RECORD 2023/8

# 6IAS: 6th INTERNATIONAL ARCHEAN SYMPOSIUM – ABSTRACTS

K Gessner, TE Johnson, MIH Hartnady and D Wiemer (compilers)

2023 Perth

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

Geological Survey of Western Australia

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

RECORD 2023/8

# 6IAS: 6th INTERNATIONAL ARCHEAN SYMPOSIUM – ABSTRACTS

K Gessner, TE Johnson, MIH Hartnady and D Wiemer (compilers)

PERTH 2023

**Geological Survey of Western Australia**

**MINISTER FOR MINES AND PETROLEUM**
**Hon Bill Johnston MLA**

**DIRECTOR GENERAL, DEPARTMENT OF MINES, INDUSTRY REGULATION AND SAFETY**
**Richard Sellers**

**EXECUTIVE DIRECTOR, GEOLOGICAL SURVEY AND RESOURCE STRATEGY**
**Michele Spencer**

**REFERENCE**

**The recommended reference for this publication is:**
K Gessner, TE Johnson, MIH Hartnady and D Wiemer (compilers) 2023, 6IAS: 6th International Archean Symposium – abstracts: Geological Survey of Western Australia, Record 2023/8,196p.

**ISBN** 978-1-76148-015-7
**ISSN** 2204-4345

**About this publication**
This Abstracts Volume accompanies the 6th International Archean Symposium held in Fremantle, Western Australia, from 25 to 27 July 2023.



**Acknowledgement of Country**
We respectfully acknowledge Aboriginal peoples as the Traditional Custodians of this land on which we deliver our services to the communities throughout Western Australia. We acknowledge their enduring connection to the lands, waterways and communities and pay our respects to Elders past and present.

**Published 2023 by the Geological Survey of Western Australia**

This Record is published in digital format (PDF) and is available online at <www.dmirs.wa.gov.au/GSWApublications>.



**Further details of geoscience products are available from:**
First Floor Counter
Department of Mines, Industry Regulation and Safety
100 Plain Street
EAST PERTH WA 6004
Telephone: +61 8 9222 3459  Email: publications@dmirs.wa.gov.au
**www.dmirs.wa.gov.au/GSWApublications**

**Cover image:** Aerial view of the boxwork set of hydrothermal chert–barite veins that directly underlie and are synchronous with deposition of the c. 3.48 Ga Dresser Formation of the Pilbara Craton. They are host to the world's oldest and most convincing evidence of life. They were visited during the 6IAS Field trip 1 across the Pilbara Craton. Field of view about 500 m. Photo by Martin Van Kranendonk

# Contents

## Themes

## T2 Emergence of atmosphere and life on early Earth and other terrestrial planets

Invited Speaker

**Dr Raphael Johannes Baumgartner**

*School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney*

*CSIRO Mineral Resources, Perth, Australia*



Keynote Speaker

**Dr Eva Stüeken**

*School of Earth and Environmental Sciences, University of St Andrews, St Andrews, Scotland*



### Abstracts

## T3 Early Earth geodynamics: insights from geochemical, isotopic, phase equilibrium, and numerical modelling

Invited Speaker

**Dr Priyadarshi Chowdhury**

*Assistant Professor, School of Earth and Planetary Sciences, National Institute of Science Education and Research, Bhubaneswar, India*



Keynote Speaker

**Professor Michael Brown**

*Department of Geology, University of Maryland, College Park, USA*



### Abstracts

## T4 The role of Archean lithosphere in the evolution of younger terranes



## T5 Cratons and craton margins: structure, composition and tectonic history

## T7 Mineral systems of Archean terranes and their margins

Invited Speaker

**Dr Patricia Durance**

*Chief Geologist, SensOre Ltd*



Keynote Speaker

**Dr Patrick Mercier-Langevin**

*Research Scientist, Geological Survey of Canada (GSC), Canada*



### Abstracts

# Theme 1

# Early Earth evolution: perspectives from the oldest minerals and rocks

Invited Speaker

**Professor Monika A. Kusiak**
*Department of Polar and Marine Sciences*
*Institute of Geophysics, Polish Academy of Sciences, Warsaw*

Keynote Speaker

**Professor Martin Whitehouse**
*Swedish Museum of Natural History,*
*Department of Geosciences, Stockholm, Sweden*

# Eoarchean crust in East Antarctica

**MA Kusiak[1], SA Wilde[2], DJ Dunkley[1], MJ Whitehouse[3], SJ Harley[4], ATS Kemp[5], P Król[1], K Yi[6], S Li[6]**

* corresponding author: monika.kusiak@igf.edu.pl

1. Institute of Geological Sciences, Polish Academy of Sciences, Warsaw, Poland
2. School of Earth and Planetary Sciences, Curtin University, Perth, Australia
3. Swedish Museum of Natural History, Stockholm, Sweden
4. School of GeoSciences, University of Edinburgh, Edinburgh, UK
5. School of Earth Sciences, University of Western Australia, Perth, Australia
6. Korea Basic Science Institute (KBSI), Ochang Campus, Republic of Korea

The Napier Complex of Enderby and Kemp Lands is predominantly composed of gneisses metamorphosed at c. 2.8 Ga and/or c. 2.5 Ga at high to ultra-high temperature (Harley et al., 2019). Protolith ages up to 3.75 Ga are recorded, with a few zircon ages approaching 4.0 Ga in felsic orthogneiss of the Tula Mountains at Mount Sones and Gage Ridge (Harley et al., 2019; Kusiak et al., 2013) and east of the Tula Mountains at Mount Jewell and Budd Peak (Król et al., 2020) in Enderby Land and in adjacent Kemp Land at Aker Peaks (Belyatsky et al., 2011; Kusiak et al. 2021). The relationship between these isolated outcrops of Eoarchean crust is little understood. The aim of this study is to determine the extent of ancient crust across the Napier Complex in order to shed new light on the source and conditions prevailing on the early Earth. Geochemical diversity is demonstrated in Eoarchean protoliths from the Tula Mountains, where they can be subdivided into Y-HREE-Nb-Ta depleted and undepleted groups (Krol et al., 2020, 2022). Medium to high-pressure melting of basaltic crust can account for Y-HREE-Nb-Ta depletion in granitoids, whereas undepleted granitoids can be generated by low-pressure melting. The lack of a simple correlation between protolith age and geochemical type is an indication that magmatism throughout the Archean involved different sources and processes, including re-melting and recycling of crustal components, rather than just the formation of juvenile crust. The identification of Eoarchean crust in both Enderby and Kemp Lands, at localities about 300 km apart, may indicate that ancient crust is widespread throughout the complex. Most likely the Napier Complex represents a composite of continental crust formed at different times during the Archean that was assembled as late as 2.5 Ga.

Research conducted within grants UMO2019/34/H/ST10/00619 to MAK and RES-SE-SEP-SL-61901-1 to SAW.

## References

Belyatsky, BV, Rodionov, NV, Antonov, AV, Sergeev, SA 2011, Doklady Earth Sciences, 438, 770-774.

Harley, SL, Kelly, N., Kusiak, MA 2019, Earth's Oldest Rocks, Elsevier, pp. 865-897.

Król, P, Kusiak, MA, Dunkley, DJ, Wilde, SA, Yi, K, Lee, S., Kocjan, I 2020, Gondwana Research, 82, 151-170.

Król, P, Kusiak, MA, Dunkley, DJ, Wilde, SA, Yi, K, Whitehouse, MJ, Lee, S, Harley, SL 2022, Precambrian Research 370: 106530.

Kusiak, MA, Dunkley, DJ, Wilde, SA, Whitehouse, MJ, Kemp, AIS 2021, Gondwana Research, 93: 227-241.

Kusiak, MA, Whitehouse, MJ, Wilde, SA, Dunkley, DJ, Menneken, M, Nemchin, AA, Clark, C 2013, AJS, 313, 933-967.

# Perspectives and progress on Earth's Hadean evolution

**MJ Whitehouse***

* corresponding author: martin.whitehouse@nrm.se

Department of Geosciences, Swedish Museum of Natural History, SE104-05 Stockholm, Sweden

During the Hadean eon the Earth developed from a protoplanetary disk to a cool, water-covered and ultimately habitable planet. Studying this period; however, is hampered by the lack of a preserved rock-record. Piecing together the Hadean Earth requires multifaceted study that includes evidence from (1) rare >4 Ga zircon crystals, (2) imprints of Hadean processes in post-Hadean rocks, including their zircon, and (3) planetary analogues.

