table 1 of Hollis et al., 2014). Mineralization is hosted in a c. 2690 Ma bimodal-mafic sequence that includes calc-alkaline basalts and andesites, FII to FIII affinity felsic volcanic rocks, and back-arc basin-like basalts, with ore closely associated with deep-marine argillaceous metasedimentary rocks (Belford et al., 2014).

At Erayinia in the southern Kurnalpi Terrane, the King deposit occurs as two small stratiform replacive lenses in a structurally overturned volcanic–sedimentary sequence dated at c. 2680 Ma. Mineralization is dominated by pyrite–sphalerite (with minor chalcopyrite) and is closely associated with pyrrhotite–magnetite. Preliminary examination of drillcore suggests the local stratigraphy includes: BIF/exhalite in the stratigraphic hangingwall, black shale (replaced) at the ore horizon, and silica ± sericite ± epidote-altered intermediate volcaniclastic rocks and mafic lavas in the footwall. Recent Exploration Incentive Scheme (EIS) drilling northwest of Erayinia has also identified massive pyrite associated with graphitic shale, and stringer pyrite (with trace Zn) in hydrothermally altered FII-affinity felsic volcaniclastic and metasedimentary rocks in a sequence dominated by amphibolite-facies metabasalt.

Silver–zinc mineralization at Nimbus

The Nimbus Ag–Zn deposit (4.9 Mt at 149 g/t Ag-equivalent) is located approximately 265 km south of Teutonic Bore and 17 km east-southeast of Kalgoorlie.

Initially discovered in 1995, the deposit lies in the uppermost felsic rocks of the Boorara Domain of the Kalgoorlie Terrane (c. 2680 Ma). Its origin has been debated for a number of years, with previous workers either favouring a fault-controlled high-sulfidation system (Henderson et al., 2012) or sub-seafloor VHMS mineralization (Hadlow et al., 2011). The stratigraphy at Nimbus comprises a northwesterly trending and steeply dipping bimodal package of FI-affinity (i.e. relatively low temperature) quartz–feldspar porphyritic dacite and less common basalt, plus their autoclastic equivalents, with subordinate carbonaceous black shale, chert, and polymict conglomerates.

Compared with other VHMS occurrences in the Eastern Goldfields, the Nimbus deposit is unusual in terms of its tectono-stratigraphic position, the geochemistry of its host sequence, mineralogy (e.g. low Cu–Au through most of the deposit, abundance of Ag and Sb sulfosalts), and quartz–sericite–carbonate-dominated alteration assemblage. Classification of Nimbus as a shallow-water and low-temperature VHMS deposit with epithermal characteristics is consistent with its position outside the margin of the Kurnalpi paleo-rift zone and having more radiogenic Pb isotope values than Teutonic Bore.

Conclusions

Recent work on the timing (from at least c. 2970 to 2680 Ma), setting, and style of VHMS mineralization in the Yilgarn Craton has emphasized the importance of episodic linear zones, which apparently provide strong controls on the focus of mineralization. It has also given rise to an investigation of the potential for additional discoveries in similar geodynamic settings. Quantitatively, we show that felsic geochemical prospectivity studies can highlight several areas where further exploration is warranted (e.g. Bore Well, Mount Gill, Gum Creek, Erayinia). In the Yilgarn Craton we suggest a focus of exploration efforts on identifying environments and tectonic histories favourable for the formation and preservation of deposits. In addition, we highlight diverse styles of Archean VHMS mineralization and hence the need for a wide exploration perspective for these commodities.

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The Carson–Hart Large Igneous Province intrusive complex: implications for Speewah-style vanadium–titanium–iron mineralization in the Kimberley region

by

K Orth*

The Hart Dolerite is the intrusive portion of the Carson–Hart Large Igneous Province (LIP; Hoatson et al., 2006; Tyler et al., 2006) in the Kimberley region of northern Western Australia. It forms a series of sills and some dykes that intrude the lower Kimberley Basin (King Leopold Sandstone and Carson Volcanics of the Kimberley Group) and the underlying Speewah Basin at a depth of 2–3 km beneath the eruptive surface. Although large areas of the Kimberley and Speewah Basins are underlain by the sills, they are particularly well exposed around the upturned and folded margins of the basins (Fig. 1). The mean U–Pb crystallization ages of zircon and baddeleyite obtained from the granophyre and upper mafic sills in the Hart Dolerite is 1797 ± 11 Ma (Sheppard et al. 2012).

The combined volume of the Carson–Hart LIP is about 300 000 km^3, comparable to smaller volume LIPs, such as the Columbia River Flood Basalts with an estimated volume of 206 400 km^3 (Reidel et al. 2013). The sill complex comprising the Hart Dolerite is 83% of the Carson–Hart LIP.

The sill complex was examined around the margins of the Kimberley and Speewah Basins, where it forms two exposed belts, each about 400 km in length. One trends northeast along the eastern margin of the basins and the other trends northwest along the southern margin of the basins. The northeastern arm contains the Speewah Dome, host to V–Ti mineralization. Fifteen sections were completed around the whole margin, including two south of Speewah Dome, two northwest and northeast of the inflection point, nine in the Millie Windie valley and two on the Yampi Peninsula (Fig. 1).

Detailed work in the Millie Windie valley reveals a sill architecture that is consistent over 65 km along strike. Four main sills are hosted in sandstone of the Speewah Group (Fig. 2a). The lower body is a compound sill that is made up of three units. The lowest sill (about 450 m thick) intrudes the lowest unit of the Speewah Group. It is marked by a thin chilled base, which grades from less than a metre to several hundred metres of dark, vaguely columnar jointed gabbro. A slightly finer grained, feldspar-rich portion in the middle of the sill (<150 m thick) displays rhythmic centimetre-scale banding. Some of these bands appear cross bedded. Feldspar crystals display alignment in section, but are randomly oriented on bedding-parallel surfaces. The crystal organization suggests compaction rather than flow-caused crystal alignment. Near the top of the sill the banding is not apparent and the sill becomes fine grained. Overlying the lower sill is a dark, coarse inclusion-rich gabbro (<100 m thick, Fig. 2b), with elevated magnetic susceptibilities (40–90 × 10^{-3} SI units). A sharp contact separates the magnetic sill and the overlying coarse, more felsic sill. On the Lennard River 1:250 000 map sheet, Griffin et al. (1993) mapped this unit as granophyre. It contains granophyric intergrowths of K-feldspar and quartz, which become more abundant towards the top of the sill. It consists of granite (syenogranite, monzogranite), quartz monzonite, and diorite (IUGS, Le Bas and Streckeisen, 1991), and, in the Millie Windie area, the <300 m-thick felsic sill is readily weathered and forms the valley floor.

A fourth, higher, sill is hosted in Speewah Group sandstone above the compound lower sill and below the King Leopold Sandstone. In one place the sill climbs higher to form a dyke into the King Leopold Sandstone. Along the valley this upper sill can bifurcate or form a thicker compound sill (<400 m thick). It is mainly dolerite with some banding in the middle and coarse segregations near the top.

The middle magnetic gabbro provides a strong magnetic signature that is distinctive in the magnetic dataset and shows that this unit is traceable along the whole of the Millie Windie valley.

Comparison of the architecture of the Hart Dolerite at Millie Windie with the sills elsewhere around the Kimberley Basin reveals some broad similarities. Lower composite gabbroic sills are capped by felsic, granophyric intrusions. Three composite sills with this architecture dominate the thickest portion of the intrusive complex in the central area south of Mornington Station. On the Yampi Peninsula, the complex has the same architecture, but is only 700 m thick.

The Speewah Dome is a gentle anticline cut by later faults (Plumb, 1968; Thorne et al., 1999). Detailed mapping combined with drillhole information (Alvin, 1993, 1998;

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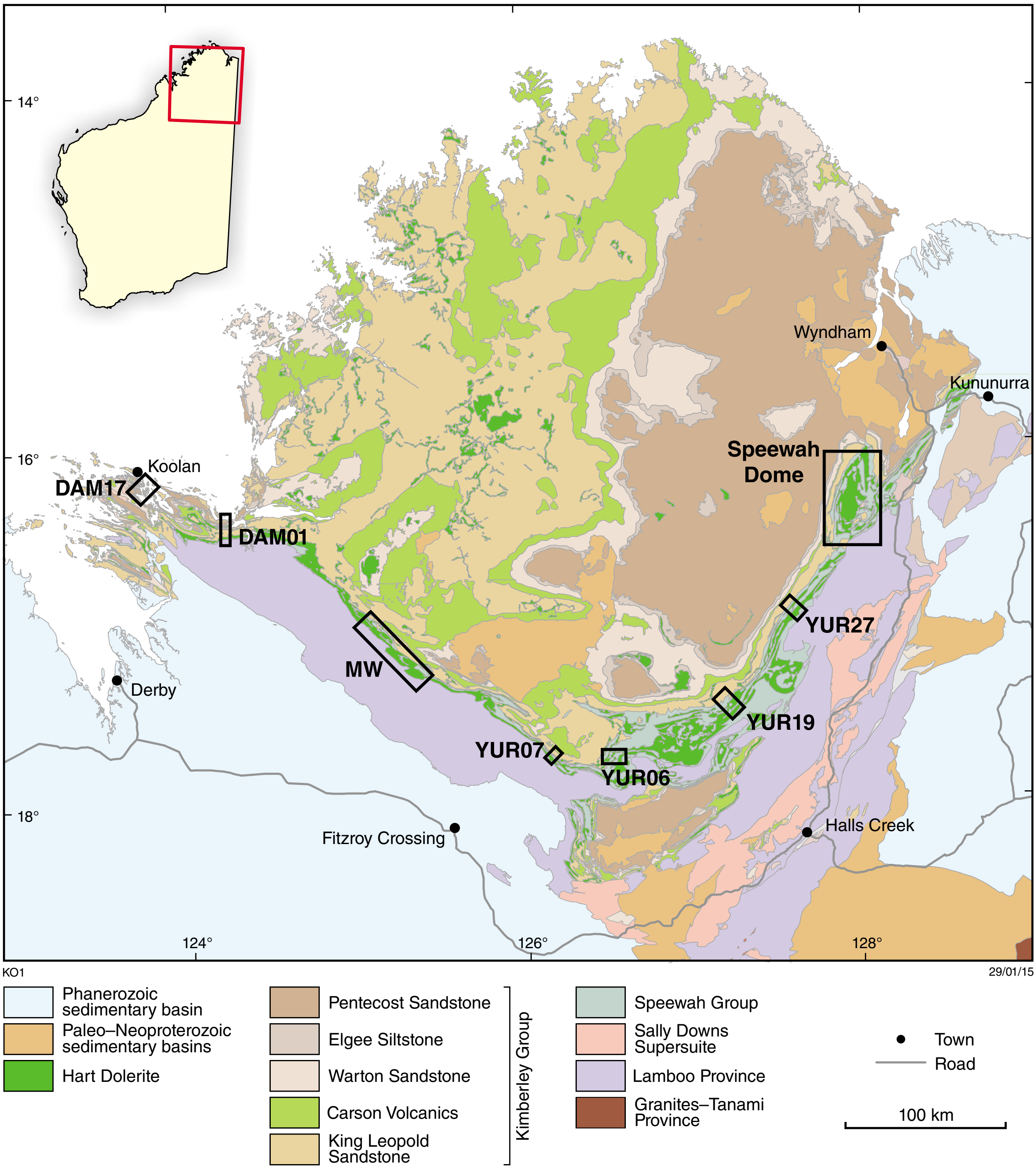

