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

RECORD 2013/2

GSWA 2013 EXTENDED ABSTRACTS
Promoting the prospectivity of Western Australia




Geological Survey of Western Australia

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Geological Survey of Western Australia

MINISTER FOR MINES AND PETROLEUM
Hon. Norman Moore MLC

DIRECTOR GENERAL, DEPARTMENT OF MINES AND PETROLEUM
Richard Sellers

EXECUTIVE DIRECTOR, GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
Rick Rogerson

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Melting, mixing, and emplacement: evolution of the Fraser Zone, Albany–Fraser Orogen

by

CV Spaggiari, RH Smithies, CL Kirkland, HM Howard, WD Maier[1], and C Clark[2]

The Fraser Zone of the Albany–Fraser Orogen is an approximately 425 km long, up to 50 km wide, northeast-trending, fault-bounded unit that lies between the predominantly Paleoproterozoic basement rocks of the Biranup and Nornalup Zones (Fig. 1). As indicated by its dense gravity signature (Fig. 2), the Fraser Zone is dominated by metagabbroic rocks. Only the southwestern portion is exposed, which contains the c. 1305–1290 Ma Fraser Range Metamorphics. These comprise thin to voluminous sheets of metagabbroic rocks that range in thickness from several centimetres up to several hundred metres, interlayered with sheets of monzogranitic to syenogranitic gneisses, pyroxene-bearing granitic gneisses, and hybrid, metamorphosed magmatic rocks. The magmatic rocks are interlayered at various scales with amphibolite to granulite facies pelitic, semipelitic to calcic, and locally iron-rich metasedimentary rocks of the Mesoproterozoic Arid Basin. The Fraser Zone has been previously interpreted as an exhumed block of lower crust (Doepel, 1975), a layered mafic intrusion emplaced into older basement represented by the granitic and metasedimentary rocks (Myers, 1985), multiple accreted magmatic oceanic arcs (Condie and Myers, 1999), and an oceanic arc related to southeast-dipping subduction, accretion, and collision of the Mawson Craton (Bodorkos and Clark, 2004). We interpret the Fraser Zone as a structurally modified, lower crustal hot-zone where voluminous gabbroic magmas were variably mixed with contemporaneous granitic magma and country-rock melts. The presence of these gabbroic magmas, regional granite magmatism, and previously published peak metamorphic conditions in the metasedimentary rocks of >800°C and 8–9 kbars (Oorschot, 2011), are all indicative of a regional thermal anomaly from at least 1305–1290 Ma that coincided with the formation of the Fraser Zone. Based on these findings, and on a range of other recent geological evidence, the preferred tectonic setting is either a distal back-arc or an intercontinental rift (Spaggiari et al., 2011; Smithies et al., 2013). We summarize the main features below.

[1] Department of Geosciences, University of Oulu, Linnanmaa, Oulu 90014, Finland

[2] Department of Applied Geology, Curtin University, Perth, WA 6845, Australia

Arid Basin

The c. 1450–1305 Ma Arid Basin is a regionally extensive basin system containing metasedimentary rocks of highly variable compositions that have maximum depositional ages that are younger than the 1710–1650 Ma Biranup Orogeny, but have been affected by Stage I of the Albany–Fraser Orogeny (1345–1260 Ma). The Arid Basin represents the second major cycle of erosion and sediment deposition in the orogen, and includes the metasedimentary component of the Fraser Range Metamorphics, as well as the Malcolm Metamorphics (formerly the Malcolm Gneiss), and the Gwynne Creek Gneiss in the northeast (Fig. 1; Spaggiari et al., 2011). The tectonic setting of the Arid Basin is not known, but basin formation, generation of the Fraser Zone intrusions, regional granite magmatism (1330–1280 Ma Recherche Supersuite), high-temperature metamorphism, and the inferred regional thermal anomaly are almost certainly directly linked.

In the Fraser Zone, the thickest exposures of Arid Basin metasedimentary rocks lie along its northwestern edge, and are typically interlayered with sheets or sills of mafic granulite or amphibolite derived from the gabbroic intrusions. Whereas pelitic and semipelitic rocks dominate the metasedimentary component in the southern part of the Fraser Zone, the northern exposed section contains metasedimentary rocks that have calc-silicate affinities, and may represent metamorphosed marls, or volcaniclastic protoliths. Partial melts of the metasedimentary rocks of the Arid Basin are inferred to have contaminated some of the gabbroic intrusions in the Fraser Zone, forming one of two groups of hybrid rocks (Smithies et al., 2013).

Summary of the age relationships of the Fraser Range Metamorphics

All isotopic results from the Fraser Zone indicate a short time interval for sediment deposition, coeval mafic and felsic igneous crystallization, and near coeval granulite-facies metamorphism. Maximum depositional ages of the metasedimentary rocks indicate they were deposited immediately prior to magmatism. For example, garnet–biotite metasedimentary gneiss south of Verde Austral quarry (Fig. 2) yielded a maximum depositional age

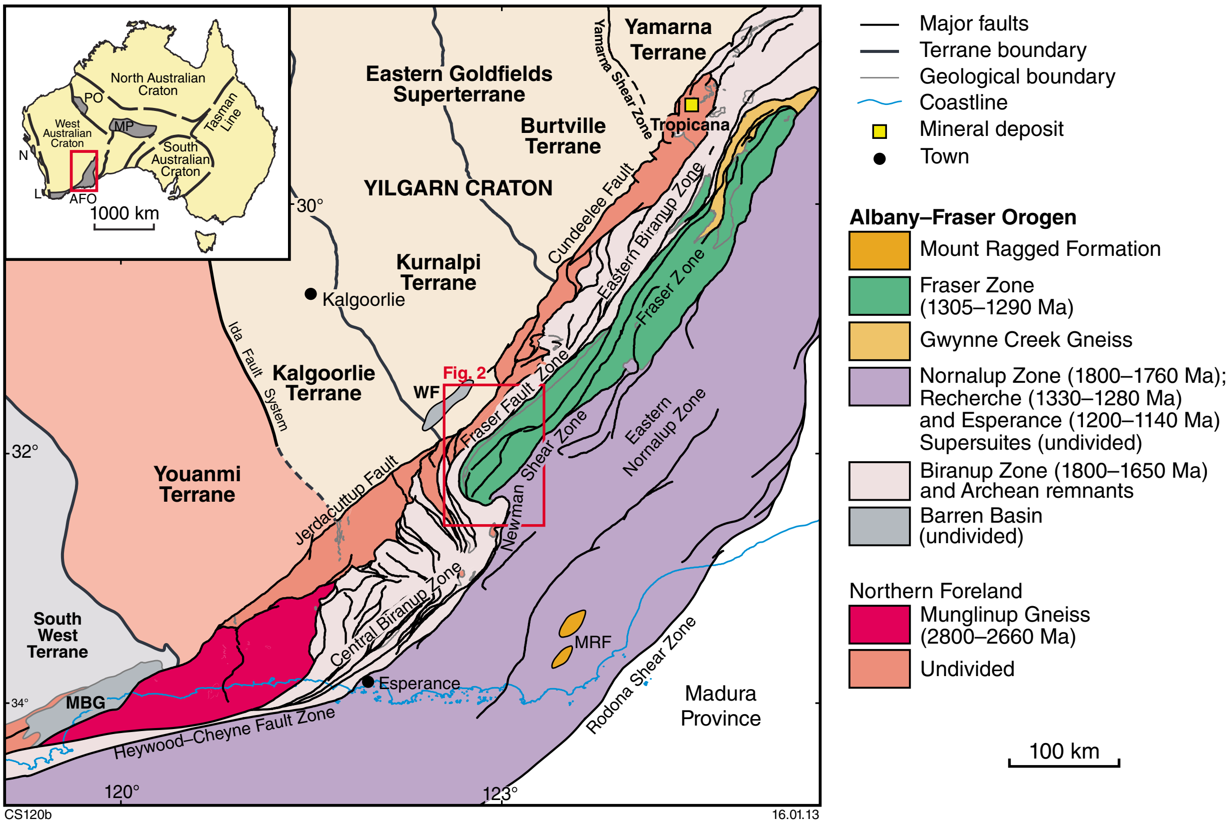

Figure 1. Simplified, pre-Mesozoic interpreted bedrock geology of the eastern Albany–Fraser Orogen and tectonic subdivisions of the Yilgarn Craton (from Spaggiari et al., 2011) Abbreviations used: MBG – Mount Barren Group; WF – Woodline Formation; MRF – Mount Ragged Formation; AFO – Albany–Fraser Orogen; MP – Musgrave Province; PO – Paterson Orogen; L – Leeuwin Province; N – Northhampton Province

of 1332 ± 21 Ma (single zircon analysis), or the more conservative estimate of 1363 ± 9 Ma (24 youngest analyses; GSWA 194778, preliminary data). Zircon rims from the same sample yielded a metamorphic date of 1298 ± 12 Ma, identical to metamorphic zircons from mafic granulite at the American quarry (Fig. 2; 1292 ± 6 Ma; GSWA 194718, Kirkland et al., 2011). Magmatic crystallization of two-pyroxene metagabbro from the Fraser Range Black quarry has been dated at 1299 ± 3 Ma (Fig. 2, GSWA 194717, preliminary data), and at 1299 ± 10 Ma and 1291 ± 8 Ma from southwest of Symons Hill (Fig. 2, De Waele and Pisarevsky, 2008). Metasyenogranite from near Symons Hill yielded a magmatic crystallisation date of 1298 ± 5 Ma (Kirkland et al., 2011). Similar results, between c. 1300 and 1290 Ma, have been obtained for other metagranitic rocks, and both felsic and gabbroic pegmatitic intrusions. The close correspondence between magmatism and granulite facies metamorphism, predominantly between 1305 and 1290 Ma, implies magmatism as a thermal driver of metamorphism.

Petrogenesis of the Fraser Zone gabbroic rocks

Two broad geochemical groups can be recognized: the 'main gabbros' which show no field, petrographic, or geochemical evidence of having interacted with country-rock; and the 'hybrid gabbros' which show considerable evidence for such interaction. The main gabbros are dominantly olivine gabbro to olivine gabbronorite containing up to 15% olivine, 35–60% plagioclase, generally greater abundances of clinopyroxene to orthopyroxene, up to 20% brown hornblende, up to 10% brown biotite, and up to 5% magnetite (Smithies et al., 2013). The hybrid gabbros commonly include the presence of subhedral K-feldspar phenocrysts (or perthitic or antiperthitic mixtures) and high and unevenly distributed modal proportions of quartz and K-feldspar, which are commonly developed as stringers or blebs. Garnet up to 6 mm or so occurs in some layers. In comparison to the main gabbros, they typically contain less, or no, olivine.

The hybrid gabbros can be further subdivided geochemically into low La/Th rocks that have incorporated material from contemporaneous high-Th monzogranitic sheets (Group 1 hybrid gabbros), and high La/Th rocks that have assimilated low-degree partial melts of metasedimentary country-rock at the level of emplacement (Group 2 hybrid gabbros). The main gabbro is parental to the hybrid gabbros but escaped hybridization during ascent or emplacement. However, they still contain an enriched crustal component acquired at a deeper level. Previous accounts have suggested this enrichment

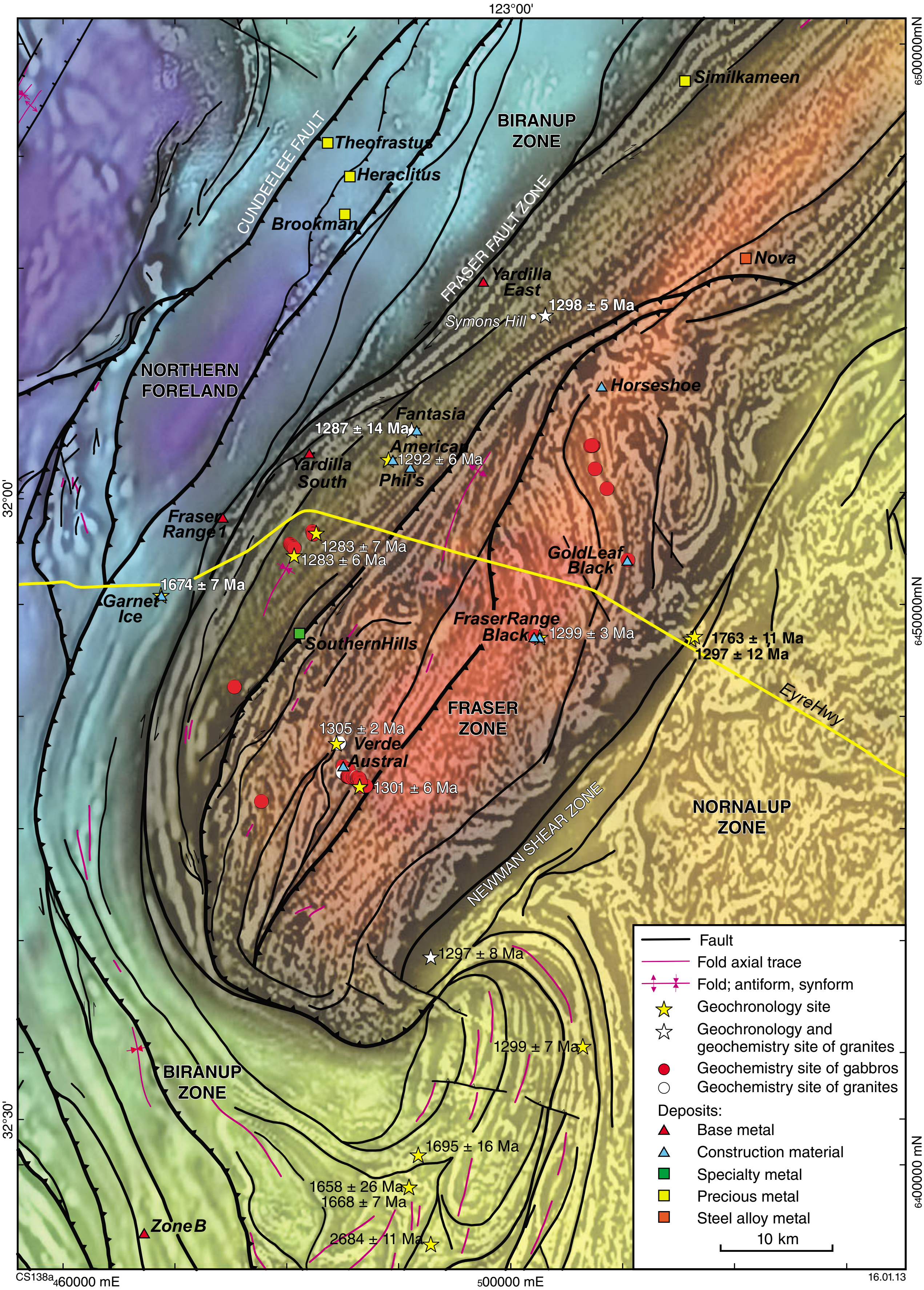

Figure 2. Colour gravity image with black and white, first vertical derivative aeromagnetic drape of the southwestern part of the Fraser Zone, showing major structures, geochemistry sample locations, and U–Pb (SIMS) ages

reflects a subduction addition to the mantle sources of the gabbros during the evolution of a series of oceanic island arcs (Condie and Myers, 1999). All previous and recent Nd- and Hf-isotopic data are inconsistent with that interpretation — trace element enrichments are better explained in terms of assimilation of basement that included a low-Sr component of Archean, or reworked Archean, crust. The presence of this type of crust in the adjacent Biranup Zone, and potentially in the Nornalup Zone (Figs 1 and 2), lends substantial weight to these interpretations. Following early basement contamination, the 'main gabbro' sheets that form the dominant component of the Fraser Zone were emplaced into a lower crustal hot-zone where they variably mixed with contemporaneous granite magma and country-rock melts.

Structural emplacement of the Fraser Zone

The Fraser Range Metamorphics are dominated by a well-developed, northeast-trending, predominantly steeply southeast-dipping foliation, although massive rocks occur locally. In general, this foliation is axial planar to tight to isoclinal, northeast-trending folds of the layering, which are cut by thrust faults and shear zones. Whereas much of the northwestern side of the Fraser Zone is dominated by folding and strongly foliated to mylonitic rocks, the least deformed and thickest examples of metagabbroic sheets occur in the southeast, reflecting a significant difference in strain before reaching the Newman Shear Zone, which defines the southeastern boundary of the Fraser Zone (Fig. 2). Aeromagnetic and gravity data indicate a repetition of this architecture along strike to the northeast, beneath the Eucla Basin.

Late, metagranitic veins containing large euhedral garnets crosscut the foliation and have been dated at 1283 ± 8 Ma (GSWA 194780, preliminary data), indicating that deformation under high temperature conditions took place shortly after emplacement of the gabbroic and granitic sheets. This suggests the stress field may have rapidly switched from extensional or transtensional (accommodating basin formation and magma emplacement) to compressional or transpressional. This switch may also have contributed to the exhumation of the Fraser Zone along the bounding shear zones, possibly by formation of a pop-up architecture between the Biranup and Nornalup Zones.

Metagranitic rocks along the Newman Shear Zone commonly contain a strong subvertical lineation. Locally, the metagranites are L-tectonites, or occur as L-S tectonites in discrete mylonite zones. Kinematic indicators suggest southeast side up. However, less commonly the lineation and kinematics indicate subhorizontal sinistral shear. In contrast, the Fraser Fault Zone, which defines the northwestern boundary of the Fraser Zone, contains strongly mylonitized rocks with a subhorizontal mineral lineation and kinematics indicative of a dextral shear sense. These shear zone fabrics formed under lower temperature conditions than the folding and associated high temperature fabric formation described above, and probably relate to the final emplacement of the Fraser Zone during Stage II of the Albany–Fraser Orogeny (1215–1140 Ma). The differential kinematics suggest southwestward translation of the Fraser Zone, contributing to the formation of the 'S-bend' termination, and potentially a component of clockwise rotation exposing deeper levels on the northwestern side.

Mineralization

Mineralization at the recently discovered nickel–copper sulphide deposit (Nova, Fig. 2) by Sirius Resources NL at The Eye prospect occurs as pyrrhotite, pentlandite, and chalcopyrite, which display typical magmatic textures including massive, matrix, net-textured, breccia, blebby, and disseminated forms (Sirius Resources NL, 2012a). Although described as magmatic, the mineralization does locally crosscut garnet-bearing metamorphic layering (Sirius Resources NL, 2012b). The host rocks are dominantly gabbroic granulites (Sirius Resources NL, 2012a,b), similar to the main and hybrid gabbros described above. Based on the available geochronological data, metamorphism occurred shortly after magmatism, and may have been a significant secondary control on the mineralization. Diamond drillcore of metamorphosed gabbroic to ultramafic rocks that did not intersect the main zone of mineralization (i.e. is structurally above it) contains a non-economic, disseminated sulphide assemblage of pyrrhotite, pentlandite, and chalcopyrite (Gollam, 2012). This is crosscut by lower temperature alteration, including serpentinite and talc–carbonate veins (Gollam, 2012) that have colloidal, vuggy, laminated, and brecciated textures and locally contain sulphides. This indicates a phase of remobilization that probably post-dates the main high temperature, ore-forming event.

With respect to their potential to yield Ni–Cu mineralization, the main gabbros of the Fraser Zone have relatively high Ni/Cu ratios (Ni/Cu = 2–3), which also appears to be a feature of the Nova discovery (e.g. Sirius Resources NL, 2012a,b). In this respect, it is reasonable to relate the host gabbro at Nova to the main gabbro suite. If this is the case, then the entire Fraser Zone may be prospective for similar Ni–Cu sulfide mineralization. Whereas the Ni concentration of the main gabbro is comparable to those of many other basalts globally with similar MgO contents, Cu concentrations are relatively low (average Cu content of main gabbro ~54 ppm). This is also apparent in their low Cu/Zr ratios (typically <1). It is possible that Cu was extracted more efficiently than Ni as a result of early sulfide segregation during magma crystallization, or was retained in the mantle during partial melting. However, at this early stage of investigations, these data only tell us that the Fraser Zone magmas underwent early equilibration with sulphide, and the relatively unaltered state of the rocks suggests that this occurred before final emplacement.

The hybridization processes leading to Group 1 and 2 hybrid gabbros may have caused additional sulfur saturation in these magmas but it remains unclear whether this process was a factor in producing the Nova deposit, or whether the sulphides there were entrained in magma ascending from a deeper crustal level.

References

Bodorkos, S and Clark, DJ 2004, Evolution of a crustal-scale transpressive shear zone in the Albany Fraser Orogen, SW Australia: 2. Tectonic history of the Coramup Gneiss and a kinematic framework for Mesoproterozoic collision of the West Australian and Mawson cratons: Journal of Metamorphic Geology, v. 22, no. 8, p. 713–731, doi: 10.1111/j.1525-1314.2004.00544.x.

Condie, KC and Myers, JS 1999, Mesoproterozoic Fraser Complex: geochemical evidence for multiple subduction-related sources of lower crustal rocks in the Albany–Fraser Orogen, Western Australia: Australian Journal of Earth Sciences, v. 46, p. 875–882.

