Government of Western Australia
Department of Mines, Industry Regulation and Safety

RECORD 2019/2

GSWA 2019 EXTENDED ABSTRACTS
Advancing 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 Bill Johnston MLA

DIRECTOR GENERAL, DEPARTMENT OF MINES, INDUSTRY REGULATION AND SAFETY
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EXECUTIVE DIRECTOR, GEOLOGICAL SURVEY AND RESOURCE STRATEGY
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Cover image: Sunset over the Yalgoo Mineral Field. Photograph by T Ivanic, DMIRS

GSWA Open Day 2019 program — 22 February 2019, Fremantle

8.15 – 8.45	REGISTRATION		
8.45 – 9.00	Welcome and opening remarks	Hon Bill Johnston MLA, Minister for Mines and Petroleum	
SESSION 1	***Chair: Jeff Haworth***		
9.00 – 9.30	The future of mineral exploration geoscience at GSWA: EIS 4 and MinEx CRC	Klaus Gessner	EXPLORATION INCENTIVE SCHEME
9.30 – 9.50	A new look at lamprophyres and sanukitoids, and their relationship to the Black Flag Group and gold prospectivity	Hugh Smithies	EXPLORATION INCENTIVE SCHEME
	Morning tea 9.50 – 10.50		
SESSION 2	***Chair: Charlotte Hall***		
10.50 – 11.15	Mineral Systems Atlas — a new approach to the delivery of mineral exploration data	Sidy Morin-Ka	EXPLORATION INCENTIVE SCHEME
11.15 – 11.40	Ultrafine soils — the technique, the advances and the application to GSWA regional map products	Ryan Noble, CSIRO	EXPLORATION INCENTIVE SCHEME
11.40 – 12.05	Sulfur sources and magmatic sulfide mineralization in the Fraser Zone: insights from mineral prospects	Alex Walker, Curtin University	EXPLORATION INCENTIVE SCHEME
12.05 – 12.25	Application of innovative geochronology techniques in geoscience mapping and exploration	Brent McInnes, John de Laeter Centre	EXPLORATION INCENTIVE SCHEME
	Lunch 12.25 – 1.40		
SESSION 3	***Chair: Simon Johnson***		
1.40 – 3.00	In this session, eight 10-minute talks will be given on the following: Eastern Goldfields seismic survey; Capricorn Orogen passive seismic array; State regolith map of Western Australia; The Abandoned Mines Program; Metamorphic studies at GSWA; Carnarvon Basin SEEBASE model; The Yilgarn 2020 project; and Carbon storage in the South West	David Howard, Ruth Murdie, Sara Jakica, Ian Mitchell, Fawna Korhonen, Charmaine Thomas, Steve Rowins (CET), Dominique Van Gent	EXPLORATION INCENTIVE SCHEME
	Afternoon tea 3.00 – 3.30		
SESSION 4	***Chair: Klaus Gessner***		
3.30 – 3.55	Microbialites: an untapped resource	Heidi Allen	EXPLORATION INCENTIVE SCHEME
3.55 – 4.20	The complexity of sediment recycling as revealed by common Pb isotopes in K-feldspar	Simon Johnson	EXPLORATION INCENTIVE SCHEME
4.20 – 4.30	Interactive feedback session	Angela Riganti	
	Sundowner 4.30 – 5.30		

Contents

The future of mineral exploration geoscience at GSWA: EIS 4 and MinEx CRC

by

K Gessner, IM Tyler, CE Hall, CV Spaggiari, TJ Beardsmore, P Duuring, SP Johnson, RH Smithies and MTD Wingate

Introduction

The State Government announced in the May 2018 State budget that the Exploration Incentive Scheme (EIS) would continue at $10 million per year, with ongoing funding raised from an increase in the Mining Tenement Rent (MTR). This new funding mechanism, starting in full from July 2019, represents the fourth phase of the scheme and is designated EIS 4 (Fig. 1).

EIS was launched in April 2009, with funding of $80 million provided from the Royalties for Regions (RfR) program for a more than four-year initiative that ran until the end of June 2013 (Phase 1). An additional $20.6 million was allocated to the scheme from RfR funds for 2013–14 (Phase 1A). Funding for EIS (Phase 2) was then extended for three years until the end of 2016–17 with $30 million from the Consolidated Revenue Fund. A further extension to the scheme (EIS 3) saw an allocation of RfR funding of $20 million in the 2017 budget for two years to the end of June 2019.

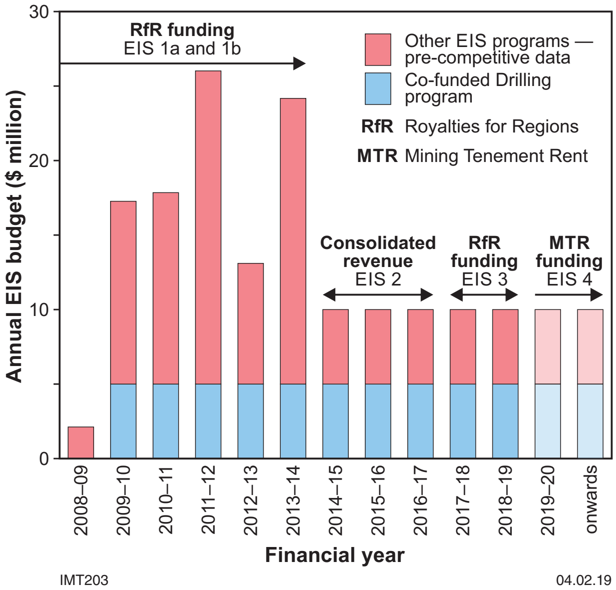

Figure 1. Funding sources for phases of the EIS from April 2009 to 2019–20 onwards

The proposed programs for EIS 4 include funding for the National Drilling Initiative (NDI) within the recently launched $218 million Mineral Exploration Cooperative Research Centre (MinEx CRC; <www.minexcrc.com.au>). EIS 4 is aligned to the National Mineral Exploration Strategy (Geoscience Working Group, 2017) and National Petroleum Exploration Strategy (Geoscience Working Group, in prep.) of the Council of Australian Governments (COAG) Energy Council, and to the UNCOVER AUSTRALIA/AMIRA industry roadmap 'Unlocking Australia's Hidden Potential' (AMIRA International, 2017) for exploration under cover. UNCOVER involved extensive consultation with, and input from, the mineral exploration industry and its representative bodies in Australia, together with Geoscience Australia (GA) and the other State and Territory geological surveys, CSIRO and Australian university research leaders.

Mineral exploration geoscience at the Geological Survey of Western Australia (GSWA)

The objective of EIS is to promote exploration in Western Australia, with a particular emphasis on greenfields areas that are underexplored for mineral deposits and on frontier petroleum basins. The aim is to maintain investment and exploration activity at levels required for the long-term sustainability of the State's resources sector, requiring an increase in the discovery rate of economic deposits, with the opening up of new search spaces. EIS is integrated with GSWA's recurrent geoscience, mineral systems, and basins and energy programs.

There is a recognition that near- or at-surface mineral deposits are becoming increasingly difficult to find in Australia, with exploration success declining relative to effort and expenditure (AMIRA International, 2015, 2017). In order to counter the perception among international investors that Western Australia might represent a mature exploration search space, GSWA has been involved with industry in the UNCOVER roadmap process, facilitated by AMIRA International. The UNCOVER roadmap identified six themes, together with a number of very high, and high-priority focus areas (AMIRA International, 2015, 2017). These will be addressed under EIS 4.

Priority areas for encouraging greenfields mineral exploration in Western Australia under EIS 4 are:

- the eastern margins of the Pilbara and Yilgarn Cratons
- bedrock elements of the margins of the North and West Australian Cratons in the remote Paterson, Granites–Tanami and Arunta Orogens (Fig. 2).

In previous EIS phases, GSWA has been part of a 'Team WA' approach to collaborative mineral exploration geoscience research in Western Australia involving CSIRO, Curtin University and The University of Western Australia (UWA), as well as collaborations with GA, other geological surveys and research institutions across Australia (Fig. 3). With the Centre for Exploration Targeting at UWA and CSIRO Mineral Resources, both world leaders in mineral systems studies, GSWA has undertaken innovative prospectivity and targeting studies that have been published as a series of GSWA Reports (e.g. Occhipinti et al., 2016; Lindsay et al., 2015, 2016; González-Álvarez, 2014; Walshe et al., 2014; Wells et al., 2016; Hollis et al., 2017).

EIS 4

Alongside the annual $5 million EIS Co-funded Government–Industry Drilling program, a further annual $5 million of EIS 4 will fund the acquisition and interpretation of pre-competitive geoscience data including geophysical data. The integrated interpretation of these data will be supported by petrophysical, mineralogical and geochemical analyses of samples obtained from stratigraphic and mineral potential drilling through cover as part of GSWA's participation in MinEx CRC, and from industry legacy drillcores.

Program 1: innovative drilling

Program 1 consists of the Co-funded Government–Industry Drilling program, which is designed to stimulate geoscience exploration of underexplored greenfields regions in Western Australia, and contribute to their economic development by increasing exploration and new mineral discoveries. The program co-funds high-quality, technically and economically sound projects that promote new exploration concepts and new exploration technologies.

Program 2: geophysical surveys

A primary goal of EIS 4 is to complete the acquisition of airborne gravity coverage of the State at 2.5 km spacing, or better, over remote northern and northeastern parts of the State, with the assistance of GA. A targeted acquisition program for airborne electromagnetic surveys is planned in collaboration with GA as part of their Exploring for the Future program in northern Australia. Deep crustal reflection seismic and magnetotelluric surveys will provide insight into the deep crustal architecture by identifying major crustal boundaries that have the potential to act as fluid pathways. The data will be supported by passive seismic surveys, contributing to the building of a regional-scale, 3D understanding of the Western Australian crust.

Program 3: encouraging exploration through cover

Stratigraphic and mineral potential drilling will be funded as part of MinEx CRC, with the aim of developing new technologies and data systems to promote new exploration spaces under cover. Primary goals are categorizing and mapping the depth of cover (regolith and/or sedimentary basins) to identify key paleosurfaces, including the top of economic basement. NDI drilling programs will collect sample material from basement rocks for petrophysical, petrological, geochronological, geochemical and isotopic analyses to understand basement evolution through time (4D mapping). The development of smarter data management will allow integration and interrogation of multiple databases to optimize drilling and targeting and allow input of real-time data. Both historical and new data will be used to develop new tools and analytical techniques for use in exploration.

Program 4: 3D prospectivity mapping

Program 4 will enhance the understanding of the geological evolution of Western Australia and its mineral and petroleum prospectivity, and visualize and deliver that knowledge to explorers online. It will identify and map mineral and petroleum systems in Western Australia to understand distal footprints that will refine targeting and prospectivity mapping. The program also includes redevelopment or enhancement of the Department of Mines, Industry Regulation and Safety (DMIRS) geoscience databases through 'WA Geology Online' to ensure Western Australia maintains the world-class delivery and availability of geological datasets.

Program 5: promoting strategic research with industry

Program 5 will provide an annual grant of $350 000 to the Minerals Research Institute of Western Australia (MRIWA) to support focused mineral research projects that develop new science and technology for mineral exploration in Western Australia.

MinEx CRC

DMIRS, through GSWA, will contribute $350 000 annually over the 10 years of MinEx CRC from the EIS, for a total of $3.5 million, as part of the NDI (MinEx CRC Program 3). In-kind support will consist mostly of the acquisition of targeted geophysical surveys up to a value of $6 million over the life of the CRC. MRIWA is contributing $1 million to Programs 1 and 2 of MinEx CRC, bringing the total contribution from Western Australia to $4.5 million. GA is contributing $10 million, the Geological Survey of New South Wales $4.4 million and the Geological Survey of South Australia $5 million as part of the NDI.

MinEx CRC participation is an integral part of GSWA's ongoing plans for EIS through Program 3 (see above).

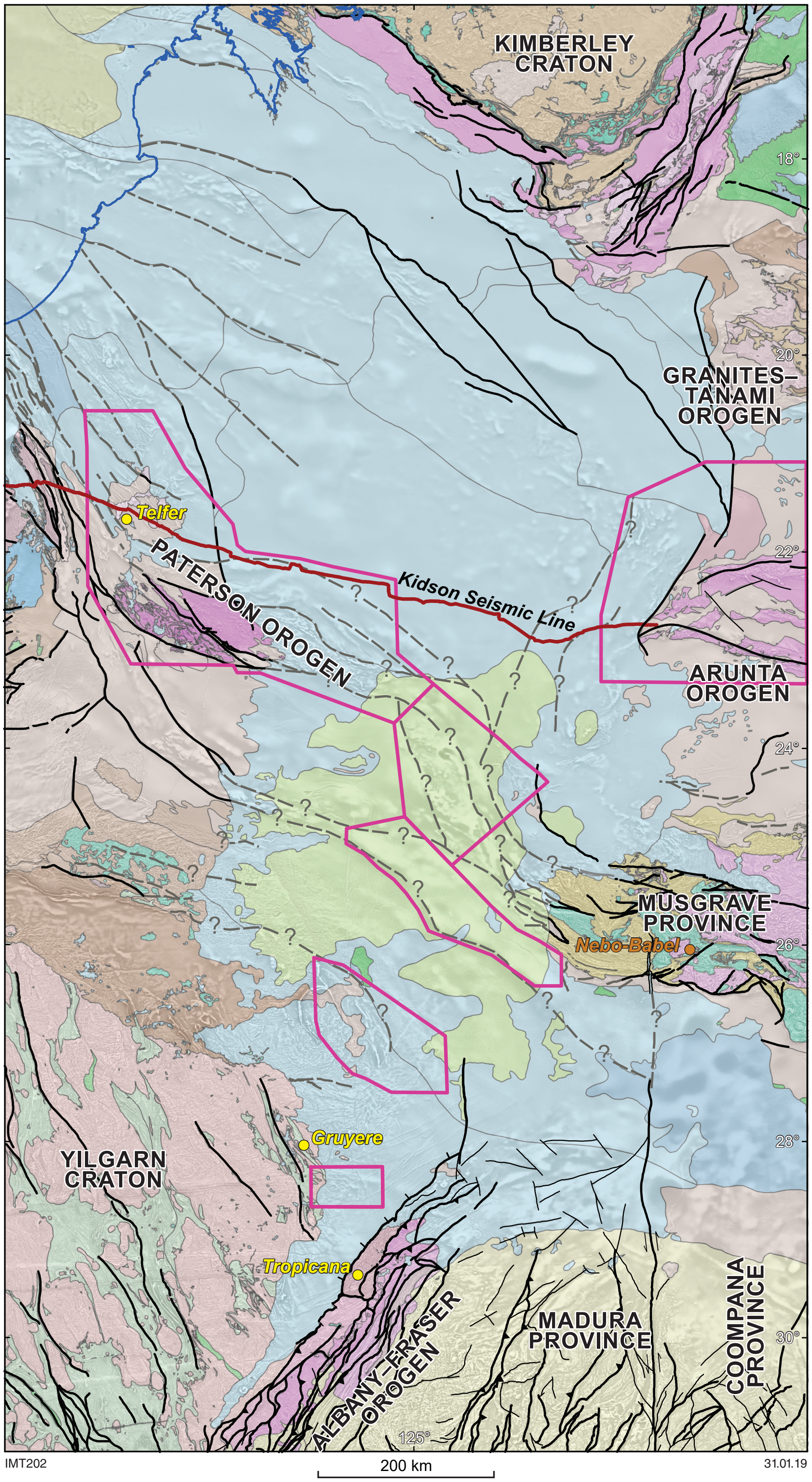

Figure 2. 'The Gap'. Mineral Exploration Cooperative Research Centre (MinEx CRC) National Drilling Initiative (NDI) priority areas in Western Australia (pink polygons). Background is Western Australian tectonic units over 1VD magnetic image

Figure 3. Collaborative research partners involved in EIS-funded projects up to June 2017

The entire $3.5 million EIS contribution will be invested in drilling programs in Western Australia, and will leverage an equivalent amount of research at CSIRO and participating universities aimed around those drilling programs. Research programs under the NDI include:

- maximizing the value of data and drilling through cover
- geological architecture and evolution
- targeting mineral systems in covered terranes.

In Western Australia, GSWA will concentrate its NDI drilling programs in a region defined as ‘The Gap’ on the eastern margin of the Pilbara Craton (the Paterson Orogen, hosting the Cu–Au deposits including Telfer), and across the Canning Basin to the border region with the Northern Territory. The programs will be concentrated around the line of the recent GA/GSWA-funded Kidson deep seismic reflection survey (Fig. 2). The aim is to reduce risk for mineral explorers in a very remote greenfields setting in desert country covering the Proterozoic Paterson, Granites–Tanami and Arunta Orogens.

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A new look at lamprophyres and sanukitoids, and their relationship to the Black Flag Group and gold prospectivity

by

RH Smithies, Y Lu, CL Kirkland[1], KF Cassidy[2], DC Champion[3], J Sapkota, M De Paoli and L Burley

The relative contributions that crustal and magmatic sources have made to the Archean gold endowment of the Eastern Goldfields Superterrane (EGST) of the Yilgarn Craton have been debated for several decades without any ensuing clear consensus. From an empirical perspective, several specific intrusive magma types have been directly linked to gold mineralization. These include lamprophyres (e.g. Rock and Groves, 1988; Rock et al., 1989) and high-Mg dioritic to granodioritic magmas derived from metasomatized lithospheric mantle (i.e. sanukitoids; e.g. Beakhouse et al., 1999). Recent work has established a clear, statistically valid basis for these empirical observations (Witt et al., 2013, 2015; Witt, 2016).

A significant increase in the amount of high-quality lithogeochemical data from volcanic and subvolcanic rocks of the EGST further allows a robust assessment of links between calc-alkaline lamprophyric intrusions and trace element-enriched sanukitoid intrusions, links between these and felsic volcanic rocks (including the Black Flag Group) and links between all of these and gold prospectivity.