Figure 1. The geology of the Kimberley region. The Kimberley Group, in the middle of the area, is flanked by the Lamboo Province and Speewah Group. The Carson Volcanics (light green) are the extrusive portion of the Carson–Hart LIP. They overlie the basal King Leopold Sandstone and are overlain by the Warton Sandstone, Elgee Siltstone, and Pentecost Sandstone. The Hart Dolerite (dark green) is the intrusive portion of the Carson–Hart LIP and intrudes the Speewah Group and the King Leopold Sandstone around the Speewah and Kimberley Basins. Units are deformed around the Kimberley Basin and in the Speewah Basin. The Yampi (c. 1000 Ma) and King Leopold (c. 560 Ma) Orogenies caused this deformation as thrusting accompanied sinistral strike-slip movement in the east Kimberley. Boxes locate the sections measured through the Hart Dolerite

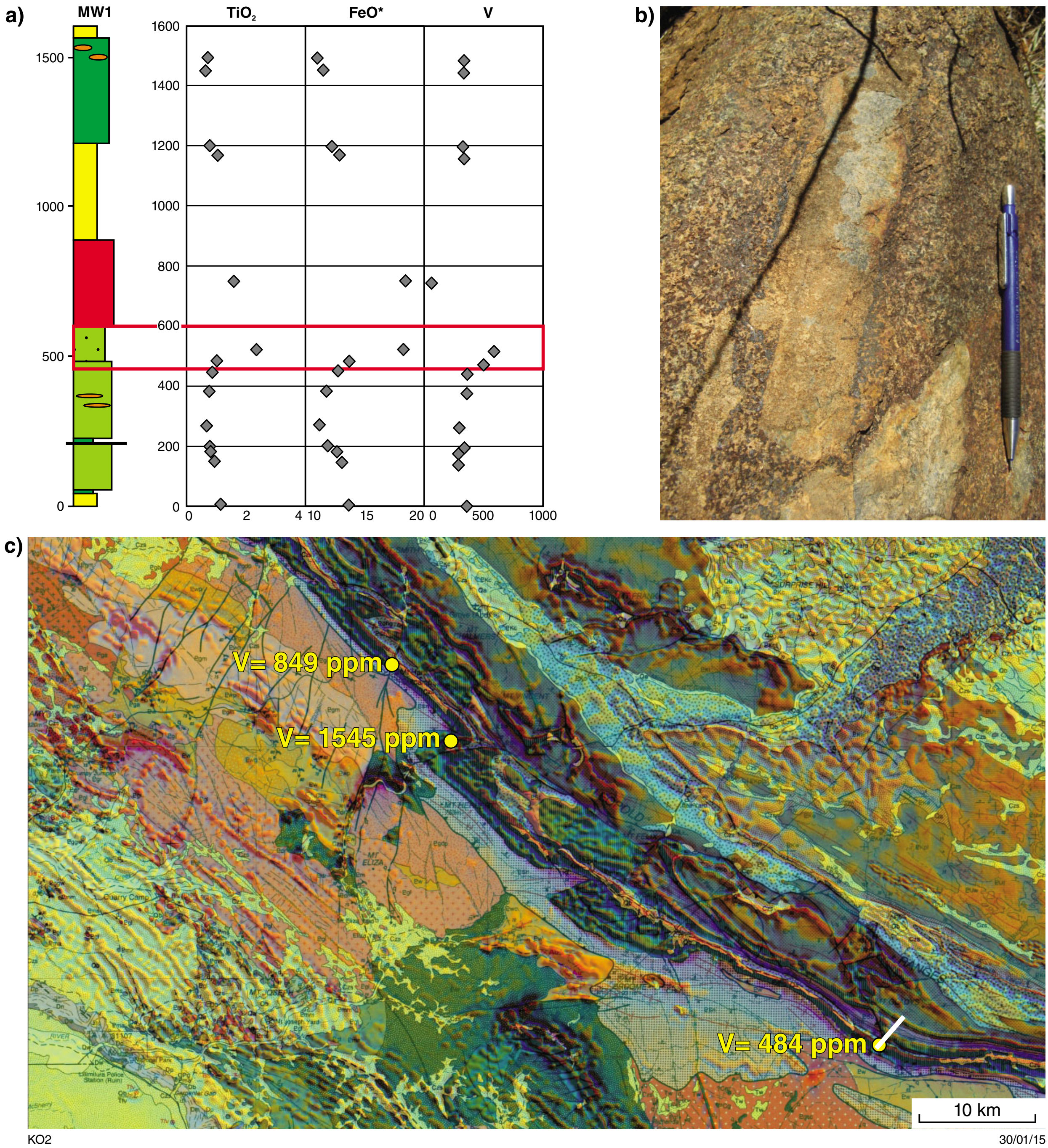

Figure 2. Section information from the Millie Windie valley area: a) summary log (MW1) through the four main units of the Hart Dolerite. The lower sill complex comprises three units: lower gabbro (green), magnetite gabbro (green with red) and granophyric microgranite (red). The upper sill (dark green) is separated from the lower sill by Speewah Group (yellow) and capped by the King Leopold Sandstone. Plots of TiO_2 (wt%), total iron (FeO*, wt%) and V (ppm) from analyses taken along the measured section; b) photograph of typical outcrop of the magnetite gabbro with inclusions; c) geological map draped with aeromagnetic data from the Millie Windie area. A high magnetic signature is associated with the magnetite gabbro. The locations of samples with elevated V in this area are plotted. White line marks the location of section MW1

Eves, 2010; Andrew et al., 2012) has identified a V–Ti deposit with a measured resource of 322 Mt at 0.32% V_2O_5 and 2% Ti (King River Copper Ltd, 2014). Drillhole SDH09-01 (a co-funded government–industry drillhole; Eves, 2010), intersected the lower sill complex, hosted in the Speewah Group. In SDH09-01, the deepest unit is the spotted magnetite gabbro (289 m thick). Mafic and felsic granophyric units are present over the upper 130 m. Between the upper granophyric units and deeper spotted magnetite sill is a magnetite gabbro (100 m thick), which hosts three V–Ti–Fe prospects at Red Hill, Buckman, and Central. Overall the magnetite gabbro contains abundant feldspar-rich inclusions, displays elevated magnetic susceptibility (60×10^{-3} SI units), and is enriched in Fe, Ti, and V. Ti and V are in titanomagnetite, which is most abundant in the lower 15–25 m of the disseminated magnetite gabbro.

Elevated Ti and V associated with high Fe are present in samples from the gabbro with elevated magnetic susceptibility in the Millie Windie area (Fig. 2). The gabbro is similar in geochemistry, appearance, and location within the sill architecture to the sill hosting Ti–V at Speewah Dome. Non-systematic sampling of the sill in this area suggests that this unit has elevated vanadium values along strike (Fig. 2c). The unit can be targeted by its position in the sill architecture, elevated TiO_2, V, and FeO, and its characteristic magnetic response. It is traceable for up to 100 km along strike in some areas. These factors combine to indicate a high prospectivity for more Speewah-style V–Ti–Fe deposits in the Kimberley region.

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Regional-scale mineral systems analysis of the Halls Creek Orogen, east Kimberley — putting geological common sense into a semi-automated approach

by

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Mineral systems analysis involves understanding the geodynamic processes required to form and preserve ore deposits at a range of scales (Wyborn et al., 1994). To carry out mineral systems analysis the key controlling processes on the formation and preservation of mineral systems must be understood. These processes include features from a range of scales — as large scale as the secular evolution of the earth, tectonic-scale factors that control lithospheric enrichment, and tectonic- to district-scale aspects such as geodynamic drivers (McCuaig et al., 2010; McCuaig and Hronsky, 2014). Of these processes, lithospheric enrichment and geodynamic drivers are often directly related to plate tectonics and the kinematics of plate motion, which can be fundamentally linked to the formation and breakup of supercontinents (Goldfarb et al., 2001). Mineralization processes related to the secular evolution of the earth require that some styles of ore deposits only formed during certain periods of the Earth's history (Cawood and Hawkesworth, 2013; Cline et al., 2005; Leach, 2010). Other controlling processes, such as the requirement of specific lithologies as depositional sites (e.g. carbonate–evaporite sequences) require understanding plate reconstructions to ascertain the paleolatitudes one can target for certain styles of ores (Cline et al., 2005; Leach, 2010).

To complete mineral systems analysis a number of factors must be addressed, including the lithospheric architecture of the terrane (through time, if possible), the tectonic evolution, possible zones of fertility in the region that may be linked back to its tectonic evolution, and the presence of plausible depositional sites. Other factors that we contemplate are the depth of current-day exposure of crust, rock types (as hosts, or as chemical scrubbers or reactive rocks), and structural-trap sites. For the Halls Creek Orogen, proxies to these components were derived from the existing suite of Geological Survey of Western Australia (GSWA) pre-competitive maps and other data, including its WAROX database, GSWA publications, and journal articles.

The geological evolution of the Kimberley region spans more than two billion years and involves periods of accretion, convergence, and rifting, along a margin that was affected by vastly changing tectonic environments through this time (Griffin et al., 2000; Hollis et al., 2014; Sheppard et al., 1999; Tyler and Griffin, 1990; Tyler et al., 2012). These temporal changes have resulted in a region where rock types that formed in different tectonic settings now co-exist. Contact relationships between these units are varied — they may be tectonically interleaved, conformable, or unconformable over each other, or be intrusive, together metamorphosed to different grades and tectonically juxtaposed, or interleaved. A summary of the tectonic development of the region through time, as currently published, is illustrated in Figure 1, which is largely derived from Griffin et al. (2000), Spratt et al. (2014), and Tyler et al. (2012). Within this summary the geodynamic throttles, fertility, and plausible depositional sites for disparate mineralization styles can be ascertained for the mineral systems analysis.

Deep crustal-scale structures that may control the lithospheric architecture of the Halls Creek Orogen, or act as mineralizing fluid pathways have been mapped using various parameters including tomography data, gravity, magnetics, and surface or shallow subsurface geology. Contact zones between rocks of different metamorphic grade, are sometimes zones of large crustal-scale faults. Such zones in the Halls Creek Orogen have been delineated from information in historical GSWA databases to produce metamorphic maps, which are also used to represent crustal-preservation levels and relative heat flow in the area.

A regional-scale automatic mineral systems analysis using a fuzzy-logic inference network was completed for the Halls Creek Orogen, based on the delineation of deep crustal-scale structures, geodynamic throttle or tectonic triggers, depositional sites, and crustal preservation levels for seven groups of commodities. These include: Au-only, Cu–Au–Mo, Pb–Zn–Cu–Ag, REE, diamonds, Sn–W, and Ni–Cu–PGE–V–Ti.