De Waele, B and Pisarevsky, SA 2008, Geochronology, paleomagnetism and magnetic fabric of metamorphic rocks in the northeast Fraser Belt, Western Australia: Australian Journal of Earth Sciences, v. 55, p. 605–621.

Doepel, JJG 1975, Albany–Fraser Province, in The geology of Western Australia: Geological Survey of Western Australia, Memoir 2, p. 94–102.

Gollam, M 2012, Final drilling report 'The Eye'; Sirius Gold Pty Ltd: Geological Survey of Western Australia, Statutory mineral exploration report, A092733 (unpublished).

Kirkland, CL, Wingate, MTD and Spaggiari, CV 2011, 194718: mafic granulite, American Granulite Quarry; Geochronology Record 993: Geological Survey of Western Australia, 4p.

Myers, JS 1985, The Fraser Complex: a major layered intrusion in Western Australia, in Professional papers for 1983: Geological Survey of Western Australia, Report 14, p. 57–66.

Oorschot, CW 2011, P–T–t evolution of the Fraser Zone, Albany–Fraser Orogen, Western Australia: Geological Survey of Western Australia, Record 2011/18, 101p.

Sirius Resources NL 2012a, Best hit yet at Nova: Report to Australian Securities Exchange, 26 September 2012, 5p.

Sirius Resources NL 2012b, First diamond hole intersects sulphide where expected at Nova: Report to Australian Securities Exchange, 20 August 2012, 5p.

Smithies, RH, Spaggiari, CV, Kirkland, Howard, HM and Maier, WD 2013, Petrogenesis of gabbros of the Mesoproterozoic Fraser Zone: constraints on the tectonic evolution of the Albany–Fraser Orogen: Geological Survey of Western Australia, Record 2013/5, 29p.

Spaggiari, CV, Kirkland, CL, Pawley, MJ, Smithies, RH, Wingate, MTD, Doyle, MG, Blenkinsop, TG, Clark, C, Oorschot, CW, Fox, LJ and Savage, J 2011, The geology of the east Albany–Fraser Orogen — a field guide: Geological Survey of Western Australia, Record 2011/23, 97p.

Western Australia's unique gemstones

by

JM Fetherston

Introduction

Western Australia contains numerous rare and often unusual gemstones that are described in the new book, Gemstones of Western Australia (Fetherston et al., 2013). This publication is long overdue, since — apart from a series of small booklets on gemstones produced between 1975 and 1994 — a substantial and systematic work on gemstones in the State has not been produced by the Geological Survey of Western Australia since its formal inception in 1896.

The book is a joint publication between GSWA and the Gemmological Association of Australia in which the authors have assembled a comprehensive resource on virtually all gemstones and decorative stones used in jewellery and ornamental sculpture known in the State. Although diamonds command a certain pride of place in the Western Australian mining industry, far less is known about occurrences of gemstones such as emerald, aquamarine, turquoise, topaz, variscite and gaspeite. Also, decorative stones peculiar to the State such as zebra stone, orbicular granite, grunerite, black jade, and mookaite are discussed, as are pearls, fossil wood, and precious metals in jewellery and monumental applications.

Western Australia's 'unique' gemstones

The use of the term 'unique' as applied to this paper is not meant to imply that gemstones described do not occur elsewhere in the world but rather tend to be rare and somewhat unusual in different geological environments around the State.

Accordingly, six rare or somewhat unusual gem and ornamental stones from Western Australia have been selected for this talk. These include: Ellendale diamonds, tourmalite, gaspeite, mookaite, orbicular granite and zebra stone.

Ellendale diamonds

The Ellendale diamond field is located in the Lennard Shelf, about 140 km east-southeast of Derby. This area contains 50 discrete lamproite intrusions, 38 of which are known to be diamondiferous. About 60% of diamonds recovered from these intrusions are of gem quality but overall grades from most pipes tend to be uneconomic (Fetherston et al., 2013). In 2007, the Ellendale mining operation was acquired by Gem Diamonds Ltd, whose operations centred on the rich Ellendale 9 diamond pipe. The mine is well known internationally as a source of fancy yellow diamonds as it contains the highest proportion of these stones occurring in any known kimberlite or lamproite worldwide (Fig. 1). The strong yellow colouration in the diamonds is due to the presence of nitrogen in the gems' crystal lattice in the range of 100 to 1000 parts per million. Ellendale 9 contributes about 50% of world production of fancy yellow diamonds. Diamonds from Ellendale 9 are sold under a marketing agreement to Laurelton Diamonds Inc. (a subsidiary of Tiffany & Co.) (Western Australian Museum, 2012). In the year ending 30 September 2012, diamond production from Ellendale was almost 156 000 ct. In early December 2012, Gem Diamonds announced that the Ellendale mine was to be sold to Goodrich Resources effective 31 December 2012.

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Figure 1. Diamonds from Ellendale showing cushion cut, fancy yellow diamonds (each approximately 1 ct) among Ellendale rough stones (courtesy Kimberley Diamond Company)

Tourmalite

Tourmalite is a tourmaline-rich rock defined as a ‘rock composed almost entirely of tourmaline and quartz, with a mottled appearance and a texture ranging from dense to granular to schistose’. The Warriedar tourmalite deposit is located on an island in the centre of Mongers Lake, about 45 km west-northwest of Paynes Find. Although the presence of tourmaline in the Warriedar area was reported by Simpson (1951), the discovery of tourmalite on the island in Mongers Lake was made in 1962 by a prospector who recognized the lapidary potential of the massive, fine-grained tourmalite. In the early 1990s, mineralogical analysis of specimens was carried out and a system for grading ore samples was devised. Lapidary testing was carried out with carving and polishing of figurines and spheres using different grades of material (Fig. 2). In 2002–03, about 34 t of massive, black, microcrystalline dravite–schorl was extracted for test manufacture of high-quality ornamental jewellery and carved artwork, such as statuettes. The tests demonstrated the material’s extreme hardness, durability, ultra fine grained texture, uniform black colour, and ability to polish to a high lustre. This led to the name ‘Warrierite’ being devised for marketing purposes (Fetherston et al., 1999).

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Figure 2. A highly polished sphere of lapidary-grade warrierite, approximately 13 cm in diameter

Gaspeite

Gaspeite is a green nickel carbonate generally formed by surface or near-surface alteration of nickel sulfides. Gaspeite was named after the Gaspé Peninsula in eastern Canada and was first described in 1966. Gaspeite’s bright apple-green colour and rarity make it a popular gemstone and it is most commonly cut as cabochons or slabbed and polished (Fig. 3). Gaspeite has been recorded from a number of nickel mines in the Eastern Goldfields and the Pilbara Craton. The best known and main source was the Mount Edwards 132N mine near Widgiemooltha in the Eastern Goldfields (Fetherston et al., 2013).

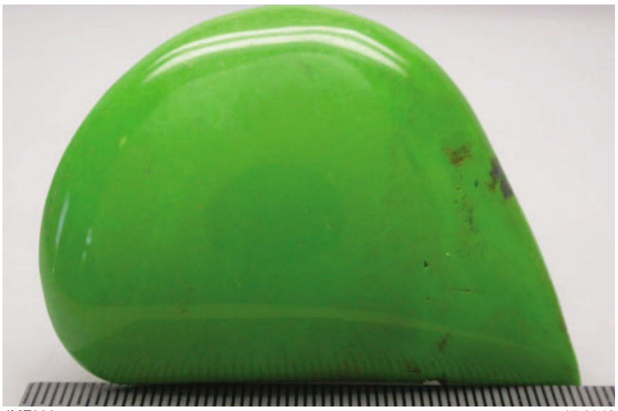

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Figure 3. A highly polished cabochon of bright apple-green gaspeite

Mookaite

Mookaite is a commercial name for the varicoloured ornamental stone taking its name from the former Mooka Station where it has been quarried since the mid-1960s. It is a popular lapidary material suitable for cutting and polishing and with other desirable qualities, including a wide range of colours. It displays attractive, mottled patterns combined with a very fine grained nature and adequate hardness (Fig. 4). Mookaite is mined from a comparatively small area of Early Cretaceous Windalia Radiolarite at several sites on Mooka Creek, about 32 km northwest of Gascoyne Junction. In this area, mookaite only occurs in specific zones where the effects of surface and near-surface secondary silicification of the radiolarite have resulted in the localized development of cherts or porcellanites. Localized colour mottling and varicolouration of these cherts are the result of blotchy iron staining by later meteoric water activity (Stocklmayer and Stocklmayer, 2010).

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Figure 4. Tumbled, polished mookaite stones showing a wide range of colours and patterns

Orbicular granite

Orbicular granite, also known as orbicular granodiorite, is a relatively rare orbicular form of granitic rock known only from a few sites around the world, including Western Australia and Scandinavia. In Western Australia, the Boogardie Orbicular granite deposit is located on Boogardie Station, 35 km west of Mount Magnet. The orbicular granite is hosted by a pink, medium-grained, late Archean biotite granodiorite that becomes tonalitic in places. Data from diamond drilling programs suggests that the orbicular granite bodies may have formed as saucer-shaped, sill-like structures within the host rock. Orbicular granite has a very distinctive appearance. It is crowded with black and white, concentrically formed orbicules that are mostly ellipsoidal in shape and composed largely of hornblende and plagioclase feldspar within a lighter coloured matrix of granitic composition. Individual orbicules average 140 mm in diameter, and up to 12 distinct shells have been observed in many of these structures (Fig. 5). The granite is an unusual and attractive igneous rock used as a spectacular lapidary material that is carved into artworks, including sculptures, bookends and coasters as well as cut and polished into spectacular tabletops, and wall and floor tiles (Fetherston, 2010).

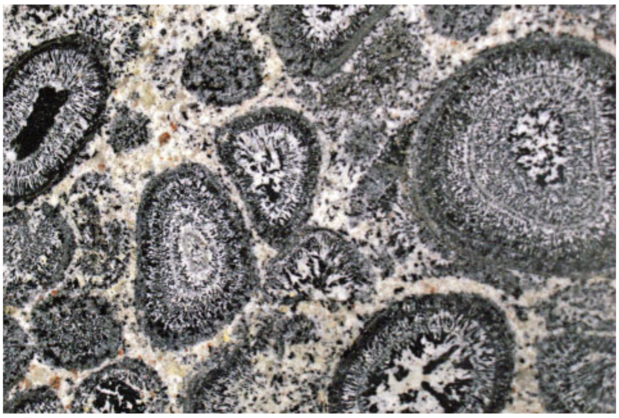

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Figure 5. A polished tile of Boogardie orbicular granite. The hornblende diorite orbicules are composed largely of white plagioclase feldspar, and large, black, radially aligned hornblende crystals.

Zebra stone

Zebra stone is an attractive, distinctively banded, brown and white, argillaceous, fine-grained siltstone. It is found in the Kununurra region around Lake Argyle in the far north of the State. In this area, it is present in lens-like structures within the upper part of the Neoproterozoic Ranford Formation. Today, a number of known deposits are submerged below the surface of Lake Argyle. Zebra stone generally occurs as regularly spaced, ferruginous, brown bands on a white to pale-brown clay-rich matrix. These bands are commonly arcuate and vary in thickness from 1–25 mm according to the width of individual beds (Fig. 6). Other forms include ovoid-shaped rods and irregular blebs that extend through the rock in parallel rows. Currently, there are three operating zebra stone openpits (Fetherston et al., 2013). Zebra stone is sufficiently soft to precisely cut and carve using hand tools. The stone has a smooth, silky texture that results in an extremely smooth and semi-gloss finish that is sealed and treated to obtain a satin or gloss finish as required. Zebra stone products include jewellery, bowls, jugs, and many other attractive artefacts.

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Figure 6. High-quality zebra stone from Lake Argyle. Bands and rods are approximately 5–6 mm wide.

References

Fetherston, JM 2010, Dimension stone in Western Australia; Volume 2, Dimension stones of the southern, central western, and northern regions: Geological Survey of Western Australia, Mineral Resources Bulletin 24, p. 35–43.

Fetherston, JM and Abeysinghe, PB (GSWA), and Jiang Shanqing and Wang Guowu (DGMR) 1999, Six industrial minerals of significance in Western Australia —bentonite, feldspar, kaolin, micaceous iron oxide, talc, and tourmaline: Geological Survey of Western Australia, Report 67, p. 69–80.

Fetherston, JM, Stocklmayer, SM and Stocklmayer VC 2013, Gemstones of Western Australia: Geological Survey of Western Australia, Mineral Resources Bulletin 25, 306p.

Simpson, ES 1951, Minerals of Western Australia, v. 2: Government Printer, Perth, 675p.

Stocklmayer, S and Stocklmayer V 2010, Mookaite — a Western Australian ornamental rock: The Australian Gemmologist, v. 24, no. 3, p. 56–60.

Western Australian Museum 2012, Ellendale diamond collection: viewed 16 January 2013, <http://museum.wa.gov.au/research/collections/earth-and-planetary-sciences/mineral-collection/ellendale-diamond-collection/#disqus_thread>.

Setting and prospectivity of a large igneous province: the 1800 Ma Hart Dolerite, Kimberley region

by

JA Hollis, K Orth[1], S Sheppard[2], IM Tyler, CL Kirkland, and MTD Wingate

The 1800 Ma Hart Dolerite intrudes the Speewah and Kimberley Groups in the Kimberley region and constitutes a large igneous province. The Hart Dolerite contains orthomagmatic V–Ti and epithermal fluorite mineralization and may have significant potential for orthomagmatic Ni–Cu–PGE mineralization. However, little is known about its petrogenesis, duration of magmatism, and the crustal architecture into which it was emplaced, all of which are important in understanding its mineralizing systems. Historical and recently acquired geochemical and isotopic data from the Hart Dolerite also provide a window into the nature of the underlying Kimberley Craton, which is thought to comprise — at least in part — Archean or reworked Archean crust (Hancock and Rutland, 1984; Griffin et al., 2000). This basement is now unexposed, blanketed by sedimentary and volcanic cover of the Paleoproterozoic Speewah and Kimberley Groups (Fig. 1).

The Speewah and Kimberley Groups

The Speewah Group unconformably overlies Paleoproterozoic igneous and metamorphic rocks of the 1910–1800 Ma Lamboo Province (Halls Creek Orogen, Fig. 1). The Speewah Group is c. 1.5 km thick and comprises a dominantly fluvial succession of quartz and feldspathic sandstone, interbedded with mudstone and minor felsic volcanic rocks (Fig. 2). Paleocurrent data indicate that sediment was derived from the uplifted Lamboo Province to the northeast, and transported along a fault-bounded northeast-trending trough (Gellatly et al., 1975). Felsic volcanic rocks yield a SHRIMP U¬–Pb zircon age of 1835 ± 3 Ma for the group (Page and Sun, 1994; Sheppard et al., 2012), which indicates that basin formation was coeval with active-margin magmatism and deformation in the Lamboo Province, associated with collision of the Kimberley and North Australian Cratons (Sheppard et al., 2012).

The >1800 Ma Kimberley Group is c. 3 km thick and unconformably overlies the Speewah Group or, locally, Paleoproterozoic rocks of the Lamboo Province (Fig. 2). It comprises mineralogically and texturally mature siliciclastic rocks, intercalated with tholeiitic basalts of the Carson Volcanics. The Kimberley Group was deposited in a broad, semi-enclosed shallow marine basin, with paleocurrent measurements suggesting a dominant sediment supply from the north and northwest (Gellatly et al., 1970).

The Hart Dolerite

The Hart Dolerite underlies an area of about 160 000 km^2 of the Kimberley Basin and northeast into the Bonaparte Gulf, with an estimated volume of 250 000 km^3 (Griffin et al., 1993). It comprises a network of massive dolerite sills and less extensive dykes and granophyre that intruded the Speewah Group and can be traced up into the two lowermost units of the Kimberley Group (Fig. 2). Undated dolerite sills also intruded the upper part of the Kimberley Group, although these cannot be traced into stratigraphically lower units, and are not accompanied by granophyre (Fig. 2). Sills are up to 1.8 km thick, though commonly composite, with a combined thickness of up to 3 km (Plumb and Gemuts, 1976). Rock types include olivine dolerite and gabbro, quartz dolerite and granophyric dolerite, and diorite (Gellatly et al., 1975; Thorne et al., 1999). Locally olivine-bearing cumulates are present at the base of sills (Elemental Minerals, Fiorentini, 2007).

The Hart Dolerite was emplaced at 1797 ± 11 Ma, based on SHRIMP U–Pb crystallization ages for two samples of granophyre (Sheppard et al., 2012). These are inferred to be comagmatic with the Hart Dolerite based on their occurrence at the tops of sills, rare gradational relationships (Gellatly et al., 1975), consistent geochemical trends (Fig. 3), and similar initial $^{143}Nd/^{144}Nd$ ratios (Sheppard et al., 2012).

1 CODES ARC Centre of Excellence in Ore Deposits, University of Tasmania, TAS 7001

2 Brockman Mining Australia, Level 1, 117 Stirling Highway, Nedlands WA 6009

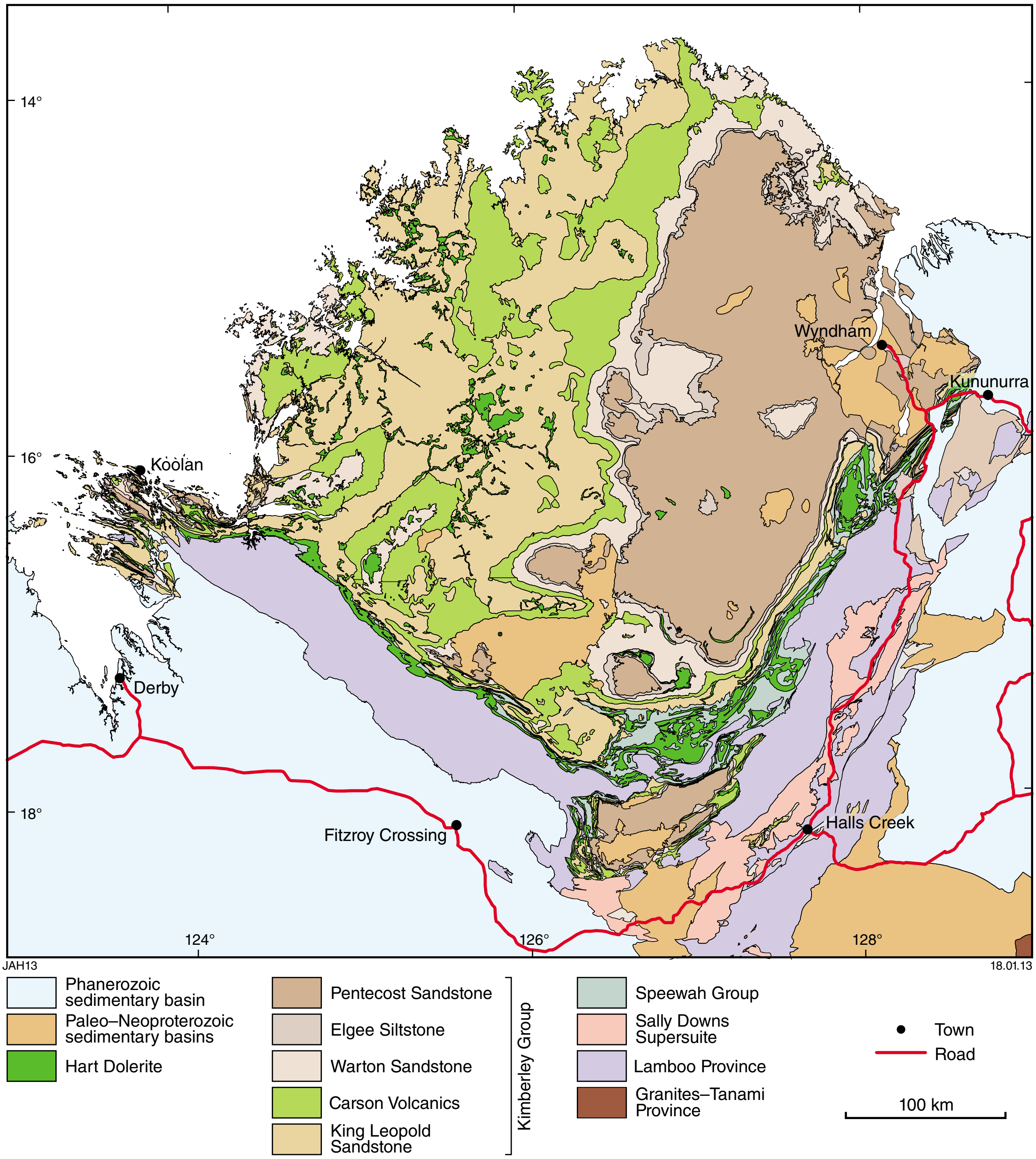

Figure 1. Distribution of the Hart Dolerite in the Kimberley region

Geochemical and isotopic character of the Hart Dolerite

Available geochemical data for the Hart Dolerite are mainly from the Speewah Dome, about 100 km southwest of Kununurra (Speewah Mining, Eves, 2010; Ramsay et al., 2011; 2012), and from near Lansdowne Homestead in the southernmost Lamboo Province, about 100 km west-northwest of Halls Creek (Elemental Minerals, Fiorentini, 2007). Limited regional data are available in Sheppard et al. (1997) and WACHEM (<www.dmp.wa.gov.au/geochem>).