To do this, we used an extract from the larger geochemical dataset currently being accumulated as part of the Eastern Goldfields greenstone geochemical barcoding project, an initiative under the Exploration Incentive Scheme (EIS) that aims to geochemically characterize greenstone stratigraphy throughout the EGST. The data subset initially comprised 845 analyses of volcanic and subvolcanic rocks, with broadly contemporaneous crystallization ages between 2.69 and 2.64 Ga. The number of analyses was reduced to 691 after filtering to only include the 'least-altered'. The broad geochemical patterns observed within the remaining dataset appear most consistent with igneous processes, and suggest that our sampling and filtering strategies considerably minimized the number of samples with whole-rock compositions that were significantly affected by metamorphism or hydrothermal alteration. Sampling has a significant bias to the Menzies–Kambalda portion of the Kalgoorlie Terrane (Fig. 1), primarily because this was the region selected for the initial phase of the Eastern Goldfields greenstone geochemical barcoding project.

Current petrogenetic models discount a direct genetic relationship between sanukitoid and calc-alkaline lamprophyric magmas, because the former are often found to be more primitive than the latter (e.g. Stern et al., 1989). However, our study, which considers only samples with a close spatial relationship, supports the suggestion that the EGST sanukitoids are in fact directly related to lamprophyric magmas (Fig. 2; Perring and Rock, 1991) through a liquid line of descent involving hornblende fractionation, rather than through direct extraction from lithospheric mantle.

Together, lamprophyre and sanukitoid define a low-Nb, high-P_2O_5 and high La/Nb magmatic association that distinguishes them from all other Archean magmatic associations of the EGST, except for the Mafic granites, one of the four main granite groups of the Yilgarn Craton (Champion and Sheraton, 1997; Cassidy et al., 2002). More than 75% of Mafic granites also fall within this association and are sanukitoid intrusions. Most significantly, more than 75% of the igneous rocks forming the Black Flag Group also fall within this distinct 'enriched' association (Figs 3, 4), that is, most Black Flag Group rocks are volcanic equivalents of evolved sanukitoid. Smaller occurrences of similar felsic volcanic rocks lie throughout the EGST.

The origins of the enriched magmas can be traced back to a metasomatized lithospheric source, thus the occurrence of such magmas indicates proximity to a translithospheric structure. The significance of a genetic link between lamprophyric magmas and sanukitoid, and further to more evolved dacitic compositions of the Black Flag Group, is that intrusion and fractionation of wet, hornblende-bearing lamprophyric magma involves exsolving large volumes of relatively oxidized fluids, which are subsequently also channelled along translithospheric pathways.

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2 Bare Rock Geological Services Pty Ltd, PO Box 1633, Fremantle WA 6959

3 Geoscience Australia, GPO Box 378, Canberra ACT 2601

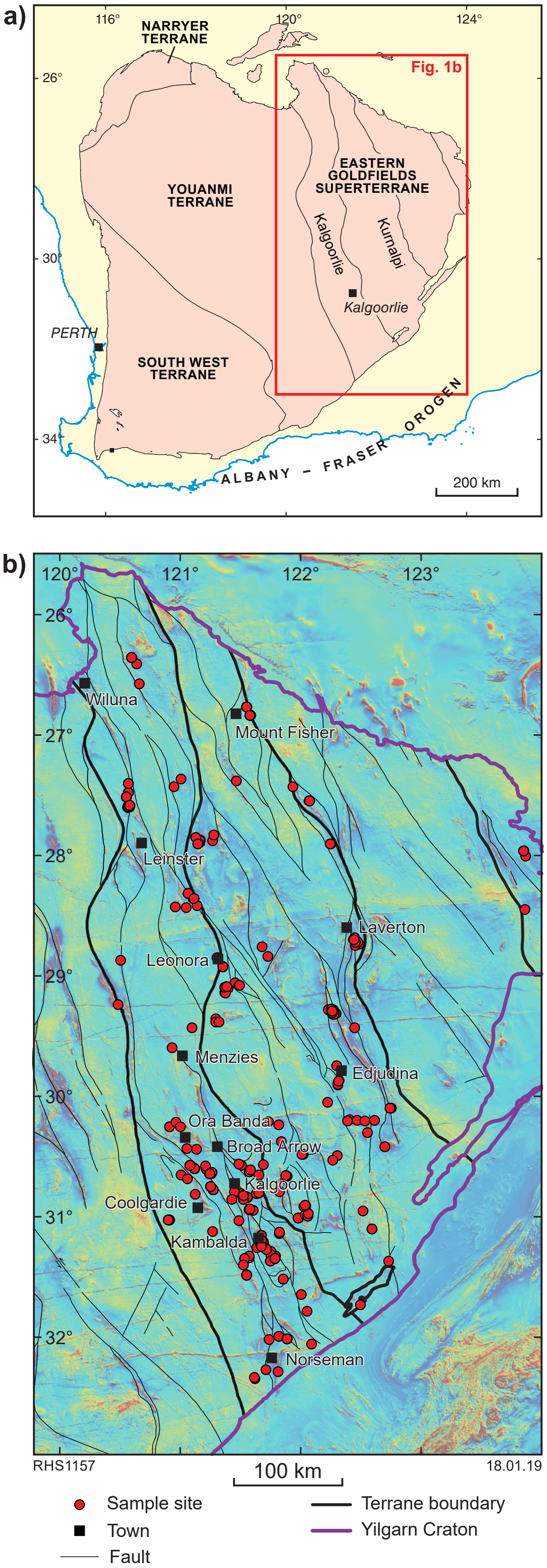

Figure 1. a) Terrane subdivision of the Yilgarn Craton, with outline indicating the study area shown in b); b) aeromagnetic image of the Eastern Goldfields Superterrane (EGST) showing the locations of samples used for this study. Note that many sites represent the location of a diamond drillhole, cores from which commonly yielded several samples

Even if such fluids are not initially intrinsically gold rich, they likely scavenge a significant metal cargo as they ascend through the crustal greenstone sequences. Additionally, even if such a process seldom directly produced primary gold mineralization, it may have represented a critical enrichment process along long-lived fluid pathways. The extraordinary gold endowment of the areas within and peripheral to the Black Flag Group might indicate that these very shallow systems reflect the most favourable crustal level in terms of (magmatic) gold enrichment. Alternatively, the extraordinary volume of lamprophyre–sanukitoid magmatism in that region might reflect either an extremely efficient translithospheric fluid pathway, or a particularly volatile-rich and fertile lithospheric mantle source, or a combination of all these factors.

The regional distribution of Mafic granites and the composition of felsic volcanic and subvolcanic units, in terms of their ‘enriched’ or ‘unenriched’ characteristics, remain poorly established but potentially significant indicators of gold prospectivity.

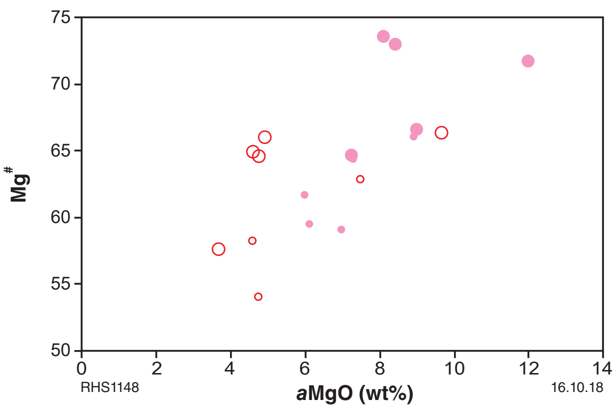

Figure 2. Variation of Mg# with *a*MgO (MgO calculated on an anhydrous basis) for closely spatially associated lamprophyric rocks (open red circles) and associated enriched diorites (sanukitoid = pink circles) from two diamond drillcores taken from the Kambalda region (CD16056A = larger symbols; LD7006 = smaller symbols). In both cases, when spatially associated magmas are independently assessed, lamprophyric magmas have more primitive compositions than the associated sanukitoid and clearly permit a direct genetic relationship

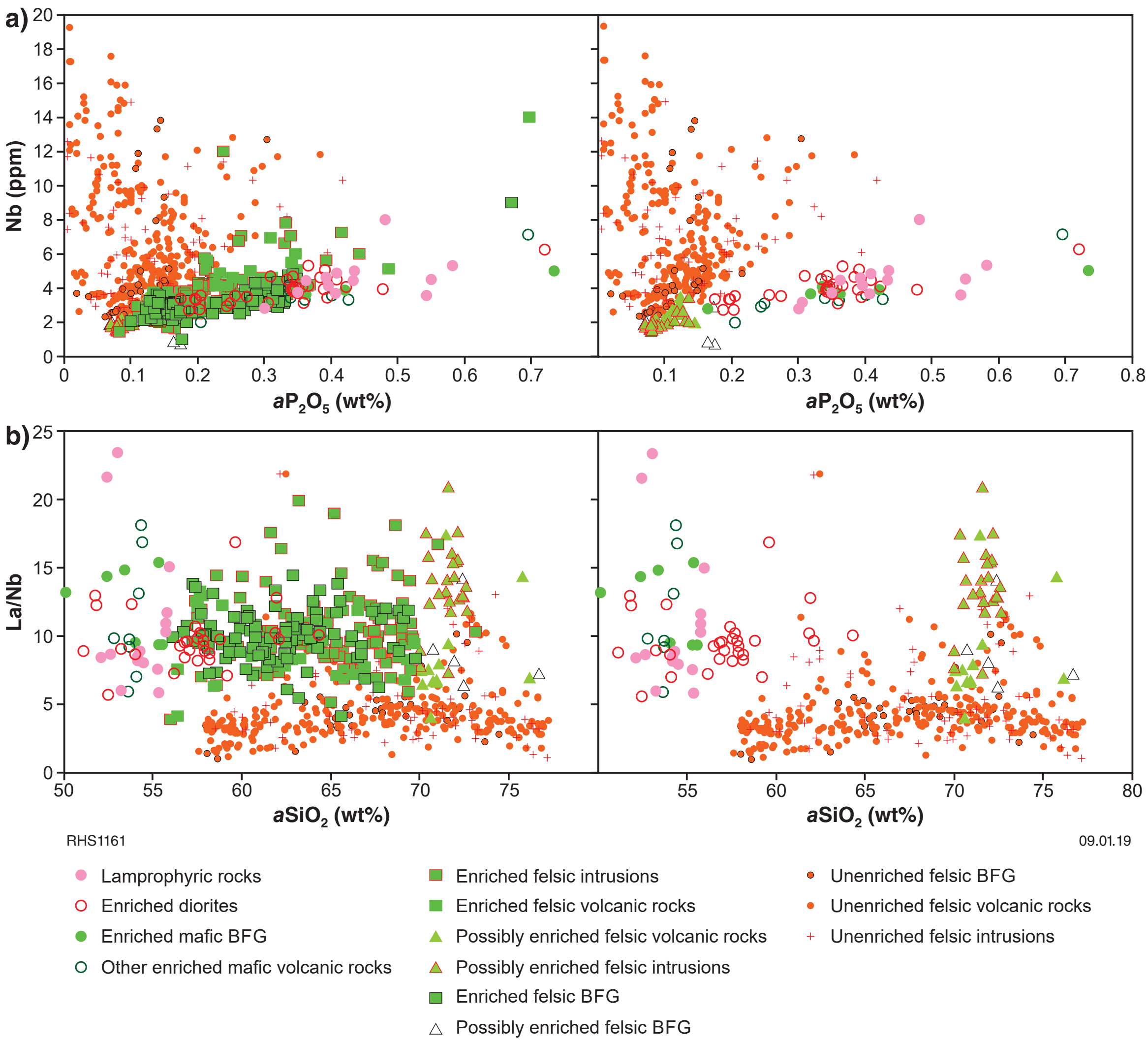

Figure 3. a) Variation of Nb with aP_2O_5 (P_2O_5 calculated on an anhydrous basis); b) variation of La/Nb with $aSiO_2$ (SiO_2 calculated on an anhydrous basis). Plots on the left show all data. Data for the enriched felsic rocks (volcanic and subvolcanic) have been removed from the plots on the right so that the compositional range of the unenriched felsic rocks can be more readily distinguished. BFG, Black Flag Group

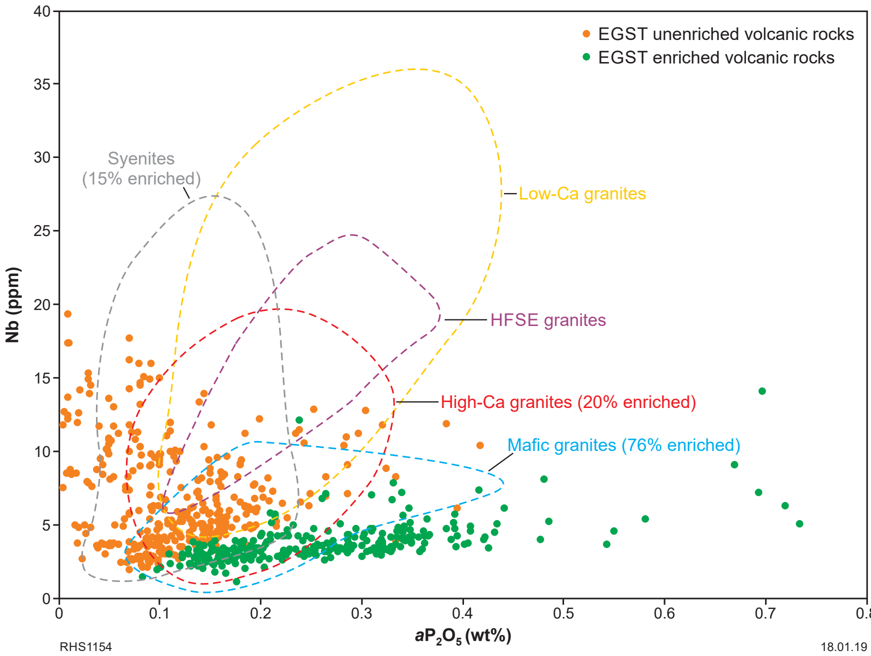

Figure 4. Variation in Nb with aP_2O_5 comparing the enriched and unenriched felsic rocks (volcanic and subvolcanic) with Yilgarn Craton granitic rock groups described by Champion and Sheraton (1997) and Cassidy et al. (2002). Also indicated for some granitic rock groups are the proportions of samples that fall within the field for 'enriched' rocks as defined here. In the case of the Mafic granite group, 76% overlap the enriched volcanic rock field defined by the spread of green circles

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Mineral Systems Atlas — a dynamic approach to the delivery of mineral exploration data

by

S Morin-Ka, P Duuring, L Burley, J Guilliamse and TJ Beardsmore

The premise

An important remit of the Geological Survey of Western Australia (GSWA) is to support mineral exploration in Western Australia by providing pre-competitive geoscience data that reduce the risks related to discovery. Such data are stored in a variety of databases that have varying levels of interconnectedness and ease of querying. Currently, the onus is on the user to locate and download the relevant database(s), then extract appropriate subsets of data for use in prospectivity evaluations and target generation (e.g. Fig. 1a). This approach requires considerable understanding of the structure and content of GSWA data holdings, and for mineral explorers can be a time-consuming, inefficient use of scarce resources that could be better employed testing prospective targets sooner. GSWA recognizes that there is an opportunity to streamline the equitable delivery of pre-competitive geoscience data, by systematically interrogating its own databases to provide tailored derivatives that are of more immediate use to all mineral explorers (e.g. Fig. 1b).

Introducing the Mineral Systems Atlas

The Mineral Systems Atlas is a new online product that collates and delivers map-based geoscience data filtered to be specifically relevant to understanding and exploring for mineral deposits in Western Australia. We adopt a systematic approach to creating content by applying the mineral systems concept advocated by Wyborn et al. (1994) and McCuaig et al. (2010). The premise of this concept is that mineral deposits will only form and remain preserved where there has been a spatial and temporal coincidence of critical earth processes (i.e. geodynamic setting; lithosphere architecture; fluid, ligand and ore component reservoir(s); fluid flow drivers and pathways; depositional mechanisms; and post-depositional processes), and that the occurrence of these critical processes might be recognized from mappable geological features expected to result from them. It is these geological features ('targeting elements' in the parlance of McCuaig et al., 2010) that can potentially be extracted as digital map layers from geoscience datasets, and that may subsequently be used in Geographic information system (GIS)-based prospectivity studies.

We analyse particular mineral systems (as defined by Fraser et al., 2007) to define mappable geological proxies for critical mineralizing processes, drawing on in-house expertise, existing literature and collaborations with subject-matter experts. We then rank these proxies in terms of their robustness as targeting elements, how readily they may be generated from available GSWA databases, and how useful they are at different scales of mineral exploration (i.e. regional, camp, deposit). Structured queries are then created to extract relevant data from one or more statewide GSWA geoscience databases, for those proxies that can be practicably produced (e.g. Fig. 2). These queries operate directly on, and are dynamically linked to, primary GSWA geoscience data sources. No new data are acquired or created, although some information may be reformatted to meet the internal requirements of particular map layers. Furthermore, queries are scheduled to automatically update the derived proxy map layers whenever new data are added to the primary databases. Users may, therefore, be confident that the data layers portrayed in the Mineral Systems Atlas are always current.

Mappable proxies are delivered via an interactive online platform. The online Atlas categorizes map layers by mineral system (based on Fraser et al., 2007), or alternatively by commodity group (as defined in the MINEDEX database), and allows users to view, select and download only those datasets they require. An integral component of the Mineral Systems Atlas is an online guide that documents all aspects of the creation of the constituent map layers, and the relationships between primary and derived data (e.g. Fig. 3). The guide provides descriptions of current metallogenic models for each mineral system, the outcome of the mineral systems analyses to define the potentially mappable geological proxies and the procedures used to generate these layers. Included are query syntax and data dictionaries listing the terms used in specific queries to identify particular geological features in GSWA databases, so that users may adapt and apply the data extraction methodology to their own working environment and proprietary data.