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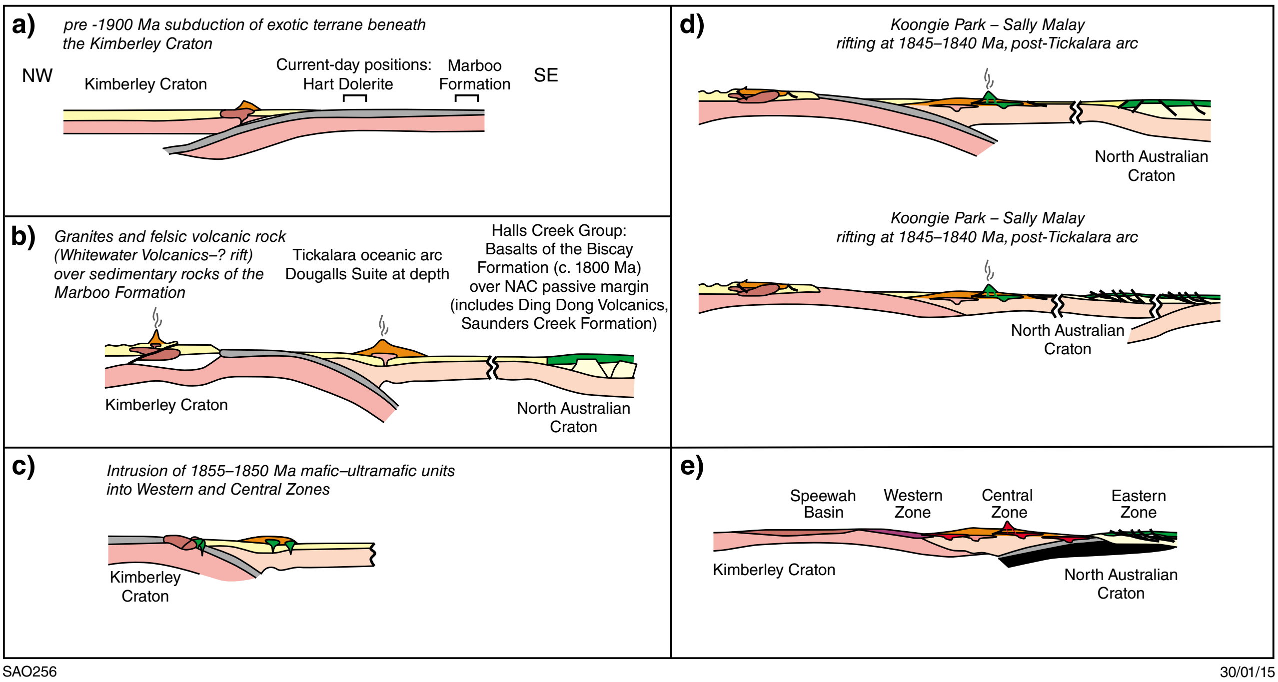

Figure 1. Tectonic development of the Halls Creek Orogen – east Lamboo Province through time as described in Griffin et al. (2000), Spratt et al. (2014), Tyler et al. (2012); a) west-dipping (current-day coordinates) subduction of an unknown crustal fragment beneath the Kimberley Craton prior to the formation of the Paperbark Supersuite; b) in the west, intrusion of crustally derived felsic granites of the Paperbark Supersuite and extrusion of its upper crustal felsic Whitewater Volcanics into the Kimberley Craton (at c. 1860 Ma in the Western Zone). To the east, development of the Central Zone through east-dipping subduction of the Kimberley Craton produces the juvenile mafic volcanic and felsic intrusive rocks of the Tickalara oceanic arc during the 1865–1850 Ma Hooper Orogeny (Sheppard et al., 1999; Tyler et al., 2012). The relationship of the Eastern Zone (lower Halls Creek Group) to the Central Zone is enigmatic; c) intrusion of the 1855–1800 Ma mafic to ultramafic magma in the Western Zone (including Paperbark Supersuite) and Central Zone (including Tickalara arc rocks) at c. 1855–1850 Ma during a period of local extension post-Hooper Orogeny; d) formation of a volcano-sedimentary basin over the Central Zone to form the Koongie Park Formation, and intrusion of its equivalent mafic–ultramafic Sally Malay Suite post-Hooper Orogeny, either during the waning stages of subduction (roll back; top diagram), or after subduction had ceased (bottom diagram); e) west-dipping subduction of the North Australian Craton (NAC) during the Halls Creek Orogeny produces the juvenile Sally Downs Supersuite in the Central Zone, and eventually the docking of the Eastern Zone (Halls Creek Group) onto the Central Zone

Results from this analysis generally identified all known deposits and mines (these data points, or specific ideas regarding these deposits were not used as training points), and produced maps that illustrate the possible potential for other groups of the aforementioned commodities to be present in different areas in the Halls Creek Orogen (Fig. 2).

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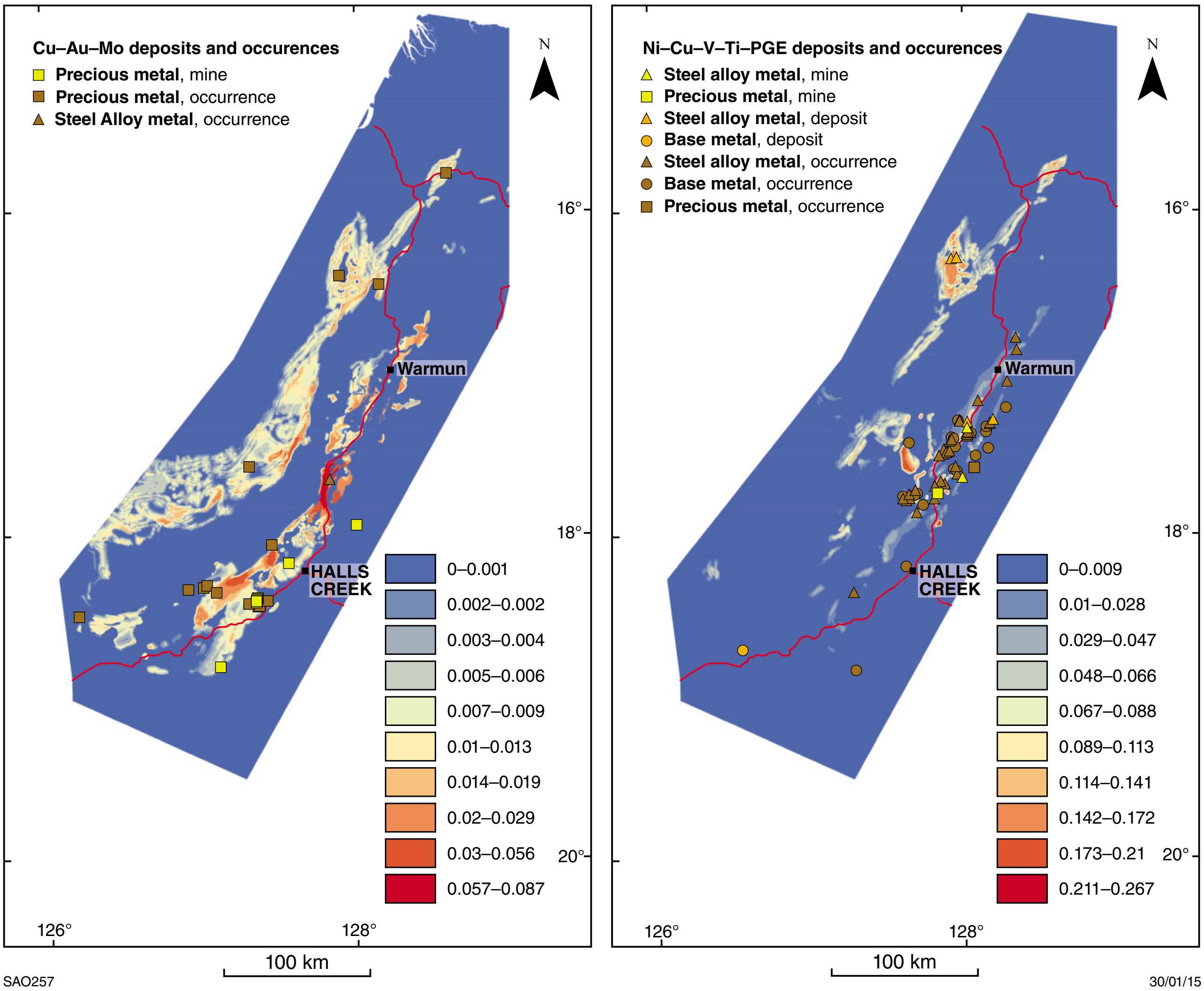

Figure 2. **Results of regional-scale prospectivity analysis for the Halls Creek Orogen for the commodity groups Cu–Au–Mo and Ni–Cu–PGE–V–Ti**

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Regolith geochemistry in the Kimberley Science and Conservation Strategy — links to bedrock

by

PA Morris

Part of the State government's Kimberley Science and Conservation Strategy involved collection of grid-based regolith samples to provide a better understanding of the relationship between regolith and bedrock, and the evolution of the Kimberley landscape. The first sampling program was carried out in the Balanggarra area in the north Kimberley (Fig. 1; Scheib et al., in prep.). Bedrock of the Balanggarra project area is dominated by Paleoproterozoic rocks of the Kimberley Group, a largely undeformed and gently dipping succession of quartz-rich siliciclastic sedimentary rocks of the King Leopold, Warton, and Pentecost Sandstones, the more siltstone-rich Elgee Siltstone, and mafic volcanic rocks of the Carson Volcanics.

The regolith geochemistry program involved collection and analysis of samples from 407 sites, at a nominal sample density of 1 per 25 km^2. An interpretive regolith–landform map (GSWA, 2014), compiled as part of the Kimberley Science and Conservation Strategy, showed that of the 10 300 km^2 of the project area, 61% encompassed thin regolith in areas of outcrop, with a further 11% comprising largely residual deposits developed in situ. This, combined with site observations, indicates the regolith is both thin and has developed in place, meaning that there is high probability that regolith composition is a reliable proxy for that of bedrock. This is illustrated by two examples, using regolith from the Carson Volcanics and Pentecost Sandstone, respectively.

Changes in flow chemistry with stratigraphic height in the Carson Volcanics

In the Balanggarra project area, mafic volcanic and less common intercalated quartz-rich sedimentary rocks occupy 2 900 km^2 or 28% of the area. Elements such as chromium show a wide range in concentration (9–376 ppm; median 91 ppm; n = 116), but a number of samples with statistically anomalous Cr concentrations (i.e. >210 ppm) are found at or near the lower contact of the unit with the King Leopold Sandstone (Fig. 1a). As most of these samples are from regolith in areas of outcrop, elevated Cr concentrations do not result from chemical weathering. A plot of Cr (ppm) against the distance of the sample from the lower contact shows a clear decrease in concentration, which is also seen for MgO and As. Although only seven samples returned detectable Pt concentrations in regolith from the Carson Volcanics (1 ppb), four of these are found in samples within 1500 m of the base of the unit. These regolith data show that less fractionated, chalcophile- and PGE-rich lavas are found in the lower parts of the Carson Volcanics. Higher values for total dissolved solids (TDS; mg/kg) in regolith from lower in the succession may be related to more common alteration there. Stratigraphic control on copper mineralization within the Carson Volcanics has been reported (Marston, 1979), but there is no obvious change in the Cu concentration of regolith with stratigraphic height.

Heavy mineral concentrations in the Pentecost Sandstone

The Pentecost Sandstone occupies 3 500 km^2 or 34% of the Balanggarra project area, and accounts for 141 regolith samples, of which 104 (74 %) are from areas of outcrop. The unit is composed of medium-grained quartz sandstone, which is both massive and cross bedded, along with less common interbeds of feldspathic sandstone. Current bedding indicates a general provenance from the north. A bubble plot of Zr (ppm) in regolith from the Balanggarra project area shows that most regolith samples with anomalous concentrations (i.e. > 654 ppm) are found in the Pentecost Sandstone, and these samples form a linear belt parallel to strike (Fig. 1b). All of these regolith samples also have anomalous concentrations of Hf, but not other high field strength elements (HFSE) such as Nb or Ta. As these samples are from areas of outcrop, high Zr and Hf cannot be explained by chemical weathering of bedrock. Instead, the association of Zr and Hf is consistent with concentration of zircon derived by physical weathering of the bedrock. As other elements commonly associated with resistate minerals are not in anomalous concentrations (e.g. La, Th, Nb, Ta), it is likely that the concentration of zircon reflects the lithology of the source area of the Pentecost Sandstone and the effects of density sorting during sandstone deposition. The orientation of these samples parallel to strike indicates that these regolith samples represent a zircon-enriched heavy mineral unit within the Pentecost Sandstone.