The Hart Dolerite is dominantly tholeiitic basalt to basaltic andesite, though there is a considerable compositional spread, including picro-basalt, trachybasalt, and trachyandesite compositions. The bulk of available data have Mg numbers of 30–53 and 50–53% SiO_2, though there are indications of other significant compositional groups

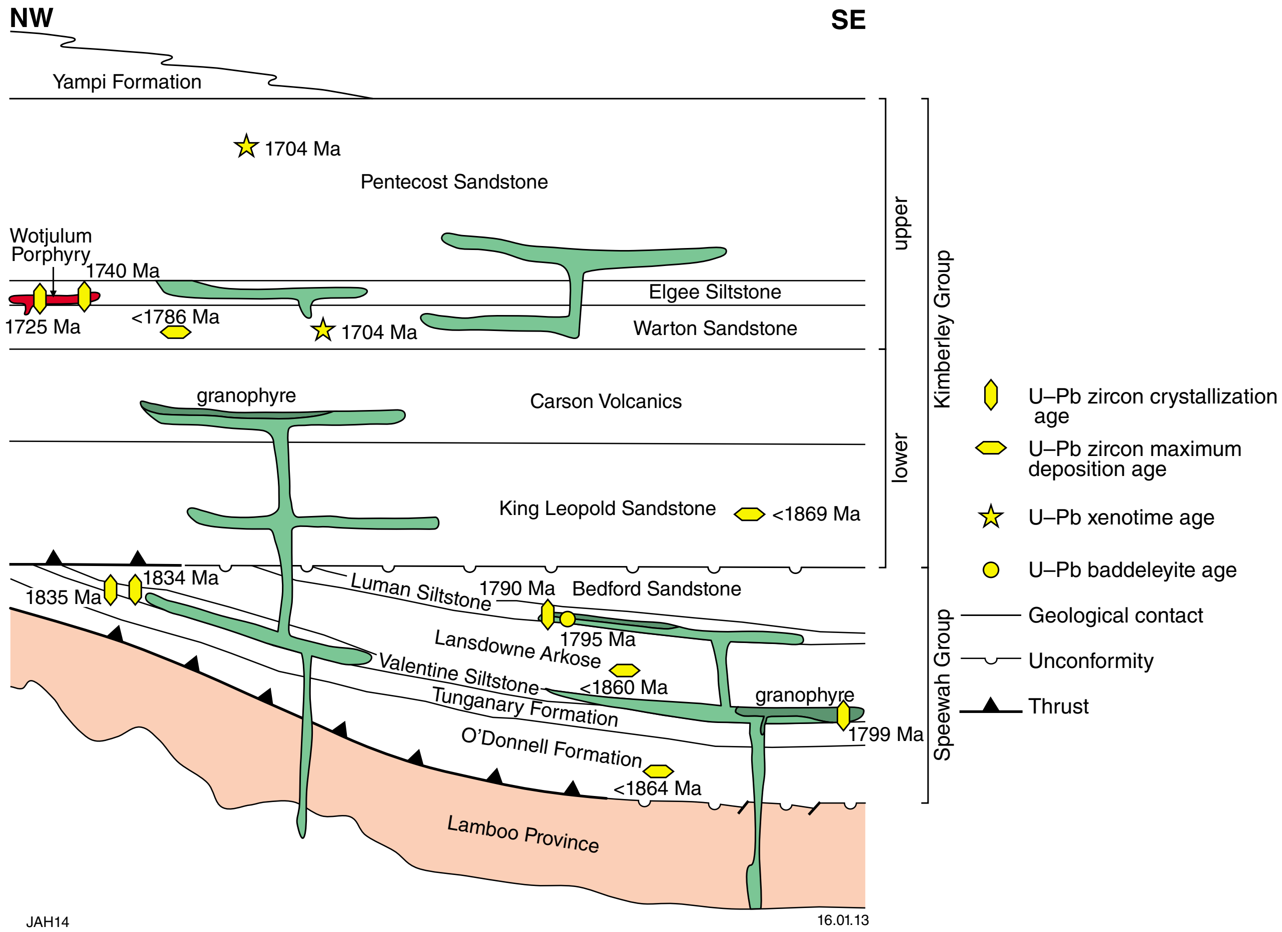

Figure 2. Schematic stratigraphic and structural relationships of the Kimberley and Speewah Groups (from Sheppard et al., 2012). Dolerite sills and dykes are shown in light green; granophyre in dark green.

characterized by distinct Mg numbers, SiO_2, TiO_2, and CaO content (Fig. 3). Correlation between Ni and MgO, and between Cr and MgO, probably reflects fractionation and accumulation of olivine and pyroxene. Ti-rich varieties (c. 4 wt% TiO_2) are characterized by low Mg numbers, with high TiO_2 also correlative with elevated Cu (Fig. 3).

All dolerite and granophyre samples have moderate rare earth element (REE) abundances, which, coupled with a weak negative Nb and Ta anomaly in most samples, indicates assimilation of crustal material during emplacement (see also Elemental Minerals, Fiorentini, 2007). The majority of dolerite samples are slightly (light) LREE-enriched with a weak negative to absent Eu anomaly, consistent with some fractionation of plagioclase. LREE-enriched varieties have strong negative Eu anomalies (Fig. 3). Granophyres show similar REE trends to the LREE-enriched Hart Dolerite, consistent with their formation by fractionation of the same, crustally contaminated source (Fig. 3). The granophyre and main group of the dolerite define a common $^{143}Nd/^{144}Nd$ vs $^{147}Sm/^{144}Nd$ array, also consistent with a common source (Sheppard et al., 2012).

Notably, the few samples of dolerite from the upper part of the Kimberley Group have distinctly high Mg numbers (65–69), low SiO_2 (44–46 wt%), and flatter REE curves with positive Eu anomalies and low total REE abundances. They have strongly radiogenic Nd, consistent with a distinct magmatic source (Sheppard et al., 2012) and may be unrelated to (and younger than) the Hart Dolerite.

Links with basaltic volcanism

The Carson Volcanics in the lower Kimberley Group comprise 10 to several hundred metres thick, regionally extensive, tholeiitic basalt flows intercalated with feldspathic and quartz sandstone and minor mudstone. These flows may have been comagmatic with the Hart Dolerite. The timing of volcanism has not been directly determined, though basalts are locally intruded by the Hart Dolerite, so must have been extruded between 1835 Ma and 1800 Ma. Available geochemical data for the Carson Volcanics are very limited, but show similar major, trace, and REE trends and ranges as the main cluster of Hart Dolerite data (Fig. 3).

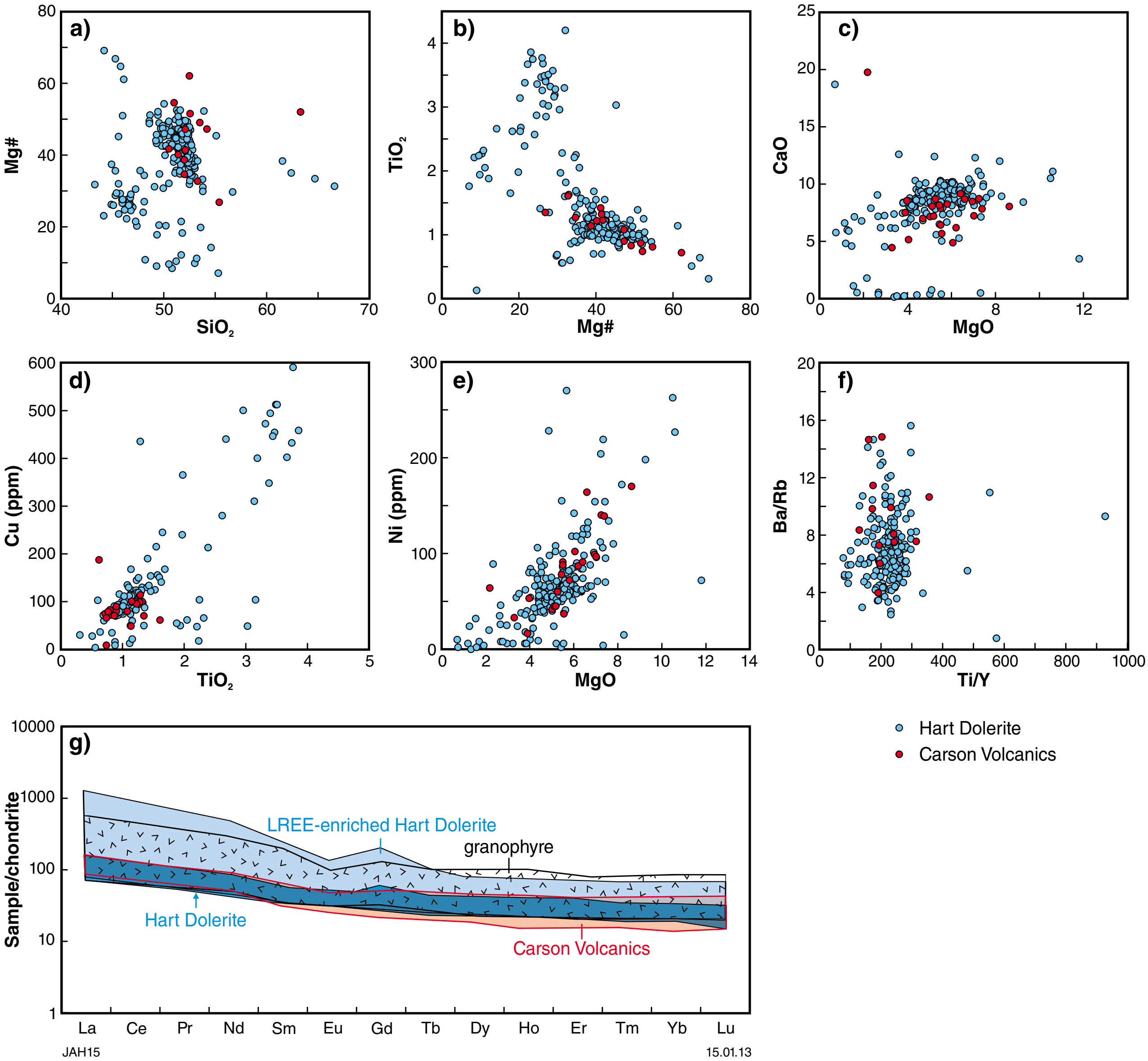

Figure 3. a–f) Selected major and trace element variation diagrams showing the Hart Dolerite (blue) and Carson Volcanics (red); g) Chondrite-normalized REE variation diagram for the Hart Dolerite (dark blue), LREE-enriched Hart Dolerite (light blue), granophyre (stippled) and Carson Volcanics (red).

Tectonic setting

Intrusion of the Hart Dolerite immediately follows 1835–1805 Ma magmatism in the Halls Creek Orogen, associated with c. 1820 Ma collision of the Kimberley Craton with the North Australian Craton. In the same period, a distinct change in provenance — from dominantly Paleoproterozoic to Archean sources — during deposition of the Speewah and Kimberley Groups, is recorded in their detrital zircon age spectra (Kirkland et al., 2010a; Kirkland et al., 2010b; Kirkland et al., 2010c; Kirkland et al., 2010d; Kirkland et al., 2010e; Kirkland et al., 2010f; Wingate et al., 2012). This suggests that the Hart Dolerite (and possibly also the Carson Volcanics) was the product of crustal thinning and mantle upwelling during post-collisional extensional uplift of the Lamboo Province, possibly also associated with plate reorganization during c. 1800 Ma collision of the North and West Australian Cratons (Sheppard et al., 2012).

Mineralization

Large igneous provinces are associated in particular with orthomagmatic Ni–Cu–PGE as well as Au, Cr, and Fe–Ti–V mineralization. Orthomagmatic V–Ti–Fe mineralization (and minor PGE+Au) has been reported from the Speewah Dome in the northeast of the Halls Creek Orogen (e.g. Eves, 2010; Ramsay et al., 2011, 2012). Speewah Mining reported a combined resource estimate of 4 712 Mt @ 0.30% V_2O_5 (using a 0.23% V_2O_5 cut-off). The vanadium is contained in titanomagnetite in a disseminated magnetite gabbroic phase of the Hart Dolerite. This gabbro is characterized by higher magnetic susceptibility and lower SiO_2 (44–50 wt%) and Mg numbers (20–30) than unmineralized Hart Dolerite (Eves et al., 2010; Ramsay et al., 2011, 2012). The transition from a basal high-grade mineralized zone (15–20 m thickness) to lower grade is also marked by a laterally extensive PGE+Au reef (0.1 m) with a maximum PGE+Au content of c. 700 ppb (Ramsay et al., 2012). Fiorentini (2007) notes that samples from near Lansdowne Homestead (Elemental Minerals) have highly depleted PGE concentrations, also consistent with attainment of sulfide saturation in at least some of these dolerite sills.

The largest fluorite deposit in Western Australia is also hosted by the Hart Dolerite and sedimentary rocks of the Speewah Group in the Speewah Dome, where epithermal fluorite–barite– (Cu±Au) veins, associated with breccias and carbonate-rich veins, are related to north-northeast-trending faults associated with the Greenvale Fault (Hassan, 2000). Current drilling has delineated 6.7 Mt @ 24.6% CaF_2 (using a 10% CaF_2 cut-off, Ramsay et al., 2012).

Summary

The limited geochemical data available reveal the tholeiitic nature of the Hart Dolerite and Carson Volcanics, but also indicate diversity in the composition of the Hart Dolerite. This may be the product of multiple distinct magma batches and has, at least locally, been affected by epithermal alteration. The data indicate that the Hart Dolerite assimilated crustal material, increasing the potential for sulfide saturation and PGE mineralization. The recognition that V–Ti–Fe and PGE mineralization is restricted to a particular phase of the Hart Dolerite at Speewah Dome (Eves, 2010; Ramsay et al., 2011, 2012) has potential regional implications for targeting mineralization. The highest-level sills, in the upper Kimberley Group, are geochemically and isotopically distinct and may be part of an unrelated, possibly younger, dolerite; however, more data are required to verify this hypothesis. Additional data are also needed to determine the relationship between the Hart Dolerite and the Carson Volcanics, although limited data show common geochemical and isotopic trends. If the Carson Volcanics represent an extrusive phase of the Hart Dolerite, this significantly increases the volume of mafic magmatism in the Kimberley at 1800 Ma.

References

Eves, A, 2010, Speewah Mining Pty Ltd, Co-funded Government–Industry Drilling Programme 2009–2010 Final Report, Diamond drilling of the Speewah Platiniferous Vanadium Deposits East Kimberley, Western Australia: GSWA Open File Mineral Exploration Report a089887.

Fiorentini, M, 2007, Prospectivity of the Hart Dolerite, Halls Creek Orogen, North Kimberley, Western Australia, *in* Smith, G 2007, E80/3277, E80/3278, E80/3445, E80/3446, E80/3447, E80/3448 Relinquishment Report, Elemental Minerals: GSWA Open File Mineral Exploration Report a076531.

Gellatly, DC, Derrick, GM and Plumb, KA 1970, Proterozoic palaeocurrent directions in the Kimberley region, northwestern Australia: Geological Magazine, v. 107, p. 249–257.

Gellatly, DC, Derrick, GM and Plumb, KA 1975, The geology of the Lansdowne 1:250 000 Sheet Area, Western Australia: Bureau of Mineral Resources, Geology and Geophysics, Report 152, 100p.

Griffin, TJ, Page, RW, Sheppard, S and Tyler, IM 2000, Tectonic implications of Palaeoproterozoic post-collisional, high-K felsic igneous rocks from the Kimberley region of northwestern Australia: Precambrian Research, v. 101, p. 1–23.

Griffin, TJ, Tyler, IM and Playford, PE 1993, Explanatory notes on the Lennard River 1:250 000 geological sheet SE 51-8, Western Australia (3rd edition): Geological Survey of Western Australia, Record 1992/5, 85p.

Hancock, SL and Rutland, RWR 1984, Tectonics of an early Proterozoic geosuture: the Halls Creek Orogenic Sub-province, northern Australia: Journal of Geodynamics, v. 1, p. 387–432.

Hassan, LY 2000, Mineral occurrences and exploration potential of the east Kimberley: Geological Survey of Western Australia, Report data package 74.

Kirkland, CL, Wingate, MTD and Tyler, IM 2010a, 182104: quartz sandstone, Saddler Spring; Geochronology Record 885: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD and Tyler, IM 2010b, 182105: quartz sandstone, The Bench; Geochronology Record 886: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD and Tyler, IM 2010c, 182106: feldspathic sandstone, Mount Vincent; Geochronology Record 887: Geological Survey of Western Australia, 6p.

Kirkland, CL, Wingate, MTD and Tyler, IM 2010d, 182107: quartz sandstone, Inglis Gap; Geochronology Record 888: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD, Tyler, IM and Sheppard, S 2010e, 182101: quartz sandstone, Pentecost River; Geochronology Record 883: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD, Tyler, IM and Sheppard, S 2010f, 182102: quartz sandstone, Bindoola Creek; Geochronology Record 884: Geological Survey of Western Australia, 5p.

Page, RW and Sun, S-S 1994, Evolution of the Kimberley Region, WA and adjacent Proterozoic inliers — new geochronological constraints: Geological Society of Australia; Geoscience Australia — 1994 and Beyond, Abstracts v. 37, p. 332–333.

Plumb, KA and Gemuts, I 1976, Precambrian geology of the Kimberley region, Western Australia: 25th International Geological Congress, Excursion guide 44C, 69p.

Ramsay, R, Eves, A and Andrew, B 2011, Speewah Mining Pty Ltd Exploration Incentive Scheme 2010-2011 Final Report, Diamond drilling of Speewah Dome carbonatites, epithermal fluorite–barite–Cu–Au mineralised veins and the associated potassic-alteration systems, East Kimberley, Western Australia: GSWA Open File Mineral Exploration Report a090163.

Ramsay, R, Eves and A, Andrew, B 2012, Speewah Mining Pty Ltd Exploration Incentive Scheme 2011–2012, Final Report, Diamond drilling of Speewah Dome carbonatites, epithermal fluorite–barite–Cu–Au mineralised veins and the associated potassic-alteration systems, East Kimberley, Western Australia: GSWA Open File Mineral Exploration Report a093375.

Sheppard, S, Griffin, TJ and Tyler, IM 1997, Compilation of whole-rock geochemical data for the King Leopold and Halls Creek Orogens: Geological Survey of Western Australia, Record 1997/4, 138p.

Sheppard, S, Page, RW, Griffin, TJ, Rasmussen, B, Fletcher, IR, Tyler, IM, Kirkland, CL, Wingate, MTD, Hollis, J and Thorne, AM 2012, Geochronological and isotopic constraints on the tectonic setting of the c. 1800 Ma Hart Dolerite and the Kimberley and Speewah Basins, northern Western Australia: Geological Survey of Western Australia, Record 2012/7, 28p.

Thorne, AM, Sheppard, S and Tyler, IM 1999, Lissadell, Western Australia (2nd edition): Geological Survey of Western Australia, 1:250 000 Geological Series Explanatory Notes, 68p.

Wingate, MTD, Kirkland, CL, Sheppard, S and Hollis, JA 2012, 190639: quartz sandstone, Gibb River Road; Geochronology Record 1035: Geological Survey of Western Australia, 5p.

Mineral systems revealed: hyperspectral insights from exploration drilling at Yeneena, Speewah, and Hercules deposits

by

EA Hancock

Introduction

The HyLogging[TM] system is a suite of spectroscopic and imaging tools developed by CSIRO as part of its Minerals Down Under Flagship program, for logging rock-forming and alteration mineralogy in drillcore and chips, (Huntington et al., 2007). It uses rapid reflectance spectroscopy in the visible-near infrared (VNIR), short-wave infrared (SWIR) and — since May 2011 — thermal infrared (TIR) wavelength ranges to identify a broad suite of hydrous and anhydrous minerals. The Geological Survey of Western Australia's HyLogger has been successfully used by academic, government and industry geologists, and has scanned more than 60 000 m of core from 250 holes since commissioning in July 2009.

One of the major avenues for collaboration between GSWA and mineral and petroleum exploration companies is via the Co-funded Drilling Program, one of the pillars of the Western Australia Government's Exploration Incentive Scheme (EIS). Diamond drillcore generated as part of this program is delivered whole or in part to the Perth or Kalgoorlie core libraries, and is then routinely scanned with the HyLogger on a requested priority basis. Processed data are initially provided to the participant companies as graphic images, spreadsheets, and The Spectral Geologist (TSG) software files, and the results discussed with company staff. All data are then released to the public domain upon expiry of the brief confidentiality period.

Three successful EIS drilling projects are chosen here to demonstrate the value of the HyLogger for objective logging of drillcore, hence providing insights into mineral systems.