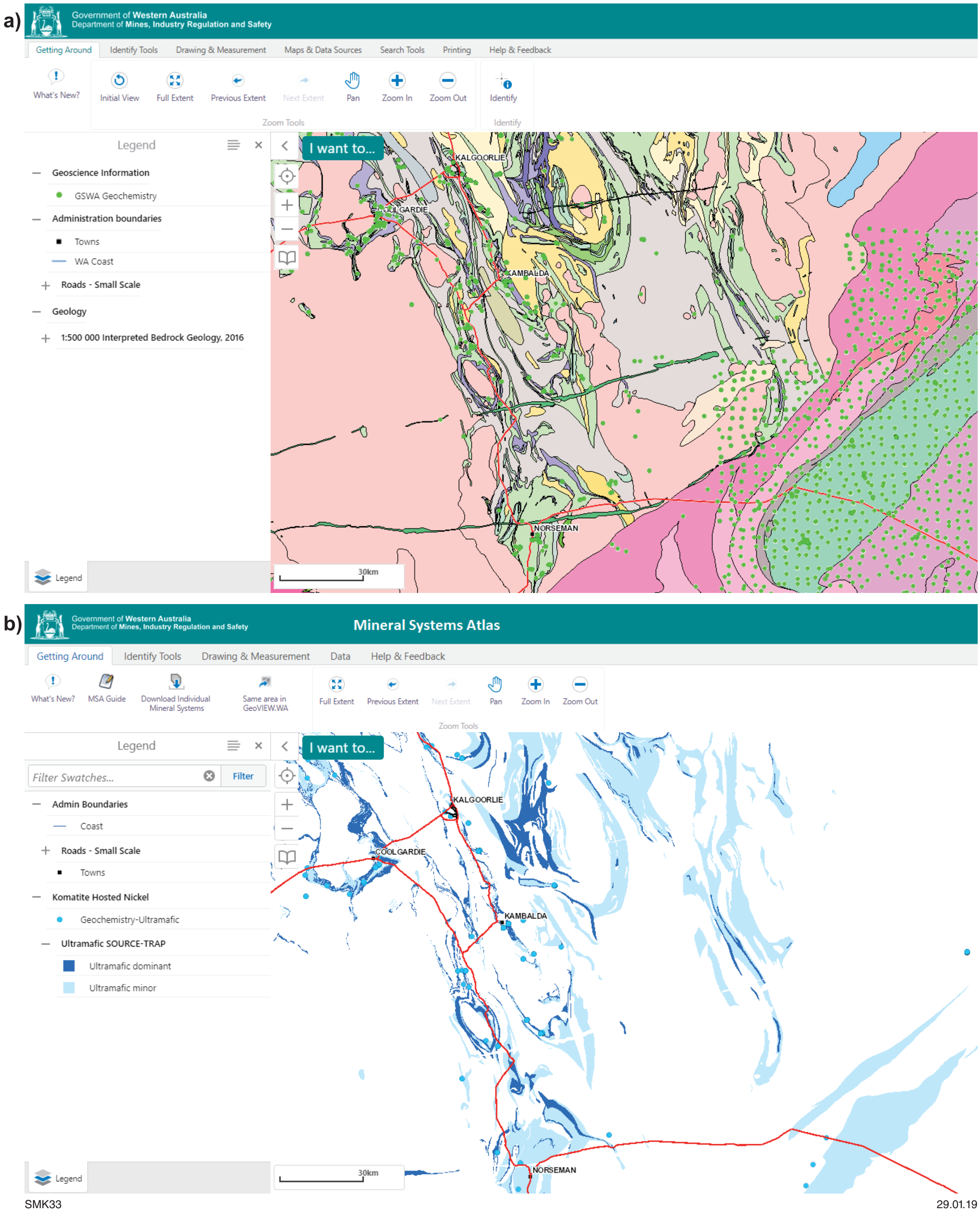

Figure 1. Then and now — an illustration of the difference between the delivery of unfiltered data to stakeholders via GeoVIEW.WA, and providing queried data tailored to a specified mineral systems via the Mineral Systems Atlas: a) statewide 1:500 000 interpreted bedrock geology polygons are displayed for all rock types and GSWA geochemistry samples; b) a new, merged 1:500 000 and 1:100 000 interpreted bedrock geology map has been filtered to show only ultramafic rocks and GSWA geochemistry samples filtered for ultramafic rocks. Both maps are dynamically linked to the same data and are automatically updated as the source data change. Map b) is more relevant to nickel exploration and is better suited as an input for prospectivity analysis

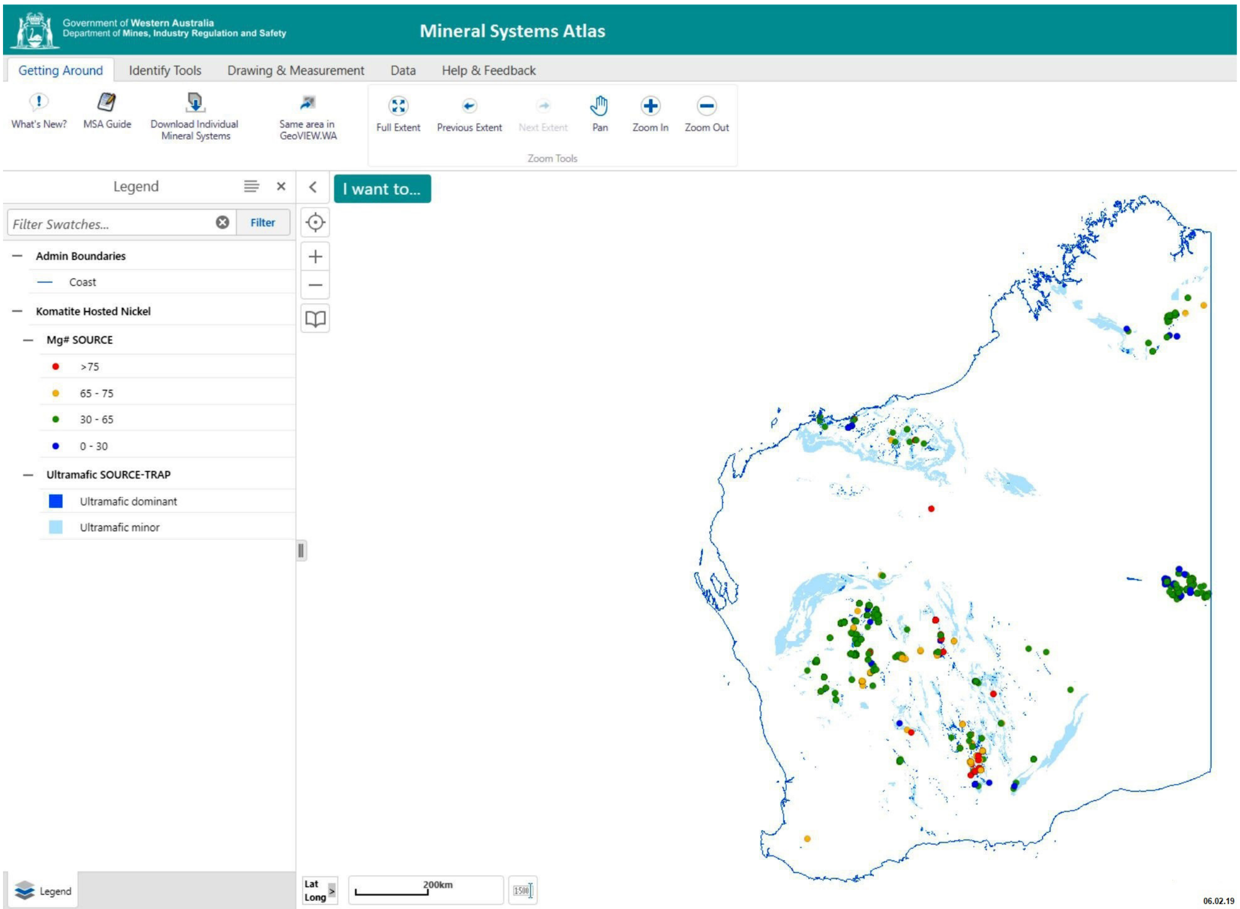

Figure 2. Western Australian geochemistry data have been queried by selecting for ultramafic rocks and then calculating Mg numbers (100 * (MgO% / (MgO% + Fe_2O_3T%)) as defined by Rollinson (1993). Ultramafic rocks are shown in blue

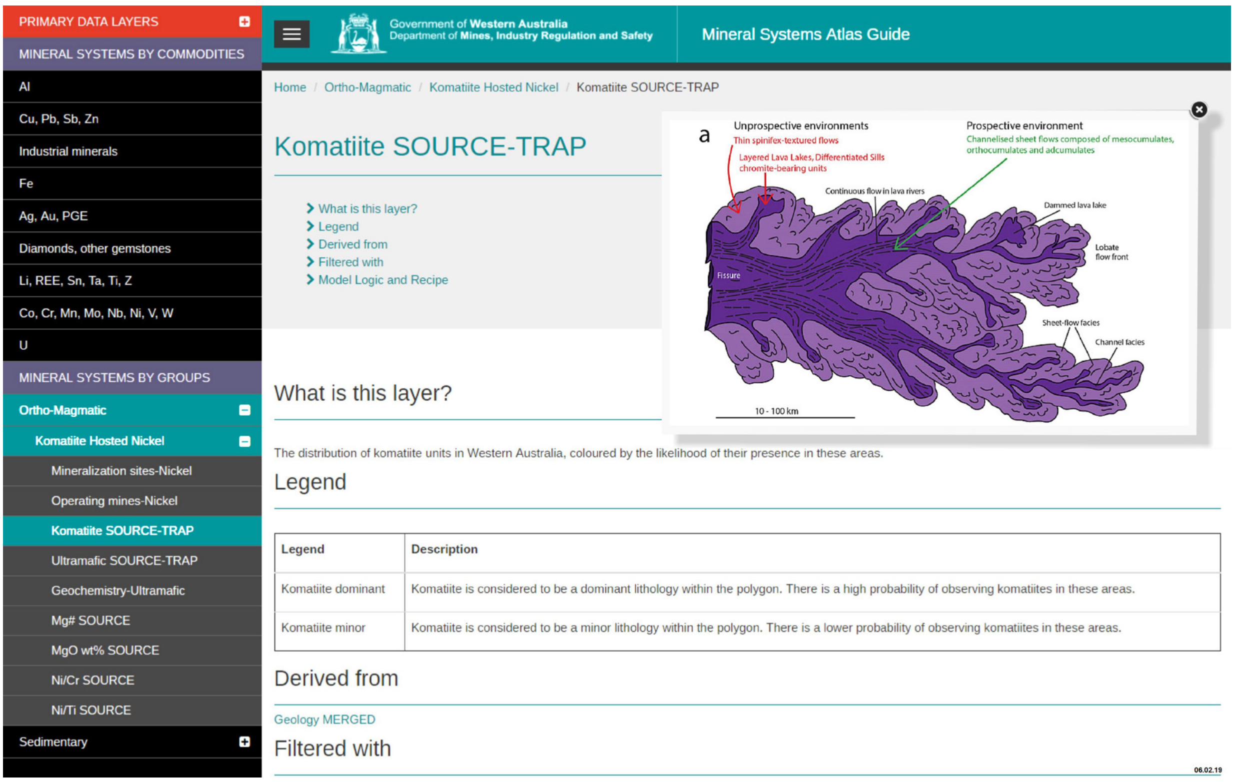

Figure 3. Example description of the komatiite layer with an expanded model of a komatiitic lava flow. The online Mineral Systems Atlas Guide complements the GIS platform by describing the derived data layers, explaining the reasoning behind their inclusion in the specific mineral systems, and documenting their creation via an SQL query of GSWA source data

Population of the Mineral Systems Atlas is at an early stage. Mineral systems analyses have been completed for the economically important komatiite-hosted Ni sulfide and BIF-hosted iron ore deposits, and a selection from the large list of potential geological proxy layers has been created — enough to demonstrate the utility and potential of the Atlas. The modular and hierarchical design of the online platform and user guide will readily permit the addition of new mineral systems and new geological proxy layers as these progressively become available, and there will be close engagement with end-user stakeholders throughout the future development of the Atlas.

An influential tool?

The Mineral Systems Atlas marks a significant step towards streamlining the delivery of pre-competitive geoscience data, and should assist mineral explorers to more efficiently generate and test potential prospects. It will also have a significant influence on GSWA activities. Ongoing effort will focus on expanding Atlas content to include all the major mineral systems and commodity groups in Western Australia, particularly those elements that represent critical and constituent metallogenic processes common to many systems (for instance, those mapping lithosphere architecture as potential channel ways for mineralizing fluid flow, or orogenic [high-energy] events that might have driven mineralizing processes).

The short-term focus will therefore be on generating proxy maps that are realistically obtainable using current datasets. However, not all possible target-element maps defined in mineral systems analyses can necessarily be produced from current data holdings. This requires GSWA to thoroughly examine these maps, with the consequence that any inadequacies will quickly become apparent. For example, required data may be incomplete or entirely absent from databases capable of storing these data. Furthermore, existing databases may not be capable of storing such data, or the appropriate data and their associated database(s) may not yet exist. Awareness of these gaps will inevitably compel GSWA to review and improve its strategies, systems and work programs dealing with data acquisition, management and accession — considerations that might include incorporation of appropriately high-quality third-party geoscience data relevant for Western Australian geology and mineralization.

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Ultrafine soils — the technique, the advances and the application to GSWA regional map products

by

RRP Noble*

Greenfields exploration in Australia is in decline, and the technical challenge of exploring in deeply weathered and covered regions has not been fully addressed, yet exploration success in these areas is critical to the future economy. Commonly, soil sampling is paired with acid digestion and multi-element measurement. This established approach has not changed significantly over the past 30 years — that is, digest the <250 µm or <180 µm soil fraction and analyse the solution for elemental concentrations. In transported cover, the mobile element signature is contained in the smallest size fractions, so we tested the 'ultrafine' clay size fraction (<2 µm) as an improved sample medium for mineral exploration and applied the method to regional orientation studies, including large soil surveys undertaken by the Geological Survey of Western Australia (GSWA).

The M462 Project, which was sponsored by GSWA, the Minerals Research Institute of Western Australia (MRIWA) and industry, recently concluded. This project was conceived to develop and test a new analytical workflow to separate the <2 µm soil and sediment fractions for multi-element analysis, along with other, commonly unutilized physico-chemical parameters that should aid exploration. The project delivered the method, workflow and commercialized platform (UltraFine+ certified trademark pending), and demonstrated our success in experiments, orientation field surveys and new regional geochemical map products for Western Australia.

A series of experiments was conducted to demonstrate the value of using <2 µm fractions for exploration geochemistry. Twenty-seven bulk reference soils were collected in the vicinity of known mineral deposits (importantly, including mainly background areas) that reflect the common soil types of Western Australia. By analysing fine fractions (<2 µm), we generated reproducible, reliable results, with higher concentrations than from the <250 µm fraction (average increase of 100–250%). Key benefits were the reduction of nugget effects (for Au) and the challenges with detection limits in materials that are dominated by quartz sand. Testing submicron fractions showed that although the <0.2 µm fraction was slightly different from the <2 and <0.75 µm fractions, there was not significant additional value. The <2 µm fraction represents the most effective and cost-efficient sample medium to use. The overall method development showed that ultrasonics were not required, a dispersant was critical for solid recovery and that Na-hexametaphosphate (technical or laboratory grade) was the most effective dispersant. The developed method proved the use of a small weight for analysis was effective (0.2 g) and microwave-assisted aqua regia was the best analytical method for Au detection. Our research shows obvious benefits in using fine fractions for Au. Copper and Zn were consistently and abundantly extracted from the fine particle size fraction.

We applied the UltraFine+ workflow to a number of small orientation site studies in Western Australia, and reprocessed archived regional soil samples from GSWA to test the method's potential to improve exploration targeting. The orientation program involved approximately 200 samples from the LEONORA and SIR SAMUEL 1:250 000 Geological Series map sheets, an area that hosts known major Au and base metal deposits. We then applied this approach to the KINGSTON 1:250 000 Geological Series map sheet, analysing a further 300 samples in a largely greenfields region on the Yilgarn Craton margin. There has been little exploration in the region, and the original geochemical survey data was heavily censored due to the dominance of transported regolith dominated by quartz-rich sand. Of most relevance, the study revealed a marked decrease in censored results for Au (~67% to 10% below detection limit; Fig. 1) using historic samples, and re-assaying them enabled us to produce a new geochemistry map of the KINGSTON 1:250 000 Geological Series map sheet.

The new maps show geochemistry, some example indices for mineral exploration, and lithology indicators through cover (Fig. 2), as well as map products of new interpretations using the additional spectral mineralogy proxies and particle size measurements. Adding spectral mineralogy, particle size and other physico-chemical parameters to this style of mapping is valuable, although not commonly done, and is certainly not currently integrated.

The application of the <2 µm particle size separation and the UltraFine+ workflow demonstrate the importance of the additional value from (re-)assaying regional soil and sediment samples to generate new targets and improve regional geochemical maps (Figs 1, 2). This is an exercise that can be applied to new greenfields surveys and, when exploration budgets are lean, to abundant historically collected samples.