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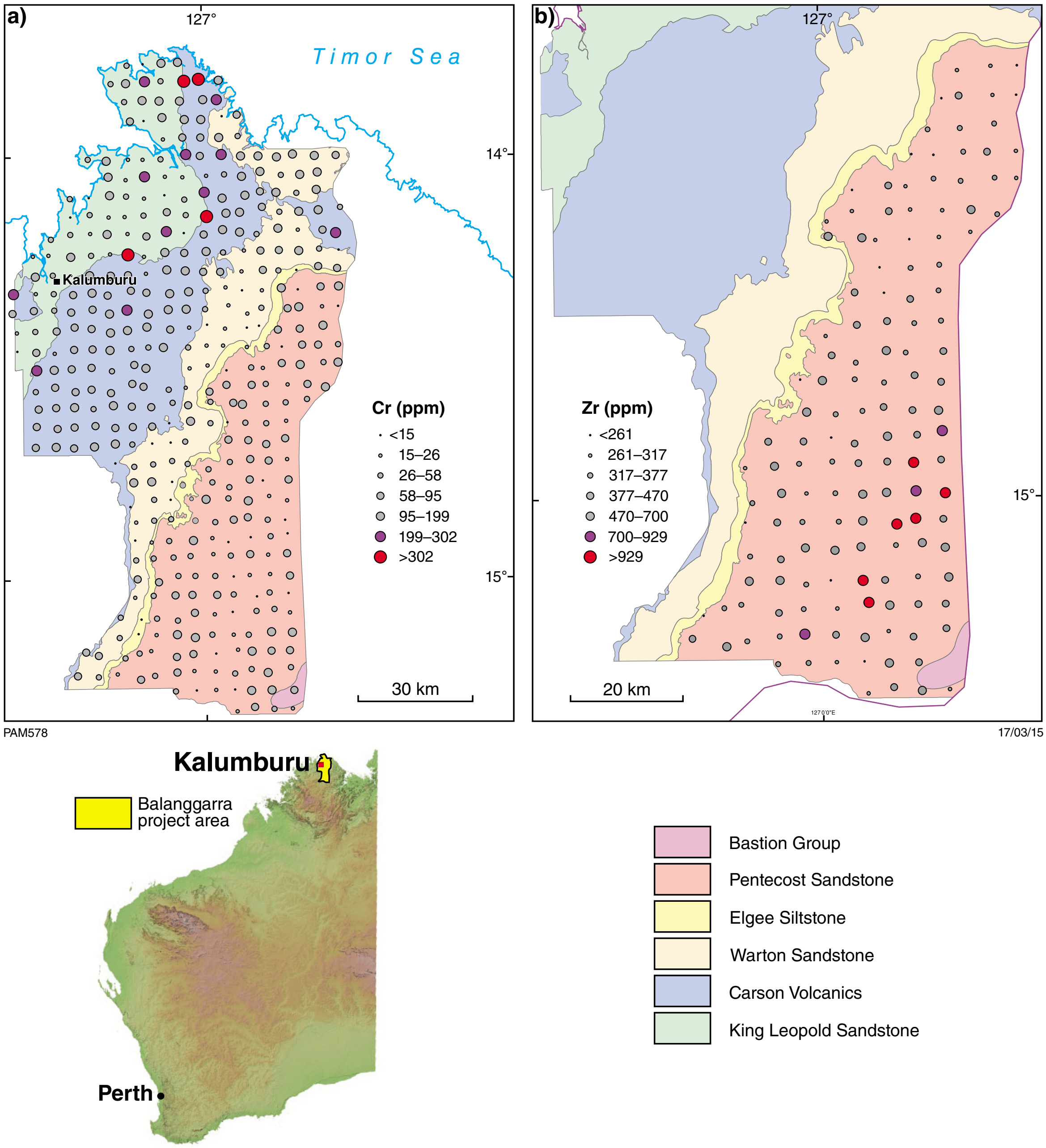

Figure 1. a) Chromium (ppm) in regolith shown against 1:500 000-scale bedrock geology for the Balanggarra project in the north Kimberley. Samples with anomalous concentrations shown as purple (outlier) and red (extreme); b) Zirconium (ppm) in regolith from the Pentecost Sandstone shown against 1:500 000-scale bedrock geology. Samples with anomalous concentrations shown as purple (outlier) and red (extreme)

Conclusions

The high proportion of exposed bedrock, thin regolith, and relatively little transported regolith means that regolith chemistry is a reliable proxy for bedrock in parts of the Kimberley area. Two examples discussed here show how regolith chemistry can be used to examine regional stratigraphic variations in compositionally diverse lithological units. A key aspect of using regolith chemistry in this fashion is to understand the effects of chemical weathering and the spatial context of regolith samples in terms of regolith–landform mapping.

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The burning heart — the Musgrave Province

by

HM Howard, RH Smithies, CL Kirkland*, and R Quentin de Gromard

The Musgrave Province is one of the most geodynamically significant of Australia's Proterozoic orogenic belts, lying at the intersection of the continent's three cratonic elements — the West, North, and South Australian Cratons. It consists of an east-trending Mesoproterozoic to Neoproterozoic belt up to 800 km long and 350 km wide, bounded by Neoproterozoic to Paleozoic sedimentary rocks of the Amadeus, Officer, Canning, and Eromanga Basins (Fig. 1). The province is dominated by granites formed and deformed during several major events.

The earliest major crust-forming event is recorded in Hf-isotopic data from magmatic and inherited zircon crystals, which define an evolutionary array with an inferred mantle extraction event at 1950–1900 Ma. Mantle oxygen isotopic signatures in zircon crystals that have c. 1950 Ma model ages also testify to the juvenile nature of this crust-forming event. Age and isotopic data from zircons derived from Archean sources have defined a reworking trend, commencing at c. 1900 Ma (Kirkland et al., 2013). These zircons are all of detrital origin and there is no evidence that the Musgrave Province evolved over Archean crust.

A cryptic juvenile basement is exposed mainly in the east Musgrave Province as 1600–1550 Ma orthogneisses. This likely reflects exposure of progressively deeper Mesoproterozoic crust to the east. In the west Musgrave Province there are isolated outcrops of granulite-facies metagranites of the c. 1575 Ma Warlawurru Supersuite in the Wanarn area. The 1600–1550 Ma period probably involved evolution within a primitive arc setting, perhaps developed on 1950–1900 Ma oceanic or oceanic-arc crust (Fig. 2a,b).

Metagranites of the c. 1400 Ma Papulankutja Supersuite occupy a very small outcrop area in the west Musgrave Province. Gabbros and plagiogranites of a similar age (c. 1410 Ma) form a component of the Madura Province, which separates the Albany–Fraser Orogen from the Musgrave Province and Coompana Province (Fig. 1). These rocks share the juvenile Nd- and Hf-isotope signatures of the basement to the Musgrave Province (Spaggiari et al., 2014; Smithies et al., 2014; Kirkland et al., 2014). Certainly, the mineralogy and geochemistry of rocks of the Papulankutja Supersuite are similar to those of calc-alkaline granites of the Wankanki Supersuite and on that basis an arc setting has tentatively been proposed (Howard et al., 2011).

The 1345–1293 Ma Mount West Orogeny is the oldest event for which there is widespread direct evidence. The voluminous calc-alkaline plutonism that dominated this event formed the Wankanki Supersuite. The Ramarama sedimentary basin also developed throughout this period, into which clastic and volcaniclastic sediments were deposited. These volcano-sedimentary units were subsequently metamorphosed during the 1220–1150 Ma Musgrave Orogeny to form the Wirku Metamorphics (Fig. 1).

The Mount West Orogeny is a stage in the geological history of the Musgrave Province that traced the evolution of a continental arc (Fig. 2c). It reflects the final amalgamation of the combined North and West Australian Craton with the South Australian Craton. The intervening c. 1400 Ma primitive crust — the Madura Province — on which the proto-Musgrave Province most likely evolved, was consumed during amalgamation. The thickened crust resulting from this accretion was drastically thinned at the beginning of the Musgrave Orogeny as this central part of the new combined craton entered an extraordinary period of high heat flow.

Time-constrained ultra-high-temperature assemblages in the Wirku Metamorphics indicate c. 100 Ma of ultra-high-temperature metamorphism. The magmatic rocks produced during the Musgrave Orogeny were the high-temperature, anhydrous, alkali-calcic magmas of the Pitjantjatjara Supersuite. The granites show a transition from Yb-depleted to Yb-enriched compositions at the beginning of the Musgrave Orogeny, reflecting a change from garnet-present to garnet-absent crustal melting, thus indicating a decrease in the depth of granite formation. Sustained high heat flux allowed lower crust partial melts to accumulate and mix with fresh inputs of basaltic magma in an expanding lower crustal hot-zone or MASH chamber developed at the base of the thinned crust (Smithies et al., 2010). The persistence of Pitjantjatjara Supersuite magmatism and of ultra-high-temperature conditions indicates that the crust remained thin (~35 km) throughout the Musgrave Orogeny, likely until at least c. 1120 Ma.

The rigid cratonic architecture, during the 1220–1150 Ma Musgrave Orogeny, and a massive accumulation of high radiogenic heat-producing granites within the mid-crust, perpetuated a thin crustal regime. Voluminous magmas intruded into, and erupted onto, the

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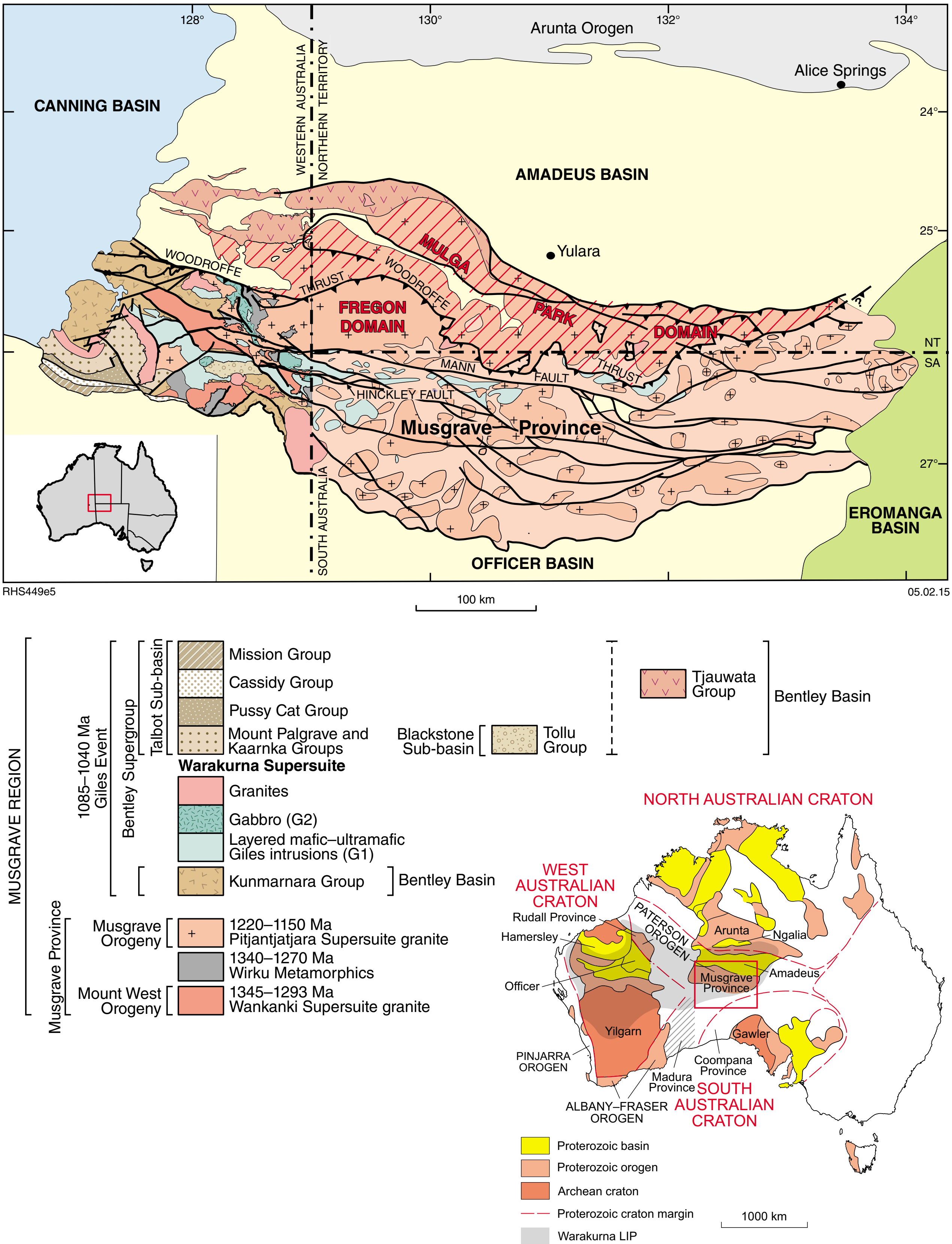