Following the discovery of Hadean zircon in the Jack Hills over three decades ago, these invaluable time capsules have been subjected to an increasingly diverse range of mineralogical, geochemical and isotopic investigations aimed at extracting the maximum information possible (several methods have probably developed more rapidly because of the existence of these grains). As more Hadean grains emerge from sediments worldwide, the potential to expand our knowledge of the Hadean increases, and while we are beyond the point where a single >4 Ga zircon merits a high-profile paper in its own right, their continued rarity deserves that they are investigated with the greatest care in order to avoid geological red herrings. In this regard, the large zircon suite from the Jack Hills provides important lessons in how to determine whether enclosed isotopic and geochemical signatures truly represent the age and initial isotopic state of any individual grain or simply result from some later disturbance that renders the information at best misleading. Providing a given grain is sufficiently large, replicate analyses, at least for both U–Pb geochronology and $\delta^{18}O$ are essential.

In contrast to direct information available from zircon, post-Hadean magmatic rocks provide indirect evidence of their mantle and/or mafic proto-crustal source region via a wide range of measurable geochemical parameters, either in the bulk rocks themselves or their mineral constituents, including zircon. Critically, the record of the evolving mantle-crust system in the early Earth may be discerned by careful investigation of Eo- to Paleoarchean additions to the continental crust, both felsic and mafic. The use of feldspar Pb isotope data from Eoarchean tonalite–trondhjemite–granodiorite (TTGs) in southwest Greenland to infer a Hadean basaltic stagnant lid and its destruction is fully consistent with Hf isotope data from the Jack Hills zircon suite, highlighting the value of multi-method approaches to understanding the earliest Earth. Models based on vast detrital zircon datasets that result in estimates for substantial amounts of continental crust at the end of the Hadean cannot be reconciled with this and are likely wrong, pointing to the need for a better understanding of crustal-mantle co-evolution throughout geological time.

Planetary analogues suffer from limitations in studying the early Earth given the lack of samples and the fact that the Earth, probably uniquely in our solar system, experienced the 'reset' of the Moon-forming giant impact. Nonetheless, ancient cratered surfaces of our closest neighbours testify to the intensity of meteorite bombardment that has to be considered in Hadean evolutionary models, while understanding planetary diversity has terrestrial implications with regard to compositional modifications from accreted late veneers.

# U–Pb age and Hf isotope systematics of zircons from rocks of the Bilozerka Greenstone Belt, the Middle Dnieper Domain of the Ukrainian Shield

**GV Artemenko[1*], LV Shumlyanskyy[2], A Hoffmann[3], SA Wilde[2], A Bekker[3]**

* corresponding author: regulgeo@gmail.com

1. M.P. Semenenko Institute of Geochemistry, Mineralogy and Ore Formation, Kyiv, Ukraine
2. School of Earth and Planetary Sciences, Curtin University, Perth, U1987, Australia
3. Department of Earth and Planetary Sciences, University of California, Riverside, USA

The Middle Dnieper Domain of the Ukrainian Shield is a typical granite-greenstone province that hosts several Mesoarchean (c. 3.2–2.9 Ga) greenstone belts. The volcano-sedimentary sequence found in these belts is subdivided into two series separated by an unconformity. The lower Konka Series overlies basement rocks and comprises komatiites, tholeiitic basalts, andesites, felsic volcanic rocks, and banded iron formations (BIFs). The upper Bilozerka Series consists of metaterrigenous rocks, BIFs, and subordinate volcanic rocks. The age of the Bilozerka Series is still debated. The Bilozerka Greenstone Belt is located in the SE part of the Middle Dnieper Domain. The lowermost portion is composed of mafic and ultramafic volcanics and metasedimentary rocks of the Konka Series that were metamorphosed in the greenschist to epidote-amphibolite facies. Volcanics of dacite-andesite-tholeiite and rhyodacite compositions represent the upper part of the Konka Series and were dated at 3037 ± 9 Ma. The rocks of the overlying Bilozerka Series differ significantly in composition. Felsic volcanic rocks have much higher $K_2O$ content in contrast to the $Na_2O$-rich metavolcanics of the Konka Series, and its terrigenous sediments are more mature. To constrain the eruption age of felsic volcanic rocks of the Bilozerka Series and to estimate the degree of their possible contamination with terrigenous sediments, we applied LA-ICP-MS U-Pb zircon dating to two samples of metarhyolites (quartz porphyry), one specimen of metadacite (quartz-plagioclase porphyry), and one sample of metasandstone. In addition, we measured Hf isotope composition in dated zircons. Distribution of zircon ages in metasandstone and metadacite (quartz-plagioclase porphyry) is very similar, with the main peak at 3062 Ma and a small additional grouping between 3215–3235 Ma. These reflect the local sources of detrital material as represented by tonalite-trondhjemite-granodiorite (TTG) and granites. Both samples contain also a few zircon grains crystallized between 2850–2875 Ma; this age probably corresponds to the time of metamorphism of the sediments and emplacement of large intrusions of two-feldspar granitoids. Two metarhyolite samples yielded mutually consistent results. Both of them contain a main population that crystallized at 2943 ± 13 (sample 89-412) and 2932 ± 14 Ma (sample 84-213), with an additional smaller population at c. 3200 Ma. We assume that the 2930–2940 Ma populations may reflect the age of crystallization of felsic volcanics, and the older population as xenocrystic material from the basement rocks. Hafnium isotope systematics of zircons isolated from metarhyolites indicates their predominantly juvenile nature. εHf values vary in zircons of the older population from 4.6 to 2.6, and in the younger populations from 4.7 to -1.3, indicating significant input of mantle-derived material. A few zircon grains in both populations have significantly lower εHf values (to -13.9) that may indicate the presence of significantly older (up to 4.0 Ga) crustal material in their source. Our results provide new information regarding the still poorly studied greenstone belts of the Middle Dnieper Domain of the Ukrainian Shield and confirm the importance of the 3.1–2.8 Ga tectonomagmatic event in the early history of the Middle Dnieper Domain, including remelting of older crustal materials and input of juvenile mantle magmas.

# The Paleoarchean (c. 3300 Ma) tonalite-trondhjemite-granodiorite of the West Azov Domain of the Ukrainian Shield

**GV Artemenko[1*], LV Shumlyanskyy[2,3], SA Wilde[2]**

* corresponding author: regulgeo@gmail.com

1. M.P. Semenenko Institute of Geochemistry, Mineralogy and Ore Formation, Kyiv, Ukraine
2. School of Earth and Planetary Sciences, Curtin University, Perth, Australia
3. Institute of Geological Sciences, Polish Academy of Sciences, Research Centre in Kraków, Poland

The West Azov Domain of the Ukrainian Shield comprises rocks of a Mesoarchean (3.2–2.9 Ga) granite-greenstone association and relics of an older basement. Several major anticlinal and synclinal folds affect the area. The synclines are composed of supracrustal rocks of the Paleoproterozoic Temryuk Suite of the Central Azov Series, while anticlines (Oleksiivo, Lantsevo and so on) are composed of Archean metaigneous plagioclase gneisses and two-pyroxene crystalline schists, and banded iron formations (BIFs). We investigated plagioclase gneisses that crop out in the anticlinal structures in the Verkhnii Tokmak and Lantsevo areas.

At Verkhnii Tokmak, tonalite gneisses crop out along the Tokmak River for about 30 km, extending through Verkhnii Tokmak village. They have the following chemical composition: $SiO_2$ = 62.93–63.51%; $Al_2O_3$ = 15.76–16.01%; $Na_2O$ = 4.30–4.99%; $K_2O$ = 1.00–1.22%; #Mg = 0.36-0.38, fractionated rare earth elements (REE) patterns $(La/Yb)_N$ = 6.65 at $Yb_N$ = 17.65, and negative Eu anomalies – Eu/Eu* = 0.63. Zircon from two samples of tonalites yielded a LA-ICP-MS U–Pb concordia age of 3310 ± 8 Ma (sample C13-10) and an upper intercept age of 3337 ± 10 Ma (sample C13-6+7). Zircons in these samples have negative εHf values ranging from -2 to -13. In addition, these rocks have depleted mantle Nd model ages of 3.3–3.4 Ga, and $\varepsilon Nd_{(3300)}$ = +0.3 to +1.8.

In the Lantsevo area, which is located 30 km east of Verkhnii Tokmak, a sample of biotite gneiss was collected in the upper reaches of a tributary of the Berda River, on the north-eastern outskirts of Lantsevo village. The biotite gneiss is granodiorite ($SiO_2$ = 65.05%; $Al_2O_3$ = 14.79%; $Na_2O$ = 4.40%; $K_2O$ = 1.16%, #Mg = 0.34). The REE pattern is fractionated: $(La/Yb)_N$ = 15.5 at $Yb_N$ = 4.4, with a positive Eu anomaly (Eu/Eu* = 1.2). Zircon from the gneiss yielded a LA–ICP–MS U–Pb concordia age of 3296 ± 8 Ma. The rock has a juvenile Hf isotope composition with εHf values ranging from +0.5 to +3.

In the Lantsevo area, biotite gneiss hosts large relics of strongly metamorphosed supracrustal rocks represented by a banded succession of pyroxene schists and pyroxene-magnetite quartzites (BIFs), up to 50 m thick. Geochemically, the pyroxene schists correspond to basaltic komatiites. The BIFs have high $Ni/Fe\times10^{-4}$ ratios of 0.39, which is characteristic of Archean BIFs of the Algoma type.