Yeneena Base Metals project

The Yeneena project is located in the Paterson Province, 40 km southeast of the Nifty copper mine. Mineralization is associated with regionally extensive faults in Neoproterozoic shales and dolomites of the Broadhurst Formation, a constituent of the Yeneena Basin (Bewick et al., 2010).

Encounter Resources Limited (ERL) was a successful recipient of EIS Co-funded Drilling grants in 2009, 2010, and 2012. ERL subsequently announced that this diamond drilling had intersected significant mineralization — a broad zone of hydrothermal copper within dolomitic shale (12 m @ 3.2% Cu) at the BM1 prospect, and a thick zone of zinc mineralization (188 m @ 0.35% Zn) as sphalerite in quartz–siderite–pyrite veins overprinting brecciated argillite/shales at the BM2 prospect. There is also secondary copper enrichment in the oxidation zone of the BM2 prospect.

Six drillholes totalling 1800 m of core were analysed using the GSWA HyLogger at Perth Core Library. Carbonate–quartz–sericite+/–chlorite+/–hematite alteration is widespread throughout fresh argillite/shale host rocks and the clay-rich weathering zone. But some lateral and vertical variations in the distribution of alteration in the area might be useful as vectors to mineralization (Fig. 1):

- The carbonate composition changes from pervasive dolomite at the BM1 prospect, associated with Cu mineralization, to abundant Ca–Mn-rich siderite and calcite veining at the BM2 prospect, associated with Zn (and Pb) mineralization.
- Secondary (supergene) copper in clays and brecciated argillite is accompanied by muscovite, quartz, goethite, and Fe/Mg chlorite. Hypogene copper-rich zones in dolomitic shales at the BM1 prospect are instead associated with phengite alteration.

Speewah Ti–V–PGE–Au–Cu–fluorite project

The Speewah Dome is an anticline structure exposing Paleoproterozoic sediments and intrusive Hart Dolerite in the East Kimberley region. The dome is host to several commodities. Vanadium–titanium–iron mineralization with minor platinum group elements and gold is hosted in vanadiferous titanomagnetite gabbro of the Hart Dolerite. Fluorite occurs with minor copper and gold in epithermal, sub-vertical quartz–fluorite veins up to 10 metres thick and stockworks of smaller veins, along major north- and north-northeast-trending faults cutting Speewah Group sedimentary rocks (King River, Pentecost and Central Faults). Carbonate veins also occur locally along these faults (Ramsay et al., 2011).

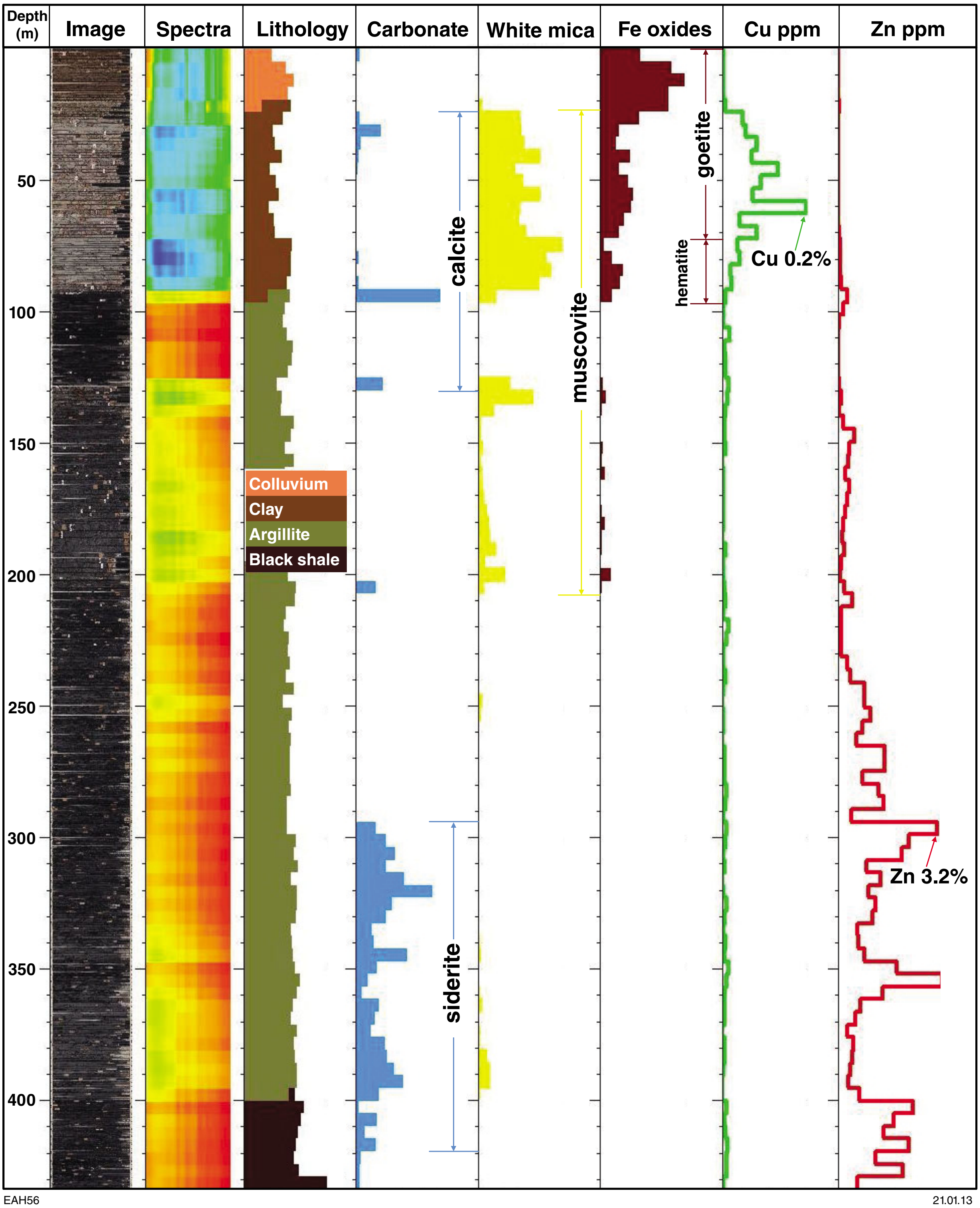

Figure 1. TSG graphic logs for core (drillhole EPT1174) of the BM2 Prospect at the Yeneena: distribution of carbonate, muscovite, Fe oxides, and Cu–Zn mineralization

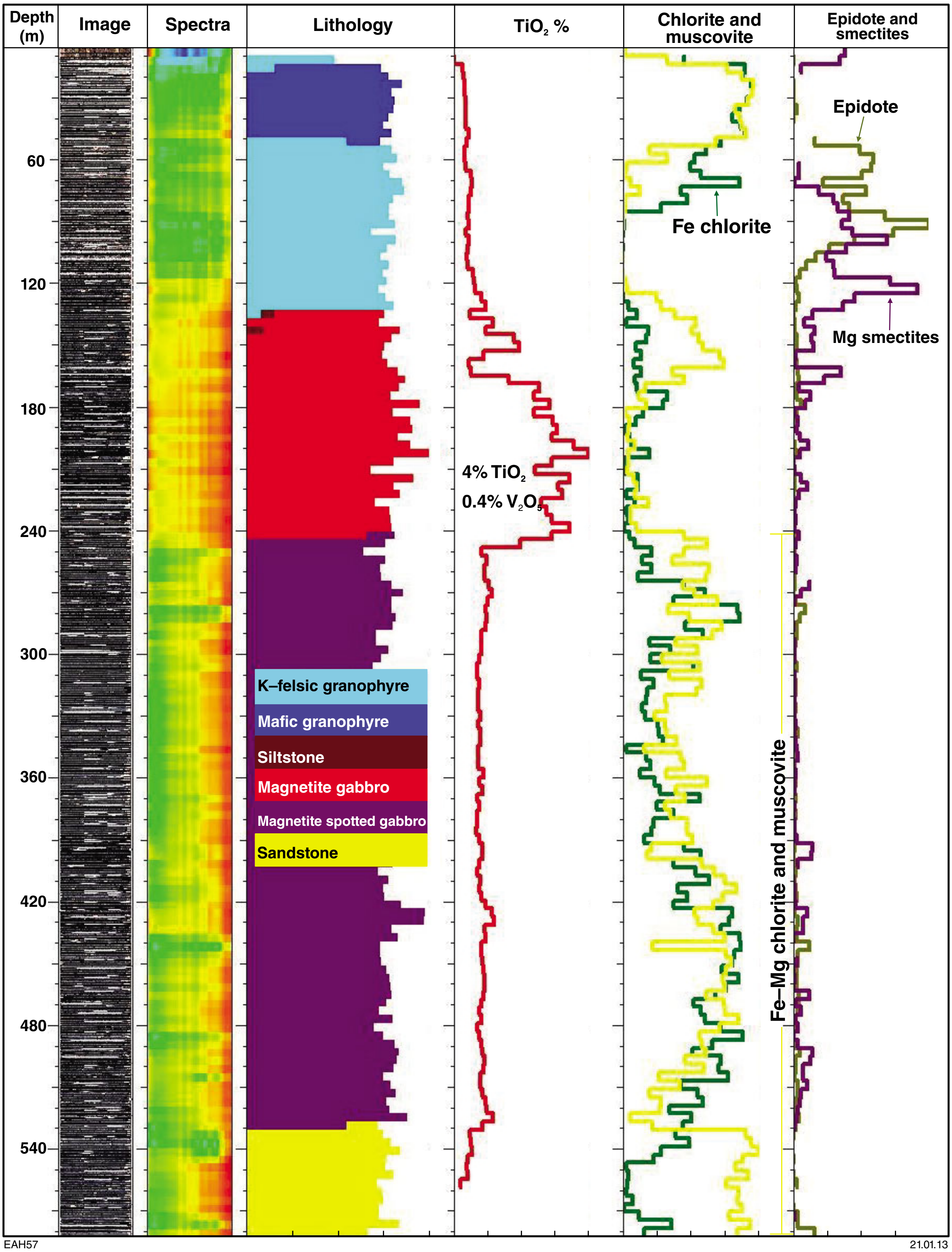

Figure 2. TSG graphic logs for core (drillhole SDH09-01) of the Central V–Ti deposit at Speewah: distribution of lithological units, TiO_2 assays, chlorite–muscovite, and epidote–smectite

Speewah Mining Ltd (a subsidiary of NiPlats Australia Ltd) has been extensively exploring, and in March 2012 announced a significant increase of 32% in the resource of titanium/vanadium grading 0.3% V_2O_5 and 2% Ti at the Central, Buckman, and Red Hill deposits (Ramsay et al., 2012). The company was granted EIS co-funding for drilling in the Speewah Dome in 2009, 2010, and 2011. Twelve of these drillholes (6850 m) targeted fluorite-bearing mineralization at the ABCE deposit along the King River Fault, and several zones along the Central Fault. Another two holes (746 m) tested the Central and the Red Hill vanadium deposits. All drillholes were scanned using the HyLogger.

Non-mineralized gabbro and granophyres of the Hart Dolerite at the Central Ti–V deposit show widespread chlorite–sericite alteration, and minor prehnite and calcite veining (drillhole SDH09-01; Fig. 2). Fe–chlorite and muscovite are relatively abundant in the hanging wall felsic granophyres and footwall magnetite spotted gabbro, but are more uneven distributed and substantially diminished in the mineralized disseminated magnetite gabbro, where abundances of TiO_2 and V_2O_5 are up to 4% and 0.36%, respectively.

The ABCE fluorite deposits are associated with widespread chlorite and sericite alteration in the surrounding gabbro and sandstone units, and the compositions of these minerals reflect the lithological Fe–Mg variations (drillhole SDH10-01). The B Vein prospect has intense potassic alteration throughout the sandstone and gabbro, highlighted also by pink colouration (drillhole SDH11-02). Unusual spectra from secondary epithermal veins in the gabbro of the Wilmott carbonate prospect (drillhole SDH10-05) indicate the presence of datolite, natroapophyllite, and laumontite.

Hercules gold project

The Hercules project is located 60 km northeast of the Tropicana gold deposit. High-grade gold mineralization occurs in steeply dipping quartz veins associated with biotite–pyrite alteration and silicification. It is contained entirely within the Hercules Shear Zone, which lies along the boundary between the Archean Yilgarn Craton and the Proterozoic Albany–Fraser Province. Mineralization and basement gneisses, granites, and minor schists and meta-arenites are buried beneath a thick cover of Permian and Cenozoic sediments (Copping, 2012).

Beadell Resources Ltd announced the discovery of high-grade gold mineralization at the Atlantis and Hercules Prospects in 2011. Seven diamond drillholes (704 m) were submitted to the Perth Core Library for collaborative research, some of which were co-funded as part of Round 3 of the EIS scheme.

Hyperspectral data from the Hercules prospect (drillhole NLD210) show pervasive quartz, albite, and sericite, and subsidiary, patchily distributed chlorite, amphibole, and carbonate (Fig. 3, see page 18). Two principal lithological units can be interpreted in the core based on varying mineral assemblages:

- granite — characterized by abundant quartz, albite and muscovite, lesser chlorite, epidote and dolomite, and no mineralized quartz veins
- gneiss — dominated by quartz, albite and phengitic white mica, lesser amphibole, calcite/siderite, and phlogopite, and mineralized quartz veins.

The decline in major mineral abundances above ca. 50 m depth may reflect the presence of cover rocks, and weathering.

The mineralized intervals appear to be highlighted by visible pyrite, grunerite, and quartz veins and perhaps an increase in chlorite and calcite–siderite abundance. There is only minor dark mica (<2%).

Conclusion

The spectral range of the new generation HyLogger (encompassing VNIR, SWIR and TIR) now allows us to identify a broad suite of hydrous and anhydrous rock-forming minerals in drillcore. This improves our capacity to objectively characterize the type and distribution of rocks, alteration and ore-hosting mineral assemblages, hence defining potential vectors to mineralization. Mineral exploration companies can benefit from this application of hyperspectral data to their mineral systems by becoming involved in the EIS Co-funded Drilling Program or otherwise engaging with GSWA in collaborative research.

References

Bewick, P and James, S 2010, Encounter Resources Ltd, Exploration Incentive Scheme (EIS) Program 2: co-funded government industry drilling program, Final Report, Yeneena Project: GSWA Open File Mineral Exploration Report a087537.

Copping, C 2012, Beadell Resources Limited, Atlantis Prospect EIS report for period 2/08/2011 to 10/12/2011 Tropicana East (Neale E38/1913): GSWA Open File Mineral Exploration Report a092586.

Huntington, JF, Whitbourn, LB, Quigley, MA, Yang, K, Mason, P, Cudahy, TJ, Connor, P, Coward, D, Hewson, R and Phillips, R 2007, Development and implementation of advanced automated core logging technology for enhanced mine feasibility and development in Western Australia: final report — Project M373: CSIRO, Exploration and Mining Report P2007/958, 62p.

Ramsay, R, Eves, A, and Andrew, B 2011, Speewah Mining Pty Ltd, Exploration Incentive Scheme 2010–2011, Final Report: Diamond drilling of Speewah Dome carbonatites, epithermal fluorite–barite–Cu±Au mineralised veins and the associated potassic-alteration systems, East Kimberley, Western Australia: GSWA Open File Mineral Exploration Report a090163.

Ramsay, R, Eves, A and Andrew, B 2012, Speewah Mining Pty Ltd, Exploration Incentive Scheme 2011–2012, Final Report: Diamond drilling of Speewah Dome carbonatites, epithermal fluorite–barite Cu±Au mineralised veins and the associated potassic-alteration systems East Kimberley, Western Australia: GSWA Open File Mineral Exploration Report a093375.

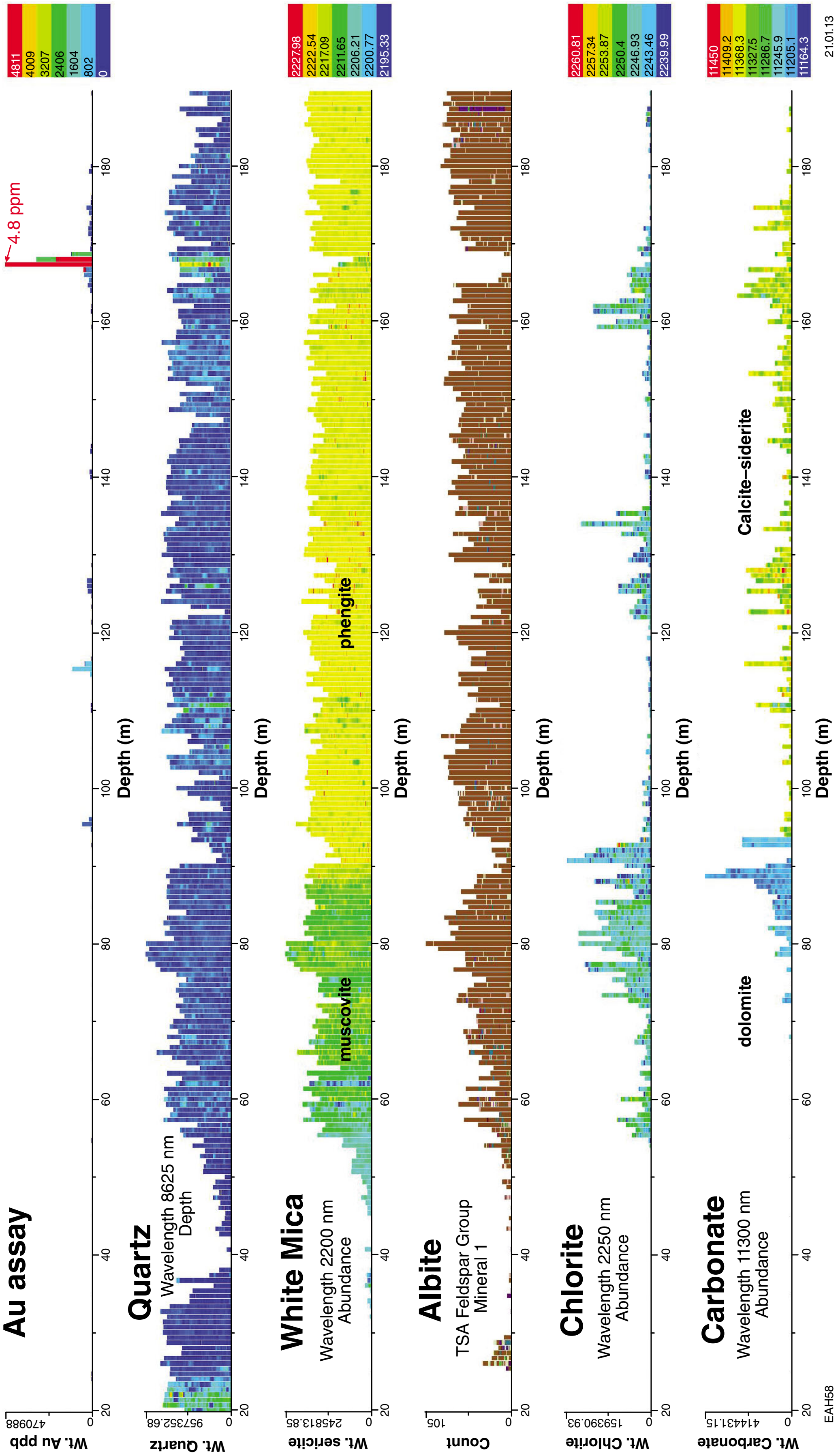

Figure 3. TSG graphic logs for core (drillhole NLD210) of the Hercules: gold assays, distribution of quartz, white mica, albite, chlorites, and carbonate

What the Land Use Geoscience group does for you

by

WR Ormsby

The Land Use Geoscience group within the Geological Survey of Western Australia (GSWA) provides geological advice to government on land use planning, with a strong emphasis on maintaining access for resource exploration and development. Although many people realise the importance of the resource industry to the Western Australian economy, the very success of that industry since 2003 has created its own challenges with respect to land use conflict and public perception of the industry. The rapidly expanding population has led to pressures on land availability for urban development and the industry itself has generated an increased demand for land for industrial purposes and infrastructure, such as railways and ports. At the same time, increasing awareness of the importance of the natural environment and environmental protection has led to more conservation initiatives, such as proposals for formal conservation reserves and requirements for environmental offsets associated with land and resource development.

Sustainability was defined in the 2003 State Sustainability Strategy as ‘meeting the needs of current and future generations through integration of environmental protection, social advancement and economic prosperity’. The Land Use Geoscience group contributes to the future of the resources industry in Western Australia by working with government to minimize impacts arising from land use changes on access for exploration and development of the State’s mineral, basic raw material, petroleum and geothermal energy resources.

The Land Use Geoscience group helps to maintain access for the resources industry in three main ways:

- responding to specific proposals for land tenure changes from other government agencies (referrals)
- interacting with other government agencies to shape land use and policy
- providing resource potential mapping to government and the public.