Figure 1. **Tectonic map of Australia (modified from Myers et al., 1996) and a regional geological map of the Musgrave Province (modified from Glikson et al., 1996; Edgoose et al., 2004)**

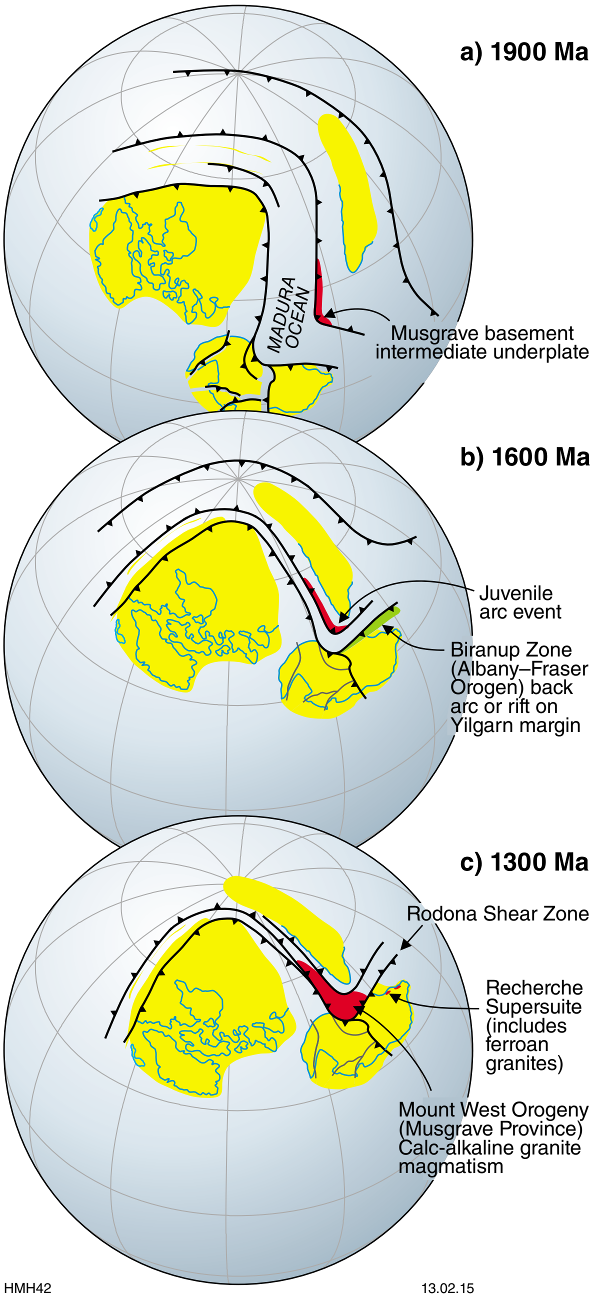

Figure 2. Schematic continental reconstruction of Proterozoic Australia for the interval 1900–1300 Ma (modified from Betts et al., 2008)

province during the 1090–1040 Ma Giles Event. These magmatic units and associated high-volume rhyolitic deposits (in the order of super volcano-class eruptions), and the volcano-sedimentary fill of the regional Bentley Basin, together form the Bentley Supergroup. This magmatism dominated the evolution of the failed intracontinental Ngaanyatjarra Rift. The Giles Event was likely initiated through renewed movement along translithospheric faults that intersected the thermally perturbed Musgrave Province, pinned at a cratonic junction. Mantle-derived bimodal magmatism extended more or less continuously for 50 Ma, producing one of the world's largest layered mafic intrusions and super volcano-size additions of juvenile felsic crust, in the form of alkali-calcic to alkali, A-type, rhyolite deposits. Together, the Albany–Fraser Orogen — which developed over the southern margin of the West Australian Craton — and the Musgrave Province mark the preserved edge of the North and West Australian Cratons. These two belts show remarkable chronological links between c. 1345 and 1150 Ma, but contrasting histories before and after that period. Their period of shared evolution reflects collision and accretion of the South Australian Craton, but their tectonic setting and basement geology throughout that event were very different.

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Building the crust of the Albany–Fraser Orogen: constraints from granite geochemistry

by

RH Smithies, CV Spaggiari, and CL Kirkland*

The Albany–Fraser Orogen (Fig. 1) is dominated by Paleoproterozoic to Mesoproterozoic igneous rocks formed through a complex series of events that involved varying degrees of crustal recycling and periods of refertilization through juvenile-mantle input (Spaggiari et al., 2014a). We use a large database of whole-rock geochemical analyses from felsic rocks of the central and eastern Albany–Fraser Orogen to place critical constraints on models for the geological evolution of the region.

Of the ~160 whole-rock granite analyses, 82 samples dated by U–Th–Pb SIMS are assigned to groups based on zircon crystallization age. Most (70%) of the dated samples crystallized during or before the 1710–1650 Ma Biranup Orogeny. The remaining dated samples crystallized during either Stage I (1345–1260 Ma) or Stage II (1215–1140 Ma) of the Albany–Fraser Orogeny. Undated samples were assigned to a specific age group based firstly on their field characteristics (e.g. structural relationships, petrography) and then on geochemistry.

Archean granites

Isolated fragments of Archean crust that remain in the Albany–Fraser Orogen (Kirkland et al., 2011; Spaggiari et al., 2014a) are clearly recognized based on their geochemistry, which includes elevated Na_2O and LILE (e.g. Sr) concentrations and depleted K_2O and HREE (e.g. Yb) concentrations typical of most Archean granites (Fig. 2).

Archean felsic rocks in the Northern Foreland and the Tropicana and Biranup Zones can be divided between granites representative of the tonalite–trondhjemite–granodiorite (TTG) series and Archean sanukitoids (Fig. 2). Sanukitoids are subduction-related granites (Martin et al., 2005) characterized, at ~60 wt% SiO_2, by Mg#>60 and Cr and Ni concentrations >200 and 100 ppm, respectively, coupled with high concentrations of large-ion lithophile elements (LILE). Their occurrence in the Tropicana Zone and elsewhere in the Northern Foreland might be used to indicate close proximity to ancient plate boundaries relating to assembly of the Yilgarn Craton. Sanukitoids are elsewhere commonly directly associated with Archean gold deposits and we suggest that latest Neoarchean gold mineralization recently found in the Tropicana Zone has remobilized Archean sanukitoid-related gold (Kirkland et al., in prep.).

Paleoproterozoic granites of the Tropicana, Biranup, and Nornalup Zones

Geochemical data strengthen earlier conclusions based on geochronological and Hf-isotopic data (Kirkland et al., 2011) that the post-Archean crustal evolution of the Tropicana, Biranup, and Nornalup Zones of the Albany–Fraser Orogen involved recycling of dominantly Archean felsic material in several episodes. Each episode also involved variable input of juvenile-mantle material. These events progressively mask, but do not destroy, the Archean compositional heritage of the crust.

The period from c. 1800 Ma to the end of the Biranup Orogeny at c. 1650 Ma can be divided into ‘early’ and ‘late’, and the respective granites grouped into ‘early Biranup magmas’ and ‘late Biranup magmas’ (see legend to Fig. 1), which can be broadly distinguished on plots of SiO_2 v Na_2O, K_2O/Na_2O or Rb/Sr (Fig. 3). For the early Biranup magmas, the compositional characteristics of Archean TTG (e.g. high Al_2O_3, Na_2O, Sr and low HREE) remains well developed but progressive recycling leads to increasing K_2O/Na_2O ratios (Fig. 3). In contrast, the late Biranup magmas are typical of medium- to high-K calc-alkaline rocks, albeit with slightly more ferroan compositions, and show none of the enduring major or trace element compositional features that mark the source as recycled Yilgarn Craton crust. Nevertheless, Nd-isotopic data indicates that Archean material remained a major source component, although geochemical arguments (e.g. the high K_2O content) suggest that this was via recycling of the early Biranup magmas, again with addition of a younger and more isotopically juvenile-mantle component. Thus, the later magmatic period (c. 1680 to 1650 Ma) of the Biranup Orogeny heralds a change in the style of crustal evolution to one that involved recycling of previously recycled Archean felsic crust, and trends to higher concentrations of HREE (Fig. 3) might suggest that this recycling occurred at higher crustal temperatures and/or in thinner crust than was the case during the period when the early Biranup magmas were produced.

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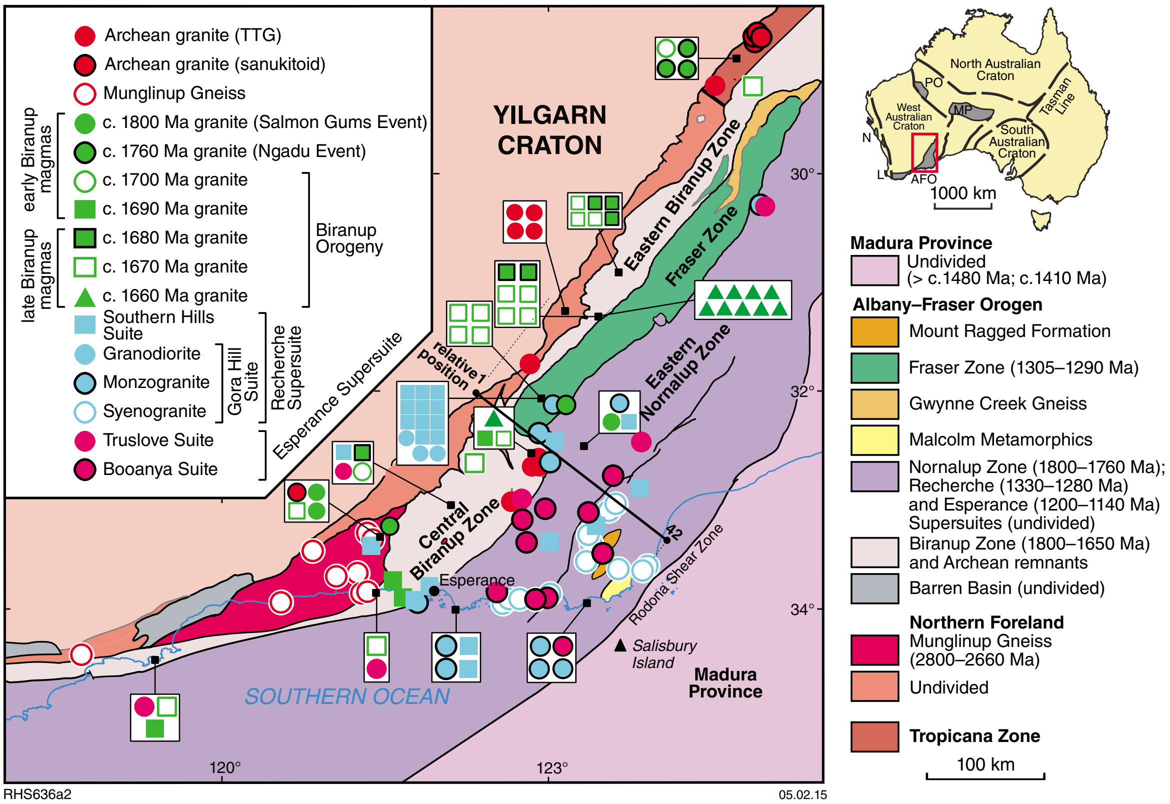