Paleoarchean (c. 3.3 Ga) felsic to intermediate rocks of the West Azov Domain represent remnants of a craton that served as a basement for accumulation of the Mesoarchean (3.2–2.9 Ga) granite-greenstone association. They were formed as a result of partial melting of mafic proto-crust at low and intermediate pressure. Relics of the supracrustal section composed by pyroxenite komatiites and BIFs possibly represent remnants of Paleoarchean (>3.3 Ga) greenstones.

# Geologically integrated isotopic ($^{142}$Nd, $^{143}$Nd and $^{176}$Hf) data from Meso-Eoarchean terranes (SW Greenland) reveals extensive Hadean formed chemical heterogeneity

**VC Bennett[1*], AP Nutman[2]**

* corresponding author: vickie.bennett@anu.edu.au

1. Research School of Earth Sciences, The Australian National University, Canberra, 2601, ACT, Australia
2. GeoQuEST, School of Earth, Atmospheric and Life Sciences, University of Wollongong, NSW, Australia

The recognition of variations in extinct nuclide signatures persistent in ancient terrestrial rocks provided a new window into early Earth processes from accretion to the start of the rock record. Additionally, these Hadean formed signatures are powerful tracers of subsequent chemical reservoir mixing and in combination with other geochemical data, illuminate crustal differentiation processes. Variations in $^{142}$Nd where both the parent ($^{146}$Sm; half-life = 103 myr) and daughter are lithophile elements record silicate differentiation events occurring in the first ca. 300 ma of Earth history. Unlike for siderophile/chalcophile element signatures, for example $^{182}$W, mass balance considerations preclude modifying $^{142}$Nd compositions by late veneer additions or core-mantle interactions. Previous studies have demonstrated the existence of positive (up to +20 ppm) anomalies compared with modern rocks throughout the Eoarchean Itsaq gneiss complex (IGC) of Southwest Greenland. Here we extend this work in both space and time and present new, high precision $^{142}$Nd data for dykes cutting the IGC and from samples dated by U–Pb zircon SHRIMP from presently adjacent Mesoarchean terranes including Kapisilik, Tuno, Akia and Tasiusarsuaq (Friend and Nutman, 2019). The youngest dated dyke (3.27 Ga) with +6 ppm $^{142}$Nd documents the persistence, but diminishment of the Hadean anomaly within the IGC. As most previously measured $^{142}$Nd anomalies have been confined to >3.6 Ga rocks, a significant result is that the analysed Mesoarchean rocks from adjacent to IGC terranes are characterised by positive $^{142}$Nd anomalies (+4 to +8 ppm) for both felsic samples and mafic samples and including all samples from the 3.07 Ga Ivisaartoq mafic/ultramafic pillow basalt complex. This suggests that the source is a long-lived, mantle feature rather than reworking of Eoarchean crust. As the Mesoarchean terranes did not amalgamate and share a common history until later in the Archean (Friend and Nutman, 2019) the high $^{142}$Nd domain was likely originally a much larger, regional, chemical feature.

Initial e$^{176}$Hf is not simply correlated with $^{142}$Nd. For example, some Mesoarchean rocks from Ivisaartoq that have positive $^{142}$Nd, also have positive e$^{176}$Hf and positive e$^{143}$Nd, and with the e$^{176}$Hf- e$^{143}$Nd array similar to the IGC and distinct from the traditional Hf–Nd isotopic array. Also, at 3.72 Ga the Isua supracrustal belt 'garbenschiefer' unit of boninitic-like chemistry and units of the same age with island arc tholeiite – like chemistry, show positive and chondritic initial e$^{176}$Hf respectively, but have identical +13 ppm $^{142}$Nd anomalies. This requires that the Lu/Hf fractionation event post-dated and was thus unrelated to Hadean Sm/Nd fractionation, which generated the $^{142}$Nd signatures. This isotopic pattern likely reflects residual garnet storage, rather than magma ocean scenarios to generate high Lu/Hf domains.

Contrasting isotopic patterns for SW Greenland terranes as compared with other Archean regions emphasises that Hadean formed and persistent (>1.5 byr) chemical heterogeneity may be a key characteristic of early Earth and reflect different co-existing thermal and geodynamic regimes.

## Reference

Friend, CRL and Nutman AP, 2019, Tectono-stratigraphic terranes in Archean gneiss complexes as evidence for plate tectonics: The Nuuk region, southern West Greenland. Gondwana Research 72, 213-237.

# The Paleoarchean record of the São Francisco craton from zircon U–Pb and Hf isotope systematics

**M Botero[1*], JD Vervoort[1], VT Meira[2]**

* corresponding author: manuela.botero@wsu.edu

1. School of the Environment, Washington State University, Pullman, WA 99164 USA
2. Institute of Geosciences, University of Campinas, Campinas, São Paulo, Brazil

The Paleoarchean (3.6–3.2 Ga), a pivotal time in the Earth's history, was marked by major geological events such as important crustal growth episodes, craton formation, and a shift in tectonic modes from stagnant lid to mobile lid. The Paleoarchean crustal record, therefore, provides valuable insights into fundamental processes that defined a crucial transitional period in the evolving Earth. In this research we focus on the Mairi complex of the São Francisco craton, Brazil, which is host to the oldest known rocks in South America and preserves an important Paleoarchean rock record.[1,2] Here, we report new zircon U–Pb age, Hf isotope data, whole-rock Hf, Nd isotopes from granitic gneisses and a leucosome from the Mairi complex. The U–Pb data have well-defined zircon populations with $^{207}Pb/^{206}Pb$ ages at about 3.6 Ga. One gneiss yields a $^{207}Pb/^{206}Pb$ age of 3.4 Ga with evidence of 3.6 Ga inherited zircons. No zircon xenocrysts older than 3.6 Ga were determined in any samples. The Hf isotope compositions of all zircon are consistently subchondritic, with a narrow range of initial $\varepsilon_{Hf(3600)}$ from -1.6 to -3.2 and $\varepsilon_{Hf(3400)}$ of -3.6. The bulk-rock data, on the other hand, exhibit a large range in Hf and Nd isotope compositions with initial $\varepsilon_{Hf(3.6-3.4 Ga)}$ ranging generally from +2 to -5 with a couple of outliers with $\varepsilon_{Hf(i)}$ of -8 and -14 and $\varepsilon_{Nd(3.6\text{-}3.4 Ga)}$ with mostly positive values from +7 to 0, with outliers at -4 and -17. Complex samples with evidence of ancient Pb-loss and multi-component zircons show the higher discrepancies between bulk-rock and zircon isotope compositions, similar to that documented in Greenland Eoarchean gneisses.[3] The isotopic variability in whole-rock data reflects mixing of different components during analysis and/or open-system behaviour due to post-crystallization tectono-thermal events. In samples where the age can be tightly constrained, the Hf isotope composition in the zircon is extraordinarily homogenous. Accordingly, we rely our interpretations on the robust zircon Hf isotope data. The subchondritic Hf isotope compositions of the 3.6–3.4 Ga gneisses indicate derivation from a homogenous reservoir and are consistent with melting and/or reworking/assimilation of about 3.8 Ga pre-existing chondritic crust. Our interpretation on the genesis of these rocks is at odds with previous studies that suggest Hadean-early Eoarchean precursors for these rocks based on the assumption of derivation from a depleted mantle reservoir.[1,2] Instead, we suggest that the Hf isotope data reported in this study for the 3.6–3.4 Ga Mairi complex gneisses are consistent with derivation from melting of a about 3.8 Ga precursor of broadly chondritic composition, similar to the Hf isotope compositions of other 3.8–3.6 Ga gneisses worldwide.[4-7]

## References

Oliveira et al., 2019, Terra Nova.

dos Santos et al., 2022, Precambrian Research.

Vervoort and J. Blichert-Toft, 1998, Geochimica et Cosmochimica Acta.

Amelin et al., 2011, Canadian Journal Earth Sciences.

Bauer et al., 2017, Earth and Planetary Science Letters.

Fisher and Vervoort, 2018, Earth and Planetary Science Letters.

Kemp et al., 2019, Geochimica et Cosmochimica Acta.