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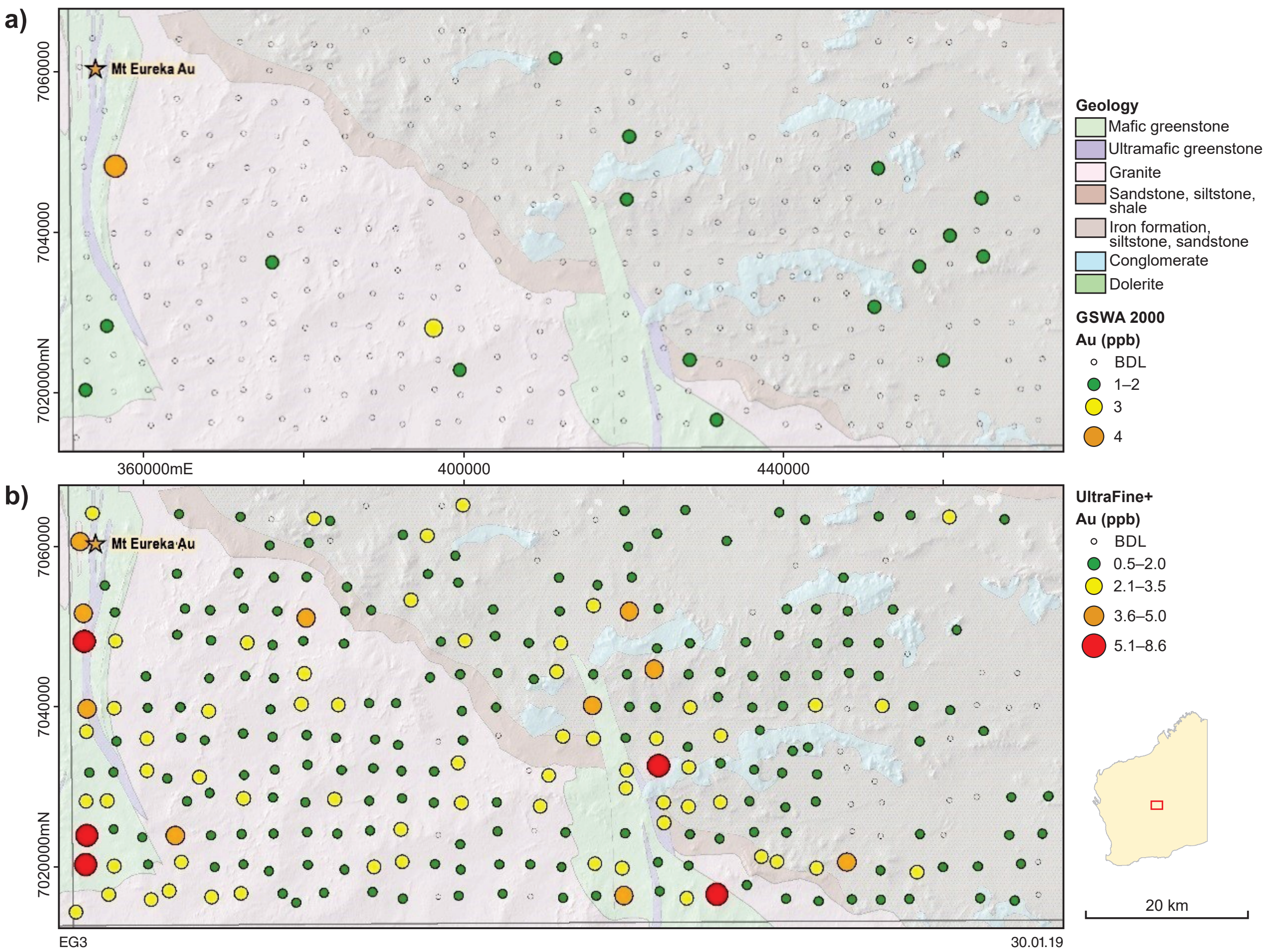

Figure 1. Gold (ppb) in soils on the KINGSTON 1:250 000 Geological Series map sheet: a) original GSWA data with only a few detectable Au values; b) new results from the Ultrafine+ method developed during this MRIWA project using the same samples, clearly showing the vast improvement in Au information. Mt Eureka is the only known small Au deposit in the region (mined in the 1930s). Geology is generalized and based on data from Martin et al. (2014). BDL, below detection limit

The developed workflow (UltraFine+) has been transferred to a commercial laboratory partner (currently Lab West Pty Ltd) and is available to all. We anticipate other laboratories will also offer this service in the near future. The technique was designed to be robust for industry and streamlined enough to be economically viable.

Over the course of the project, we determined a number of additional developments that will ensure this process is the world leader for providing better high-quality data in a useable format for future explorers. The next iteration of this workflow should improve the UltraFine+ method, particularly estimating organic C and building algorithms and machine learning to cloud-process the various data streams. This should be part of the service from commercial laboratories in the future. We envisage a second project of similar size will realize the full potential of the workflow developed in this project over the next few years, and lead to a subsequent improvement to the success rate of greenfields exploration in Western Australia.

The final report (Noble et al., 2018), additional data products and the public data release for the regional maps are hosted in the Department of Mines, Industry Regulation and Safety's eBookshop at <www.dmp.wa.gov.au/ebookshop> and are accessible in GeoVIEW.WA.

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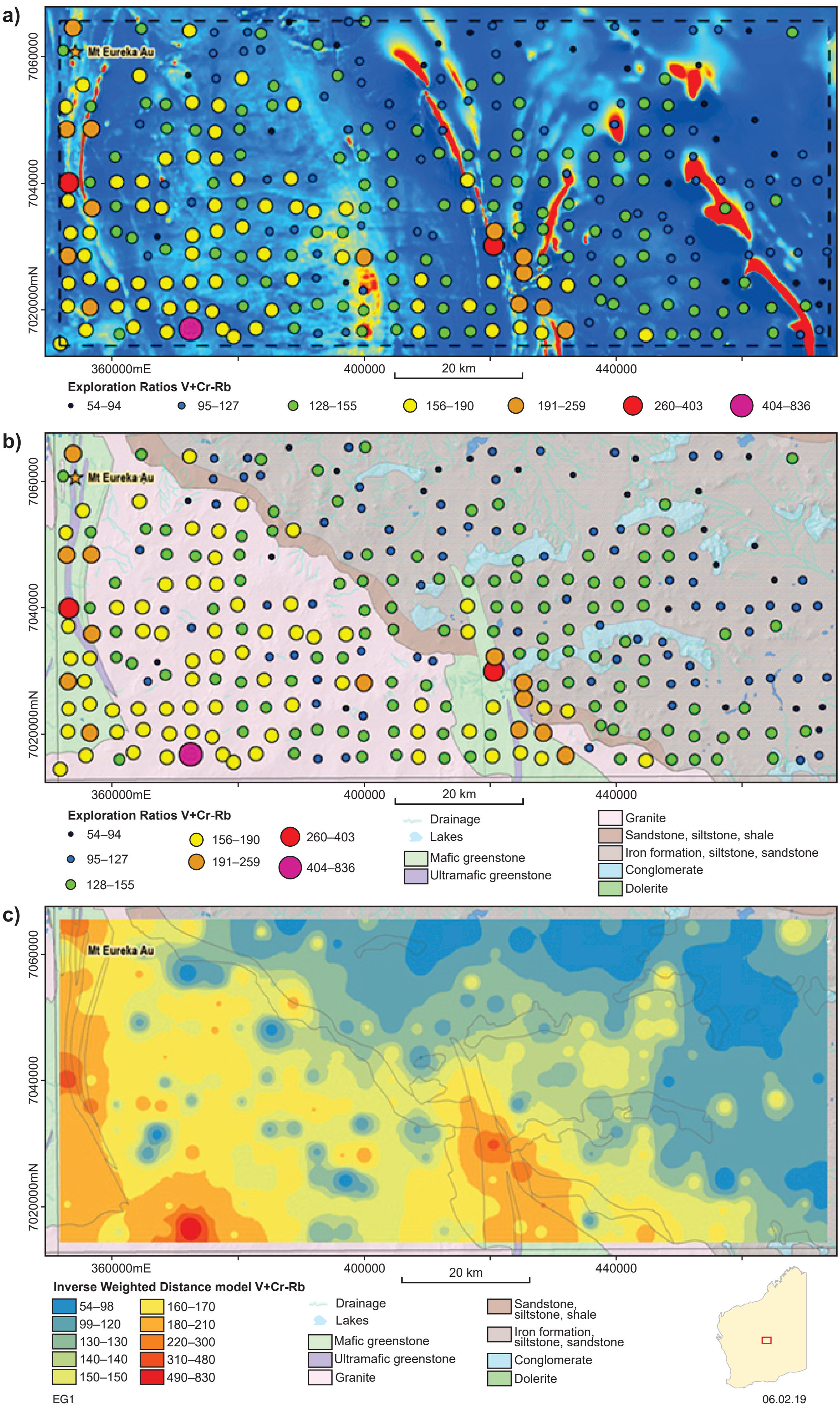

Figure 2. a) Lithology ratio using V, Cr and Rb data from the <2 µm fraction analysis with magnetics underlay; b) the ratio with geology underlay; c) the inverse weighted distance interpolation of this data and the outlines of major geological units underneath showing a very close association. Geology is generalized and based on data from Martin et al. (2014)

Sulfur sources and magmatic sulfide mineralization in the Fraser Zone: insights from mineral prospects

by

A Walker[1,*], K Evans[1], CL Kirkland[1,*], O Kiddie[2] and CV Spaggiari

Introduction

The Albany–Fraser Orogen (AFO) is a Paleoproterozoic to Mesoproterozoic orogenic belt located along the southern and southeastern margin of the Archean Yilgarn Craton (Fig. 1). The AFO contains multiple economic mineral deposits, including Tropicana Au and the Nova-Bollinger Ni–Cu deposits, the latter hosted within the Fraser Zone of the AFO. The Fraser Zone includes the 1310–1283 Ma Fraser Range Metamorphics, a sequence of amphibolite to granulite metamorphic-grade metasedimentary rocks, intruded by significant volumes of gabbroic and granitic rocks (Spaggiari et al., 2011). As the host for the Nova-Bollinger deposit, the Fraser Zone is a prospective area for significant magmatic sulfide mineralization.

The formation of a magmatic sulfide deposit requires sources of both sulfur and metals. The former is frequently assimilated as a component of country rock by the parental mafic melt (Naldrett, 2004), while the latter is usually sourced from a substantial volume of the parental magma itself. Once sulfur has been incorporated into a melt to the degree that it is no longer soluble, an immiscible sulfide phase precipitates into which metals will partition from the silicate melt. Sulfides are present in the Fraser Zone in several forms: pyrrhotite (±chalcopyrite) within metasedimentary rocks; and pyrrhotite, pentlandite and chalcopyrite (±pyrite) within mineralized metagabbros. To better understand magmatic sulfide formation within the Fraser Zone, isotopic tracers can be utilized to track the sources of sulfur and understand how metals have partitioned between the different sulfide phases.

Identifying sulfur sources and Archean sulfur in the Fraser Zone

Sulfur isotope geochemistry is a powerful tool that can fingerprint sulfur incorporated into mineral prospects. Geological processes fractionate sulfur isotopes based on differences in mass (mass-dependent fractionation), with deviations expressed in delta (δ) notation and measured per mil (‰) relative to a reference isotopic ratio (0.0‰; Vienna Canyon Diablo Troilite, VCDT). Mantle-derived sulfur, such as the minimal sulfur content found within a typical mantle-derived melt, characteristically has a $\delta^{34}S$ isotopic signature between –2 and 2‰. Concurrent assimilation of sulfur-bearing crustal material during magmatic emplacement drives the $\delta^{34}S$ isotopic signature of the magma towards a value between the initial $\delta^{34}S$ signatures of both the melt and the assimilated sulfur, depending on the degree of assimilation. By identifying the sulfur isotopic signatures of both mineralized and unmineralized magmatic bodies and crustal sulfur sources, we can identify the sulfur sources involved in mineralization, estimate the degree of assimilation of external sulfur involved in mineralized bodies and potentially highlight unexplored areas in which similar mineralization is likely to be present. Furthermore, sulfur isotope systematics also allow fingerprinting of Archean sulfur. Differences in the Archean atmosphere, relative to present conditions, facilitated mass-independent fractionation of sulfur isotopes via photochemical processes that can be identified by non-zero $\Delta^{33}S$ sulfur isotopic signatures. The presence of mass-independent fractionation within a sulfur source would indicate the presence of an Archean sulfur component, and provide further information on the origin of sulfur-hosting crustal material.

With regard to sulfur isotopes, this study aims to address the following questions: 1) which sulfur isotope ranges characterize the magmatic and sedimentary geology of the Fraser Zone; 2) are these signatures related to (or the absence of) mineralization; and 3) can an Archean sulfur component be identified in the Fraser Zone, as previous radiogenic studies indicate limited evolved Archean input into melts (Kirkland et al., 2011; Smithies et al., 2013). In this work, we present new $\delta^{34}S$ (Fig. 2) and $\Delta^{33}S$ data from weakly mineralized (Plato) through to strongly mineralized (Octagonal) prospects using in situ sulfur isotope measurements from several sulfide phases. Magmatic sulfides from both prospects were analysed, in addition to metasedimentary material from Octagonal to characterize local sulfur sources in the Fraser Zone.

Distinct sulfur isotopic signatures at each of the mineral prospects indicate variable degrees of assimilation of local metasedimentary rocks. Analysis of two samples of sulfide-bearing metasedimentary rock from Octagonal provide a mean sedimentary $\delta^{34}S$ signature of 6.07 ± 1.86‰. A near mantle (1.05 ± 0.85‰) $\delta^{34}S$ isotopic signature characterizes rocks from Plato

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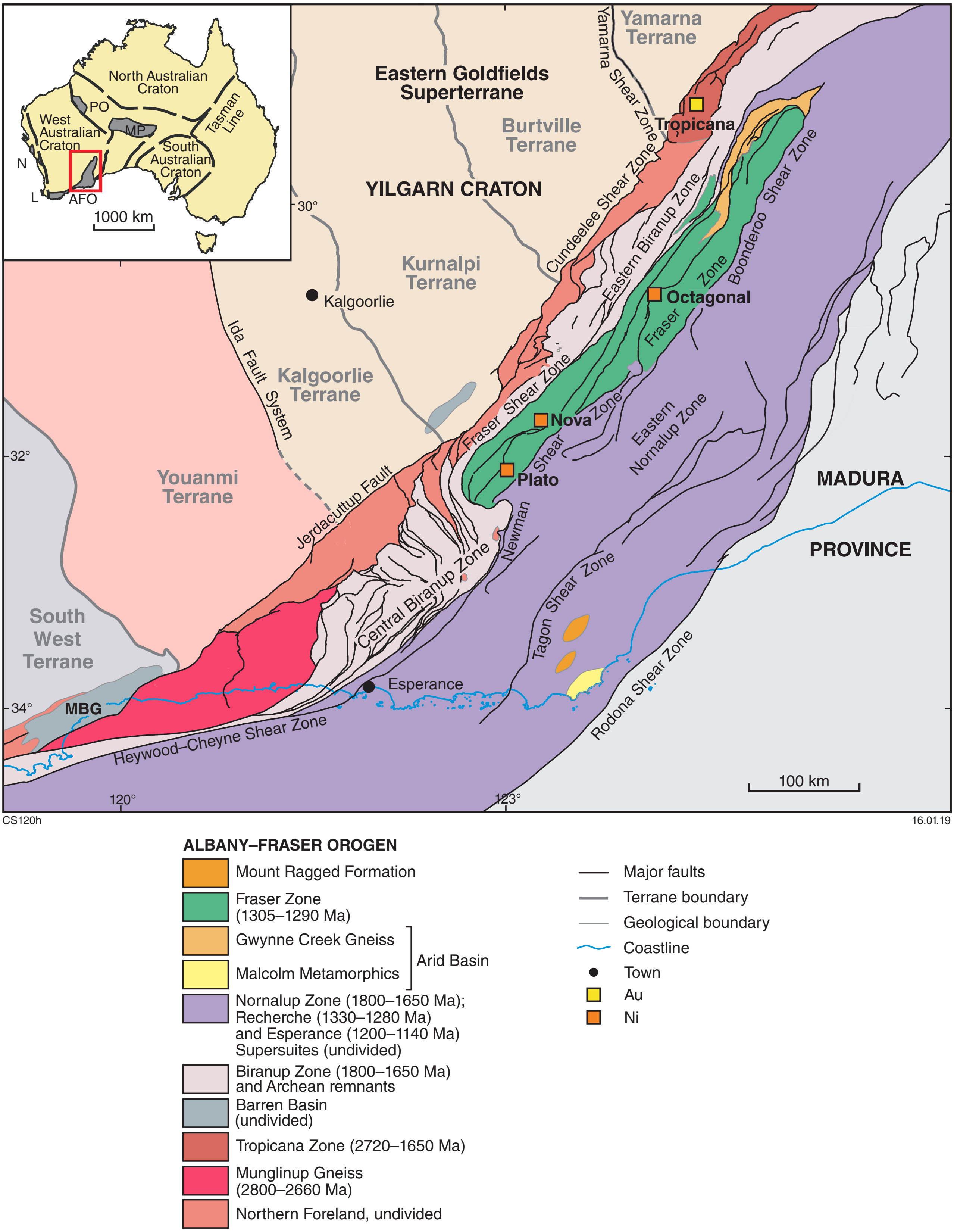

Figure 1. **Simplified geological map of the Albany–Fraser Orogen (modified after Spaggiari et al., 2015). Abbreviations: AFO, Albany–Fraser Orogen; L, Leeuwin Province; MBG, Mount Barren Group; MP, Musgrave Province; N, Northhampton Province; PO, Paterson Orogen**

(Fig. 2), which likely reflects minimal assimilation of external sulfur by Plato parental magmas. In contrast, Octagonal exhibits a more positive $\delta^{34}S$ mean signature of 4.31 ± 0.80‰ (Fig. 2), indicating a greater degree of sedimentary assimilation and mixing between magmatic and sedimentary sulfur sources. These results highlight a coupling between variable assimilation of external sulfur by Fraser Zone magmas and the mineralization present at the prospects studied — sulfides from more mineralized material possess more positive $\delta^{34}S$ sulfur isotopic signatures. However, sulfur contents within mineralized samples exceed the concentrations possible solely through assimilation processes and likely require the involvement of additional processes such as tenor upgrading.

There is no indication of an Archean sulfur component within the material analysed. However, this is at odds with evidence from other isotopic systems and geochemical modelling that strongly suggest an Archean component to the Fraser Zone. Two-component mixing models indicate this discrepancy is unlikely to be due to dilution of Archean sulfur within the parental magmas. Hence, we advocate a decoupling of the sulfur-bearing component from the majority of the Archean sedimentary material incorporated into the Fraser Zone magmas via a process operating in the surface weathering and erosion cycle, where more reactive sulfide phases are removed in preference to resistant minerals such as zircon.

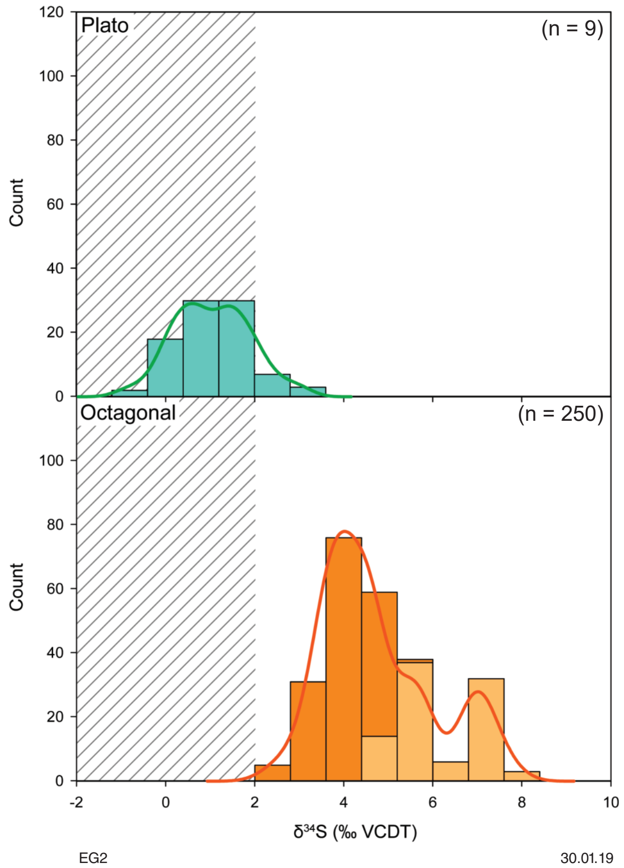

Figure 2. **Histograms illustrating distributions of $\delta^{34}S$ values in samples analysed from the Plato and Octagonal prospects (Kernel Distribution Estimate overlaid). Octagonal magmatic analyses are shown in darker orange and sedimentary analyses in lighter orange. Hashed area indicates accepted range of values for mantle-derived sulfur**

Laser ablation mapping of multiple sulfide phases

Magmatic sulfide deposits concentrate a range of metals beyond those of economic interest (primarily Ni, Cu, Co). Many processes involved in the formation of a deposit affect the partitioning of metals between the constituent sulfide minerals. Characterization of elemental partitioning between sulfides provides insight into the processes occurring during the formation of a deposit. Hence we sought to identify the partitioning of metals between magmatic sulfides by laser ablation mapping, and couple these spatial observations to those processes involved in magmatic sulfide mineralization in the Fraser Zone.

Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) and Tescan Integrated Mineral Analysis (TIMA) were used to map elemental concentrations across sample surfaces composed of multiple sulfide phases. Elemental mapping highlighted Mn concentrations within later, magnetite-infilled fracture networks (Fig. 3) with only minimal levels of Mn within the sulfide material surrounding fractures. The presence of Mn is attributed to transport via fluids within the fracture network during formation. The observation of apparent co-localization between Mn and fracture material provided an excellent opportunity to apply a novel, quantitative statistical analysis to quantify the strength of this spatial relationship.

Application of co-localization analysis to elemental maps

Co-localization requires both co-occurrence and correlation — co-occurrence is the spatial overlap of two datasets, whereas correlation is not only overlap but co-distribution of datasets in proportion to one another within and between structures (Dunn et al, 2011). Co-occurrence and correlation were assessed using Mander's Colocalization Coefficient (MCC) and Pearson's Correlation Coefficient (PCC), respectively. Analysis was undertaken on spatial datasets describing distributions of elements and fracture networks on two samples of magmatic sulfide breccia from the Octagonal prospect. A range of elements exhibiting different distributions was selected to test the robustness of the technique. Our analysis reveals a statistically significant relationship between the distribution of fractures and the distribution of Mn, in which Mn is co-localized with the fracture material. Fluid flow and consequent remobilization of metals via fracture networks syn/post-mineralization within a deposit is a means by which metal tenor may be upgraded. Alternatively, pervasive and prolonged fluid alteration might also destroy a deposit, with remobilization stripping and dispersing metal content from once-economic horizons.

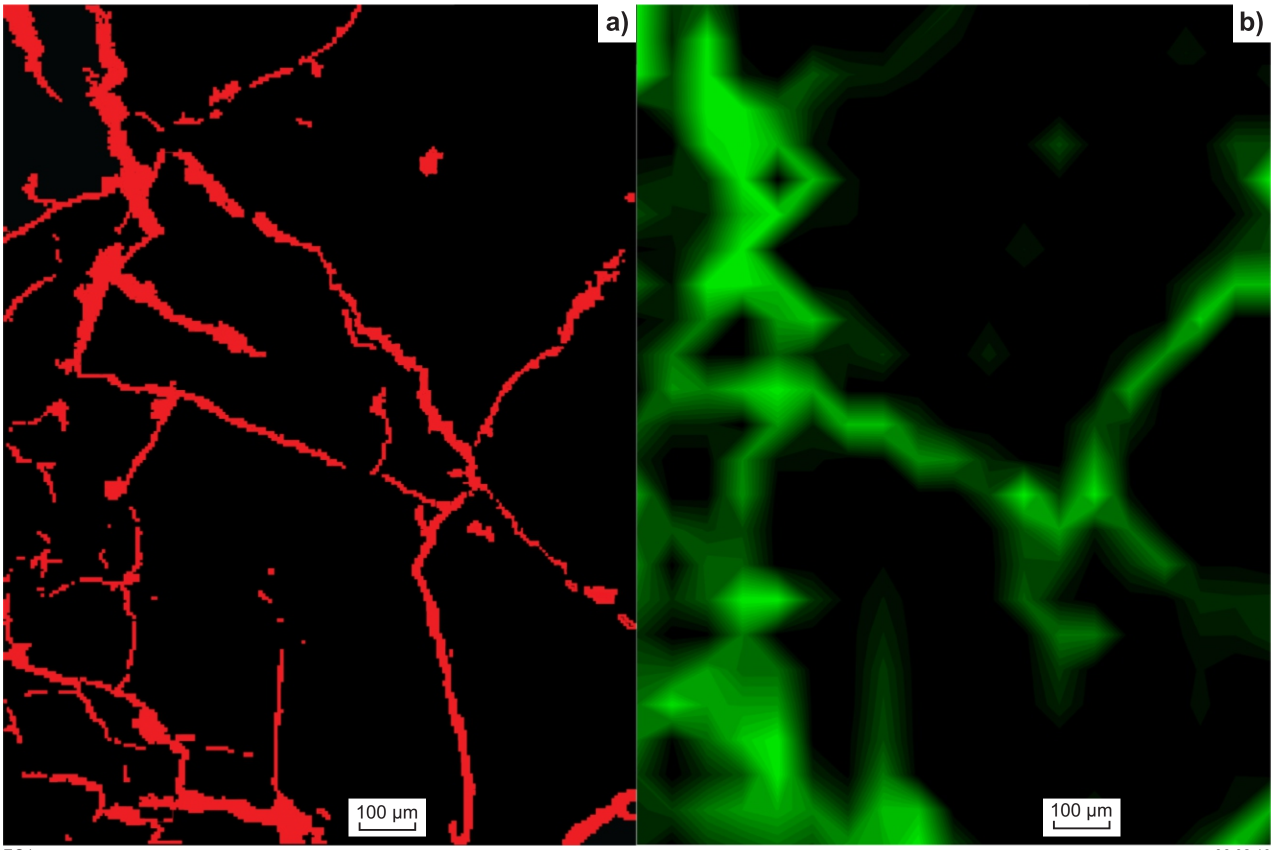

Figure 3. Elemental mapping images: a) the fracture network (in red) across the analysed surface of sulfide breccia GSWA 219070; b) elemental map illustrating the distribution of Mn across the sample surface. Higher green intensity indicates higher Mn concentrations. Images were overlaid for Mn co-localization analysis

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Application of innovative geochronology techniques in geoscience mapping and exploration

by

BIA McInnes*

The John de Laeter Centre (JdLC) at Curtin University hosts $35 million in high-precision microanalytical and characterization facilities that support basic and applied research. The Centre is named after its founder, John de Laeter (1933–2010), a physicist who applied mass spectrometry techniques to quantitatively understand the origin and evolution of the Universe. In collaboration with Alec Trendall at the Geological Survey of Western Australia (GSWA), Prof de Laeter established a geochronology capability at Curtin University that would permit a quantitative understanding of the geology of Western Australia.

A key milestone for the collaboration was the installation of a sensitive high-resolution ion microprobe (SHRIMP) for zircon U–Pb geochronology in 1993, which eventually led to the development of additional isotope capabilities relevant to geoscience research (e.g. $^{40}Ar/^{39}Ar$, $^{187}Re–^{187}Os$, $^{87}Rb–^{87}Sr$, U–He, Pb–Pb, Sm–Nd, Lu–Hf). In 2013, Curtin University amalgamated its sample preparation, electron microscopy and mass spectrometry capabilities within the JdLC in order to increase efficiencies in instrumentation management and analytical workflow. The purpose of this talk is to promote awareness of the applied research capabilities that are now available to industry and government geoscientists in Western Australia.

Geochronology of mineral systems

Zircon U–Pb geochronology using the SHRIMP has played an important role in the geological mapping of granite–greenstone terranes of Western Australia. GSWA uses the JdLC SHRIMP facility to analyse between 60 and 90 samples each year and has published about 1550 Geochronology Records since 1995 (Fig. 1).

However, zircon can rarely be directly linked to ore formation; therefore other minerals that incorporate U during ore deposition may need to be investigated. The rare earth element (REE) phosphates monazite and xenotime have proved particularly useful in determining the absolute timing of orogenic gold formation in the Yilgarn Craton (McNaughton et al., 2005). Vielreicher et al. (2015) used this technique to determine that Kurnalpi Domain gold ores were about 20 million years older than similar orebodies formed about 100 km distant in Kalgoorlie at around 2640 Ma (Fig. 2). The difference in ages is thought to reflect the timing of orogenic processes linked to the westward accretion of granite–greenstone terranes onto the eastern Yilgarn Craton.

The direct dating of ore minerals can also be applied in geochemical exploration. For example, Sn anomalies detected in geochemical surveys may indicate the presence of cassiterite (SnO_2) derived from granite-related Sn–W mineralization. Due to its mechanical and chemical stability, cassiterite can survive transport and weathering and is commonly recovered during heavy mineral sampling campaigns. The incorporation of U and relative exclusion of Pb during crystallization makes this ore mineral a good candidate for direct U–Pb dating of Sn–W mineralization. As an example, Figure 3 shows an age comparison between detrital cassiterite (c. 1812 Ma) and adjacent granite country rocks (c. 1650 Ma) in the Birrindudu region. The distinct age difference sterilizes the granite as a Sn–W exploration target, and suggests a more distal (or eroded) provenance.

The $^{187}Re–^{187}Os$ system is another example of using isotope methods to determine both the age of formation of ore deposits and the provenance of metals (McInnes et al., 2008). Following a successful demonstration of the technique on massive sulfide ores in Russia (Tessalina et al., 2008), a team from the JdLC was funded (MRIWA 446) to investigate the application of the technique at volcanic-hosted massive sulfide (VMS) deposits in Western Australia. The results of this work (Barrote et al., 2019) are highly encouraging in that they have successfully dated both the massive sulfide ore (c. 2705 Ma) as well as black shales (c. 2705 Ma) overlying the Nimbus Zn–Pb–Ag–Au deposit. Both ages are within error of zircon U–Pb ages for a dacitic volcanic rock hosting stringer sulfide mineralization at Nimbus (c. 2704 Ma; Hollis et al., 2017).

Geochronology of regolith materials

Perhaps more than any other continent, Australia has been shaped by the forces of chemical weathering. Regolith materials provide a time-integrated record of the weathering process, and particularly of the periods

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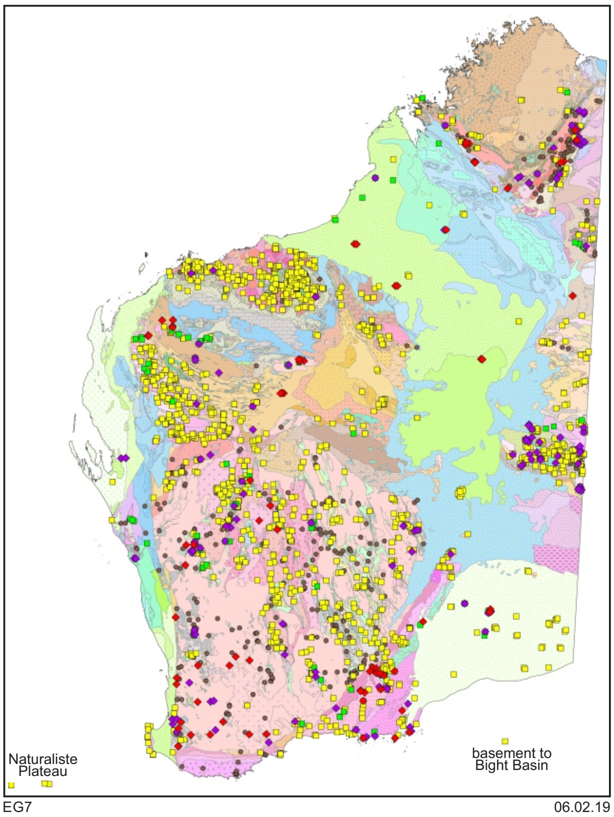

Geochronology sample locations, January 2019

New results and data in preparation:
- GSWA, new samples dated in 2018 (n = 90)
- GSWA, in preparation (n = 158)

Published data
- GSWA, published in 2017–18 (n = 92)
- GSWA, published 1995–2017 (n = 1436)
- Geoscience Australia data

Figure 1. **GSWA geochronology sample locations between 1995 and 2019. Analyses by Geoscience Australia are also shown. GSWA analyses were conducted using the SHRIMP in the JdLC at Curtin University (GSWA, 2019)**

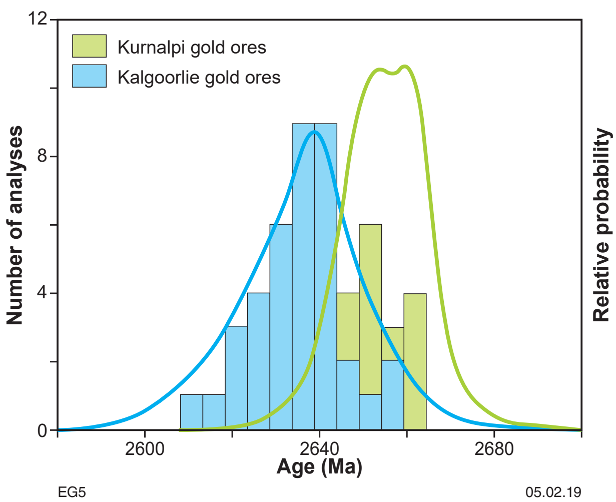

Figure 2. **Monazite and xenotime U–Pb ages from gold ores in the Kalgoorlie and Kurnalpi regions (Vielreicher et al., 2015)**

of relative groundwater abundance. The passage of groundwater over zones of economic mineralization increases the potential for soluble ore elements to be distributed over a wide area. Understanding the absolute timing of regolith formation, particularly where the regolith contains chemical anomalies, is therefore important in both exploration targeting and understanding the Australian climate record.

Goethite, hematite and maghemite are ubiquitous mineral phases occurring in the regolith. Multiple studies over the last decade have demonstrated that the (U–Th)/He isotope system can be used to determine the age of regolith materials (Pidgeon et al., 2004; Shuster et al., 2005; Wells et al., 2018) as well as the economically important channel iron deposits of Western Australia (Heim et al., 2006; Danišík et al., 2013).

A recent application of the (U–Th)/He technique on Fe-oxide pisolites and fragmental duricrusts at the Boddington gold mine (Wells et al., 2018) found evidence for episodic regolith formation from 5.8 to 1.0 Ma (Fig. 4). These ages are comparable to (U–Th)/He ages of the Toodyay pisolites (Pidgeon et al., 2004), suggesting that the processes of regolith formation and/or modification throughout the Darling Range were broadly synchronous. The relative youthfulness of regolith formation in the Darling Range is a remarkable finding, and further regolith dating studies are necessary to determine whether this is geographically unique.

Conclusions

Over the past 30 years, a series of deep collaborations between government, industry and academia in the application of mass spectrometry and isotopic analysis has dramatically changed the geological map of Western Australia and our understanding of its mineral systems. The SHRIMP facility, established in 1993 by Curtin University, The University of Western Australia and GSWA has produced almost 900 research publications which have been cited over 88 000 times (JdLC, 2019). The announcement by the Federal Government in January 2019 that it will provide $5 million in new funding (AuScope, 2019) to replace the 25-year-old SHRIMP at Curtin University augurs well for continued partnerships leading to new innovations in isotope geoscience and a better understanding of Western Australia's geology and mineral endowment.

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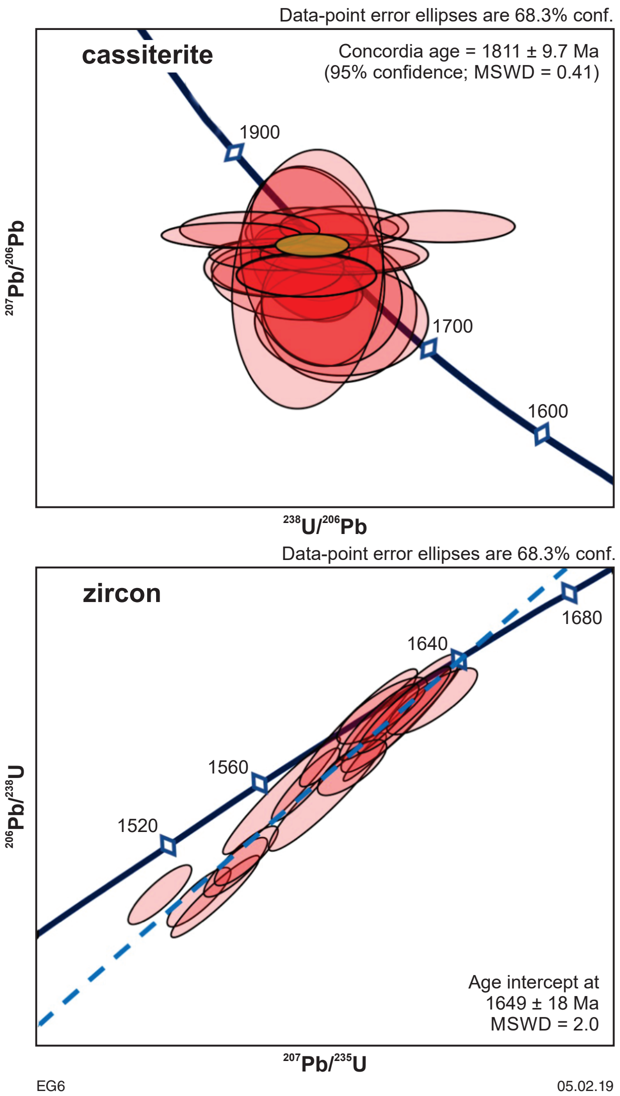

Figure 3. **SHRIMP U–Pb dating of detrital cassiterite (SnO_2) can be used to determine the age of its original Sn–W granite host. In this example from the Birrindudu region, the zircon age of the adjacent granite is too young to be the source of the detrital cassiterite**