Figure 1. **(above) Location of granite samples within the Albany–Fraser Orogen. Legend details the various granite groups**

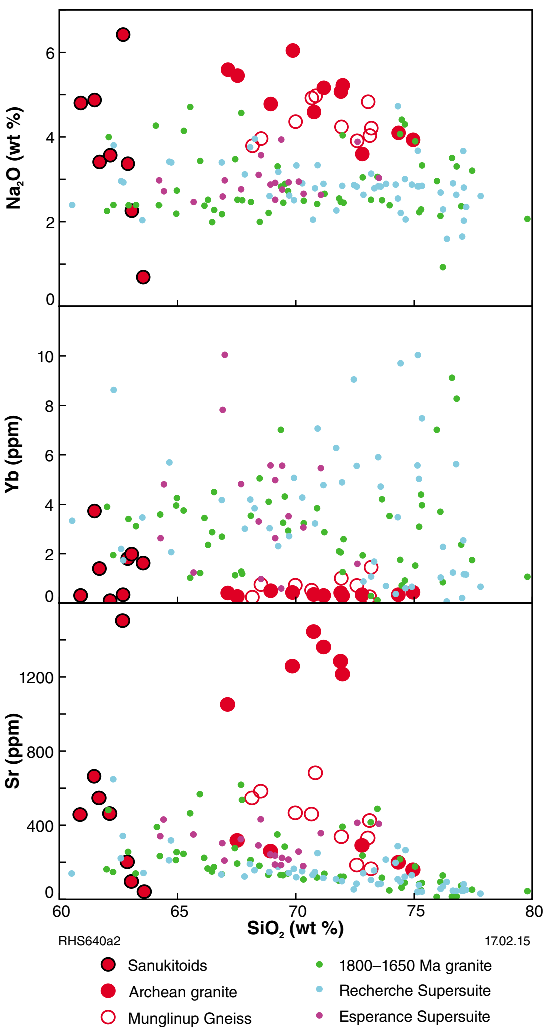

Figure 2. **(left) Compositional variation diagrams emphasizing geochemical characteristics of Archean granites from the Albany–Fraser Orogen**

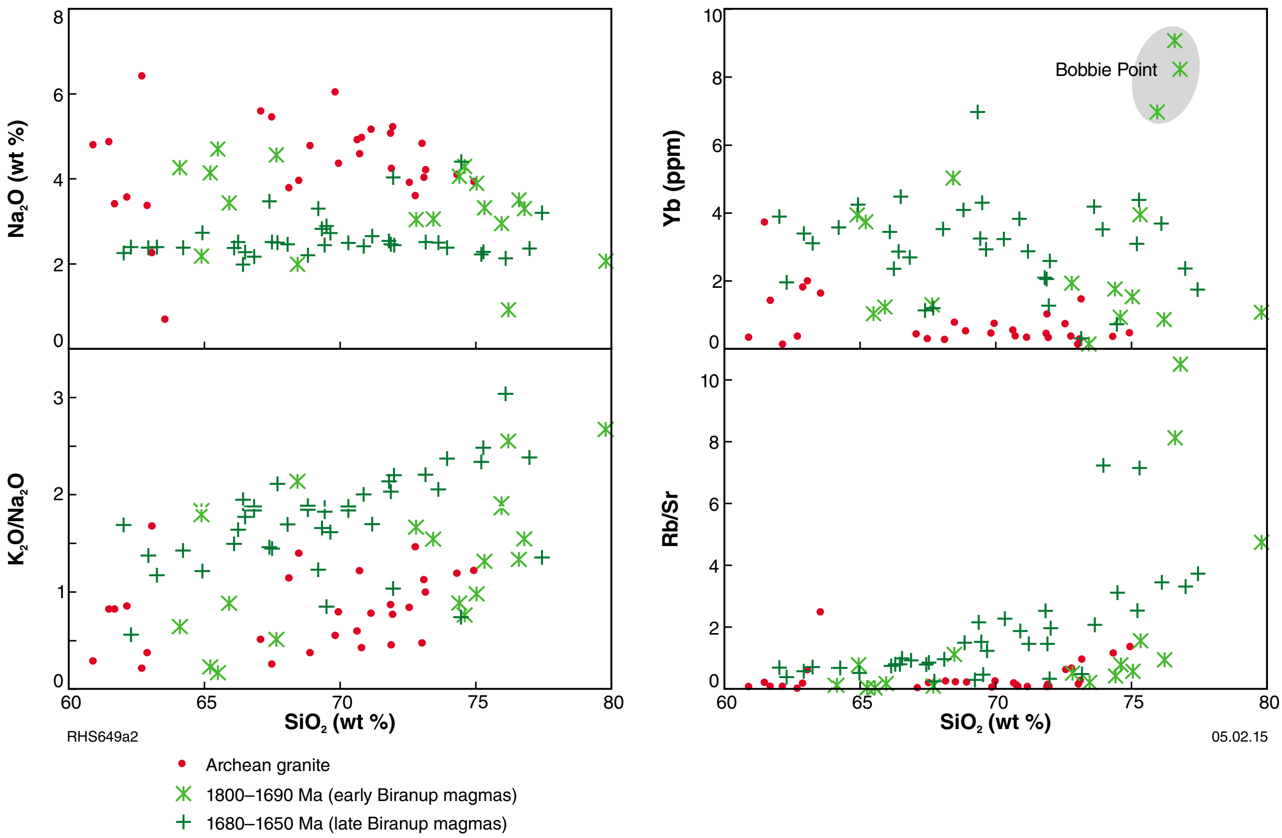

Figure 3. Compositional variation diagrams emphasising contrasting geochemical characteristics of early and late Biranup magmas

The c. 1700 Ma granites from Bobbie Point, in the Tropicana Zone, are very different to either early or late Biranup magmas. They have A-type compositions reflecting very high temperature (and likely anhydrous) crustal melting. They also show a significant degree of Nd- and Hf-isotopic decoupling that suggests low-pressure melting of a crustal source that previously resided at a deeper level within the garnet stability field (Kirkland et al., 2011). This is consistent with c. 1700 Ma melting of the Archean rocks of the Tropicana Zone after their emplacement to shallow crustal levels via thrusting along the Plumridge Detachment at c. 2520 Ma (Occhipinti et al., 2014). This thrust event is not recognized elsewhere in the Albany–Fraser Orogen, but the c. 1700 Ma magmatism likely reflects a period of significant crustal thinning throughout, perhaps heralding the beginning of a period of enhanced thinning and uplift of deep crustal source components that continued for the rest of the Biranup Orogeny.

Granites of the Mesoproterozoic Albany–Fraser Orogeny

Stage I — Recherche Supersuite

Granites that crystallized during Stage I of the Albany–Fraser Orogeny (Recherche Supersuite) are divided into the Southern Hills and Gora Hill Suites (Fig. 1). Granites of the Southern Hills Suite are mainly concentrated in and around the Fraser Zone, are highly silicic (SiO_2 >72 wt%) and are depleted in Nb, Ta, Zr, Hf, Ti, REE, Th, and U (Fig. 4) compared to the Gora Hill Suite. They reflect melting of supercrustal sequences dominated by sedimentary rocks whose bulk source was isotopically more primitive than known older crustal components of the Albany–Fraser Orogen. Age and Hf-isotopic signatures suggest that this bulk source included juvenile detritus derived from the Madura Province to the east (Spaggiari et al., 2014b).

Except for a few critical trace elements (e.g. Cr, Ba, Sc; Fig. 4), it is extremely difficult to separate the Gora Hill Suite from the late Biranup magmas, all of which are generally calc-alkalic and weakly ferroan. However, concentrations of Nb, Ta, and Yb increase with increasing SiO_2 for the Gora Hill Suite, but show the opposite trend in the late Biranup magmas.

Based on geochemical and isotopic variations, the source of the Gora Hill Suite included both crustal material (e.g. early and late Biranup magmas) and mantle material. The petrogenesis is similar to that of the late Biranup granites, although the Nd-isotopic compositions of the Gora Hill Suite reflect a further increment in the proportion of mantle material entering granite source

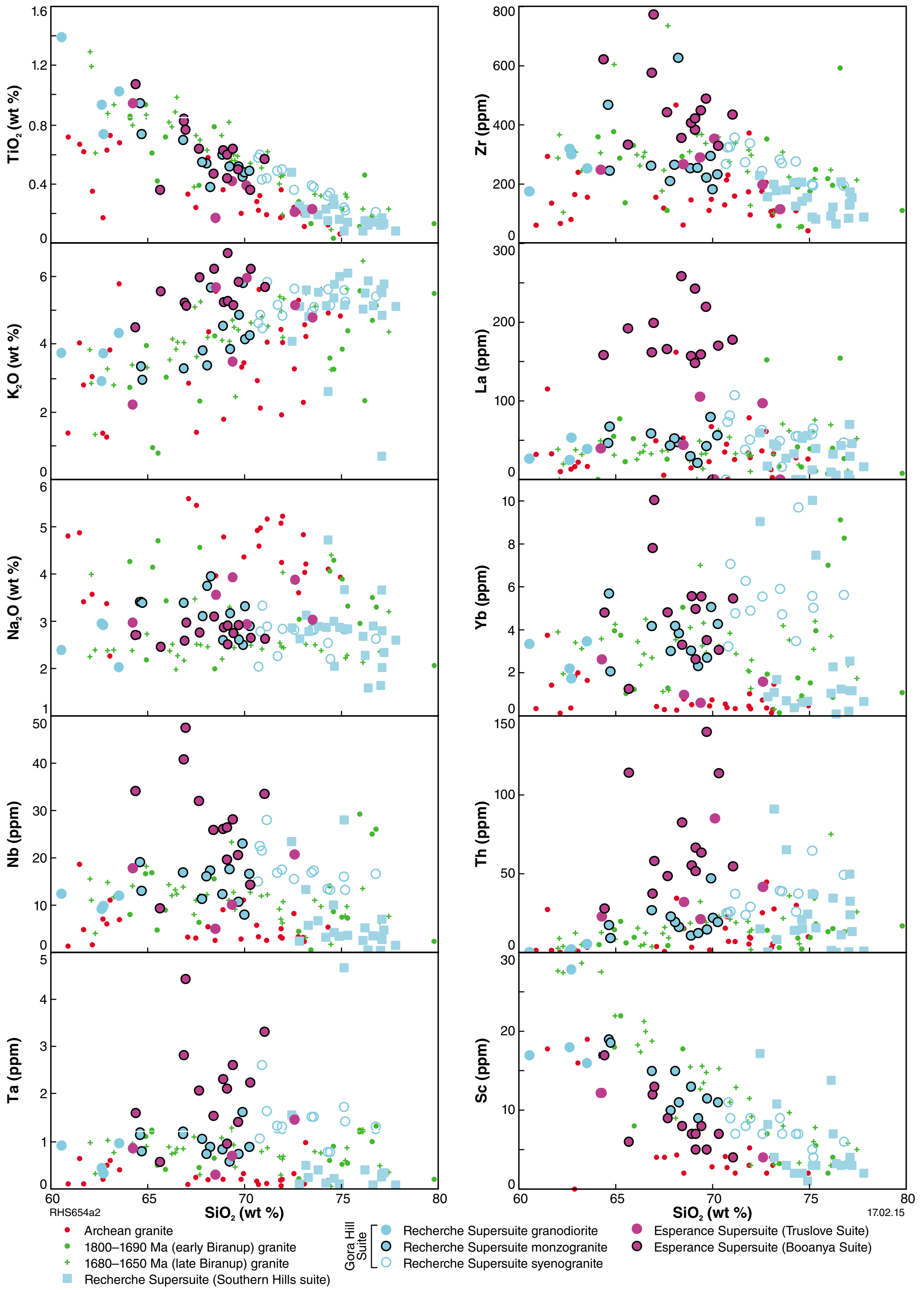

Figure 4. Compositional variation diagrams emphasising geochemical characteristics of granites formed during the Albany–Fraser Orogeny

regions. There is a systematic spatial variation in the composition of the Gora Hill Suite across the structural trend of the Albany–Fraser Orogen, such that granodiorite occurs only in the northwest and syenogranite dominates in the southeast. This reflects a similar variation in relative proportions of source components. Magmatism also appears to have migrated from southeast to northwest between c. 1330 and 1283 Ma (Fig. 5).