# Still hunting for an Archean impact structure

**AJ Cavosie*, MA Cox**

* corresponding author: aaron.cavosie@curtin.edu.au

Space Science and Technology Centre and The Institute for Geoscience Research, School of Earth and Planetary Sciences, Curtin University, Perth, WA, Australia

The absence of any identified impact structures from the early Earth remains a conundrum. The record of meteorite impacts on Earth becomes more fragmentary further back in geologic time. Several useful 'impact benchmarks' appear to have wide acceptance. The oldest terrestrial impact deposits are distal impact ejecta horizons in South Africa and Australia that were deposited c. 3.45–3.47 Gyr ago[1,2]. The oldest shocked mineral is a single grain of quartz with PDF in a 2.63 Ga ejecta horizon in Australia[3]. No source craters for any Archean-age impact structures have been reported. The oldest intact confirmed and accurately dated impact structure is the 2.23 Ga Yarrabubba structure in Western Australia[4]. The lack of Archean-age impact structures is difficult to reconcile, given the higher impact flux on the early Earth, the number of cratons, and the preservation of Hadean age detrital zircons from numerous sites[5]. Attempts to identify evidence of shock deformation in detrital populations containing thousands of early Archean zircons have thus far not been successful[6,7]. The successful identification of an Archean terrestrial impact structure requires documentation of the same types of diagnostic evidence found at terrestrial craters of any age — evidence of shock deformation at macro- and/or micro-scale, or identification of extra-terrestrial geochemical signatures of the projectile[8].

An example of a de-bunked Archean 'crater' is Maniitsoq, a site in Greenland interpreted to represent a 100 km-diameter impact crater formed at c. 3.0 Ga[9]. Despite a complete absence of diagnostic impact evidence[8], multiple papers proclaiming an impact origin have been published. Rocks across the Maniitsoq region are broadly gneissic granitoids, and thus contain ideal minerals (quartz and zircon) for recording shock deformation. A survey of 5600 zircons from 18 bedrock samples and 14 fluvial samples across the Maniitsoq region failed to identify evidence of shock deformation; the absence of any evidence for impact processes in Maniitsoq zircons precludes an impact origin[10]. The resilience of shocked zircon in bedrock[4], as well as detrital systems[11-14] is well-established, which highlights detrital zircon surveys as an effective tool to detect shocked grains in ancient sedimentary rocks. Until such grains are found, the hunt for an Archean impact structure continues.

## References

1 Byerly et al. (2002) Science.

2 Glikson et al. 2016 Precam. Res.

3 Rasmussen and Koeberl (2004) Geology.

4 Erickson et al. (2020) Nature Comm.

5 Valley et al. (2014) Nature Geosci.

6 Montalvo et al. (2014) LPSC.

7 Cox et al. (2017) LPSC.

8 French and Koeberl (2010) Earth-Sci. Rev.

9 Garde et al. (2012) EPSL.

10 Yakymchuk et al. (2021) Earth Planet. Sci. Lett.

11 Cavosie et al. (2010) GSA Bull.

12 Erickson et al. (2013) Geochim. Cosmochim. Acta.

13 Thomson et al. (2014) GSA Bull. [14] Montalvo et al. (2017) Am. Mineral.

# Hidden Antarctic continent

**B Chen[1*], IH Campbell[1], RJ Arculus[1]**

* corresponding author: bei.chen@anu.edu.au

1. Research School of Earth Sciences, Australian National University, Canberra, ACT 2601, Australia

Ice covers 99.5% of the surface of Antarctica and, consequently, little is known about its underlying geology. Here we report U–Pb dates, trace elements, and O–Hf isotope analyses for detrital zircons derived by glacial erosion of 85% of Antarctica, recovered from scientific ocean drilling sites. There are three surprises. First, existing dates of rare outcrops give the impression that Antarctica is an old continent whereas our study shows the reverse. Less than 3% of the dated zircons have Archean U–Pb ages, and significant growth started one billion years later than on other well-studied continents. Second, although the East African orogeny (650–450 Ma), produced during the amalgamation of the Gondwana supercontinent, was previously known in Antarctica, its nature and significance were not. Our study shows that it was by far the most important tectonic event to have affected Antarctica and that detritus, shed from its mountains, dominated Antarctic sedimentation, producing giant turbidite fans that extended across Antarctica into SE Australia. These sediments trapped primitive magmas, generated from underlying subduction zones, forming magma chambers that melted their sedimentary roofs. The result was sediment-predominant sources for the granites that characterize 650–450 Ma magmatism in Antarctica. Finally, although the Antarctic is relatively young, two detrital zircons have cores with concordant Hadean ages.

# Episodes of Eoarchean crustal growth and recycling in the Saglek Block of the North Atlantic Craton, Labrador

**DJ Dunkley[1], MJ Whitehouse[2], MA Kusiak[1], SA Wilde[3]**

* corresponding author: daniel.dunkley@igf.edu.pl

1. Institute of Geophysics, Polish Academy of Sciences, Warsaw, Poland
2. Department of Geosciences, Swedish Museum of Natural History, Stockholm, Sweden
3. School of Earth and Planetary Sciences, Curtin University, Perth, Australia

Over the past several years, an expanding dataset of U–Pb isotopic ages from zircon and monazite in the gneisses of the Saglek Block, Labrador have confirmed a predominance of Eoarchean granitoid (namely tonalite-trondhjemite-granodiorite or TTG) protoliths that broadly correspond to those in the more extensively studied Itsaq Gneiss Complex of southwest Greenland (Nutman, 2018). Whereas some studies have pointed to continuous crustal growth from 3.9 to 3.6 Ga, beginning with relics of supracrustals that predate the oldest granitoid crust, investigation of a large number of samples along a 100 km coastal section, involving careful statistical handling of complex ion microprobe data and interpretation of growth modification features in zircon grains, instead indicate an episodic evolution. A few felsic orthogneisses with protolith ages scattered between 3860 and 3770 Ma have been identified in several places, but with no evidence of continuity beyond the outcrop scale. These are subsumed by a widespread generation of 3750–3700 Ma Uivak TTG gneisses. Both generations of TTG crust have been recycled into c. 3.6 Ga granite sensu stricto and trondhjemite during a period that culminated in high-grade metamorphism at the end of the Eoarchean. Local discontinuous tectonic enclaves of mafic to felsic supracrustal rocks have been interpreted as predating the Uivak gneiss as far back as >3.9 Ma, but instead represent much younger metasediments (Whitehouse et al., 2019) and felsic metavolcanics with ages either similar to or younger than protoliths of the Uivak gneiss. The majority are tectonic enclaves without clear contacts with TTG gneiss, and in places where contacts are observed the intrusive phase is not proven to be Eoarchean. Occurrences of c. 3.55 Ga dioritic and felsic metavolcanics indicate a change in magmatism following a major tectono-metamorphic event at 3.6 Ga that is also recognised in West Greenland (Nutman, 2018). Following this was a half-billion year hiatus in magmatic activity, with the exception of an unknown number of dolerite dykes so commonly seen after the cratonization of Archean crust, and which are likely belong to the c. 3.4 Ga Ameralik swarm in Greenland. The dominant generation of Uivak Gneiss is sufficiently well defined to distinguish it in age from TTG protoliths in the Isukasia and Færinghavn Terranes of the Itsaq Gneiss, at 3.6 Ga. Although the tectonic nature of the 3.6 Ga event is obscured by subsequent tectonometamorphism in the Saglek Block (Dunkley et al., 2020), the wide distribution of metamorphic zircon raises the possibility of a mobile-lid tectonic regime that brought together distinct pieces of continental crust culminating in orogenesis and cratonization at the end of the Eoarchean.

This research was supported by NCN grant UMO2019/34/H/ST10/00619 to MAK.

## References

Dunkley et al. (2020) *J. Geol. Soc., 177*, 31-49.

Nutman A. (2018) *in* van Kranendonk et al. (eds) *Earth's Oldest Rocks*, 2nd edition.

Whitehouse et al. (2019) *Precambrian Res., 323,* 70-81.

# Understanding early crustal evolution using in-situ Rb–Sr and Pb isotopes in alkali feldspars

**N Eriyattukuzhiyil[1*], D Bevan[1,2], CD Coath[1], J Lewis[1], AIS Kemp[2], T Elliott[1]**

* corresponding author: n.eriyattukuzhiyil@bristol.ac.uk

1. Bristol Isotope Group, School of Earth Sciences, University of Bristol, BS8 1RJ, UK
2. School of Earth Sciences, University of Western Australia, Perth 6000, WA, Australia

The Precambrian crust of the Earth has been studied extensively to understand the growth and evolution of the continental crust. The continental crust is enriched in Rb relative to Sr, resulting in Rb/Sr ratios increasing with crustal differentiation and $SiO_2$ content.[1] Besides the Rb–Sr isotope system, varying U/Pb ratios of crust formed at different tectonic settings makes the Pb isotope composition another major proxy for crustal evolution.[2]

The Rb–Sr method has been traditionally measured by chemically separating Rb and Sr to avoid mass interferences during isotope measurements, but is time consuming and difficult to ensure all separated mineral fragments are pristine. Analysing minerals for their in-situ Rb–Sr compositions would be desirable but until recently, intractable. However, the unique collision cell, mass-filter, multi-collector, inductively coupled plasma mass-spectrometer (Proteus) when coupled with laser ablation has proven effective in analysing minerals in-situ for their Rb–Sr ratios to appropriate precision.[3] Alkali feldspars have high Rb/Sr ratios, which vary internally, making them suitable candidates for generating internal Rb–Sr isochrons. Moreover, alkali feldspars also have low U/Pb ratios, making them ideal for combined Rb–Sr and Pb–Pb isotope analysis. The initial $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ isotopes can be used to calculate the time integrated $^{238}U/^{204}Pb$ of the crustal protolith, and hence the tectonic setting of formation.