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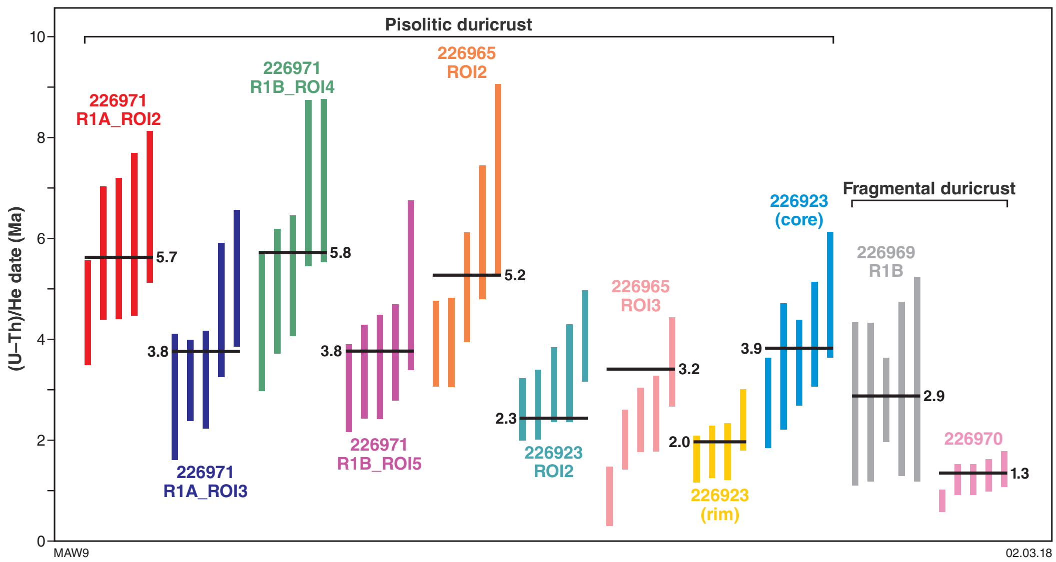

Figure 4. **(U–Th)/He dates (Ma) for Fe-oxide duricrust samples from the Boddington gold mine. Each coloured bar represents individual replicate measurements; 'size' (height) is measurement error (±1 sigma). Black horizontal bars indicate the average (U–Th)/He age (in Ma) assigned to each duricrust sample (Wells et al., 2018)**

This abstract is part of the session of 10-minute talks

The Eastern Goldfields high-resolution 2D seismic survey

by

SHD Howard, I Zibra and K Gessner

The Department of Mines, Industry Regulation and Safety manages the Western Australian Exploration Incentive Scheme (EIS) — a State Government initiative that aims to encourage exploration in Western Australia for the long-term sustainability of the State's resources sector. A major component of EIS is the acquisition of new geophysical data throughout the State, with programs managed by the Geological Survey of Western Australia (GSWA). As part of EIS, GSWA plans to acquire six high-resolution 2D seismic reflection traverses in the Eastern Goldfields for a total linear coverage of 250–300 km. Acquisition is anticipated to commence in February 2019, along sections of roads and tracks between Broad Arrow and Kambalda for completion (i.e. release of data and results) no later than November 2019 (Fig. 1). The objective of the project is to provide mineral explorers in the region with subsurface information in a depth range of about 300–5000 m to complement information from other sources, and to delineate areas that might be suitable for 3D seismic surveys for mineral exploration and targeting.

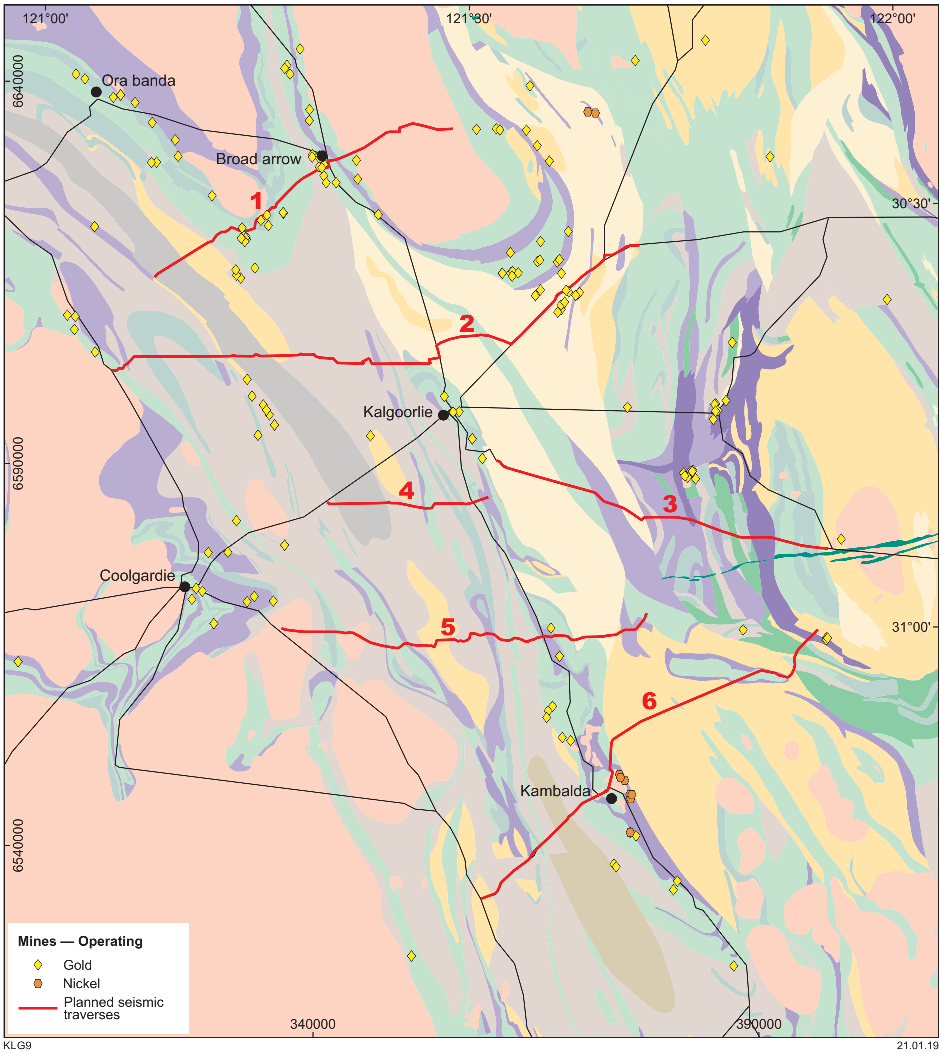

Figure 1. **Proposed locations of high-resolution seismic lines for the Eastern Goldfields survey, overlain on the 1:500 000 State interpreted bedrock geology map**

This abstract is part of the session of 10-minute talks

Capricorn Orogen passive seismic array

by

RE Murdie, H Yuan[1,2], M Dentith[1], SP Johnson and K Gessner

The study of incoming seismic waves from teleseismic earthquakes can be used to investigate the deep structure of the Earth's crust and upper mantle. Resolving the deep crustal structure and locating potential mantle-tapping structures is critical for understanding the metallogeny of mineral deposits at the surface. From 2014 to 2018, a network of 83 seismic monitoring stations was progressively moved across the Capricorn Orogen. This Exploration Incentive Scheme (EIS)-funded survey was intended to complement the previous deep crustal seismic reflection lines, and although the resolution was lower, the survey covered the majority of the orogen and provided different geophysical information.

Results already available from studies of receiver functions provide the depth to Moho and average composition of the crust for the orogen. The distribution of more felsic crust and a deeper Moho outline the extent of the Archean Glenburgh Terrane in the central part of the orogen. Common conversion point (CCP) studies provide a view of compositional layering in the crust, and have led to a revised interpretation of the 10GA-CP2 seismic reflection line (Fig. 1). Intriguing features within the upper mantle obtained by bodywave tomography have yet to be interpreted within the context of the tectonic evolution of the orogen.

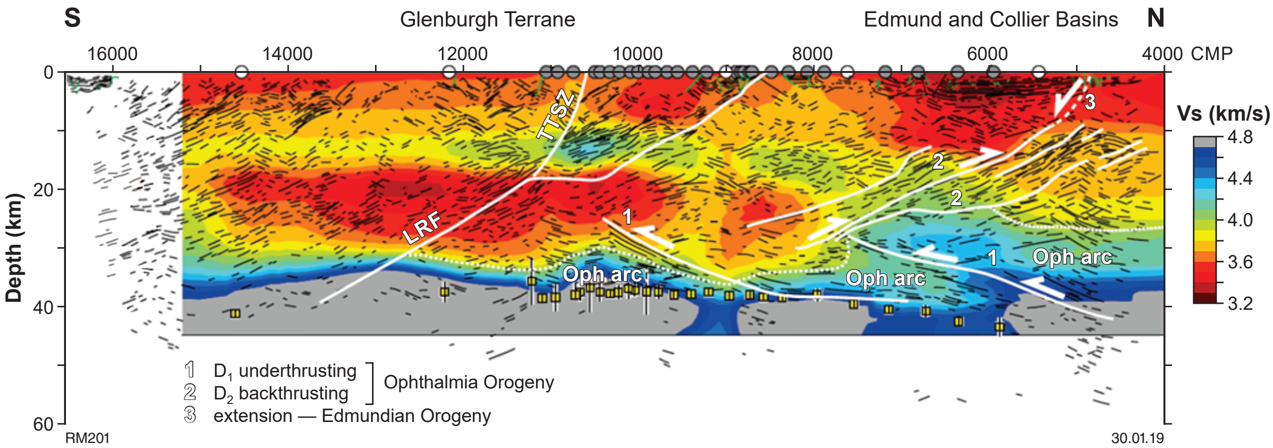

Figure 1. **Ambient noise profile of shear wave group velocity (Vs) along the 10GA-CP2 line, overlain by black line work representing the interpretation of 10GA-CP2 and a new interpretation of the tectonic features in white, as proposed after examination of the results from receiver function and ambient noise analyses. Yellow squares with error bars are depth to Moho as indicated from receiver function analysis. Grey and white circles show the position of seismometers. Abbreviations: LRF, Lyons River Fault; TTSZ, Ti Tree Shear Zone; Oph, Ophthalmia; CMP, common mid-point**

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This abstract is part of the session of 10-minute talks

Compilation of the 1:500 000 State regolith map of Western Australia

by

S Jakica and N de Souza Kovacs

The Geological Survey of Western Australia (GSWA) aims to create a seamless 1:500 000 regolith–landform digital map layer of Western Australia. This will be available in GeoVIEW.WA and will complement the current State 1:500 000-scale interpreted bedrock geology map. The layer is being compiled in two stages. The first, which covers the northern half of the State, north of the 25ºS parallel, was released in early 2019 (Fig. 1). The second, which covers the remainder of the State, is planned for release in December 2019.

Regolith geology from existing 1:100 000 and 1:250 000 Geological Series map sheets has been compiled to produce a seamless digital regolith–landform coverage. The original line work was modified in order to produce a compilation suitable for viewing at 1:500 000 scale. This included the aggregation of small polygons with the same code into larger polygons, elimination of small polygons and simplification of polygon shapes using cellular automata model (GeoScalar plug-in for ArcGIS). Following this, manual editing was required for edge-fitting and topology cleaning to improve the polygon line work and comply with cartographic scale standards. The coding of regolith polygons follows the GSWA regolith classification scheme (GSWA Record 2013/7) with the addition of a suffix representing major geomorphologic physiographic provinces across the State (Fig. 1). Earlier generations of map products that did not conform to the current GSWA regolith classification scheme were recoded accordingly. The codes consist of a primary code (landform and landform qualifier), secondary code (compositional information) and physiographic province suffix. For the scale of this product, tertiary codes (parent rock or cement) were deemed too detailed and were rolled up into higher level codes.

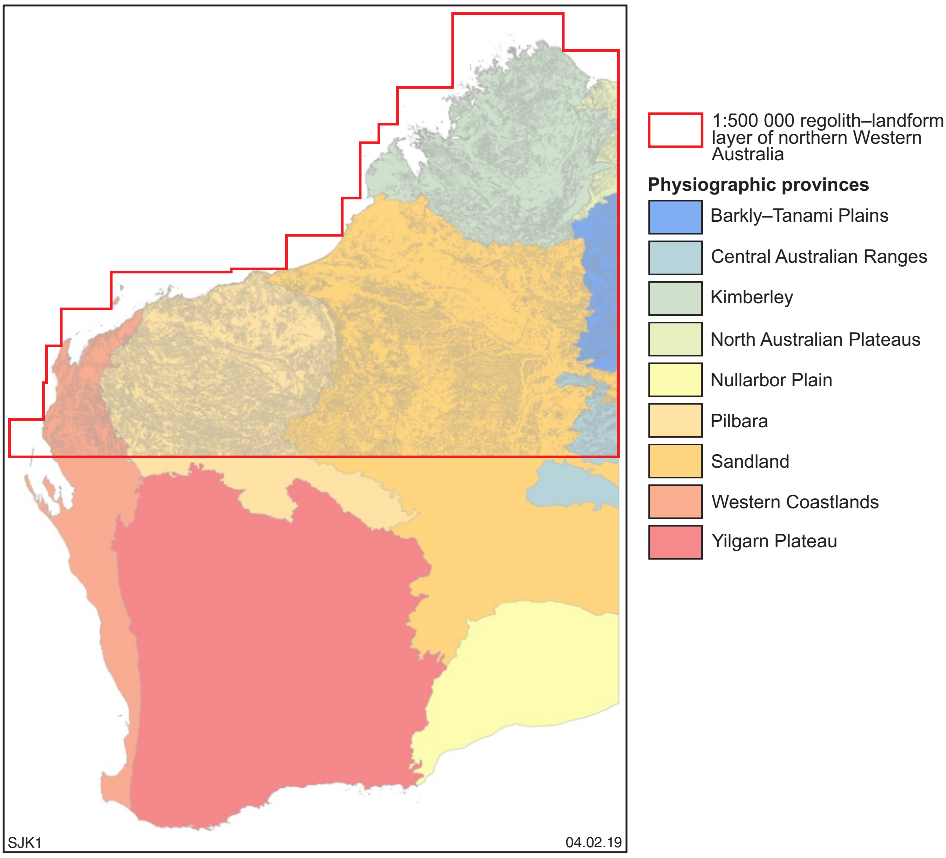

Figure 1. Simplified map showing the distribution of physiographic provinces across Western Australia, and the outline of released 1:500 000 regolith–landform polygons for the northern half of the State

This abstract is part of the session of 10-minute talks

The Abandoned Mines Program

by

I Mitchell

Mining has occurred in Western Australia for more than 150 years resulting in thousands of abandoned mine features across the State, such as shafts, costeans, large pit voids and waste rock landforms. The Abandoned Mines Program (AMP) was made possible following the enactment of the *Mining Rehabilitation Fund (MRF) Act 2012* in July 2013. The MRF provides a source of funding to address abandoned mine features in Western Australia.

The AMP was formally established following the release of the Western Australian Government's Abandoned Mines Policy in January 2016. The Department of Mines, Industry Regulation and Safety selected four pilot sites to be rehabilitated/managed to set up and test the processes and procedures required to achieve the program's objectives. This presentation will summarize the status of the pilot sites.

This abstract is part of the session of 10-minute talks

New directions of metamorphic studies at GSWA

by

FJ Korhonen, SP Johnson, IOH Fielding and SS Romano

Over the last few decades, methods have been refined to unravel the depth, thermal, temporal and deformational history of geological terranes. Detailed observations at the map, hand sample and thin section scales can now be integrated with elemental and isotope data, and inverse and forward phase equilibria modelling, to retrieve more precise pressure (P)–temperature (T)–time (t) data from rock samples. We now apply a comprehensive and standardized approach to metamorphic studies across Western Australia. Modern techniques that we routinely use to quantify P–T conditions include conventional and trace element thermobarometry, as well as phase diagrams. These diagrams use internally consistent datasets of the thermodynamic properties of minerals, fluids and melts with activity–composition models for these phases. A major advance in applying phase equilibria modelling to natural rocks is using isochemical phase diagrams (pseudosections) to explore the assemblages and reaction sequences for a particular composition. These data can be integrated with the dating and composition of accessory phases, such as monazite, that are now analysed in situ to preserve their microstructural setting (Fig. 1). In this way, age results can potentially be linked with the stability of specific major rock-forming minerals. Our aim is to obtain robust P–T–t constraints from critical data points in order to generate a statewide metamorphic map and database.

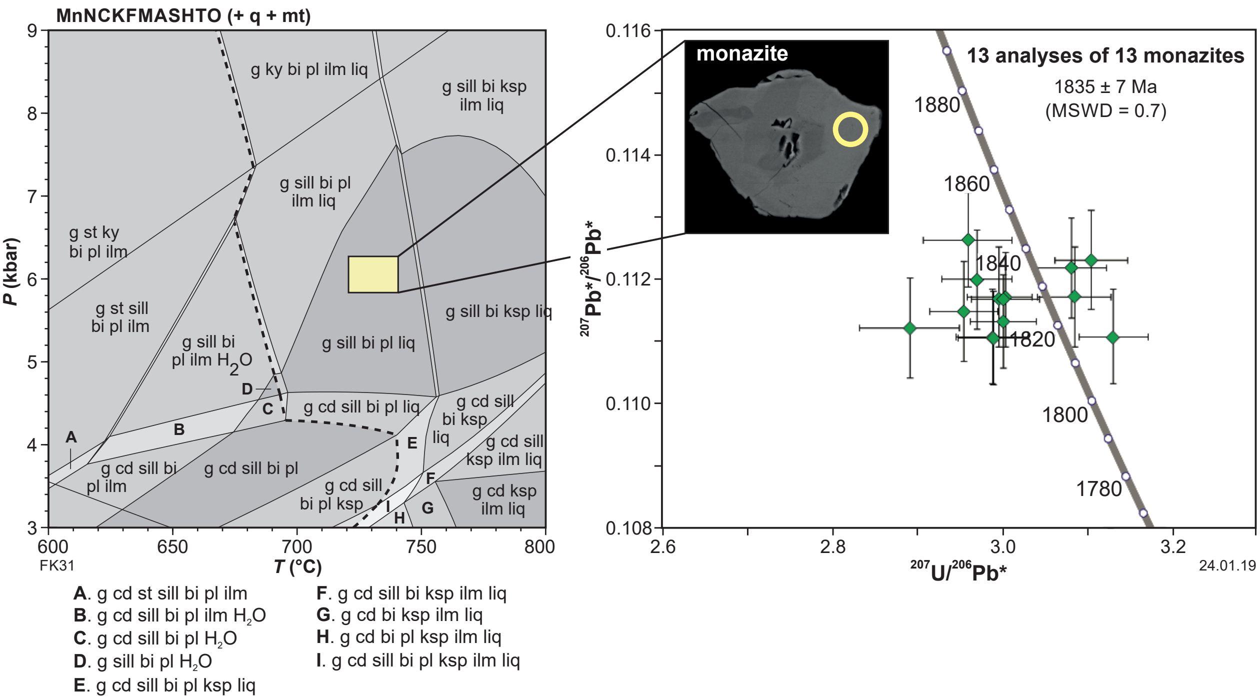

Figure 1. **P–T pseudosection and U–Pb analytical data for metamorphic monazite (backscattered electron [BSE] image shown inset). Monazites were analysed in situ, where textural relationships demonstrate that they form part of the peak metamorphic assemblage, thus providing a direct date for high-grade metamorphism**

This abstract is part of the session of 10-minute talks

Depth and composition of basement under the Carnarvon Basin — updated SEEBASE model

by

CM Thomas and G Sanchez*

Despite the many exploration successes in the offshore Carnarvon Basin, exploration in the onshore portion of the basin is hampered by sparse good-quality seismic data, which has led to many unknowns, including depth to basement and structural configuration. To help address this, Frogtech Geoscience was commissioned to update the SEEBASE (Structurally Enhanced view of Economic BASEment) grid over the Carnarvon Basin within the Western Australian jurisdiction, and to provide an interpretation of underlying basement composition. Input data included the latest gravity and aeromagnetic datasets (Fig. 1), Geological Survey of Western Australia seismic interpretations, published cross-sections and drillhole data. The Exploration Incentive Scheme (EIS)-funded 2018 Carnarvon Basin SEEBASE sees significant improvement in resolution compared to the 2005 OZ SEEBASE version.