Changes to land tenure can have serious consequences for land access for resource development. A core part of the group’s activities is responding to about 1 000 referrals for such changes each year. Most changes of land tenure involving Crown land are referred to the Department of Mines and Petroleum (DMP) for ‘clearance’ under Section 16(3) of the *Mining Act 1978*. About 87% of the State is Crown or reserved land, so these changes are the ones most likely to affect mining tenement holders. Under this part of the Mining Act, a change in tenure from Crown land to private land cannot occur without the approval of the Minister for Mines. Furthermore, governments have for many years required the agreement or support of DMP before making other changes to Crown land such as changes to reserve type and the creation of conservation reserves. This is necessary because the Mining Act is very prescriptive about the requirements for carrying out exploration and mining on different types of land tenure. Examples of land changes that can have serious consequences for a mining tenement holder include:

- a change from Crown land to private land. This may mean that the consent of the landowner will in future be required before exploration access is permitted to the upper 30 m of the land
- the creation of class A nature reserves or national parks. This would mean that the approval of both the Minister for Mines and the Minister for Environment are then needed before exploration can take place. The grant of a mining lease within a class A nature reserve or national park would require the approval of both houses of Parliament.

Proposals for land use changes on private land come to the Land Use Geoscience group under a Memorandum of Understanding (MoU) with the Western Australian Planning Commission (WAPC). These cover private land subdivisions and rezoning proposals outside of the main urban areas, mainly in the southwest of the State. Some of these proposals encroach upon areas that have traditionally supplied basic raw materials needed by the construction industry, and higher value deposits such as titanium–zircon and bauxite. Comments from DMP enable the WAPC to avoid future land use conflict by refusing some proposals or by placing a notice on land titles so that future landowners are aware of current or future mining activities.

In all cases, the Land Use Geoscience group assesses the impact that a proposal may have on access for an existing mining or petroleum tenement and, if deemed significant, refers the proposal to the tenement holder for comment. Irrespective of existing mining or petroleum tenure, the group also assesses the resources or prospectivity of the proposal area and the impact that the proposal will have on future access for exploration and mining. The group then makes recommendations accordingly, always with the aim of either avoiding or minimizing the impact on present or future access to mineral, petroleum and geothermal energy resources.

The Land Use Geoscience group interacts with other government agencies to help shape land use decisions and policy when they are in the formative stages. This is normally within the context of an existing government objective, such as conservation. In these cases, the group aims to achieve an overall balanced outcome that ensures resource access and economic considerations are taken into account. A good example of this is the resolution of new nature conservation and mining arrangements for the Mount Manning area, north of Southern Cross, which were jointly announced by the Ministers for Environment and Mines in September 2010. An evidence-based approach involving prospectivity mapping was used to negotiate new land tenure, ranging from a reserve for mining through to a reserve for conservation and mining over much of the prospective banded iron-formation, and a class A nature reserve over a less mineralized part of banded iron-formation. It is intended to apply this evidence-based, exclusive and multiple land use model to the remaining 53 pastoral leases that have been wholly or partly purchased by the Department of Environment and Conservation.

A current example of involvement across government is the Land Use Geoscience group's participation in the Strategic Assessment of the Perth and Peel regions. This project will help shape the future development of Perth to a city of 3.5 million people by taking into account matters of National and State environmental significance. Importantly, for the first time for such an assessment in Australia, DMP, with the Department of Planning, has ensured that the quarry sites required for this development are also taken into account in the assessment. This has implications not only for those companies involved in basic raw material extraction, but also for the entire community and government because it will help to reduce future private and public infrastructure construction costs. Another inevitable aspect of this process will be the identification of suitable land for environmental offset purposes. The Land Use Geoscience group plays an important role in ensuring that access to other resources and unintended impacts upon exploration and mining are also considered in the land offset selection process.

Other areas where the Land Use Geoscience group is currently involved with other parts of government include the conservation proposals associated with the Kimberley Science and Conservation Strategy, Indigenous land use agreements (ILUAs), and 'rangelands reform'.

By providing resource potential maps tailored for land use planners and the public, the Land Use Geoscience group helps to avoid land use conflicts before they occur. This mapping is targeted for those resources most at risk of sterilization in areas of current or future land development. A good example of this is titanium–zircon mineralization mapping, which now covers the entire Swan Coastal Plain from Yallingup in the south to Geraldton in the north. Recently, the group released a series of maps showing regionally significant basic raw materials, again mainly on the Swan Coastal Plain from Yallingup to Lancelin. This mapping has been used within the Strategic Assessment for Perth and Peel and will also form the basis for the new State Planning Policy on basic raw materials. The new policy is anticipated to help protect strategic basic raw material sites from encroachment by urban development.

Mapping of basic raw materials is currently underway around the State's northern regional growth centres in the Pilbara and West Kimberley under a MoU with the Department of Planning. Planners are particularly concerned that there may not be sufficient available fill material close to Karratha and Port Hedland to economically raise the level of development above flood levels. This mapping, which will be published this year, will help identify opportunities for basic raw material extraction close to these population centres.

The group also routinely prepares maps showing appropriate buffers to protect resources from sensitive land uses such as residential development, for State and local governments. Emerging issues that are of concern for resource access include:

- an increasing number of large wind and solar farms
- large plantations for carbon farming and carbon credits
- increasing pressures for more conservation areas, such as within the Great Western Woodland and for more private conservation areas
- joint management conservation areas resulting from Indigenous land use agreements
- the need for land to be set aside as environmental offsets under both State and Commonwealth legislation to facilitate land and resource development
- opposition to unconventional gas exploration and extraction
- pressure from community groups and business interests for 'no mining' areas
- possible inclusion of more areas into national and world heritage listing.

Other than resource access, the Land Use Geoscience group also maintains the State Register of Geoheritage Sites and manages access to eight geoheritage reserves, which cover sites with exceptional geoscientific and geoheritage value. The locations and significance of geoheritage sites are being incorporated into advice provided to other government agencies and are now taken into account within DMP in the environmental approval process. The group also has a role in advising government on other aspects of land use planning such as geohazards and coastal vulnerability studies.

In summary, the Land Use Geoscience group has an important role in informing government on resource access matters, thus ensuring that wherever possible the interests of the resources industry are considered and a proper balance between environmental, social and economic factors is achieved in government decision making.

Temporal controls on gold anomaly formation in regolith: evidence from the east Wongatha area

by

PA Morris

Of the 835 regolith samples from a regional regolith geochemical program carried out in the east Wongatha area (eastern Yilgarn Craton; Morris, 2011), 32 have anomalous Au concentrations (i.e. above 9 parts per billion (ppb) in the <50 µm fraction) following aqua regia digestion. These samples are spatially related to known or inferred bedrock-hosted mineralization. Analysis of Au in 50 of these samples following deionized water digestion showed a positive correlation with aqua regia data, suggesting that gold was fine grained and/or water soluble. Several sites from this program have been resampled to determine if the original Au results could be duplicated, if the fine fraction Au concentration changed with depth, and to collect stratigraphically controlled samples for dating. Data from one site (Sandpit locality) are discussed here.

Site location and sampling

The Sandpit locality is about 10 km east-northeast of the Energy and Minerals Australia exploration camp at Mulga Rock, on the Yilgarn Craton – Gunbarrel Basin margin. Mulga Rock is an unconformity-hosted uranium, gold, base metal and rare earth element (REE) deposit. In this area, extensive sandplain deposits are accompanied by longitudinal sand dunes up to four metres high, with regolith up to 55 m thick. During the regional sampling program, a sample from this locality (GSWA 200069) returned 14 ppb Au (lower level of detection (LLD) = 1 ppb) following aqua regia digestion. During follow-up work, a 1.8 m deep pit was excavated (Fig. 1), and stratigraphically controlled samples were collected for geochemical analysis and dating. Three samples were also collected for geochemistry from auger holes within a 20 m radius of the pit, using the same sampling methodology as the original program.

The sandplain is composed of pale yellow, moderately to poorly sorted, fine- to coarse-grained sand with less common silt and clay, similar to material found in the pit. However, fine-scale sedimentary structures are locally present in the pit, including low-angle cross bedding, and thin mud drapes on some bedding surfaces. Root casts and evidence of bioturbation are also found.

Geochemistry

Gold concentrations from the <50 µm fraction of the three surface samples collected at about 90 cm depth range from 11 to 14 ppb, consistent with the original result of 14 ppb. Samples from the pit range from 7 to 31 ppb Au, and show a gradual increase in concentration with depth. A pit sample collected at 15 cm depth has an Au content of 8 ppb, which is in the background range for the east Wongatha area. Gold determined in all samples following deionized water digestion (LLD = 0.05 ppb) shows a positive correlation with aqua regia data, implying that gold is either microparticulate and/or water soluble. In contrast to Au, other elements, such as Ca, Sr, Fe and As, show no consistent change in concentration with depth, indicating that gold is not controlled by either the carbonate content of regolith, ferruginization, or the presence of sulfides.

Dating

Three samples were collected from the pit for dating. Dating quartz-rich samples can be difficult, as they usually lack phases such as carbon or clay, which can be dated by

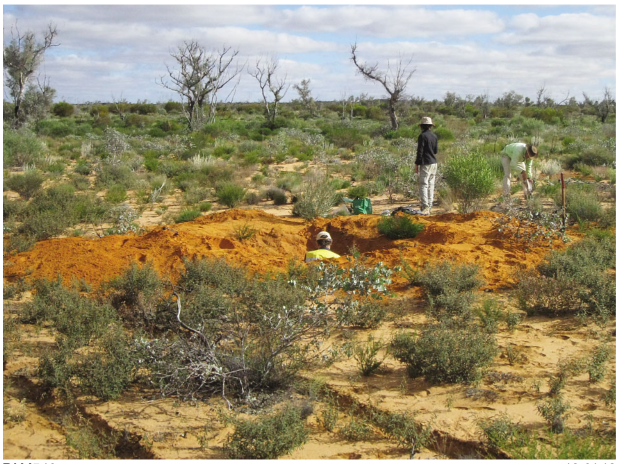

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Figure 1. Pit excavation at the Sandpit locality, east Wongatha area (51J 584048E 6687480 N)

conventional techniques such as ^{14}C or K–Ar. However, optically stimulated luminescence (OSL) is suited to such samples, as the quartz grains themselves can be directly dated by this technique. When quartz is exposed to sunlight, it is 'bleached'; that is, any trapped radiation from the natural decay of radioisotopes is removed. On burial, electrons generated from naturally occurring radiation, as a result of radioactive decay, accumulate within the crystal structure in a regular fashion. These electrons can be released using an intense light source and the resulting measured luminescence is proportional to the time since the sample was last exposed to sunlight (Huntley et al., 1985).

The results of OSL dating of three samples from the Sandpit locality show a decrease in age from 90.9 ± 19.0 ka at 180 cm, to 38.9 ± 19.7 ka at 120 cm, to 6.7 ± 1.8 ka at 60 cm. Corresponding Au concentrations are approximately 31 ppb at 180 cm, 23 ppb at 120 cm, and 20 ppb at 60 cm. If Au is sourced from buried mineralization, the vertical change in concentration with decreasing age is about 1 ppb/7 600 years. The age data indicate that over the same time interval, about 11 cm of sand would have accumulated (average accumulation rate of 1 mm/70 years).

There are few recorded dates on sandplain (i.e. dune substrate), with most dates dealing with dune-forming events. OSL ages reported for the Sandpit locality span the ages recorded for eolian dunes summarized by Sheard et al. (2006) from Birdsville (36 ka), the Strzelecki Desert in South Australia (65 ka), and various localities in Victoria, Western Australia, and New South Wales (21, 36, 43 and 68 ka). Older dune-building ages of 115–135, 145–155, 185–205 and 225–235 ka have been reported from South Australia. Sheard et al. (2006) reported optical ages for six dune samples and one dune substrate sample from two sites in the Great Victoria Desert of western South Australia. The dune ages are older than those typically reported from elsewhere, apart from two younger ages of 71 and 22 ka. A single age for the dune substrate exceeded the limit of OSL dating at >250 ka.

Conclusions

Analysis of fine-fraction Au from a single locality in the east Wongatha area confirms that gold is both fine grained and extractable using weak leaches such as deionised water. Thus, gold is water soluble and/or microparticulate. Geochemical and geochronological data from stratigraphically controlled samples at one locality shows that the concentration of fine-fraction gold decreases with decreasing age and depth. These data indicate a vertical change in Au concentration of about 1 ppb/ 7 600 years, during which time about 11 cm of sand accumulated. Thus, the youngest sand deposits would have had insufficient time to accumulate a gold signature from buried mineralization, which has implications for mineral exploration in areas of thick and transported regolith.

References

Huntley, DJ, Godfrey-Smith, DI and Thewalt, MLW, 1985, Optical dating of sediments: Nature, v. 313, p. 105–107.

Morris, PA, 2011, Fine-fraction gold chemistry of regolith from the East Wongatha area, eastern Yilgarn Craton: Geological Survey of Western Australia, Record 2011/2, p. 24–26.

Sheard, MJ, Lintern, MJ, Prescott, JR and Huntley, DJ, 2006, Great Victoria Desert: new dates for South Australia's oldest desert dune system: MESA Journal, v. 42, p. 15–26.

Western Australia's own super volcano: part of the torturous thermal history of the west Musgrave Province

by

RH Smithies, HM Howard, CL Kirkland, CC Medlin[1], and MTD Wingate

Super volcanoes are the elite of the volcanic fraternity boasting an eruptive history that includes at least one single eruptive volume of ≥450 km^3 (e.g. Sparks et al., 2005). Such events are of considerable geological interest not only because of their great 'wow value' and their potentially devastating impact on life and climate, but also because the high rates of felsic magma production, migration and accumulation required imply some quite specific geological conditions. These in turn tell us about the prevailing thermal structure, thermal evolution and architecture of the crust, revealing fundamentally significant processes that go beyond the crustal scale and that must have a major bearing on regional tectonic evolution.

Volcanic systems like the Snake River Plains – Yellowstone system of North America provide recent examples of super-volcanic eruptions, but evidence in the geological record for ancient examples is rare. However, our work in the west Musgrave region of far eastern Western Australia (Fig. 1) has recently shown that the Mesoproterozoic rhyolitic stratigraphy of the Talbot Sub-basin records one of the world's longest-lived and most voluminous known felsic volcanic systems. It includes several super-eruption units and rates as one of geological history's largest contributions of juvenile felsic material to the continental crust outside of a subduction environment.

The Talbot Sub-basin is a component of the Bentley Basin and the Ngaanyatjarra Rift (Evins et al., 2010), and is filled by rocks of the Bentley Supergroup which include the bimodal volcanic expression of the Mesoproterozoic Giles Event. This event included emplacement of the regional Alcurra Dolerite dyke swarm during the short evolution of the early (c. 1075 Ma) Warakurna Large Igneous Province (LIP) (Wingate et al., 2004). However, mantle-derived mafic volcanism and comagmatic and isotopically equivalent (i.e. juvenile) rhyolitic volcanism preceded and post-dated this LIP, lasting for >30 Ma and potentially for 100 Ma, between at least c.1077 and c.1047 Ma. This volcanism included the formation of a second LIP — in this case a silicic LIP — as a series of voluminous rhyolite deposits interleaved with regional tholeiitic basalt flows (Fig. 2). At least 20 separate rhyolite units (and many more individual eruptive units) form layers of very-high temperature (some >900ºC) ignimbrites, rheomorphic ignimbrites, flows, and sub-volcanic intrusions, with many individual eruptive volumes reflecting super eruptions (e.g. Medlin et al., 2011).

The preserved (i.e. minimum) volume of rhyolite is ~21 840 km^3. Because the isotopic and geochemical evidence indicates that the rhyolites evolved directly from the same parental magmas as the interlayered basalts, we can combine the preserved volume of extruded basalt with the volume of parental basalt required to produce the rhyolite to give a minimum of 227 760 km^3 of mantle-derived magma required to produce the total preserved volcanic pile of the Talbot Sub-basin. Notably, of the total required mantle-derived magma, <5% erupted as basalt. The Talbot Sub-basin is only one of several sub-basins of the Bentley Basin or the Ngaanyatjarra Rift. At least five additional felsic volcanic units are recognized within the other, less well studied, sub-basins. Extrapolating magma volume calculations for the Talbot Sub-basin across the other sub-basins permits speculative estimates of initial mantle-derived magma input volumes of approximately 2.19 x 106 km^3. These calculations ignore the giant layered Giles (G1) intrusions, and associated massive gabbros (G2) of the Warakurna Supersuite, as well as the basalts of the lower Kunmarnara Group into which those intrusions were emplaced, and the rocks of the Warakurna LIP.

Although the Bentley Supergroup is dominated by felsic rocks, its origin is fundamentally basaltic in composition. The abundance of rhyolitic compositions relates directly to high and sustained lower- to mid-crustal temperatures, which permitted extensive compositional evolution of magmas. Likewise, the volume of eruptive rhyolite, and in particular the occurrence of super-eruptive volumes, requires unusual circumstances which also relate directly to the sustained thermal structure of the crust. The thermal state of the lower crust has to allow the 'processing' of enormous volumes of mafic magma and rock to form felsic magmas. Complex zircon age data and zircon age/growth-structure relationships (e.g. rocks intruding or overlying rocks with 'younger' zircon ages; complex zircon growth and dissolution textures) indicate

[1] School of Geosciences, Monash University, Wellington Road, Clayton Victoria 3800

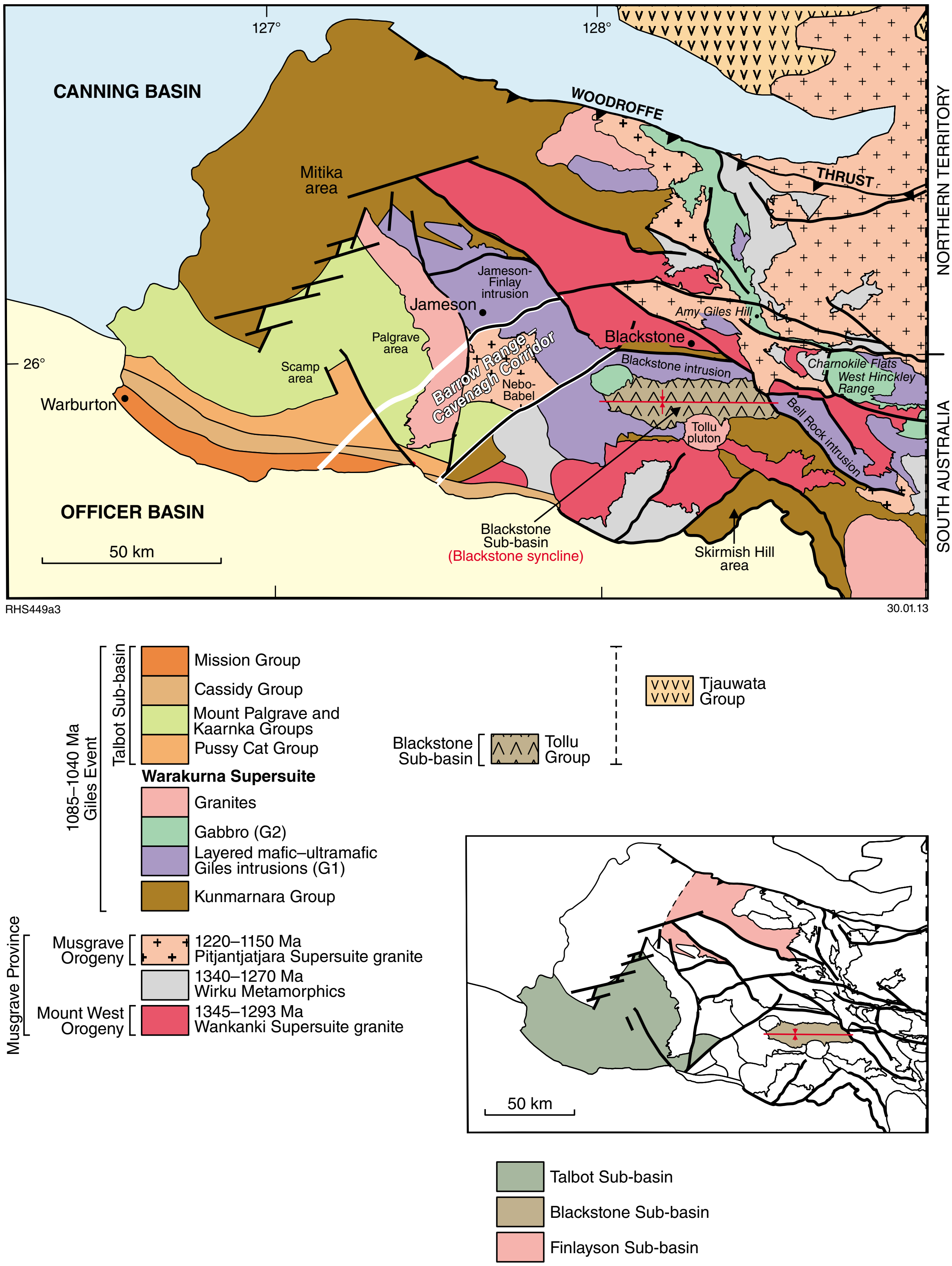


Figure 1. **Simplified interpreted bedrock geology of the west Musgrave Province, showing the preserved extents of the various sub-basins of the Bentley Basin**