We present K-feldspar internal isochrons for granite samples from the Yilgarn and Pilbara cratons of Western Australia to investigate their juvenile crustal evolution. Since Sr isotope ratios in alkali feldspars are susceptible to thermal resetting, alkali feldspar grains were screened under the SEM-CL for primary igneous features (e.g. oscillatory zoning). However, preliminary Rb–Sr ages and the initial $^{87}Sr/^{86}Sr$ ratios of the samples indicate that the Rb and Sr isotopes of the K-feldspars have been internally reset, synchronous to regional orogenic events. However, since the closure temperature of Pb in K-feldspars is higher than Sr, the in-situ Pb analysis could still yield reasonable initial Pb ratios[4] to calculate their time integrated U/Pb ratios. Potentially in situ inter-mineral Rb–Sr ages may provide constraints on the initial Sr isotope ratios of the samples. This work is in progress.

## References

1. Dhuime, B, Wuestefeld, A and Hawkesworth CJ 2015, Emergence of modern continental crust about 3 billion years ago: Nature Geosci, v. 8, p. 552–555
2. Delavault, H, Dhuime, B, Hawkesworth, CJ et.al. 2016, Tectonic settings of continental crust formation: Insights from Pb isotopes in feldspar inclusions in zircon: Geology, v. 44, p. 819–822
3. Bevan, D, Coath CD, Lewis, J, et.al. 2021, *In-situ* Rb–Sr dating by collision cell, multicollection inductively-coupled plasma mass-spectrometry with pre-cell mass-filter, (CC-MC-ICPMS/MS): J. Anal. At. Spectrom., v. 36, pp. 917–931
4. Hartnady, MIH, Kirkland, CL, Smithies, RH, e.t.al. 2022, Pb isotope insight into the formation of the Earth's first stable continents: Earth and Planetary Science Letters, vol. 578, p. 117-319

# Tracing a Hadean enriched source in the 3.5 Ga São Tomé intrusion, NE Brazil

**VB Garcia[1*], J O'Neil[1], EL Dantas[2], CT Augustin[3]**

* corresponding author: vgarc091@uottawa.ca

1. Department of Earth and Environmental Sciences, University of Ottawa, K1N 6N5 Ottawa, Canada

2. Geosciences Institute, University of Brasília, 70910-900 Brasília, Brazil

3. Mineral Deposits Laboratory, Department of Earth Science, Carleton University, 2115 Herzberg Laboratories, 1125 Colonel By Dr., Ottawa, ON K1S 5B6, Canada.

Our understanding of the early evolution of the crust and the mantle is hindered by the scarcity of preserved Eoarchean/Hadean geological records. In the last decade, the use of the short-lived $^{146}$Sm-$^{142}$Nd isotopic system has opened a new window into the earliest crust-mantle differentiation history. With a half-life of about 103 Ma, radioactive $^{146}$Sm is considered extinct by about 4 Ga and thus variations in its daughter product, $^{142}$Nd, can only be produced by Sm–Nd fractionation in the Hadean. This short-lived tracer is therefore ideal to study the early evolution of silicate reservoirs. The Paleoarchean São Tomé layered mafic-ultramafic intrusion forms a small basement inlier located in the Neoproterozoic Seridó belt in north-eastern Brazil. Dated at 3506 ± 29 Ma (Ruiz et al., 2018), the São Tomé rocks are among the oldest mantle-derived rocks from NE Brazil, representing ideal candidates to study the early mantle evolution. The intrusion consists of a central ultramafic zone with upper and lower mafic zones, each metamorphosed to amphibolite facies and variably altered by metasomatic fluids. The ultramafic zone is mostly made of tremolite-bearing serpentinite interlayered with hornblendite, while the upper and lower mafic zones are dominated by intercalations of amphibolite and hornblendite, with localized layers of Fe–Ti oxides. Samples from each lithology and zone, as well as the host rock, were analysed for their $^{147,146}$Sm-$^{143,142}$Nd isotopic compositions.

Because some samples show evidence of isotopic disturbance of the long-lived $^{147}$Sm-$^{143}$Nd system, a latent class regression using an iterative expectation-maximization (EM) algorithm (Davies et al., 2018) was applied to all samples to obtain the most pristine composition. The algorithm ran for 300 iterations repeated over 50 times, providing a best fit isochron with an age of 3582 Ma and initial $\varepsilon^{143}$Nd = -0.23. This age is in agreement with the U–Pb age of zircon previously obtained for the São Tomé intrusion and thus the $\varepsilon^{143}$Nd initial composition is taken as the best estimate of its mantle source.

Additionally, the same samples were analysed for their $^{142}$Nd isotopic composition, revealing well-resolved negative anomalies and $\mu^{142}$Nd values as low as -14.6 with an average of -9.0 ± 6.0 ppm (n=13, 2SD). The existence of resolved negative $\mu^{142}$Nd anomalies is rare and suggests an enriched source that differentiated during the Hadean. Coupling the negative $\mu^{142}$Nd with the subchondritic $\varepsilon^{143}$Nd hints towards a unique mantle source and potentially provides evidence for the existence of an enriched Hadean mantle reservoir.

## References

Ruiz, FV, Della Giustina, MES, de Oliveira, CG, Dantas, EL, Hollanda, MHB, 2018, The 3.5 Ga São Tomé layered mafic-ultramafic intrusion, NE Brazil: Insights into a Paleoarchean Fe-Ti-V oxide mineralization and its reworking during West Gondwana assembly: Precambrian Research, v. 326, p. 462–478.

Davies, JHFL, Sheldrake, TE, Reimink, JR, Wotzlaw, J-F, Moeck, C, Finlay, A, 2018, Investigating complex isochron data using mixture models. Geochemistry, Geophysics, Geosystems, v. 19, p. 4035–4047.

# Magmatic oxygen fugacity and water content of Archean granitoids indicate subduction since the Eoarchean

**RF Ge[1], SA Wilde[2], WB Zhu[1], XL Wang[1]**

* corresponding author: gerongfeng@nju.edu.cn

1. School of Earth Sciences and Engineering, Nanjing University, Nanjing 210046, PR China
2. School of Earth and Planetary Sciences, Curtin University, Western Australia 6845, Australia

Whether Earth's early continental crust was formed by subduction of oceanic plates or other processes (e.g. volcanic resurfacing, greenstone sagduction and giant impact) in a stagnant-lid tectonic regime is a fundamental question to understanding Earth's dynamic evolution and habitability. Phanerozoic arc magmas formed by subduction are characterized by high oxygen fugacity ($fO_2$) and water ($H_2O$) content, but these variables are difficult to quantify for Archean rocks due to ubiquitous metamorphism. We propose a magma oxybarometer-hygrometer based on a combination of the zircon $Ce^{4+}/Ce^{3+}$ oxybarometer (Smythe and Brenan, 2016) and the zircon Ce-U-Ti oxybarometer (Loucks et al., 2020) to simultaneously determine magmatic $fO_2$ and $H_2O$ content of zircon-bearing igneous rocks. The zircon $Ce^{4+}/Ce^{3+}$ oxybarometer is very sensitive to equilibrium magma composition, especially $H_2O$ content, so that the $fO_2$ obtained from the zircon Ce-U-Ti oxybarometer can be used to retrieve the $H_2O$ content. Our calibration using magmas with well known $H_2O$ content indicates that this zircon oxybarometer-hygrometer is able to retrieve the median magmatic H2O content within approximately 1% uncertainty.

We apply this oxybarometer-hygrometer to Archean granitoids (dominantly tonalite-trondhjemite-granodiorite or TTGs) worldwide (Acasta, Greenland, Barberton, Superior, Yilgarn and Tarim). Our results show that most Archean granitoid magmas have $fO_2$ around the FMQ buffer (median ΔFMQ+0.1 ± 1.1, 2SD), which are significantly more reducing than Phanerozoic arc magmas. However, because the Archean ambient mantle was likely more reducing than the Phanerozoic counterpart (e.g. Aulbach and Stagno, 2016; Gao et al., 2022), there is at least one log unit increase in $fO_2$ from the Archean ambient mantle-derived magmas to Archean granitoid magmas. More importantly, most Archean granitoids had high magmatic $H_2O$ contents (≥6–10 wt%) and high $H_2O$/Ce ratios (≥1000), similar to Phanerozoic arc magmas. We find that magmatic $fO_2$, $H_2O$ contents and $H_2O$/Ce ratios of Archean granitoids positively correlate with geochemical proxies of magma formation depth (e.g. Sr/Y and La/Yb ratios), indicating a deep origin of the $H_2O$ and presence of excess $H_2O$ in the magma sources. These observations are difficult to reconcile with non-subduction models of crustal formation, but can be readily explained by subduction of hydrated oceanic slabs. We note a rise in magmatic $fO_2$ and $H_2O$ content between 4.0–3.6 Ga, which coincides with a positive shift in zircon Hf isotopic compositions (Bauer et al., 2020), indicating onset of large-scale subduction during the Eoarchean.