Deliverables include a final Report, which details the methods and datasets used for interpretation of basement depth and lithology, and an ArcGIS project containing: SEEBASE grid, sediment thickness grid, processed and filtered gravity and aeromagnetic grids, crustal thickness grid, depth to Moho grid, stretching factor map, basement thickness grid, interpreted basement terrane and composition maps. The Report and ArcGIS project are available via the Department of Mines, Industry Regulation and Safety's eBookshop at <www.dmp.wa.gov.au/ebookshop> and on a USB.

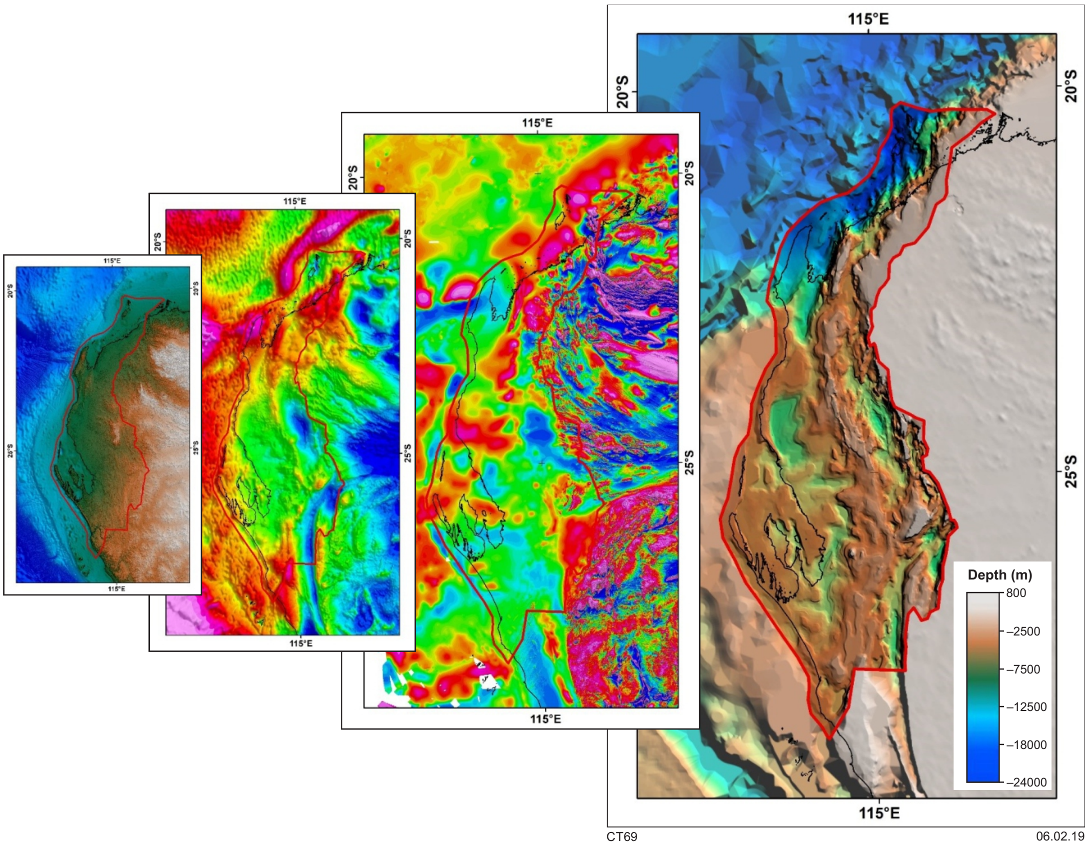

Figure 1. **2018 Carnarvon Basin SEEBASE grid (depth to economic basement, far right) and primary grid datasets used in its construction. Maps left to right: digital elevation model, Bouguer gravity, total magnetic intensity, 2018 Carnarvon Basin SEEBASE grid in project area (red polygon) compared to 2005 OZ SEEBASE version outside project area**

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This abstract is part of the session of 10-minute talks

The Yilgarn 2020 project: a multiscale mineral systems approach to identifying the next generation of gold and base metal deposits in the Yilgarn Craton

by

SM Rowins*, N Thebaud* and Yilgarn 2020 Project Team

'Yilgarn 2020' is a three-year research project lead by the Centre for Exploration Targeting in the School of Earth Sciences at The University of Western Australia, with the support of the Minerals Research Institute of Western Australia and various industry, academic and government partners. The project has three integrated research modules and uses a multiscale mineral systems approach to enhance our understanding of the metallogeny of the Archean Yilgarn Craton. The first module uses existing geological data to examine the composition and evolution of the lower crust and lithospheric mantle. The second module focuses on understanding camp-scale crustal architecture by developing criteria that can be applied to identify, rank and target the critical fluid-focusing structures within a given camp. The third module examines the metal fertility of the Craton by examining how magmatic and metamorphic processes have contributed to the formation of the mineralized camps. The new knowledge and tools developed from this project will aid in the discovery of the next generation of gold and base metal deposits in the Yilgarn Craton, and may be applied to Precambrian terranes elsewhere.

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This abstract is part of the session of 10-minute talks

Confidence in carbon storage in the South West of Western Australia

by

D Van Gent and S Sharma*

The South West Hub Project, led by the Department of Mines, Industry Regulation and Safety in Western Australia, has been investigating and characterizing the Lesueur Sandstone (Fig. 1) as a potential target for the injection and storage of carbon since 2007. As expected, with an unconfined saline aquifer, the project started with limited data, particularly when compared to sites based in oil and gas field areas. Working with research institutions and private sector expertise, the project has judiciously acquired data on a stage-gated decision basis. Starting with 2D seismic data over 110 line-km in 2011 and a deep well to 2945 m in 2012, the project was able to move through various modelling stages and uncertainty tables, before undertaking a complex 3D seismic investigation in 2014. The 3D seismic data covered over 115 km^2 and was followed in 2015 by the drilling of three shallow- to intermediate-depth wells (1350, 1550 and 1800 m) that gave good areal coverage and significant core and logging data on targeted critical subsurface formations. As more information became available, the level of sophistication and granularity of the models was revised. In 2010, the first-generation models comprised >100 layers with 10 million cells, by 2013 the second-generation models had >357 layers with 30 million cells and by 2016 the third-generation models had >1100 layers with 214 million cells. The South West Hub is unique as it relies on proving primary containment through migration assisted trapping (MAT, sometimes referred to as migration assisted storage or MAS) in the Wonnerup Member of the Lesueur Formation, a relatively homogenous sandstone layer that is 1500 m thick. Security of secondary containment is considered through the overlying paleosol packages in the Yalgorup Member, a sequence of sand and paleosol deposits that is 800 m thick.

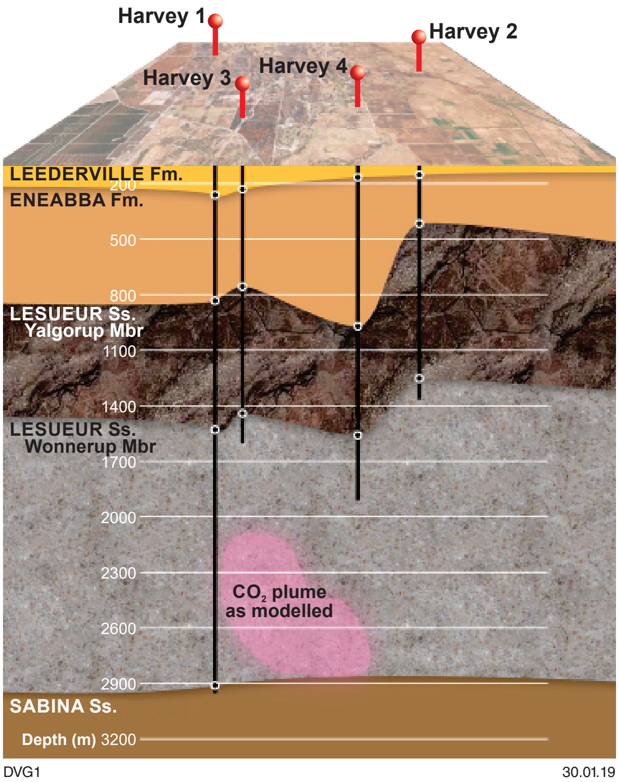

Figure 1. Schematic section showing the stratigraphy of the southern Perth Basin in the region of the Harvey drilling, and the location and depth of stratigraphic wells

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Microbialites: an untapped resource

by

HJ Allen, K Grey and SM Awramik*

Microbialites are defined as 'organosedimentary deposits that have accreted as a result of a benthic microbial community trapping and binding detrital sediment and/or forming the locus of mineral precipitation' (Burne and Moore, 1987). These include stromatolites and thrombolites, as well as the lesser known leolites, dendrolites and microbially induced sedimentary structures (MISS) (Fig. 1), and composites of the various types. Western Australia is renowned for its wealth of microbialites, with living and fossil examples in relatively close proximity allowing comparative study. Living microbialites are best known from the World Heritage Area of Shark Bay and also from saline lakes such as the Yalgorup Lakes including Lake Clifton, and Lakes Thetis, Richmond, Walyungup, Pink and those on Rottnest Island (Grey and Planavsky, 2009). Western Australian fossil microbialites span the geological timescale from Paleoarchean to Recent, with the c. 3.43 Ga Strelley Pool Formation stromatolites perhaps the most notable of these early records (Allwood et al., 2007).

A changing focus

Many early Australian microbialite studies focused on the systematic description and biostratigraphic potential of different forms (Preiss, 1972, 1973, 1974, 1977; Walter, 1972a,b), particularly in Precambrian strata due to the lack of other macroscopic fossils suitable for correlation. Over time, systematic description of microbialites diminished as studies focused on other aspects of ancient microbialites, for instance considering biogenicity of older structures (Nutman et al., 2016; Allwood et al., 2018). Research on both living and fossil stromatolites saw a shift away from comparative analogues (such as Grey and Thorne, 1984) to environmental studies with a biological (such as Suosaari et al., 2016; Johnson et al., 2018), rather than a morphologic, temporal and spatial focus. As a result of this change in emphasis, biostratigraphic applications have been neglected.

Compounding this diversification in focus of studies, the naming of microbialites and their biostratigraphic use has been contentious (Grotzinger and Knoll, 1999; Turner et al., 2000; Altermann, 2004). Preiss (1977) recognized that the biostratigraphic potential of Precambrian stromatolites could only be tested empirically by determining the time ranges of defined taxa, relying on other means of dating and correlation. Collecting such empirical data has been hampered by difficulties with terminology, naming and adequate locational and temporal data. A more balanced and consistent approach in how microbialites are described and named is needed to address problems that have historically prevented microbialite comparative studies.

A new resource

Geological Survey of Western Australia (GSWA) Bulletin 147 Handbook for the study and description of Microbialites (Grey and Awramik, 2019 in prep.), consolidates definitions and terminology from the global literature into a rational and systematic manual. This microbialite handbook presents a practical guide, extensively illustrated with actual examples. It sanctions microbialite description from the regional and outcrop scale down to the macroscopic and microscopic scale, and aims to foster more effective communication by presenting a set of procedures and terminology that should rationalize international standards for microbialite studies.

Application

GSWA continues to include microbialite studies as part of its targeted regional mapping projects and stratigraphic revisions. Recent projects to utilize microbialites for correlation include reviews of Neoproterozoic units of the Officer and Amadeus Basins, and Paleoproterozoic successions in the Hamersley province. Using stromatolites as a mapping tool is well established in Australian Neoproterozoic sections (see Allen and Haines, 2018; Allen et al., 2012, 2018; Grey et al., 2012 and references therein). The most recent stratigraphic revision of components of the Centralian Superbasin has been robustly supported by stromatolite studies (see Haines et al., 2012; Haines and Allen, 2014 and references therein). The Ediacaran *Tungussia julia* and Tonian *Baicalia burra* and *Acaciella australica* Assemblages are now well documented and extend across Australia.

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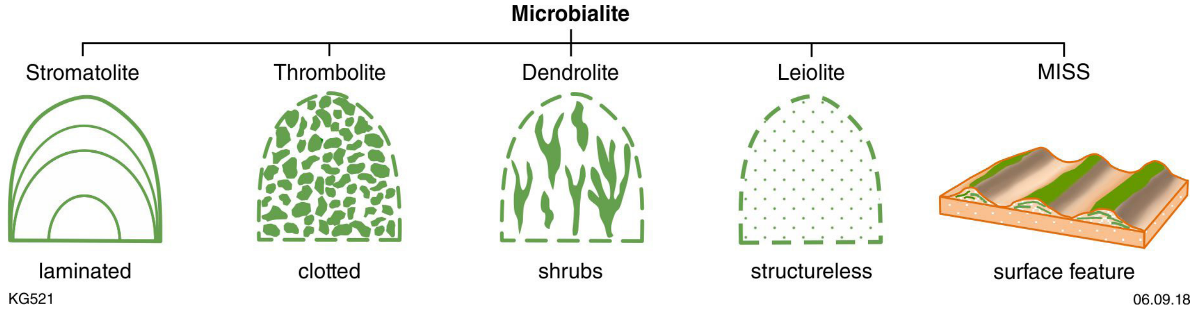

Figure 1. **Subsets of microbialites (after Grey and Planavsky, 2009, fig. 13). Stromatolites, with a laminated internal structure, are the most common in the geological record. Thrombolites have an internal clotted fabric. Dendrolites and leiolites are relatively rare in the rock record, and have a branching or structureless internal fabric, respectively. Microbially induced sedimentary structures (MISS), are included in the current broader definition of microbialites**

Most recently, correlation of Cryogenian units has also effectively utilized stromatolites, namely *Atilanya fennensis* and *Tungussia inna* (see Allen et al., 2018; Fig. 2a–e).

Previous studies indicated the applicability of microbialites to other ages and stratigraphic successions. More recently, GSWA work in the Hamersley province has successfully used microbialites as temporal markers for the Woolly Dolomite, Duck Creek Dolomite and Turee Creek Group. In particular, three microbialite assemblages of the lower and upper Kazput Formation (Fig. 2f–h) are distinct and regionally persistent (Allen and Martin, 2018). These assemblages include new microbialite Forms that have proven valuable as temporal markers during a targeted regional mapping program.

Detailed documentation of stratigraphic distributions of microbialites, particularly in Russia, India, China and Australia (Raaben et al., 2001; Cao and Yuan, 2003; Grey et al., 2012 and references therein) that demonstrated the applicability of microbialites to correlation has been expanded upon. Considerable progress has been made in documenting provenance data of Australian microbialites; a GSWA database containing more than 4000 Australia-wide entries demonstrates that microbialites are reliable temporal and stratigraphic markers. Microbialites continue to produce correlations consistent with results from other methods, such as lithostratigraphy, isotope chemostratigraphy, sequence and seismic stratigraphy, palynology and downhole geophysical correlations.

Summary

Despite being regarded as outmoded, correlation based on the systematic description of microbialites remains a viable stratigraphic tool. Bulletin 147 Handbook for the study and description of Microbialites should prove a valuable resource in furthering the application of microbialite studies. A more consistent approach to systematic description of microbialites will allow greater resolution to already established and working biostratigraphic schemes — accessing a largely untapped resource.