A sharp change in the isotopic composition of the Gora Hill Suite just west of the boundary between the Nornalup Zone and the Madura Province (the Rodona Shear Zone; Figs 1 and 5) reflects a change in basement composition and marks the southeastern edge of un-radiogenic reworked Archean crust. To the east, Gora Hill Suite granites have a Nd isotopic signature that suggests incorporation of juvenile Madura Province crust and indicates that the Madura Province and Nornalup Zone were linked by this time, and that the Rodona Shear Zone is a suture (Spaggiari et al., 2014b). Since this region is where Gora Hill Suite magmatism began, this magmatism may have initiated through orogenic collapse, following accretion and obduction of the Madura Province over the Nornalup Zone.

Stage II — Esperance Supersuite

Granites that formed during Stage II of the Albany–Fraser Orogeny (Esperance Supersuite) are divided between the Truslove and Booanya Suites (Fig. 1). The Truslove Suite forms a linear belt along the northwestern margin of the known outcrop extent of the Esperance Supersuite and in general represents low-degree partial melts of locally available lithologies with melting broadly associated with major shear zones.

The Booanya Suite is ferroan, alkali-calcic to alkali rocks with strong enrichments in incompatible trace elements (Fig. 4) characteristic of A-type magmatism and results through high-temperature melting of anhydrous lower crust, likely in association with a significant juvenile-mantle input. The suite heralds a significant change in magmatism compared with the Recherche Supersuite, probably related to higher crustal temperatures associated, again, with significant crustal extension. Nd-isotopic compositions are similar to those of both the Truslove Suite and granites of the Recherche Supersuite suggesting that the composition of the source regions might not have changed.

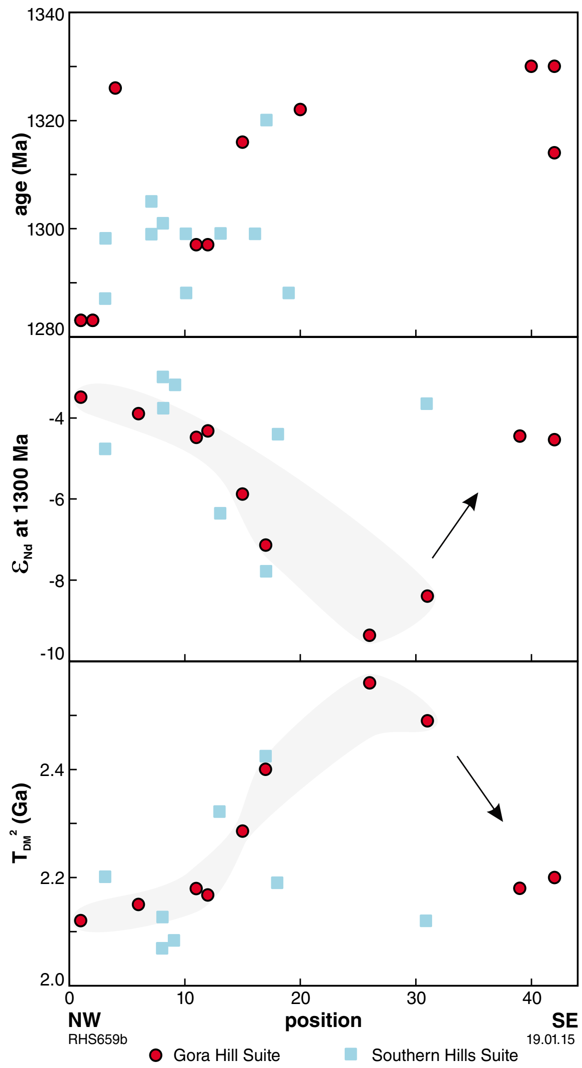

Figure 5. Variations in age and Nd-isotopic compositions of the Gora Hill Suite (Recherche Supersuite) granites along a northwest to southeast traverse through the Albany–Fraser Orogen (see location on Fig. 1)

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Tropicana translated — late Archean to early Paleoproterozoic gold mineralization in the Albany–Fraser Orogen

by

IM Tyler, CV Spaggiari, SA Occhipinti[1], CL Kirkland[2], and RH Smithies

The Albany–Fraser deep-crustal seismic reflection and magnetotelluric (MT) survey has provided new insights into the deep-crustal structure of the transition from the Yilgarn Craton into the adjacent Albany–Fraser Orogen, imaging from the surface to the upper mantle down to ~60 km (Figs 1–2). This geophysical dataset has helped to refine our understanding of the geodynamic setting, tectonic history, and mineral systems of the region through the Neoarchean and Paleo- to Mesoproterozoic, to the Paleozoic (Spaggiari and Tyler, 2014).

The seismic survey was designed to cross the Albany–Fraser Orogen and southeastern boundary of the Yilgarn Craton. Three seismic reflection lines (12GA–AF1, 12GA–AF2, and 12GA–AF3) were acquired by the Geological Survey of Western Australia together with Geoscience Australia during 2012 through the Western Australian Government's Exploration Incentive Scheme (EIS). A fourth line (12GA–T1) was also acquired in 2012 in collaboration with the Tropicana Joint Venture partners AngloGold Ashanti Limited (AGA, 70% and manager) and Independence Group NL (30%) through ANSIR (the National Research Facilities for Earth Sounding). In addition to the acquisition of seismic reflection data, MT data were also acquired in collaboration with the Centre for Exploration Targeting at UWA (CET; Spratt et al., 2014). Gravity stations at 400 m spacing were acquired on all four lines.

The northernmost seismic line (12GA–T1; Fig. 1) was acquired in the vicinity of the 7.89 M oz Tropicana gold deposit discovered in 2005 by AGA — the largest greenfields gold discovery in Australia in the last decade — as well as AGA's Voodoo Child Au–Ag deposit and Beadell Resources Limited's Hercules and Atlantis gold prospects (Doyle et al., 2013, 2014, 2015; Kirkland et al., in prep.; Occhipinti et al., 2014).

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The Plumridge Detachment and late Neoarchean gold mineralization in the Tropicana Zone

The upper crustal part of line 12GA–T1 is dominated by the Tropicana Zone, which is in fault contact with the Archean Yilgarn Craton to the northwest (obscured by the Carboniferous to Permian Gunbarrel Basin), and with the Archean of the Northern Foreland of the Albany–Fraser Orogen to the southwest (Fig. 1). To the east, it is in fault contact with the Paleoproterozoic Biranup Zone. The Tropicana Zone is considered to have a distinctly different geological history from the adjacent Northern Foreland (see also Blenkinsop and Doyle, 2014; Kirkland et al., in prep.; Doyle et al., 2015). Within the Tropicana Zone, major structures include the Pipeline, Phoenix, Rusty Nail, Angel Eyes, Tumbleweed, Thorny Devil, Black Dragon, Blue Robin, Chimera, and Sydney Simpson Shear Zones (Occhipinti et al., 2014; Fig. 2). Together, these form part of a high-crustal level, imbricate thrust stack that links into the Plumridge Detachment, defined by a very distinctive set of strong reflections that image the sole thrust to a major northwesterly directed foreland thrust system, with an apparent shallow southeast dip (Fig. 2). The detachment initially developed at c. 2520 Ma and now forms the boundary between the Tropicana Zone and the underlying reworked Yamarna Terrane of the Yilgarn Craton.

To the northwest in line 12GA–T1, the Mohorovičić discontinuity (Moho) is interpreted at about 39 km underlying the Babool Seismic Province, a section of middle to lower crust underlying the reworked Yamarna Terrane (Korsch et al., 2013, 2014; Fig. 2). To the southeast, the Moho underlies the newly defined Gunnadorrah Seismic Province to a depth of 49.5 km (Occhipinti et al., 2014; Korsch et al., 2014). The Babool and Gunnadorrah Seismic Provinces are juxtaposed along a low-angle fault with apparent moderate northwest dip that can be traced upwards into the middle crust to a depth of about 19 km at the southeastern end of the seismic line. This gives a vertical displacement of the Moho across the fault of about 10 km, indicating a thrust movement sense to the southeast (Occhipinti et al., 2014; Korsch et al., 2014).