## References

Aulbach, S., Stagno, V., 2016. Evidence for a reducing Archean ambient mantle and its effects on the carbon cycle. Geology 44, 751-754.

Bauer, A.M., Reimink, J.R., Chacko, T., Foley, B.J., Shirey, S.B., Pearson, D.G., 2020. Hafnium isotopes in zircons document the gradual onset of mobile-lid tectonics. Geochemical Perspectives Letters 14, 1-6.

Gao, L., Liu, S., Cawood, P.A., Hu, F., Wang, J., Sun, G., Hu, Y., 2022. Oxidation of Archean upper mantle caused by crustal recycling. Nature Communications 13, 3283.

Loucks, R.R., Fiorentini, M.L., Henríquez, G.J., 2020. New magmatic oxybarometer using trace elements in zircon. Journal of Petrology 61, egaa034.

Smythe, D.J., Brenan, J.M., 2016. Magmatic oxygen fugacity estimated using zircon-melt partitioning of cerium. Earth and Planetary Science Letters 453, 260-266.

# Low-δ$^{18}$O zircon in the Napier Complex, East Antarctica, indicates emergent land in the Eoarchean

**P Król[1*], MA Kusiak[1], MJ Whitehouse[2], DJ Dunkley[1], SA Wilde[3]**

* corresponding author: piotr.krol@igf.edu.pl

1. Institute of Geophysics, Polish Academy of Sciences, Warsaw, Poland

2. Department of Geosciences, Swedish Museum of Natural History, Stockholm, Sweden

3. School of Earth and Planetary Sciences, Curtin University, Perth, Australia

Isotopic systems hold the key to understanding the nature of surface environments in the Eoarchean (4.0–3.6 Ga). At that time, the Earth was mostly covered by oceans, with little evidence of emergent land (Rosas and Korenanga 2021). However, the emergence of land may have been a necessary condition for prebiotic chemical evolution and development of life (e.g. Van Kranondonk et al. 2021), as it controls the global climate feedbacks and supply of nutrients to the oceans. Sub-mantle δ$^{18}$O (<4.7‰) in magmas provide evidence for interaction with meteoric water rather than seawater (Troch et al. 2020), because the δ$^{18}$O of the latter is only approximately 5‰ lighter than typical mantle values, and thus would require high volumes to induce significant variations. Since δ$^{18}$O in magma can be preserved without significant fractionation in magmatic zircon, the latter can be used as a proxy for magmatic δ$^{18}$O.

We investigated three >3.5 Ga orthogneisses with Eoarchean magmatic protoliths from the eastern Tula Mountains, Napier Complex, East Antarctica. Oxygen isotope compositions were analyzed on zircon domains previously dated by Król et al. (2020). Two gneisses were found to have high Y-HREE-Nb-Ta, consistent with the melting of crustal sources at pressures below 1.0 GPa. These rocks contain magmatic zircon with sub-mantle δ$^{18}$O values of c. +2 ‰. Mixture modelling suggests that to produce the observed signatures, either a large amount of seawater or a small and realistic amount of light δ$^{18}$O water, such as meteoric water, needs to be provided. Similar low δ$^{18}$O signatures have been found in hot-spot or extensional environments, including Yellowstone and Iceland, where meteoric water can interact with magmatic systems at shallow depths (Troch et al. 2020). The discovery of isotopically light δ$^{18}$O values in >3.5 Ga zircon from the Napier Complex can therefore be attributed to the existence of shallow magmatic-hydrothermal systems driven by meteoric water in the early Archean. This, in turn, provides evidence for exposure of land to meteoric systems, indicating it must have emerged above sea level prior to 3.5 Ga.

This research was supported by grants UMO-2021/43/B/SR10/03161 to DJD and RES-SE-SEP-SL-61901-1 to SAW.

## References

Król, P, Kusiak, MA, Dunkley, DJ, Wilde, SA, Yi, K, Lee, S and Kocjan, I 2020, Diversity of Archean crust in the eastern Tula Mountains, Napier Complex, East Antarctica. Gondwana Research, v. 82, p. 151-170.

Rosas, JC and Korenanga, J 2021, Archean seafloors shallowed with age due to radiogenic heating in the mantle. Nature, v. 14, p. 51-56.

Troch, J, Ellis, BS, Harris, C, Bachmann, O and Bindeman, IN 2020, Low-δ18O silicic magmas on Earth: A review. Earth-Science Reviews, v. 208, p. 103299.

Van Kranendonk, MJ, Baumgartner, R, Djokic, T, Ota, T, Steller, L, Garbe, U and Nakamura, E 2021, Elements for the origin of life on land: a deep-time perspective from the Pilbara Craton of Western Australia. Astrobiology, v. 21(1), p. 39-59.

# Ocean oxygenation prior to the Global Oxygenation Event: evidence from the sedimentary record of the Dharwar Craton, India

**C Manikyamba*, GH Reddy**

* corresponding author: cmaningri@gmail.com

CSIR-National Geophysical Research Institute, Uppal Road, Hyderabad 500 007

The Meso-Neoarchean Dharwar Craton has extensive development of greenstone belts consisting of volcano-sedimentary horizons among which the Sandur, Chitradurga and Shimoga greenstone belts have excellent preservation of banded iron formations (BIF), manganese formations, manganiferous stromatolitic carbonates, carbonaceous phyllites that are associated with clastic sediments and a wide spectrum of plume-arc related volcanic rocks. The carbon isotopic signatures of the apatite and graphite bearing mineral assemblages present in the greenschist facies metamorphosed BIFs of the Sandur belt gave carbon isotopic signatures of −28.5‰, are suggested to be sourced from syngenetic organic matter. The carbon and oxygen isotopic signatures of the stromatolitic carbonates from these three greenstone belts indicate a gradual growth of bio-productivity reflecting on a steady increase of ocean anoxia, organic matter and nutrient supply in the Archean oceans. The $\delta^{18}O$ signatures indicate a 25–75°C temperature range for the Archean Sea water, which is attributed to the involvement of hydrothermal solutions that are the source for the iron and manganese in the Archean proto-oceans. These studies are supported by the $\delta^{13}C_{org}$ of the carbonaceous phyllites from the Chitradurga, Sandur and Shimoga greenstone belts, which range from 38.5‰ to -11.8‰ VPDB, collectively point to organic carbon signatures. All the stable isotopic signatures are further supported by the geochemical characteristics of these lithounits with rare earth element patterns and positive Eu anomalies endorsing hydrothermal source. The manganese sourced from hydrothermal solutions of the Archean mid-oceanic ridges appear to have played a vital role by forming a cluster with calcium, reacted with the $H_2O$ molecules in the presence of sun light and released oxygen. The U–Pb detrital zircon ages of the stromatolitic carbonates range from 3.5 to 2.6 Ga, while the carbonaceous shales range from 3.2 to 2.2 Ga age, which is also corroborated by the manganese formations (3.4–2.6 Ga). All these geochemical, stable isotopic and geochronological lines of evidence collectively support the Neoarchean oxygenation peak in the Dharwar Craton, which is 300 Ma prior to the Global Oxygenation Event (GOE) proposed at about 2.4 Ga, and the organic carbon is viewed in terms of either pre-biotic origin or the remains of Earth's earliest life forms.

# Hf–Nd isotopes of Archean komatiites: a Hadean component in the Neoarchean mantle?

**DR Mole[1*], ML Fiorentini[2], SJ Barnes[3], R Maas[4], CL Kirkland[5]**

* corresponding author: david.mole@ga.gov.au

1. Geoscience Australia, Canberra, Australian Capital Territory, Australia
2. Centre for Exploration Targeting, University of Western Australia, 35 Stirling Hwy, Perth, WA, Australia
3. Mineral Resources, CSIRO, 26 Dick Perry Avenue, Kensington, Perth, WA, Australia
4. University of Melbourne, School of Earth Sciences, Parkville, Victoria, Australia
5. Centre for Exploration Targeting (Curtin node), Curtin University, Kent Street, Perth, WA, Australia

Komatiites are extinct volcanic rocks that formed by partial melting of 20–50% of their mantle source – a unique feature that allows us to understand the composition of the mantle in the early Earth. Due to their high temperature, komatiites incorporate proximal rock types on their way to, and on, the Earth's surface. In this craton-scale study, we looked to use this property of komatiite magmas to track their interaction with the crust of the Yilgarn Craton. The results yielded Hf and Nd isotope arrays (Figure 1), that potentially have three components. The first likely represents the depleted mantle source of the magmas, and most plot in the region between +2 and +6 $\varepsilon Hf_i$ and 0 to +3.3 $\varepsilon Nd_i$. The second source represents a more unradiogenic component, most likely 3.5–3.3 Ga continental crust (minimum). This component is more notable in the 2.8 and 2.9 Ga events with values trending to CHUR and negative εNd. The 2.8 Ga dataset, and particularly the komatiitic basalts from the Marda region, appear to show the most contamination with old crust. This is likely due to this area representing the old nucleus of the craton, as shown in Hf-isotope mapping. The final component represents an ultra-depleted source. Data from Ravensthorpe, Mt Clifford, and Wiluna show trends towards this source referred to as the Early Refractory Reservoir (ERR; Nebel et al. 2014). We suggest that the 2.7 and 2.9 Ga plumes interacted with refractory Hadean plume residues, which constitute the ERR, within the Yilgarn lithosphere. Isotopic data on crustal rocks suggests the Yilgarn may have formed in the Hadean to Eoarchean, and hence the ERR could represent the residue of the Hadean crust generation process that formed the low Lu/Hf Jack Hills zircons. If correct this suggests that the ERR survived – for much longer than previously thought – as a rare component within the Earth's oldest cratons.