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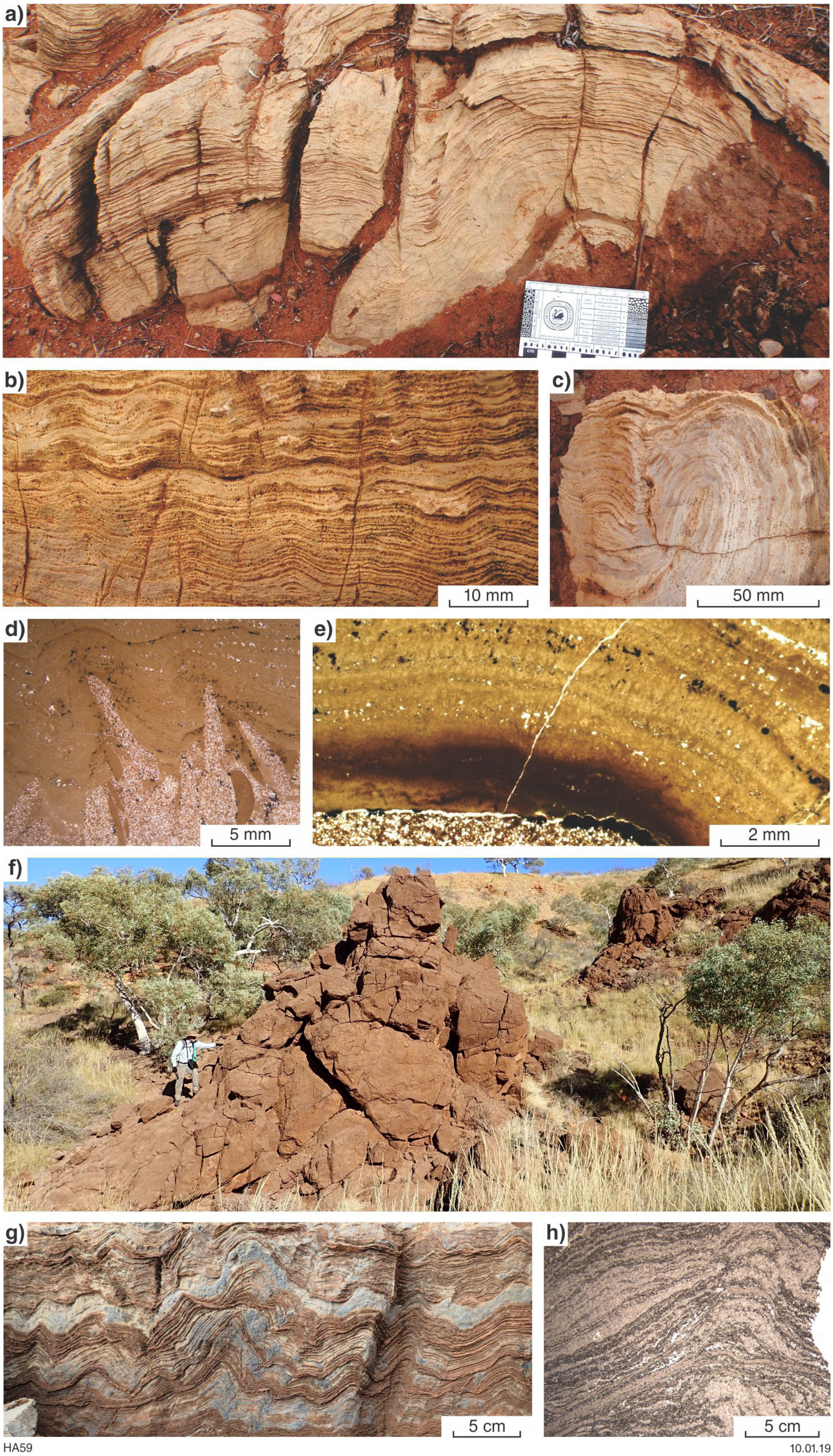

Figure 2. a–e) Stromatolite *Atilanya fennensis* used for correlating Cryogenian units in the Amadeus Basin (Allen et al., 2018). Diagnostic features of *Atilanya fennensis* (a) include its common growth mode of encrusting intraclasts (c,d) and a pillared microstructure (d,e) that is manifested as wrinkles (b) in the hand specimen scale; f–h) stromatolites from the Kazput Formation, Turee Creek Group, used as temporal markers during a regional mapping project (Allen and Martin, 2018)

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The complexity of sediment recycling as revealed by common Pb isotopes in K-feldspar

by

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Comparing the age and chemical or isotopic signature of minerals in sedimentary rocks to those in potential basement hinterlands is a fundamental tool used to fingerprint source to sink relationships. Detrital zircon geochronology has evolved as the choice for provenance studies because zircon grains are ubiquitous in sandstones, highly resistant to both chemical and physical weathering, amenable to U–Pb dating and carry other isotopic and chemical signatures (e.g. Lu–Hf, rare earth elements [REE]) that may uniquely link a zircon grain to its basement source. However, although the refractory nature of zircon provides the benefit of recording much of the high-temperature history of a geological terrane, its resistance to erosion provides a challenge to provenance reconstruction as it can be recycled numerous times (e.g. Dickinson et al., 2009; Dickinson and Gehrels, 2009; Anderson et al., 2016; Johnson et al., 2018).

One elegant approach to address the primary source to sink relationship is to compare the common Pb isotopic signature of detrital K-feldspar, a mineral unlikely to survive more than one erosion–transport–deposition cycle, with the signature of potential source basement terranes (e.g. Tyrrell et al., 2006, 2007, 2009; Flowerdew et al., 2012; Zhang et al., 2017; Lancaster et al., 2017; Johnson et al., 2018). K-feldspar is a common mineral in many clastic rocks and is a major constituent of arkosic sandstones. Lead isotope variations ($^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$) in igneous and metamorphic crustal rocks define broad spatial patterns that make the Pb signature of detrital K-feldspar grains a useful provenance tool. Regional patterns in Pb isotopic composition can be identified by characterizing a relatively small number of feldspar grains from potential granitic basement sources.

The Edmund Group

The Paleoproterozoic to Mesoproterozoic Edmund Group in the Capricorn Orogen of Western Australia (Fig. 1) is a mixed siliciclastic and carbonate sedimentary unit up to 9.5 km thick, comprising predominantly sandstone and siltstone, with subordinate conglomerate, dolomite, stromatolitic dolostone, carbonaceous siltstone and chert (Martin and Thorne, 2004; Martin et al., 2008; Cutten et al., 2016). The sedimentary rocks were deposited in a variety of fluvial to marine shelf or basinal environments, the distribution of which was strongly controlled by fluctuations in relative sea-level and synsedimentary movement on major, pre-existing basement faults (Cutten et al., 2016). The group has been divided into four informal depositional packages that includes 11 formations (Fig. 2). Each package is defined by a basal unconformity or a major marine flooding surface, both of which are the result of differential fault movements or fluctuations in sea level (Martin and Thorne, 2004).

The Edmund Group is dominated by sandstone units containing detrital zircons that are similar in age and isotopic composition to the underlying basement magmatic rocks of the Gascoyne Province (Martin et al., 2008; Cutten et al., 2016). However, abundant, well-developed paleoflow indicators throughout the basin suggest a primary source outside the province to the north (Martin et al., 2008), implying that the zircon detritus has been recycled, presumably through older sedimentary basins. In this study, we report the common Pb isotopic signature of detrital K-feldspar from two arkosic sandstones in the group, and compare the results to the composition of magmatic K-feldspar from various basement granitic rocks in order to address this issue and further clarify source to sink relationships in this basin.

Pb isotope compositions of detrital and magmatic K-feldspar

Detrital K-feldspar from two samples of arkosic sandstone from the Edmund Group, and magmatic K-feldspar from four samples of felsic magmatic rocks from the underlying Gascoyne Province and three from the southern Pilbara were analysed for their Pb isotope compositions. A total of 211 Pb isotopic analyses was collected from 211 K-feldspar crystals. Zones of alteration and inclusions identified by SEM imaging were avoided during the laser ablation analysis.

The detrital K-feldspar yields a wide range of $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ compositions similar to the basement granitic rocks of the southern Pilbara, whereas the granitic rocks of the Gascoyne Province yielded a relatively narrow and well-constrained range of Pb isotope compositions that are significantly different in composition

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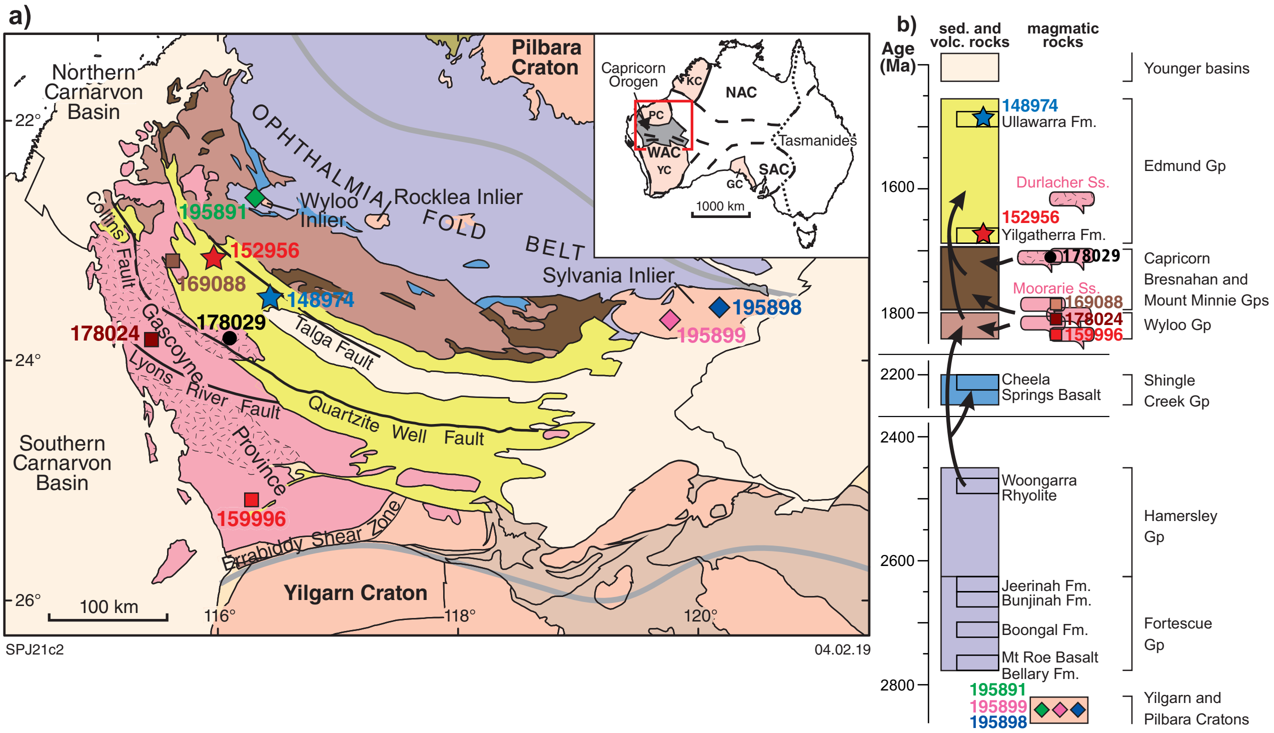

Figure 1. a) Simplified geological map of the Capricorn Orogen of Western Australia, showing the location of samples studied. Thick pale grey lines show the northern and southern limit to the Capricorn Orogen. Inset is a simplified tectonic map of Australia; b) the geological legend is provided as a stratigraphic column, showing possible pathways for recycling of detrital zircons. Abbreviations: GC, Gawler Craton; KC, Kimberley Craton; NAC, North Australian Craton; PC, Pilbara Craton; SAC, South Australian Craton; WAC, West Australian Craton; YC, Yilgarn Craton

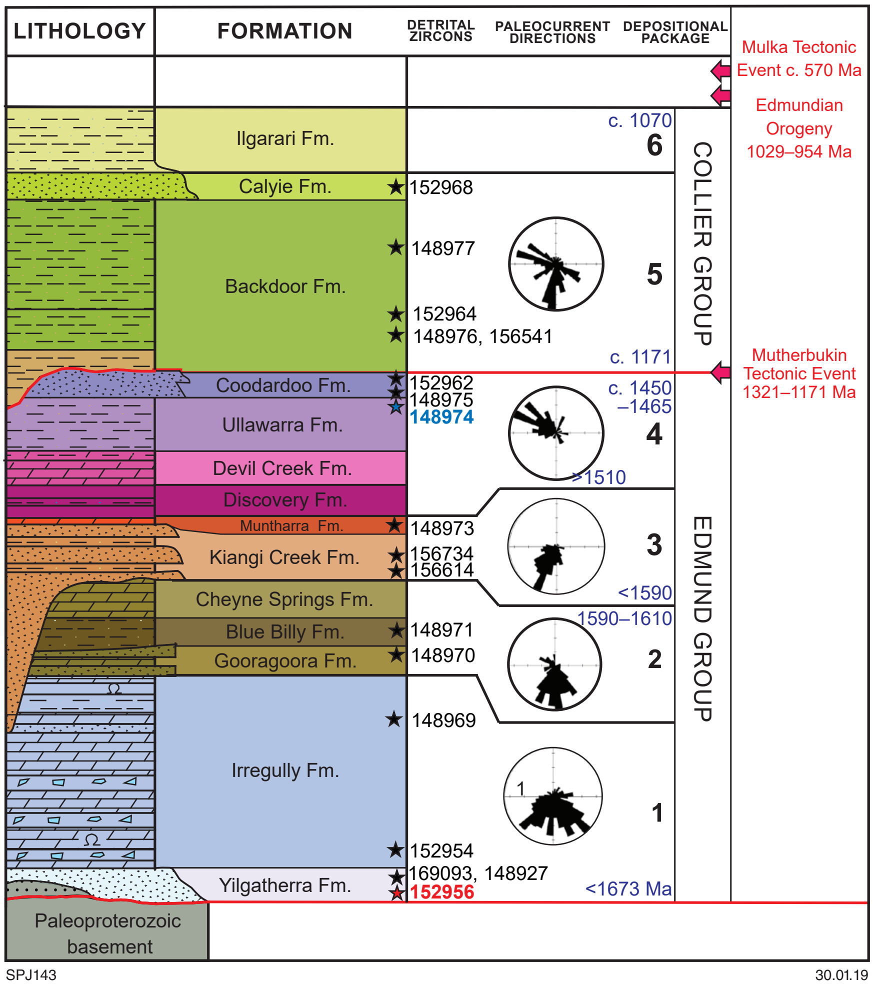

Figure 2. Stratigraphy of the Edmund and Collier Groups (after Cutten et al., 2016) showing subdivision into informal depositional packages and formations. The location of samples in this study (coloured) as well as those from Martin et al. (2008) are shown along with the timing of tectonic events and rose diagrams showing paleocurrent directions for each of the depositional packages

from the detrital grains (Fig. 3). This indicates that the detrital K-feldspar could not have been sourced from the Gascoyne Province magmatic rocks.

Implications for source provenance

The age and Hf isotopic composition of detrital zircons from the two arkosic sandstones, as well as from other sedimentary rocks of the Edmund Group, suggest that the zircon detritus was derived predominantly from the 1820–1775 Ma Moorarie Supersuite, with minor components from the 1680–1620 Ma Durlacher Supersuite and some older rocks of the Gascoyne Province. However, the Pb isotope compositions of the detrital K-feldspar within these sandstones do not match those from the potential granitic source rocks of the Gascoyne Province, particularly in the $^{206}Pb/^{204}Pb$ vs $^{208}Pb/^{204}Pb$ system. Therefore, despite these rocks containing a major cargo of detrital zircon derived from the Gascoyne Province, the basement rocks could not have been the direct source of the sediment detritus. Instead, the detrital K-feldspar compositions closely match those of Archean granitic rocks from basement inliers along the southern Pilbara margin, suggesting that this region was the primary source of detritus feeding the Edmund Basin (Fig. 3).

The K-feldspar common Pb isotope data and detrital zircon U–Pb data together suggest that the Edmund Basin was fed with detritus derived directly from the southern Pilbara margin, with most zircon recycled through older sedimentary basins such as the Capricorn, Bresnahan and Mount Minnie Groups. This interpretation is consistent with macroscopic paleoflow indicators, which suggest flow from upland regions to the north of the Edmund Basin (Martin et al., 2008).

The data indicate that during the extensional Mangaroon Orogeny, the northern margin of the orogen was subject to uplift and erosion. Detritus was shed towards the south into the Edmund Basin, which developed in the central part of the orogen as a continued expression of this extensional event. The southern part of the orogen however, remained passive, a conclusion that could not have been made from the detrital zircon data alone. This interpretation is supported by new in situ U–Th–Pb phosphate dating showing that, during this event, the northern margin of the orogen was subject to repeated fault reactivation, low-temperature hydrothermal fluid flow and associated gold mineralization (Fielding et al., 2017, 2018).

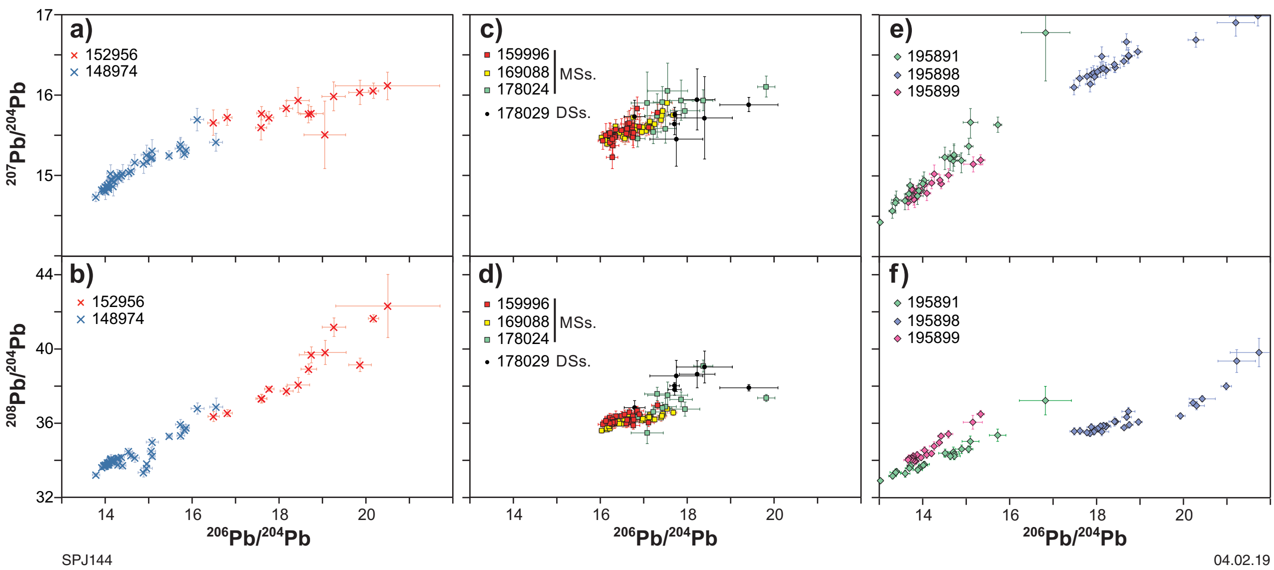

Figure 3. **a,b) Lead isotope composition of detrital K-feldspar from sedimentary rocks of the Edmund Group; c,d) Pb isotope composition of magmatic K-feldspar from felsic magmatic rocks of the 1820–1775 Ma Moorarie Supersuite (MSs.) and 1680–1620 Ma Durlacher Supersuite (DSs.) of the Gascoyne Province; e,f) Pb isotope composition of magmatic K-feldspar from felsic magmatic rocks along southern margin of the Pilbara. Uncertainties are at the 2σ level. Sample localities shown in Figure 1**

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