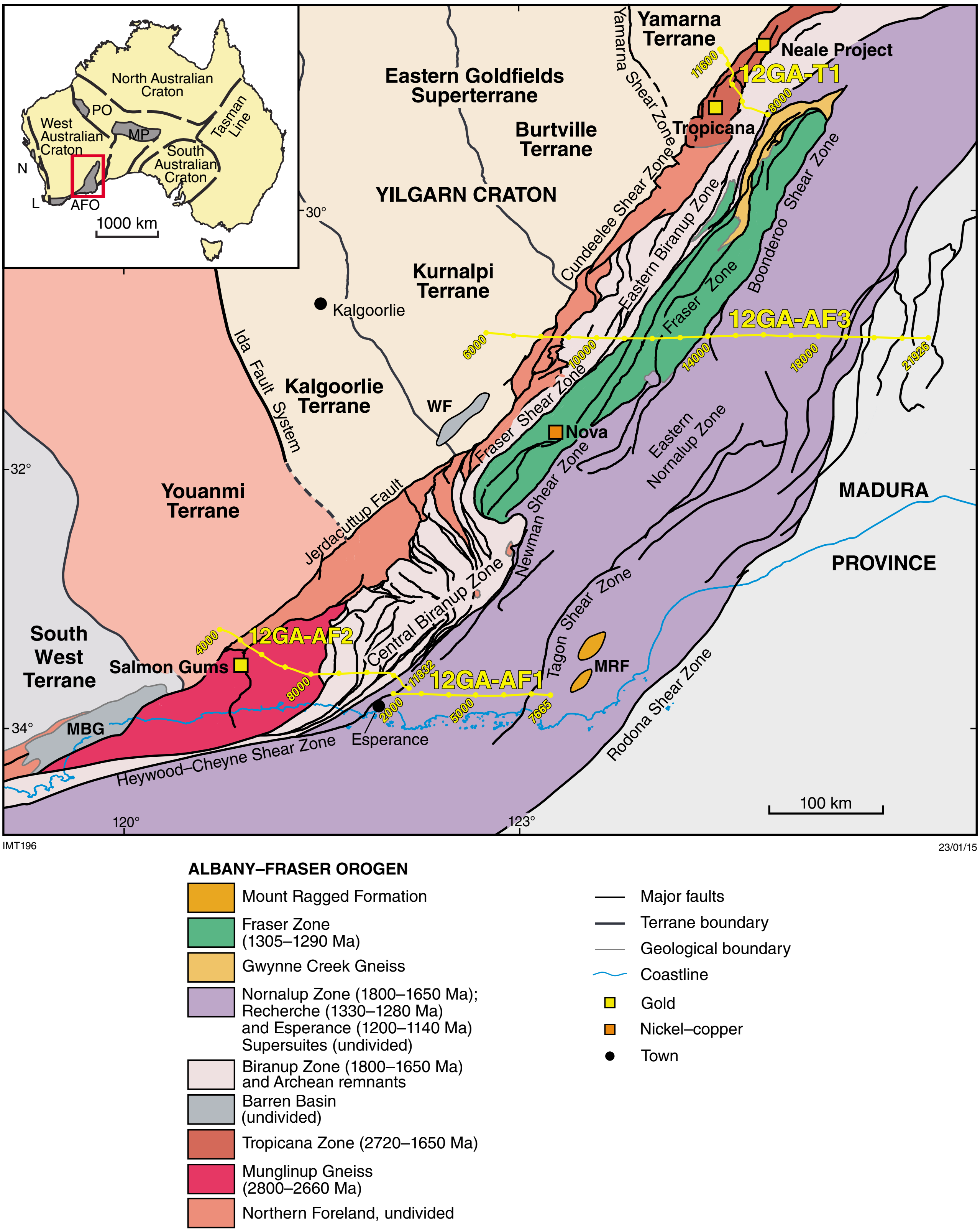

Figure 1. Simplified, pre-Mesozoic interpreted bedrock geology of the Albany–Fraser Orogen and tectonic subdivisions of the Yilgarn Craton showing the location of the Albany–Fraser deep-crustal seismic reflection lines; Abbreviations used: MBG = Mount Barren Group; WF = Woodline Formation; MRF = Mount Ragged Formation. Inset: AFO = Albany–Fraser Orogen; MP = Musgrave Province; PO = Paterson Orogen; L = Leeuwin Province; N = Northampton Province

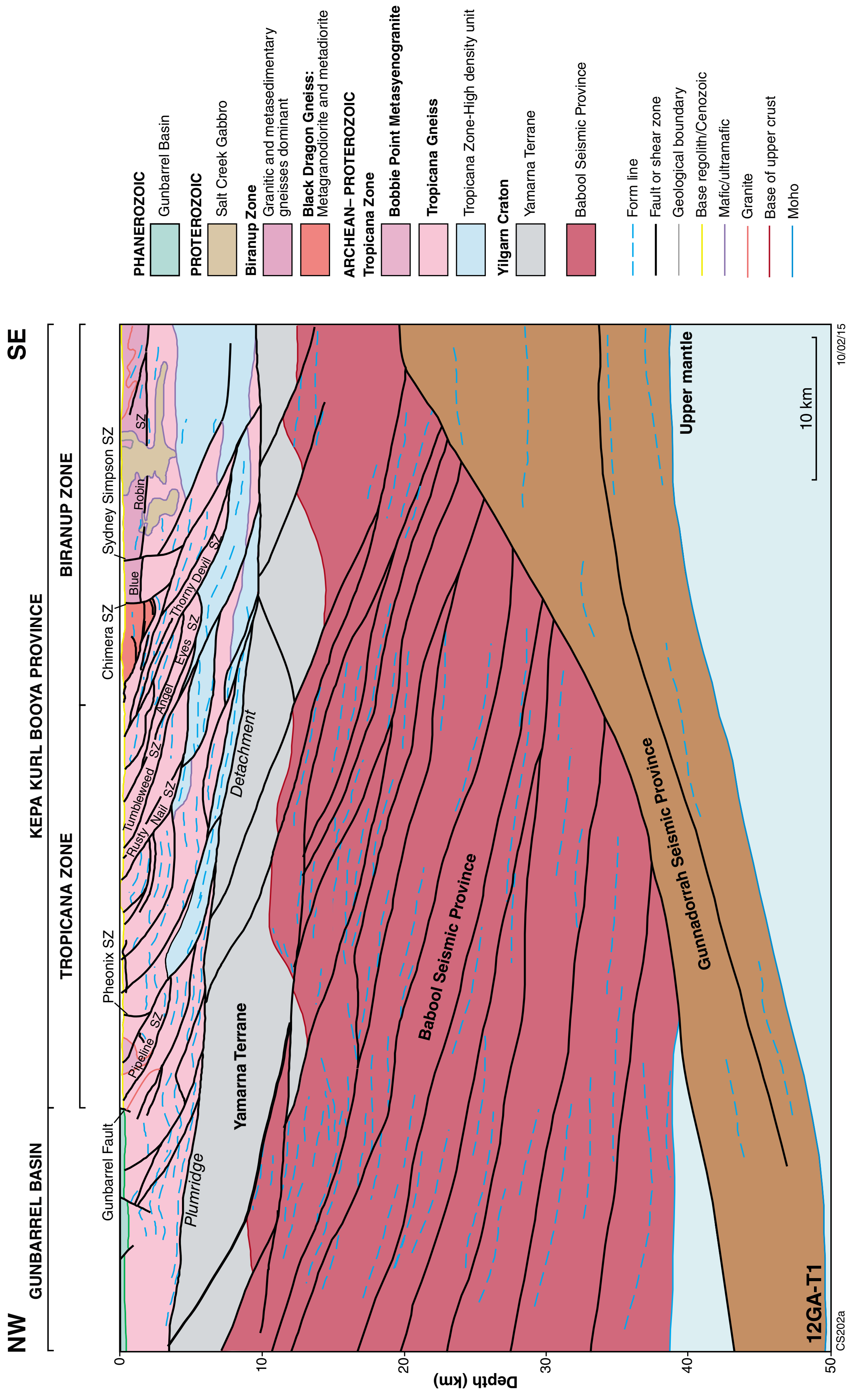

Figure 2. Interpretation of seismic line 12GA–T1 showing the interpreted line work and geological units

The 2718–2554 Ma Atlantis Event

Moderately foliated metagranite sampled close to the Tropicana mine gives an age of 2722 ± 15 Ma from analyses of the oscillatory zoned cores from four zircon crystals interpreted to represent the magmatic crystallization age of the granite (Kirkland et al., 2013). A much younger age of 2640 ± 10 Ma on 10 analyses from the unzoned highly rounded zircon rims is interpreted to represent a high-grade metamorphic overprint. This date is consistent with U–Pb zircon ages reported by Doyle et al. (2015) from the Tropicana Gneiss within the deposit. Kirkland et al. (in prep.) recognized that zircon growth at the Hercules and Atlantis gold prospects to the northeast of the Tropicana mine records a spread of U–Pb ages between 2718 and 2554 Ma. They interpreted the characteristic high-grade metamorphic textures and grain shapes as evidence of a prolonged period of granulite facies metamorphism that formed the Hercules Gneiss.

This high-grade metamorphic event is here named the Atlantis Event and its age range implies that the Tropicana Zone was held at a deep-crustal level during much of the Neoarchean prior to exhumation after 2554 Ma.

The 2520–2505 Ma Tropicana Event

The Tropicana gold deposit formed after the Atlantis Event with orogenic gold mineralization associated with the growth of biotite and pyrite under greenschist facies conditions (Doyle et al., 2014, 2015). The timing of the event is constrained by the 2515 ± 14 Ma Ar–Ar date of biotite, and a latest Neoarchean Re–Os date from pyrite of 2505 ± 50 Ma (Doyle et al., 2015). The gold mineralization at Tropicana is unlike typical Archean lode gold deposits in the Yilgarn Craton in that it is not directly associated with quartz and carbonate veining, and it formed within southeast- to east-dipping shear zones that can be interpreted as part of the imbricate thrust stack (Blenkinsop and Doyle, 2014; Doyle et al., 2015; Occhipinti et al., 2014). A U–Pb age from rutile of c. 2520 Ma records cooling through 500–550° C, and with the 2515 Ma biotite Ar–Ar age, is consistent with exhumation along a retrograde path from amphibolite facies into the greenschist facies during the Tropicana Event (Doyle et al., 2015).

Exhumation was coeval with fluid migration along the Plumridge Detachment and gold deposition under greenschist facies conditions within the thrust stack that refertilized the dehydrated Neoarchean gneisses (Doyle et al., 2015).

Additionally, Re–Os dating of pyrite suggests an age of c. 2100 Ma for the later, early Paleoproterozoic generation of quartz vein-related gold mineralization currently only known in the Hercules and Atlantis gold prospects (Kirkland et al., in prep.).

Neoarchean tectonic setting

The overall structure of line 12GA–T1 is of a northwest-directed imbricate thrust stack formed in a foreland setting by thrusting of the Tropicana Zone up along the c. 2520 Ma Plumridge Detachment onto the Yamarna Terrane and underlying Babool Seismic Province of the Yilgarn Craton, with the lower crustal Gunnadorrah Seismic Province thrust underneath them (Fig. 2).

The Hercules Gneiss of the Tropicana Zone is dominated by significant Mg- and (LILE) large-ion lithophile element-enriched granites classed as sanukitoids with a best age estimate for magmatism at 2692 ± 16 Ma (Kirkland et al., in prep.). Such an age is older than other sanukitoids found within the Yilgarn Craton (Smithies et al., 2014). Sanukitoid magmas, usually derived from metasomatized mantle above a subducting slab in an arc setting (Martin et al., 2005), are well-known for high gold fertility and are interpreted as the likely source of gold in the Tropicana Zone. Sanukitoid intrusion is interpreted to have commenced just prior to the start of the prolonged 2718–2554 Ma Atlantis Event granulite facies metamorphism in the Tropicana Zone. The presence of Paleoproterozoic granites intruded into both the Tropicana Gneiss and the Hercules Gneiss during the 1780–1760 Ma Ngadju Event, which affected much of the Albany–Fraser Orogen (Spaggiari et al., 2014a,b,c), indicate that the Tropicana Zone was located close to its present position by c. 1780 Ma (Occhipinti et al., 2014; Kirkland et al., 2014, in prep.).

The sanukitoids have a similar crystallization age to the komatiite-related Ni-sulfide mineral system at the base of the greenstones in the Kalgoorlie and Kurnalpi Terranes of the Eastern Goldfields Superterrane. However, the sanukitoids formed in a very different tectonic setting, with the Tropicana Zone developing in a possible arc setting on the margin of the Yilgarn Craton at c. 2690 Ma. The prolonged granulite facies metamorphism during the ensuing Atlantis Event until c. 2550 Ma spanned the evolution of the Eastern Goldfields and the associated orogenic lode-gold mineral system that formed deposits like the Golden Mile. The Tropicana Zone was buried at a deep-crustal level during this period before being thrust up and back onto the southern Eastern Goldfields Superterrane from the southeast at 2520–2505 Ma, accompanied by the development of a major greenschist facies gold-bearing mineral system sourced from the buried craton margin. The initial extent of this thrust sheet is unknown but would have formed a foreland fold-and-thrust belt possibly extending much further to the southwest, west, northeast, and north, and examination of other seismic lines from the region acquired across the Yilgarn Craton margin might delineate similar structures (e.g. Goleby et al., 2003; Korsch et al., 2013) This buried source region, possibly within the Gunnadorrah Seismic Province (Korsch et al., 2014; Tyler et al., 2014) had the potential to be tapped repeatedly during the subsequent Proterozoic evolution of the Albany–Fraser Orogen (e.g. to form the Mesoproterozoic Nova–Bollinger nickel deposit; Tyler et al., 2014).

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