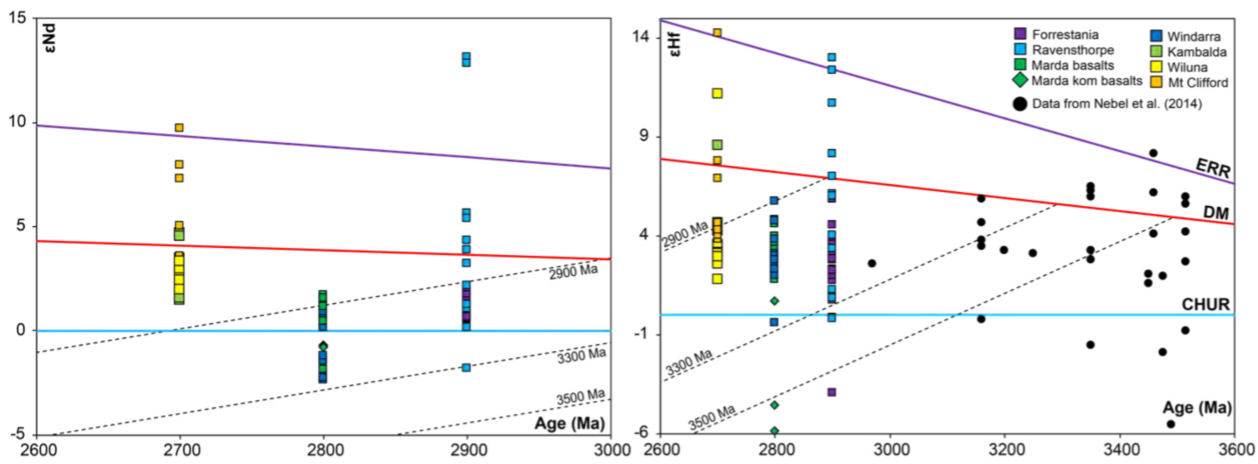



Figure 1. (a) Sm-Nd (b) Lu-Hf isotopic data for komatiites and associated basalts from the Yilgarn Craton

## Reference

Nebel O, Campbell IH, Sossi PA, Van Kranendonk MJ 2014, Hafnium and iron isotopes in early Archean komatiites record a plume-driven convection cycle in the Hadean Earth, Earth and Planetary Science Letters 397:111-120.

# Storm deposits in microbialite systems past and present: examples from Western Australia

**TE Morris[1,4*], MJ Van Kranendonk[2], BJ Nomchong[2], EV Barlow[2,3], SN Morris[4], PT Visscher[5]**

* corresponding author: therese.morris@blueearthscience.com.au

1. Applied Geology, School of Earth and Planetary Sciences, Curtin University, Perth, WA, Australia
2. School of Biological, Earth and Environmental Sciences, University of New South Wales, Kensington, NSW, Australia
3. Department of Geosciences College of Earth and Mineral Science, Pennsylvania State University, University Park, PA, USA
4. Blue Earth Science, Denham, WA, Australia
5. Department of Marine Sciences, University of Connecticut, Storrs, CT, USA

The famous microbialite deposits within Hamelin Pool (Shark Bay, Western Australia) provide important modern analogues for understanding the processes involved in the formation of Deep Time microbialite reefs. Here, we extend the potential for analogous study by comparison of the effects of Tropical Cyclone (TC) Olwyn (March, 2015) on Shark Bay microbialites to potential storm deposits from a c. 2.4 Ga microbialite reef complex from the Turee Creek Group (TCkG) of Western Australia.

Previous studies of Deep Time microbialite reef complexes have identified the effect of past storms in the form of flat pebble (or edgewise) conglomerates in very shallow water (peritidal, or lacustrine shoreline) settings, yet recent observations of the effects of TC Olwyn on Shark Bay microbialites indicate that a higher number of facies in ancient deposits may relate to storm events than has been previously recognized. A key feature relating to TC Olwyn is the formation of a number of different types of benthic microbial mucilage deposits from storm generated floc. This relatively unknown storm process drove a biogeomorphic response by the benthic microbial ecosystem that contributed to the development of microbial mats and structures with the capacity to form stromatolites (Morris et al., 2022).

The TCkG microbialite reef complex consists of five shallow- to deep-water facies associations, one of which occurs at the transition from shallow to deep water facies and includes an average of 40 m thick of 'clotted, thrombolite-like microbialite' (Barlow et al., 2016) or 'clotted microbialite aggregate' (Nomchong and Van Kranendonk, 2020). While (Barlow et al., 2016) regarded this unit as having formed as thrombolite-like microbialite in a low-energy, low-sediment subtidal environment, Nomchong and Van Kranendonk (2020) suggested an origin of the clots as '…ripped-up fragments of semi-lithified, non-laminated microbialite derived from intertidal to subtidal environments where they would be more susceptible to erosion by storm events'. Here, we collectively explore these interpretations in light of the subsequently reported impacts of TC Olwyn. Given the differences in the hydrochemistry of the Archean and Proterozoic times compared to today, rapid organomineralisation and/or silicification of benthic mucilage aggregates may have contributed to granular and clotted textures between stromatolitic structures such as those observed in the TCkG.

## References

Barlow, E, Van Kranendonk, M, Yamaguchi, K, Ikehara, M and Lepland, AJG, 2016, Lithostratigraphic analysis of a new stromatolite–thrombolite reef from across the rise of atmospheric oxygen in the Paleoproterozoic Turee Creek Group, Western Australia, 14(4): 317-343.

Morris, TE, Morris, S, Fearns, P.R.C.S., Chopra, A, Aspandair, MF, Collins, LB, O'Leary, MJ and Visscher, PT, 2022. Impacts of Severe Tropical Cyclone Olwyn and the biogeomorphic response, Hamelin Pool, Shark Bay, Western Australia. The Depositional Record.

Nomchong, BJ and Van Kranendonk, M 2020, Diverse thrombolites from the c. 2.4 Ga Turee Creek Group, Western Australia, 338: 105593.

# Bimodal Hf isotope signatures in tonalite-trondhjemite-granodiorite indicate a heterogeneous Archean mantle

**KM Musiyachenko[1*], MA Smit[1], M Kielman-Schmitt[2], E Kooijman[2], A Scherstén[3], J Halla[4], W Bleeker[5], JE Hoffmann[6], T Næraa[3], M Whitehouse[2]**

* corresponding author: kmusiyachenko@eoas.ubc.ca

1. Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, V6T 1Z4, Canada
2. Department of Geosciences, Swedish Museum of Natural History, Stockholm, SE-104 05, Sweden
3. Department of Geology, Lund University, Lund, SE-223 62, Sweden
4. Geological Museum, Finnish Museum of Natural History, Helsinki, FIN-00100, Finland
5. Geological Survey of Canada, Ottawa, K1A 0E8, Canada
6. Institut für Geologische Wissenschaften, Freie Universität Berlin, Berlin, D-12249, Germany

The Archean continental crust grew via the addition of tonalite-trondhjemite-granodiorite (TTG) magmas. The chemical and isotope compositions of TTGs provide a key to constraining the processes of early crust development. The Hf isotope analysis of zircon in these rocks is of particular interest because it can provide insights into the mantle reservoirs from which the TTG source melt was extracted. Commonly, the Hf isotope composition of zircon, or rocks in general, is interpreted in terms of juvenile (DM, depleted mantle) versus evolved (felsic crust) signatures, with DM being represented by a linear evolution line back-calculated from modern-day (MORB) values. This reservoir is considered the main source of the TTG parental melts. However, recent studies of TTGs from various cratons documented prevailing Hf isotope signatures that are distinctly less radiogenic (e.g. Whitehouse et al., 2022). The data indicate the presence of a less-depleted mantle reservoir that may have contributed to Archean crustal growth, but it is unclear whether this represents a local or global feature. To investigate this, we performed U–Pb and Hf analysis of magmatic zircon from TTG samples ranging in age from 3.8 to 2.6 Ga from seven different cratons.