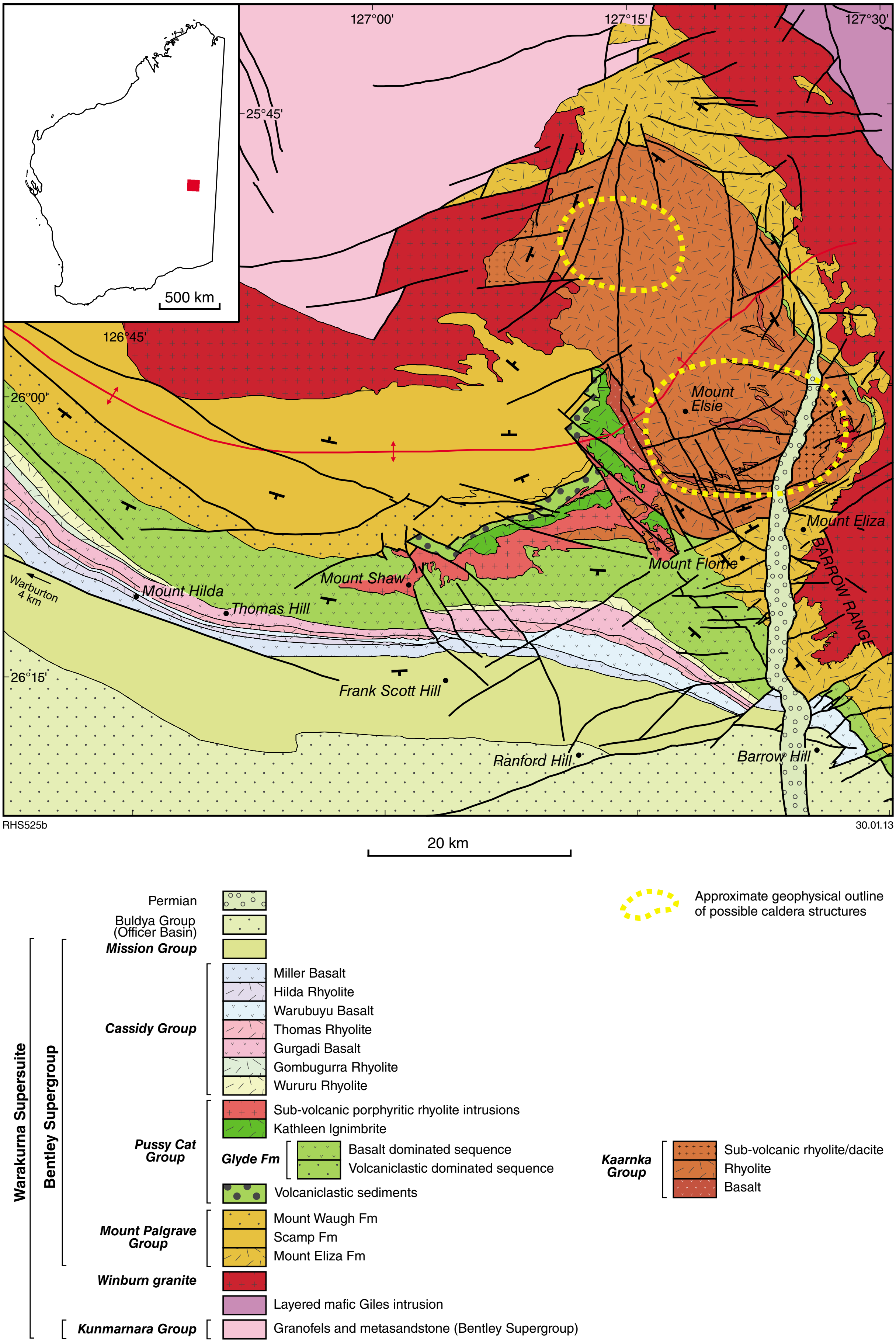


Figure 2. Detailed interpreted bedrock geology of the Talbot Sub-basin

that a significant process in rhyolite eruption involved remobilization of mid- to upper-crustal crystal-mush chambers. Hence, felsic melts generated in the lower crust must have been efficiently transported to higher crustal levels. There, the mid- to upper-crustal chamber level itself must have been unusually hot to maintain the thermal state of accumulating magmas, to reduce the thermal energy required to remobilize crystal mushes and to maximize the melt accumulation efficiency needed to form super-eruptive magma volumes.

The Bentley Supergroup, the Warakurna LIP, the giant layered Giles (G1) intrusions, and the associated massive gabbros (G2) of the Warakurna Supersuite, reflect a huge transfer of mantle material into the crust throughout the Giles Event. This has previously been linked to a mantle plume (e.g. Wingate et al., 2004). In the case of the Talbot Sub-basin, however, the >30 Ma duration of mantle-derived magmatism at a single isolated region is difficult to relate to a mantle plume. Even a conservative drift rate of 2 cm per year removes the crustal plate by >600 km from an initial stationary asthenospheric plume source.

The key to the evolution of the Giles Event is in the thermal structure established during the preceding Musgrave Orogeny. A uniquely defining theme in the geological evolution of the Musgrave Province is sustained and highly anomalous heat flow. The evolution of the Musgrave Orogeny, between c. 1220 and 1150–1120 Ma, was strongly controlled by the crustal architecture established during the earlier amalgamation of Proterozoic Australia. The anomalously thin crust developed in the Musgrave region during the Musgrave Orogeny coincided with one of the world's largest and longest-lived (c. 70–100 Ma) belts of mid-crustal ultra-high temperature (UHT) (i.e. > 900ºC) conditions. Evidence for UHT conditions stops at ~1120 Ma. However, even if the decline of mid-crustal temperatures below UHT conditions at c.1120 Ma indicates that the thermal driver of the Musgrave Orogeny had waned, rates of thermal diffusion are such that the geothermal gradient throughout the Giles Event would have been significantly higher than normal (e.g. Currie and Hyndman, 2006) simply as a result of the Musgrave Orogeny. Nevertheless, the geochronological record shows that zircon-forming events did continue between c. 1120 and c. 1090 Ma and the further, virtually continuous and voluminous, flux of basalt and isotopically juvenile rhyolite throughout the Giles Event shows that the Musgrave region continued to focus mantle heat and magma until at least 1047 Ma.

The simplest suggestion is that the torturous thermal evolution of this region has a common long-lived cause. The evolution of the Giles Event is likely linked to the earlier thermal structure established during the Musgrave Orogeny and perpetuated through regular continued mantle inputs throughout the Giles Event. The underlying cause is tectonics — the crustal architecture established as cratonic elements of Proterozoic Australia amalgamated, as well as the ongoing far-field effects of tectonic processes operating along the margins of the combined craton.

References

Currie, CA and Hyndman, RD 2006, The thermal structure of subduction zone back arcs: Journal of Geophysical Research, v. 111, B08404, doi:10.1029/2005JB004024.

Evins, PM, Smithies, RH, Howard, HM, Kirkland, CL, Wingate, MTD and Bodorkos, S 2010, Devil in the detail: the 1150–1000 Ma magmatic and structural evolution of the Ngaanyatjarra Rift, west Musgrave Province, central Australia: Precambrian Research, v. 183, p. 572–588.

Medlin, CC, Cas, RAF, Werner, M and Smithies, RH 2011, An extremely thick 1.1 Ga rheomorphic ignimbrite in the Pussy Cat Group: implications for eruption style and setting in the Musgrave Province, central Australia: Presentation and Abstract for the XXV IUGG General Assembly, Melbourne, Australia. Presentation available, IAVCEI-V10, <www.iugg2011.com/delegates.asp>.

Sparks, RSF, Self, S and Working Group 2005, Super-eruptions: global effects and future threats: Report, Geological Society of London Working Group (2nd edition), Geological Society, London, 24p.

Wingate, MTD, Pirajno, F and Morris, PA 2004, Warakurna large igneous province: a new Mesoproterozoic large igneous province in west-central Australia: Geology, v. 32, p. 105–108.

The application of oxygen isotopes of zircon in regional mapping: an example from Paleoproterozoic granites in the Gascoyne Province

by

SP Johnson, FJ Korhonen, CL Kirkland, JB Cliff[1], EA Belousova[2], S Sheppard[3], R Murphy[2], and MTD Wingate

The timing and style of crust formation or reworking are important factors in understanding regional-scale crustal evolution and architecture, which in turn provide important constraints on mineral systems (e.g. McCuaig et al., 2010; Joly et al., 2012). Since 2008, GSWA has routinely collected high-precision, Lu–Hf isotopic data (by Laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS)) in situ from dated zircon crystals. With the installation of the Cameca IMS 1280 multi-collector ion microprobe at the Centre for Microscopy, Characterisation and Analysis (CMCA) at The University of Western Australia, the measurement of oxygen isotopes from the same dated and isotopically characterized zircon crystals is now possible. The high-spatial resolutions (typically <25 µm diameter and 2 µm depth (SIMS) to 50 µm diameter and depth (LA-ICPMS)) of each of the analysis techniques allows the measurement of U–Pb, $\delta^{18}O$ and Lu–Hf from the same discrete zircon domain in a single crystal.

The ratio of measured ^{18}O to ^{16}O (reported in $\delta^{18}O$ notation, in per mil variations relative to Vienna standard mean ocean water [VSMOW]) in a zircon crystal can be used to determine whether the parental magma from which the zircon crystallized contained a contribution from near-surface rocks, since zircons in equilibrium with mantle-derived melts have specific $\delta^{18}O$ values in the range of 5.3 ± 0.6 ‰ (Valley, 2003). Incorporation of rocks or minerals altered by low-temperature near-surface processes into the magma (e.g. assimilation of country rocks, or generation of the melt from a sedimentary precursor) may dramatically increase the $\delta^{18}O$ values of the melt and thus the crystallizing zircon (Peck et al., 2001). Combined with corresponding Hf data, these data may provide information on a) magma sources, b) physio-chemical conditions, and, c) when combined with age information, processes operating during magma generation and pluton construction (e.g. Kemp et al., 2007). These time-integrated isotopic datasets provide an increasingly complete record of crustal evolution at a variety of scales, greatly increasing our ability to resolve the regional-scale crustal architecture.

1 Centre for Microscopy, Characterisation and Analysis, The University of Western Australia, 35 Stirling Highway, Crawley WA 6009

2 Centre for Geochemical Evolution and Metallogeny of Continents (GEMOC), Department of Earth and Planetary Sciences, Macquarie University, Sydney, NSW 2109

3 Brockman Mining Australia Pty Ltd, 1/117 Stirling Highway, Nedlands WA 6009

Pluton and batholith construction

Irrespective of tectonic setting, the construction of individual plutons and batholiths has been shown to be a continual and cyclical process that operates at all scales (de Saint Blanquat et al., 2011). A hand specimen sample of a plutonic rock can be considered representative of an individual magma batch, formed during the incremental process of pulsed injection into a magma chamber. Thus routine whole-rock analytical techniques — such as major and trace element and isotope chemistry — provide only an average ‘snapshot’ of all the individual components within that magma batch. Depending on the time scales of crystallization, individual major rock-forming mineral phases such as feldspar or amphibole, or accessory phases such as zircon, may record information related to processes that operate on much smaller time divisions, including those of magmatic pulsation. Thus, chemical or isotopic zonation of these crystals may reveal:

- temporal variations in the source(s) of the magma (e.g. variability of asthenospheric or lithospheric components)
- variable contamination via emplacement-related processes including pluton–wallrock interaction
- mixing of distinct magma batches
- various magma chamber processes, including fractional crystallization and crystal settling.

Additionally, the isotopic composition of any xenocrystic zircon can provide information on the country rocks which the magmas interacted with or were intruded. Data from many different magma batches (individual rocks) can yield important information on physio-chemical processes at time scales associated with pluton and batholith construction, which are vital for understanding the interplay between magmatism and regional-scale tectonism.

Paleoproterozoic batholiths in the Gascoyne Province

Following assembly of the West Australian Craton (the suturing of the Pilbara and Yilgarn Cratons with the Glenburgh Terrane of the Gascoyne Province) during the 2005–1950 Ma Glenburgh Orogeny, the Gascoyne Province has been subject to more than one billion years of intracratonic reworking (Sheppard et al., 2010). Voluminous felsic magmatism took place during two spatially and temporally distinct orogenic episodes, the 1820–1770 Ma Capricorn Orogeny and the 1680–1620 Ma Mangaroon Orogeny. During the Capricorn Orogeny, the Moorarie Supersuite was emplaced across the entire province, forming isolated plutons in the north — the Northern Gascoyne plutons — and two batholiths — the Minnie Creek and Landor batholiths — in the central and southern parts (Fig. 1a). During the Mangaroon Orogeny, the Durlacher Supersuite was emplaced into structurally bound corridors, the largest of which contains the Davey Well batholith in the central part of the province (Fig. 1a).

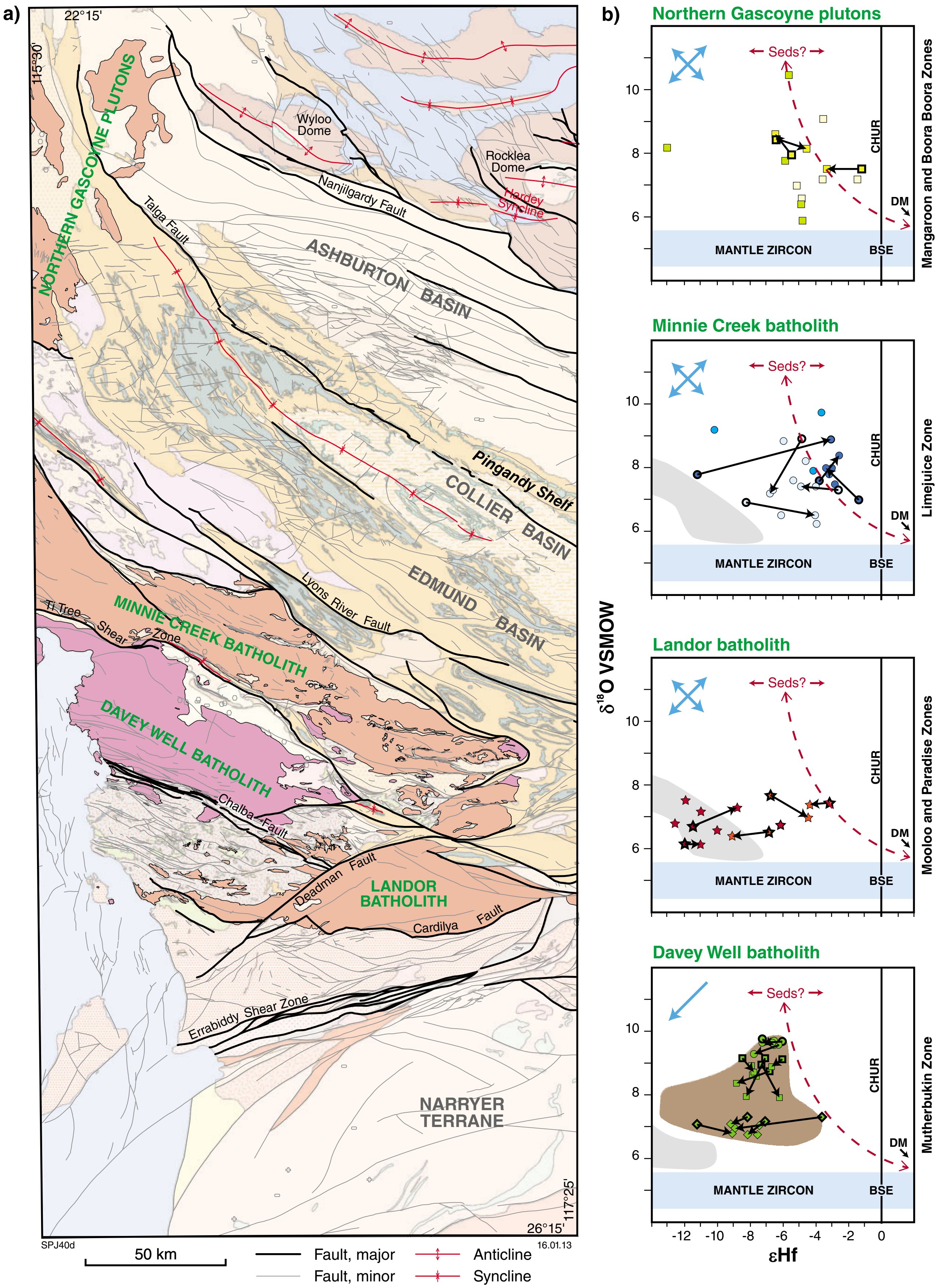
The whole-rock geochemical compositions of granites from both supersuites are remarkably similar, lacking any distinct features that might distinguish their tectonic setting or any physio-chemical processes that might have accompanied intrusion. However, the Lu–Hf and $\delta^{18}O$ isotopic compositions of the magmatic zircon crystals have revealed significant differences in the processes which operated during the formation and emplacement of the Moorarie and Durlacher Supersuites.

Magmatic zircon from the Moorarie Supersuite shows highly variable Lu–Hf and $\delta^{18}O$ compositions which indicate interaction between three distinct isotopic components — depleted mantle, surficial sediments and an old (c. 2700 Ma) radiogenic basement (Fig. 1b) — in a highly dynamic magmatic system dominated by mixing of magma pulses of different composition, and significant pluton–wallrock interaction. Depleted mantle appears to be the major source component for all the granites (Fig. 1b), although the isotopic composition of the Landor batholith is dominated by c. 2700 Ma radiogenic basement of the Glenburgh Terrane, which is not evident north of the Lyons River Fault in the Northern Gascoyne plutons (Fig. 1b). The Minnie Creek batholith and Northern Gascoyne plutons show evidence for mixing and assimilation of low-grade metasedimentary rocks, presumably by pluton–wallrock processes, indicating that the magmas were emplaced into the upper crust. This isotopic feature is not evident in the Landor batholith, implying that it was emplaced within the mid-crust.

The Davey Well batholith of the Durlacher Supersuite shows more uniform inter- and intragrain Lu–Hf and $\delta^{18}O$ isotopic compositions, indicating a source similar in isotopic composition to the Minnie Creek batholith of the Moorarie Supersuite (tan-coloured field in Fig. 1b), and may have lacked a significant depleted mantle component. Minor intragrain isotopic variations consistently suggest melting and mixing of c. 2700 Ma radiogenic basement into the main magma. The absence of a major upper crustal component also suggests emplacement of the batholith into the mid-crust.

In situ zircon isotopic data from these temporally and spatially distinct plutons and batholiths highlight important differences in the sources of the melt, melt evolution and emplacement mechanisms that are not evident at the magma batch – hand specimen scale, and which provide critical constraints on regional-scale crustal evolution and architecture. The 1820–1775 Ma Moorarie Supersuite is dominated by both mantle and upper crustal components, having been emplaced within the mid- to upper crust. The depleted mantle source, highly dynamic physio-chemical magmatic processes and high level of emplacement, particularly of the Northern Gascoyne plutons and Minnie Creek batholith, make these intrusions more prospective as they provide a pathway, and enrichment mechanism, for mantle-derived metals to be transported to the upper crust. These intrusions host known mineralization, including tungsten-bearing skarns in the northern Gascoyne Province (Davies, 1988) and disseminated and vein-hosted molybdenum at Minnie Springs (Pirajno et al., 2008). In contrast, the 1680–1620 Ma Durlacher Supersuite appears to have been generated without a significant mantle component by the melting and recycling of pre-existing crust, making this intrusion less prospective for base metals, gold and rare earth elements.

Figure 1. (facing page) a) Simplified gological map of the western Capricorn Orogen showing the distribution of batholiths and plutons associated with the 1820–1775 Moorarie Supersuite (pale pink) and 1680–1620 Ma Durlacher Supersuite (pale purple) in the Gascoyne Province (after Johnson et al., 2011); b) Hf and $\delta^{18}O$ isotope compositions of magmatic zircon from the Gascoyne Province plutons and batholiths. Black arrows show the change in isotopic composition from the centre to the edges of magmatic grains, representing the evolution of magma batches. The light grey shaded fields represent the isotopic composition of c. 2700 Ma radiogenic basement of the Glenburgh Terrane, calculated from inherited zircon xenocrysts within the plutonic rocks. The tan field in the Davey Well batholith plot represents the isotopic composition of the Minnie Creek batholith at c. 1650 Ma. Light blue arrows in all plots show the trend in isotopic evolution for the batholith or pluton. The dotted red line shows a theoretical contamination line between depleted mantle-derived melts and surficial sediments.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22°15'
115°30'
NORTHERN GASCOYNE PLUTONS
Wyloo Dome
Rocklea Dome
Hardey Syncline
Nanjilgardy Fault
Talga Fault
ASHBURTON BASIN
Pingandy Shelf
COLLIER BASIN
EDMUND BASIN
Lyons River Fault
Ti Tree Shear Zone
MINNIE CREEK BATHOLITH
DAVEY WELL BATHOLITH
Chalba Fault
Deadman Fault
LANDOR BATHOLITH
Cardilya Fault
Errabiddy Shear Zone
NARRYER TERRANE
26°15'
117°25'
SPJ40d
16.01.13
50 km
Fault, major
Fault, minor
Anticline
Syncline
b)
Northern Gascoyne plutons
Minnie Creek batholith
Landor batholith
Davey Well batholith
Seds?
CHUR
DM
MANTLE ZIRCON
BSE
Mangaroon and Boora Boora Zones
Limejuice Zone
Mooloo and Paradise Zones
Mutherbukin Zone
δ18O VSMOW
εHf
10
8
6
-12
-10
-8
-6
-4
-2
0

References

Davies, BM 1998, Proterozoic zoned tungsten-bearing skarns and associated intrusives of the northwest Gascoyne Complex, Western Australia: Geological Survey of Western Australia, Report 53, 54p.

de Saint Blanquat, M, Hosman, E, Habert, G, Morgan, S, Vanderhaeghe, O, Law, R and Tikoff, B 2011, Multiscale magmatic cyclicity, duration of pluton construction, and the paradoxical relationship between tectonism and plutonism in continental arcs: Tectonophysics, v. 500, p. 20–33.

Johnson, SP, Thorne, AM and Tyler, IM (eds) 2011, Capricorn Orogen seismic and magnetotelluric (MT) workshop 2011: extended abstracts: Geological Survey of Western Australia, Record 2011/25, 120p.

Joly, A, Aitken, ARA, Dentith, M, Porwal, AK and Smithies, RH 2012, Mineral prospectivity analysis of the West Musgrave Province: GSWA Report, Geological Survey of Western Australia, Perth.

Kemp, AIS, Hawkesworth, CJ, Foster, GL, Paterson, BA, Woodhead, JD, Hergt, JM, Gray, CM and Whitehouse, MJ 2007, Magmatic and crustal differentiation history of granitic rocks from Hf-O isotopes in zircon: Science, v. 315, p. 980–983.

McCuaig, TC, Beresford, S and Hronsky, J 2010, Translating the mineral systems approach into an effective exploration targeting system: Ore Geology Reviews, v. 38, p. 128–138.

Peck WH, Valley JW, Wilde SA and Graham CM 2001, Oxygen isotope ratios and rare earth elements in 3.3 to 4.4 Ga zircons: ion microprobe evidence for high $\delta^{18}O$ continental crust and oceans in the Early Archean: Geochimica et Cosmochimica Acta, v. 64, p. 4215–4229.

Pirajno, F, Sheppard, S, Groenewald, PB and Johnson, SP 2008, Mineral systems in the Gascoyne Complex, Western Australia, in GSWA 2008 extended abstracts: promoting the prospectivity of Western Australia: Geological Survey of Western Australia, Record 2008/2, p. 4–7.

Sheppard, S, Johnson, SP, Wingate, MTD, Kirkland, CL and Pirajno, F 2010, Explanatory Notes for the Gascoyne Province: Geological Survey of Western Australia, Perth, Western Australia, 336p.

Valley, JW 2003, Oxygen isotopes in zircon: Reviews in Mineralogy and Geochemistry, v. 53, p. 343–385.

Not-so-suspect terranes of the Rudall Province

by

CL Kirkland, SP Johnson, RH Smithies, JA Hollis, MTD Wingate, AH Hickman, IM Tyler, SG Tessalina, JB Cliff, EA Belousova, and R Murphy

Time-constrained isotopic data permit the evaluation of tectonic processes, including continental collision, rifting, and the origin of terrane fragments. The Rudall Province, in the Paterson Orogen, is part of the West Australian Craton (WAC) and now lies to the east of the Archean Pilbara Craton and overlying Fortescue and Hamersley Basins (Fig. 1). Within the region, a range of mineral systems exists, including Au–Cu (Telfer), Zn–Pb (Warrabarty), Cu (Maroochydore) and U (Kintyre). Thus, constraints on basement geology from this area have important implications for understanding mineralizing systems. The Rudall Province is divided into three lithotectonic elements, known as the Talbot, Connaughton, and Tabletop Terranes. The southern two terranes (Talbot and Connaughton) were affected by magmatism related to the 1800–1765 Ma Yapungku Orogeny.

In the Rudall Province, deformation, metamorphism, and magmatism during the Yapungku Orogeny have been interpreted as responses to Paleoproterozoic collision between the Pilbara Craton and a continent of unknown origin to the northeast (Hickman et al., 1994). In this scenario, the c. 1.8 Ga metasedimentary succession of the Rudall Province was deposited on the eastern margin of the Pilbara Craton. This interpretation was subsequently modified to suggest collision and amalgamation of the North and West Australian Cratons (Bagas and Smithies, 1997; Tyler, 2000; Li et al., 2008) during the Yapungku Orogeny. Alternatively, the event has been interpreted as a consequence of accretional processes that sutured exotic terranes to the Pilbara Craton margin (Bagas, 2004). This contribution presents time-constrained Sm–Nd, Lu–Hf, and oxygen isotope analyses to evaluate whether terranes within the Rudall Province are:

1. (para)autochthonous and related to the thickening of a Proterozoic margin of the Pilbara Craton, or
2. exotic entities that:
   a) formed part of the opposing North Australian Craton (NAC) margin, being juxtaposed with the WAC during collisional orogenesis, or
   b) have an entirely exotic source (e.g. the northern Gawler and Musgrave regions) and were juxtaposed against the WAC margin during accretionary or collisional orogenesis.

Isotopic signature of the Talbot and Connaughton Terranes

The Talbot Terrane occupies the northern and western parts of the Rudall Province, and consists of multiple deformed and metamorphosed supracrustal and felsic intrusive rocks (Bagas and Smithies, 1997; Hickman and Bagas, 1999b; 1999a). The depositional setting of the siliciclastic rocks has been interpreted as a deltaic to moderately deepwater marine basin on the southeastern margin of the Pilbara Craton (Hickman et al., 1994). The Connaughton Terrane, within the southeastern part of the province, comprises a series of poorly dated metavolcanic and metasedimentary rocks, and contains a significantly higher proportion of amphibolite than the Talbot Terrane (Bagas and Smithies, 1998). The amphibolite is interlayered with banded iron-formation, quartzite, pelitic metasedimentary rocks, chert, and ultramafic rocks (Hickman et al., 1994). In a situation similar to the Talbot Terrane, basement rocks are not exposed. Importantly, all rocks within the Connaughton Terrane were metamorphosed at upper amphibolite to granulite facies conditions during the Yapungku Orogeny (Smithies and Bagas, 1997).

The Talbot and Connaughton Terranes are dominated by granitic rocks of the 1800–1765 Ma Kalkan Supersuite (Fig. 2). In the Talbot Terrane, magmatic zircons from these granites show a range of isotopically evolved compositions, with Hf model ages (TDM2) between 3.6 and 2.6 Ga (Fig. 2). Inherited zircons in the Talbot Terrane and magmatic zircons in the Connaughton Terrane indicate crustal residence ages of 2.8 – 2.4 Ga, with strong isotopic and, in the case of inheritance, temporal affinity to detritus that originated from Capricorn Orogen basement sources (e.g. 2005–1970 Ma Dalgaringa Supersuite of the Glenburgh Terrane). Furthermore, the most evolved magmatic zircons (those with εHf < –17), from the Talbot Terrane, are also comparable with the isotopic composition of the East Pilbara Terrane, including granitic rocks of the Bridget Suite, which has a clear association with the Pilbara Craton (Fig. 3). The c. 1800 Ma Bridget Suite consists of calc-alkaline, lamprophyric syenite to monzodiorite (Budd et al., 2002), forming a north-northwest-trending belt within the East Pilbara Terrane, adjacent and subparallel to the Paterson Orogen.

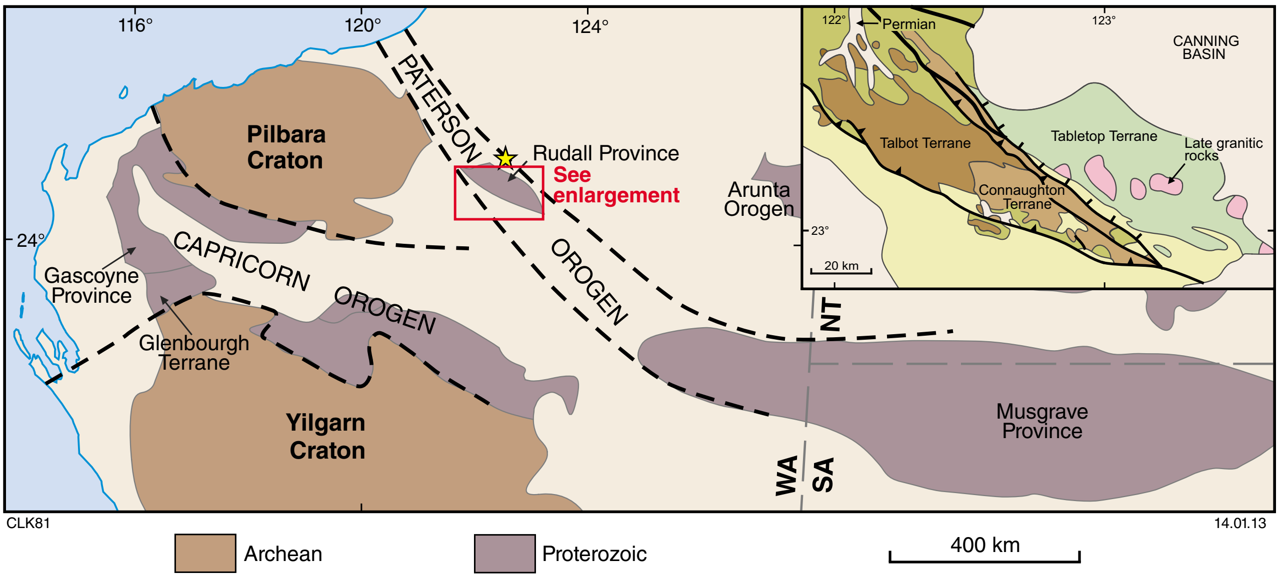


Figure 1. Location of the Rudall Province relative to Proterozoic orogens and Archean cratons in west-central Australia (modified after Bagas and Smithies, 1997; Smithies and Bagas, 1997). The inset shows the location of the three terranes of the Rudall Province. The yellow star is the Telfer gold deposit.

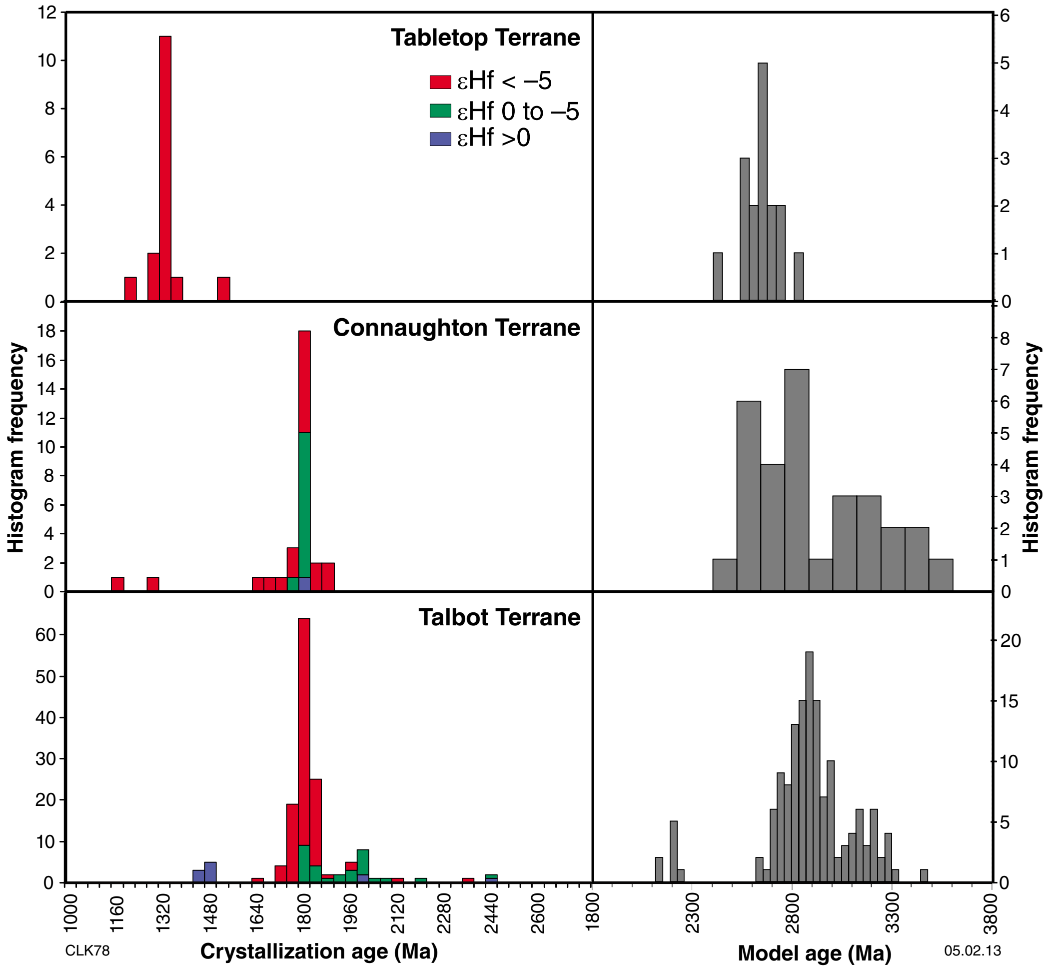
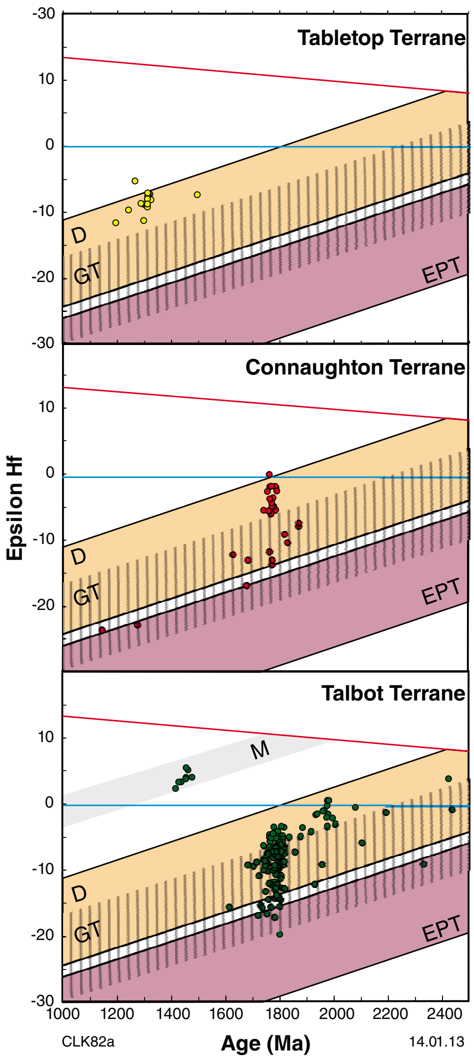


Figure 2. U–Pb magmatic crystallization ages (left) and two-stage Hf model ages (right) for zircons from Rudall Province magmatic rocks. Crystallization age data are colour-coded according to epsilon-Hf value. Although the timing of magmatism in the Tabletop Terrane is different to that in the Connaughton and Talbot Terranes, the Hf isotopic signatures of all three are broadly similar, implying that each originated from the same, or a similar, crustal source.

In the Connaughton Terrane, magmatic zircons of the Kalkan Supersuite granites are, on average, less evolved than those in the Talbot Terrane, and lie entirely within the isotopic envelope of the Glenburgh Terrane of the Capricorn Orogen. This implies less influence of a highly evolved basement (i.e. an East Pilbara Terrane component), indicating that East Pilbara Terrane basement is thinner in the Connaughton Terrane.

The broad similarity in isotopic composition and age of inherited zircons within granitic rocks of the Kalkan Supersuite in both Talbot and Connaughton Terranes, with detrital zircons in sedimentary rocks in the Capricorn Orogen, suggest that the Kalkan Supersuite granites assimilated variable degrees of sedimentary material similar to that in the Capricorn Orogen during emplacement into the upper crust (Fig. 3). Furthermore, sedimentary rocks of the eastern association of the Talbot Terrane were deposited at c. 1800 Ma during the same time as those in the Capricorn Orogen (e.g. Ashburton and Blair Basins), implying the development of a single large basin — or series of smaller, linked basins — around the southern and eastern margins of the Pilbara Craton during the late Paleoproterozoic.



Isotopic signature of the Tabletop Terrane

The Tabletop Terrane has traditionally been regarded as a far-travelled block with crust unique to the other components of the Rudall Province. This inference was based on the similar age of magmatism in this terrane to that in the northern Gawler and Musgrave regions. U–Pb geochronology in this terrane indicates magmatism at 1590–1550 Ma (Maidment et al., in prep.) and at c. 1300 Ma. The magmatic zircons from a c. 1300 Ma granite of the Tabletop Terrane are dominated by mildly evolved compositions with model ages of 2.6 Ga (Fig. 3), that are isotopically similar to the other Rudall Terranes. The similarity of source compositions throughout all three terranes of the Rudall Province implies that the Tabletop Terrane was derived from crust of similar composition to the Connaughton Terrane and the supracrustal components of the Talbot Terrane (Fig. 2).

Crust formation and underplating at 1.9 Ga

A c. 1450 Ma metamonzogranite in the Talbot Terrane contains zircons with the least evolved Hf isotopic signature in the Rudall Province (Fig. 2). The Hf isotope data indicate either extraction from the mantle at c. 1.9 Ga, or a homogenized mix of sources with a component younger than c. 1.9 Ga. However, oxygen isotopes can be used to determine whether the granitic magma within which each zircon grew contained a contribution from near-surface rocks (e.g. those with $\delta^{18}O_{VSMOW}$ >6.3 ‰). This approach provides a means to screen the corresponding Hf model age to identify model ages that represent discrete crust-forming episodes rather than mixtures of source materials and contamination by supracrustal material. Oxygen isotope values for all zircons from this sample are within the mantle zircon field ($\delta^{18}O$ = 5.3 – 0.6 ‰). Hence, the c. 1.9 Ga model age likely reflects a crust-forming fractionation event in the lithosphere.

There is only limited additional evidence for crust formation at c. 1.9 Ga in the WAC and its marginal terranes. Magmatic and metasedimentary rocks of the Musgrave Province are dominated by two major Proterozoic juvenile crust-formation events: one at 1.6 Ga and a more significant event at c. 1.9 Ga (Kirkland et al., 2012).

Figure 3. Epsilon-Hf evolution diagrams for Rudall Province samples compared to potential source regions. Shaded fields illustrate normal crustal evolution of Hf along a $^{176}Lu/^{177}Hf$ slope of 0.015. Abbreviations used: EPT — East Pilbara Terrane; M — Musgrave Province c. 1.9 Ga source; GT — Glenburgh Terrane (Capricorn Orogen basement); and D — Dalgaringa Supersuite intrusive rocks. The red line is the depleted mantle model and the blue line is the CHUR (chondritic uniform reservoir) model.

Whole-rock Nd isotopes

Whole-rock Nd isotopes from the Kalkan granites imply that three source components contributed to the magmas. An evolved component with moderate Nd content is consistent with the incorporation of variable amounts of Archean Pilbara crust. A low-Nd radiogenic component is likely a reflection of new juvenile mantle addition. A third high-Nd, moderately radiogenic, component appears isotopically similar to a putative (but unexposed) c. 1.9 Ga source in the Musgrave Province that also appears to be a source for voluminous mafic sills of the c. 1465 Ma Narimbunna Dolerite that intruded the intracratonic Edmund Basin, located between the Pilbara and Yilgarn Cratons.

Summary

The broad similarity in crustal residence ages for all terranes in the Rudall Province indicates that the terranes have a common heritage, although Mesoproterozoic reworking (infracrustal magmatism) apparently occurred only in the Tabletop Terrane. Sources for all isotopic compositions preserved within the Rudall Province can be found within the proximal WAC. There is no necessity to invoke transfer of exotic NAC lithotectonic units to the WAC margin or to suggest an accretionary style of orogenesis for the Rudall Province. The Rudall sedimentary successions are autochthonous with respect to the eastern Pilbara Craton margin. This conclusion is consistent with the view presented by Reading et al. (2012), that thinned and extended Pilbara Craton crust occurs as basement beneath the Talbot Terrane. The Hf isotopic evolution of inherited and magmatic zircons within Kalkan Supersuite granites are largely influenced by a variety of autochthonous source regions, including the sedimentary successions into which they were intruded. A phase of crust formation at 1.9 Ga is indicated by Hf isotopes in a c. 1450 Ma monzogranite in the Talbot Terrane. This isotope signature appears to be similar to a dominant basement component in the Musgrave Province and in the deep crust beneath the Edmund Basin. This may support the idea of west-directed subduction and underplating beneath the WAC (or its Archean constituent blocks) as early as c. 1.9 Ga.

References

Bagas, L 2004, Proterozoic evolution and tectonic setting of the northwest Paterson Orogen, Western Australia: Precambrian Research, v. 128, p. 475–496.

Bagas, L and Smithies, RH 1997, Palaeoproterozoic tectonic evolution of the Rudall Complex, and comparison with the Arunta Inlier and Capricorn Orogen: Western Australia Geological Survey Annual Review, p. 110–115.

Bagas, L and Smithies, RH 1998, Geology of the Connaughton 1:100 000 sheet, Western Australia: 1:100 000 Geological Series Explanatory Notes, Western Australia Geological Survey, 38p.

Budd, AR, Wyborn, LAI and Bastrakova, IV 2002, The metallogenic potential of Australian Proterozoic granites: Geoscience Australia, Record, v. 2001/12, 152p.

Hickman, AH and Bagas, L 1999a, Geological evolution of the Palaeoproterozoic Talbot Terrane and adjacent Meso- and Neoproterozoic succession, Paterson Orogen, Western Australia: Geological Survey of Western Australia, Report, 91p.

Hickman, AH and Bagas, L 1999b, Geology of the Rudall 1:100 000 sheet, Explanatory Notes: Geological Survey of Western Australia, 37p.

Hickman, AH, Williams, IW and Bagas, L 1994, Proterozoic geology and mineralization of the Telfer–Rudall region: Geological Society of Australia (WA Division) Excursion Guide, 56p.

Kirkland, CL, Smithies, RH, Woodhouse, AJ, Howard, HM, Wingate, MTD, Belousova, EA, Cliff, JB, Murphy, RC and Spaggiari, CV 2012, Constraints and deception in the isotopic record; the crustal evolution of the west Musgrave Province, central Australia: Gondwana Research, v. 23, p. 759–781.

Li, ZX, Bogdanova, SV, Collins, AS, Davidson, A, De Waele, B, Ernst, RE, Fitzsimons, ICW, Fuck, RA, Gladkochub, DP, Jacobs, J, Karlstrom, KE, Lu, S, Natapov, LM, Pease, V, Pisarevsky, SA, Thrane, K and Vernikovsky, V 2008, Assembly, configuration, and break-up history of Rodinia: a synthesis: Precambrian Research, v. 160, p. 179–210.

Reading, AM, Tkalčić, H, Kennett, BLN, Johnson, SP and Sheppard, S 2012, Seismic structure of the crust and uppermost mantle of the Capricorn and Paterson Orogens and adjacent cratons, Western Australia, from passive seismic transects: Precambrian Research, v. 196–197, p. 295–308.

Smithies, RH and Bagas, L 1997, High pressure amphibolite-granulite facies metamorphism in the Paleoproterozoic Rudall Complex, central Western Australia: Precambrian Research, v. 83, p. 243–265.

Tyler, IM 2000, Paleoproterozoic Orogeny in Western Australia, Geological Survey of Western Australia, extended abstracts: geological data for WA explorers in the new millennium, Record 8, p. 7–8.

3D architecture and mineral prospectivity of the Gascoyne Province

by

ARA Aitken[1], A Joly[1], SP Johnson, M Dentith[1], AM Thorne, and IM Tyler

The Capricorn Orogen records the Paleoproterozoic assembly of the West Australian Craton, and over one billion years of subsequent intraplate reworking (Cawood and Tyler, 2004; Johnson et al., 2011b; Sheppard et al., 2010). The core of the orogen is occupied by granitic and medium- to high-grade metamorphic rocks of the Gascoyne Province, and these are overlain by variably deformed low-grade metasedimentary rocks. Over the past decade and a half, ongoing field mapping, combined with whole rock and accessory phase geochemical, geochronological and isotope analyses, (Johnson et al., 2011a; Johnson et al., 2011c; Sheppard et al., 2007) have provided a rigorous temporal tectonomagmatic evolution for the Gascoyne Province. The results of a recent vibroseis-source, deep crustal seismic transect through the Capricorn Orogen, provide a detailed view of the deep crustal structure of the orogen (Johnson et al., 2011c). These datasets, combined with high-resolution aeromagnetic and gravity data, allow an opportunity to assess the prospectivity of the Gascoyne Province within a robust architectural framework.

Funded by the Western Australian Government's Exploration Incentive Scheme (EIS), the Centre for Exploration Targeting (<http://www.cet.uwa.edu.au>) at The University of Western Australia has undertaken a study of the crustal structure and prospectivity of the Gascoyne Province. In this work, new understanding of the structural evolution of the province and the geometry of major features is developed. From this new interpretation, and using extensive GSWA databases, a GIS-based prospectivity analysis is undertaken using a mineral systems approach.

In each tectonic zone of the Gascoyne Province (Fig. 1), structural fabrics, folds and faults were interpreted from geophysical datasets and grouped into discrete events. These were then assigned to one of eight province-wide tectonic events based on their overprinting relationships with the main lithologies. Each zone within the Gascoyne Province has a different evolution, but a regionally consistent pattern of events can be derived (Fig. 1).

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

Suturing of the West Australian Craton took place during two events — the Ophthalmian and Glenburgh Orogenies. The Ophthalmian Orogeny is not recognized in this study as it is centred further north, and any far-field effects have been overprinted. The Glenburgh Orogeny is, however, very significant and quite well preserved in the southern part of the Gascoyne Province (Fig. 1). Following the Glenburgh Orogeny, the evolution of the province is dominated by a number of intraplate reactivation events. Each has affected several zones, and most have re-utilized the pre-existing east-west structural architecture (Fig. 1). The major fault zones show the greatest tendency to be reactivated, leaving fragments of undeformed crust in-between. However, there is a general propensity for the events to have become geographically narrower, from the province-wide 1820–1770 Ma Capricorn Orogeny to the c. 570 Ma Mulka Tectonic Event, which is restricted to the central part of the province (Fig. 1).

Gravity and magnetic modelling indicates that the large-scale crustal structure defined from seismic studies (Johnson et al., 2011c; Kennett et al., 2011; Reading et al., 2012) is acceptable, given the available petrophysical constraints. However, sensitivity to the finer details of crustal structure is limited by generally low petrophysical contrast between the various granitic supersuites. This study does highlight diversity in the mid- and lower-crust, including an extremely dense layer at the base of the Glenburgh Terrane in the southern part of the Gascoyne Province (the MacAdam Seismic Province), and the high-density Bandee Seismic Province — the southern part of the Pilbara Craton — that underlies the northern part of the province.

A multi-commodity regional prospectivity analysis was undertaken. This involved the translation of inferred 4D controls on mineralization into a mineral system framework (Hronsky and Groves, 2008; Knox-Robinson and Wyborn, 1997; McCuaig and Hronsky, 2000) and implementing GIS-based prospectivity modelling. Five broad types of commodities were analysed: rare earth element (REE); orogenic and intrusive gold; surficial uranium; porphyry-base metal (PBM); and granite-hosted tin-tungsten.

The prospectivity analysis used a mineral system approach that considered, potential fluid-pathways for the transport

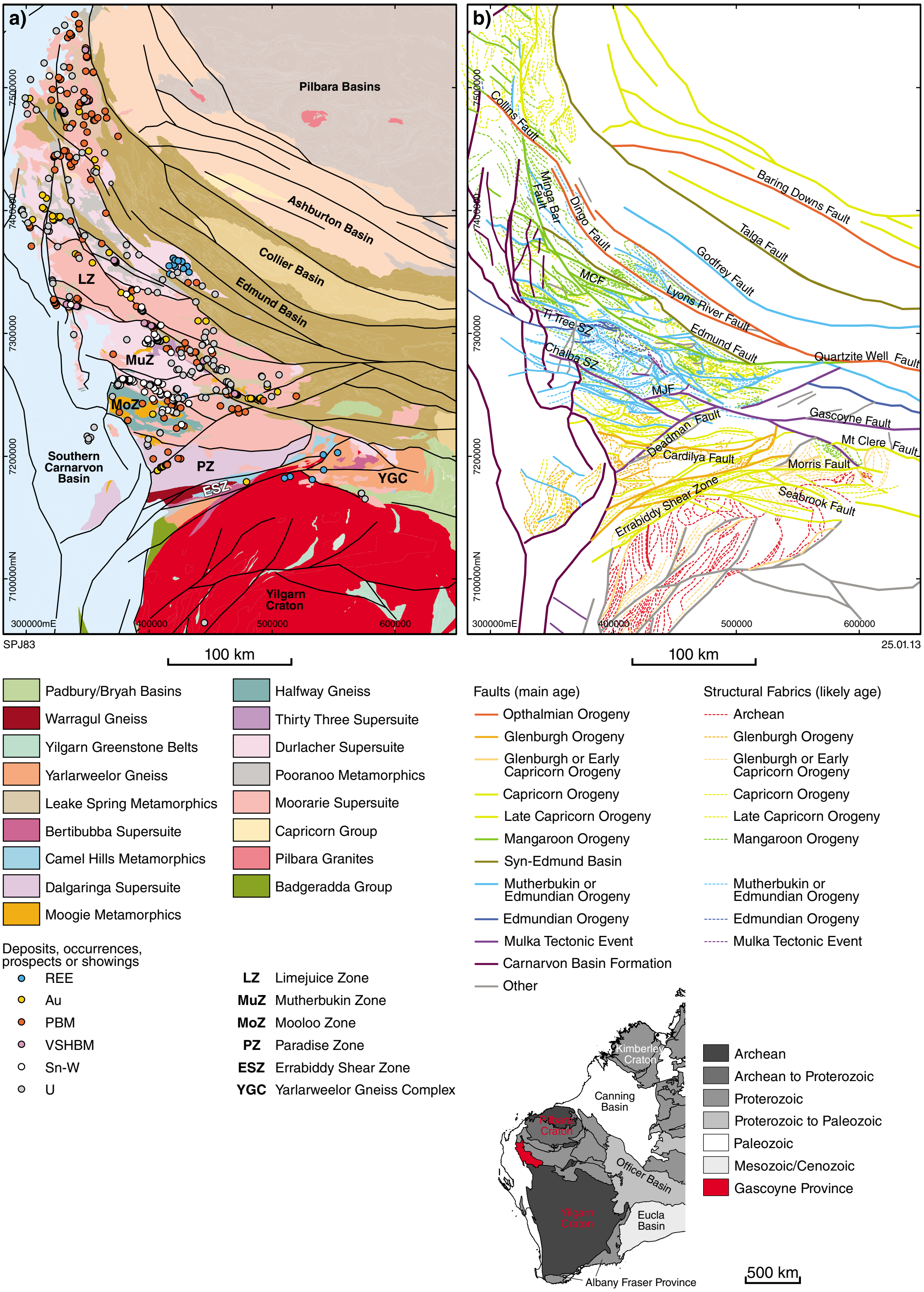


Figure 1. a) Simplified geological map of the western part of the Capricorn Orogen showing the structural zone divisions and location of mineral deposits in the Gascoyne Province; b) Gascoyne Province-wide distribution of the age of structures, including major faults in the western Capricorn Orogen. For structural fabrics, the age is the likely age inferred from overprinting relationships. As most major faults have a long history involving several activation episodes, we infer the age of the most important movement for faults. Note the narrowing of orogenic footprints through time, from the province-wide Capricorn Orogeny (yellow) to the Mulka Tectonic event (purple).

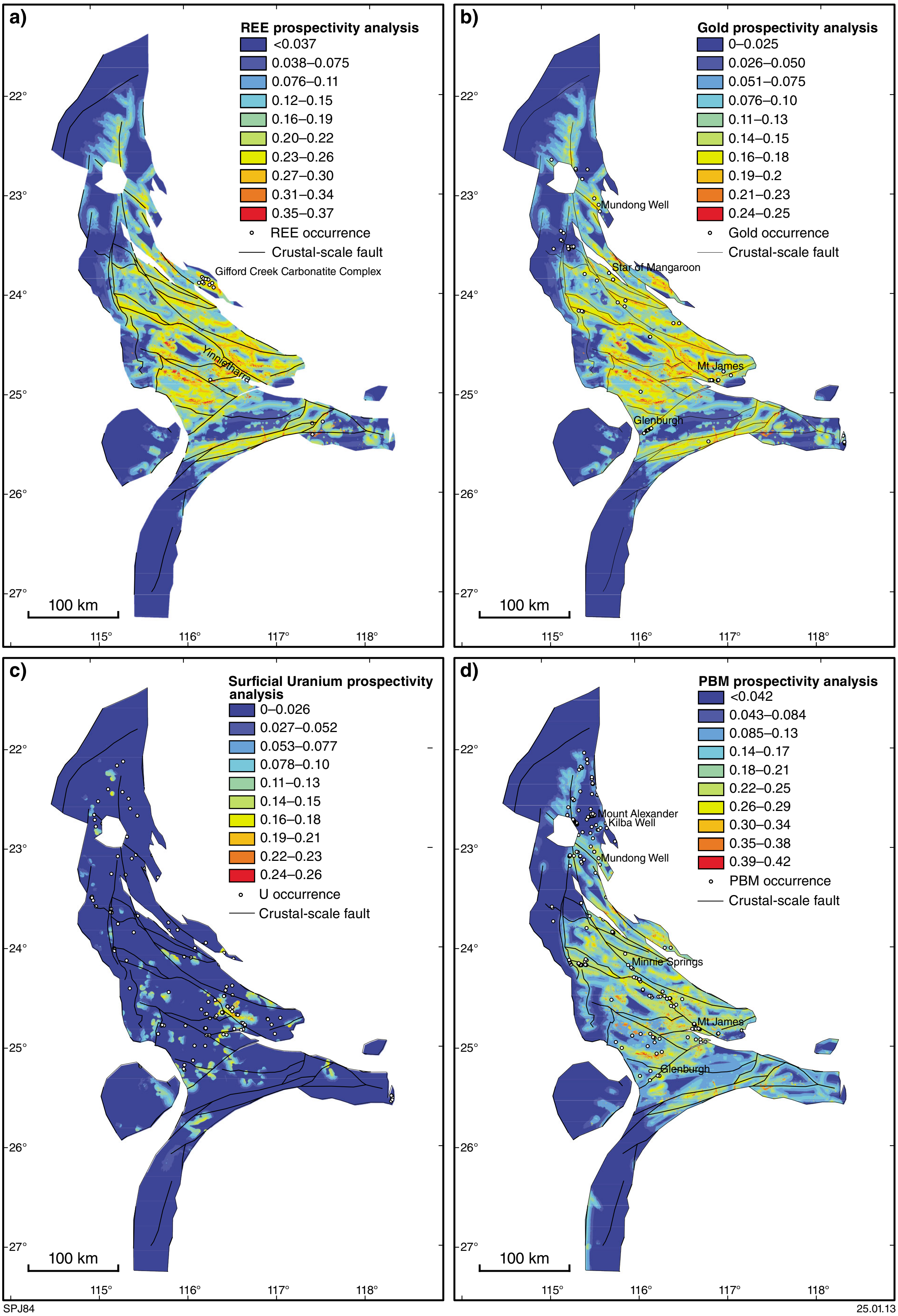


Figure 2. Final prospectivity maps for a) REE; b) orogenic gold; c) surficial uranium; d) porphyry base metals. Note that, for REE and orogenic gold, prospectivity is focused in the central parts of the Gascoyne Province, and show clear links with many, but not all, crustal-scale fault zones.

of metal into the upper crust, and the potential physical and chemical traps in which to precipitate the metals. For each component, a series of predictor maps was generated for favourable criteria, using the newly interpreted structures and other GSWA data. These were combined into a final prospectivity map using a fuzzy inference network. These analyses are not necessarily expected to show the locations of deposits themselves. Rather, they are intended to illustrate spatial variations in geological favourability for a particular type of deposit. The results are influenced by imperfect data distributions, as well as inferences made about the local geology and the way these deposits form. The results indicate the following:

- Analyses for REE indicate much of the province is prospective, with prospectivity concentrated in the central part of the province (Fig. 2a).
- The areas most prospective for gold are concentrated around major crustal boundaries, with the Limejuice Zone ('LZ' in Fig. 1) being particularly prospective (Fig. 2b).
- Surficial uranium shows the highest prospectivity in the central part of the province, but with isolated regions of increased prospectivity across the whole province (Fig. 2c).
- The analysis for porphyry base metals shows broad zones of moderate prospectivity across much of the area, with slight focusing around major crustal structures, but few areas of high prospectivity (Fig. 2d).
- Tin and tungsten occurrences cluster at the margins of the Mutherbukin Zone (Fig. 1), although the analysis suggests that a large part of the province is equally prospective.

In general, these maps showed a strong control on deposit location by crustal structure but this was significantly modified by the presence of acceptable lithological conditions for ore deposition and numerous other controls on prospectivity. Prospectivity for REE, gold and tin-tungsten deposit types is strongest in the central regions of the province, perhaps reflecting the influence of a greater degree of intraplate reworking.

References

Cawood, PA and Tyler, IM 2004, Assembling and reactivating the Proterozoic Capricorn Orogen: lithotectonic elements, orogenies, and significance: Precambrian Research, v. 128, p. 201–218.

Hronsky, JMA and Groves, DI 2008, Science of targeting: definition, strategies, targeting and performance measurement: Australian Journal of Earth Sciences, v. 55, p. 3–12.

Johnson, SP, Sheppard, S, Rasmussen, B, Wingate, MTD, Kirkland, CL, Muhling, JR, Fletcher, IR and Belousova, EA 2011a, Two collisions, two sutures: punctuated pre-1950 Ma assembly of the West Australian Craton during the Ophthalmian and Glenburgh Orogenies: Precambrian Research, v. 189, p. 239–262.

Johnson, SP, Thorne, AM, Cutten, HN, Tyler, IM and Blay, O 2011b, Geology of the Gascoyne Province in Capricorn Orogen seismic and magnetotelluric (MT) Workshop 2011: extended abstracts edited by SP Johnson, AM Thorne, and IM Tyler: Geological Survey of Western Australia, Record 2011/25, p. 27–40.

Johnson, SP, Thorne, AM and Tyler, IM 2011c, Capricorn Orogen Seismic and Magnetotelluric (MT) Workshop 2011: extended abstracts, Geological Survey of Western Australia, Record 2011/25, 114p.

Kennett, BLN, Salmon, M, Saygin, E and Group, AW 2011, AusMoho: the variation of Moho depth in Australia: Geophysical Journal International, v. 187, p. 946–958.

Knox-Robinson, CM and Wyborn, LAI 1997, Towards a holistic exploration strategy: using geographic information systems as a tool to enhance exploration: Australian Journal of Earth Sciences, v. 44, p. 453–463.

McCuaig, TC and Hronsky, JM 2000, The current status and future of the interface between the exploration industry and economic geology research: Reviews in Economic Geology, v. 13, p. 553–559.

Reading, AM, Tkalčić, H, Kennett, BLN, Johnson, SP and Sheppard, S 2012, Seismic structure of the crust and uppermost mantle of the Capricorn and Paterson Orogens and adjacent cratons, Western Australia, from passive seismic transects: Precambrian Research, v. 196–197, p. 295–308.

Sheppard, S, Bodorkos, S, Johnson, SP, Wingate, MTD and Kirkland, CL 2010, The Paleoproterozoic Capricorn Orogeny: intracontinental reworking not continent–continent collision, GSWA Report 108, 33p.

Sheppard, S, Rasmussen, B, Muhling, JR, Farrell, TR and Fletcher, IR 2007, Grenvillian-aged orogenesis in the Palaeoproterozoic Gascoyne complex, Western Australia: 1030–950 Ma reworking of the Proterozoic Capricorn Orogen: Journal of Metamorphic Geology, v. 25, p. 477–494.

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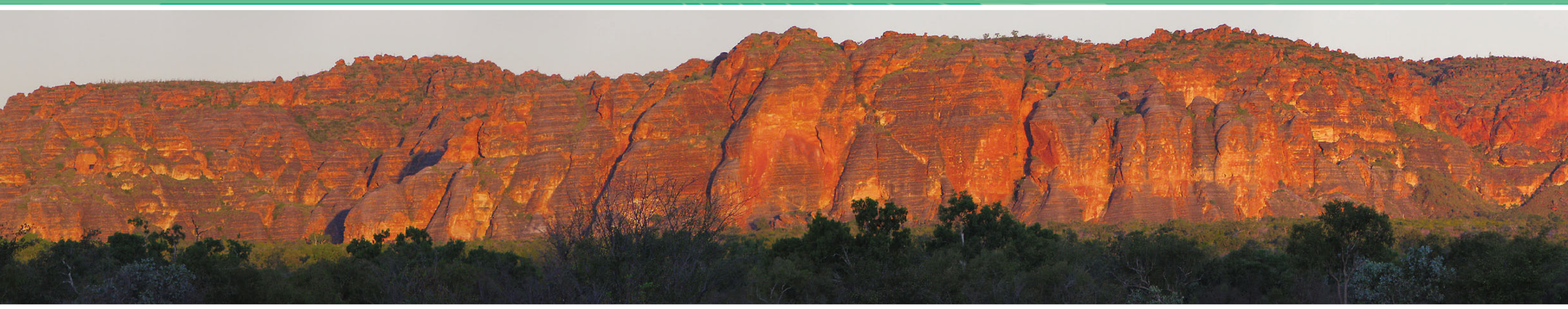

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