The Hf isotope signatures of TTGs from some of the investigated Archean cratons indicate a juvenile source close to, or indistinguishable from, the DM evolution line. However, a significant subset of TTG complexes tracks the Hf isotope evolution of a less-radiogenic mantle reservoir, which resembles that observed in the above-mentioned study. These data could be explained 'conventionally' through the contamination of DM-derived melts with the evolved crust, or through variable residence time of the TTG source. However, this would require the proportion of juvenile and evolved material to coincidentally change through time within the different cratons to maintain persistent supra-chondritic Hf isotope composition throughout the Archean. Therefore the data likely indicate that the Archean crust-producing mantle was isotopically bimodal with some regions having DM composition and others comprising a distinctly less depleted mantle with Hf compositions intermediate between DM and chondritic reservoirs. This mantle reservoir was a global, rather than local, phenomenon and may have been as prevalent as DM in producing continental crust during the Archean.

## Reference

Whitehouse, MJ, Kemp, AIS, and Petersson, A 2022, Persistent mildly supra-chondritic initial Hf in the Lewisian Complex, NW Scotland: Implications for Neoarchean crust-mantle differentiation: Chemical Geology, 606, 121001.

# Petrogenesis of the ultramafic-mafic enclaves in the Selukwe Subchamber, Great Dyke, Zimbabwe

**S Ncube[1,2*], AH Wilson[2]**

1. School of Geosciences, University of the Witwatersrand, Private Bag 3, WITS 2050, South Africa.
2. Department of Geology, University of Johannesburg, P O Box 524, Auckland Park, 2092, South Africa.

The Selukwe Subchamber (SSC) of the Great Dyke is the only subchamber that is bounded extensively by a greenstone belt (Shurugwi greenstone belt; SGB) on the western side for approximately 25 km and by Archean granitoids on the eastern side. The other subchambers of the Great Dyke are bounded on both sides by entirely by granitoids. It is also the narrowest section of the entire Great Dyke (as narrow as 4 km). This study focuses on a borehole section (PAR11 borehole) that intersects anomalous stratigraphy of the upper Ultramafic Succession of the Great Dyke as well as xenolithic fragments exposed at the surface within the SSC. The extensive xenolith suite of mainly ultramafic fragments is found on the central western flank of the SSC.

The stratigraphy of the PAR11 borehole comprises of peridotites overlain by pyroxenites with the dominant mineralogy of olivine and orthopyroxene and minor clinopyroxene, plagioclase and spinel. Comparison of the major and trace element geochemistry of PAR11 with the regular section of the sequence in close proximity reveals that the PAR11 sequence is more primitive with higher Mg# but similar rare earth element (REE) patterns typical l of an enriched source or crustally contaminated source with LREE enrichment, HREE depletion and a slight negative Eu anomaly. The mineral assemblages and proportions of mineral phases in the PAR11 borehole indicate a similar composition to that which formed the regular sequence of the Great Dyke but stratigraphically displaced, indicating crystallization of a distinctly separate entity interpreted as a feeder conduit.

This anomalous occurrence on the east side contrasts with the extensive xenolith suite on the west side, which also disrupts the normal layered sequence. The main rock types in the ultramafic-mafic xenolith suite are peridotite, pyroxenite and gabbro. The origin of some of these enclaves cannot be attributed to their derivation from the SGB because they are not present in the observed greenstone stratigraphy. Major and trace elements show a wide range of compositions, which are dissimilar to both PAR11 and the general Great Dyke stratigraphy. REE patterns show depletion of LREE with relatively flat HREEs indicating a different magma to that which gave rise to the Great Dyke. These xenoliths do not have mineral compositions that are similar to the Great Dyke and therefore precludes them as having been derived from the Great Dyke Marginal Facies, a possible source of such rocks. This group of xenoliths was therefore inherited from a currently unknown source or reflect an unknown component of the SGB.

Quartzites and banded iron formations (BIFs) have been observed in the xenolith suite but are located at the top of the Great Dyke Mafic Sequence in this area most likely reflect the roof lithologies to the SSC. In that case, the quartzites were derived from the Mont d'Or and Wanderer Formations while the BIFs are from the Upper Greenstones.

# Assessing rare earth elements mobility during supergene and hypogene alteration and the preservation of seawater signatures in the Weld Range banded iron formation, Western Australia

**SC Russo[1], AJ McCoy-West[1], P Duuring[2]**

* corresponding author: samantha.russo@my.jcu.edu.au

1. IsoTropics Geochemistry Laboratory, James Cook University, Townsville, Qld, Australia 4811

2. Geological Survey of Western Australia, Department of Mines, Industry Regulation and Safety, Perth, Western Australia, Australia 6004

Banded iron formations (BIF) preserve the elemental and isotopic signatures of the seawater in which they precipitate from. These reconstructions are supported by negligible changes in rare earth elements (REE) patterns in seawater throughout Earth's history (Ernst & Bau, 2021). Preservation of seawater signatures in BIF can be demonstrated by $Nd_{CN}/Yb_{CN}$ values > 1 (i.e. where $_{CN}$ denotes chondrite-normalized), enrichment of $LREE_{CN}$ relative to $HREE_{CN}$, and by the presence of a W-type tetrad effect on REE abundances. However, most paleo studies focus on pristine BIF units and exclude hypogene and/or supergene altered BIF from sample suites due to the risk of primary signatures being disturbed by alteration fluids. While it is reasonable to assume that the precipitation of secondary minerals can affect bulk-rock signatures, conducting fraction-specific analyses of altered BIF greatly expands sample availability for paleo reconstructions and improves our understanding of the evolution of our oceans through time, where primary minerals are preserved. BIF mineralogy consists of three main fractions: carbonates (e.g. siderite), iron oxides (e.g. magnetite, hematite and goethite) and silicates (e.g. quartz and Fe-silicates). Through sequential extraction techniques each fraction is targeted using reagents (sodium acetate, ammonium oxalate and $HF\text{-}HNO_3$ digestions, respectively) to analyse major and trace element and isotopic signatures (Oonk et al., 2017).

This study focuses on fraction-specific analysis of the c. 2.7 Ga Weld Range BIF, Yilgarn Craton, Western Australia – with samples ranging from least-altered BIF (likened to pristine BIF) to progressively hypogene- and/or supergene-altered BIF. Sequential extractions have shown that seawater signatures are preserved across the carbonate, iron oxide and silicate fractions of the Weld Range BIF. Coupled with undisturbed textural relationships within the silicate fraction, the $Nd_{CN}/Yb_{CN}$ values > 1 and the W-type tetrad effect supports a primary seawater origin and primary signatures. However, seawater signatures within the carbonate and iron oxide fractions are not considered to be primary due to secondary mineral textures, and lack of $Nd_{CN}/Yb_{CN}$ values > 1 and W-type tetrad effects. Instead, these signatures are likely the product of hypogene alteration fluids, which contain an Archean seawater mixing component alongside magmatic-derived fluids (Duuring et al., 2018). This study shows that primary mineralogical fractions in altered BIF can serve as a reliable proxy and reservoir for understanding ancient ocean chemistry.

## References

Ernst, DM and Bau, M 2021, , *Gondwana Research 91*, p 97-111.

Oonk, Tsikos, Mason, Henkel, Staubwasser, Fryer, Poulton & Williams (2017) *Chemical Geology* 474, 17-32

Duuring, Hagemann, Banks & Schindler (2018) *Ore Geology Reviews 93*, 211-254

# Age constraints on crustal overturn and juvenile granitic magmatism in the Paleoarchean Pilbara Craton

**R Salerno[1*], N Roberts[2], J Vervoort[1], B Tikoff [3]**

* corresponding author: ross.salerno@wsu.edu

1. School of the Environment, Washington State University, Pullman WA, 99164
2. Geosciences Department, Hamilton College, Clinton NY, 13323
3. Department of Geosciences, University of Wisconsin Madison, Madison WI, 53706

Archean granite-greenstone terranes provide important information about how early continental crust was formed and preserved. Early Archean cratons – such as in the Pilbara Craton of Western Australia – have a distinct dome-and-keel architecture in which large (approximately 70 km) ovoid granitic batholiths are surrounded by curvilinear metavolcanic greenstone belts. Dome-and-keel structures are often interpreted to result from gravity-driven crustal overturn processes in the early Archean, which are intrinsically linked with the production of preservable sialic crust (Collins et al., 1998). The timescales of this process; however, have yet to be constrained using the combined approaches of garnet Lu-Hf and Sm-Nd geochronology and structural analyses. In this study, we focus in the Pilbara Craton on the granitic rocks in the Mt. Edgar Granitic Complex and on the adjacent deformed supracrustal rocks of the Warrawoona Syncline. To better understand the evolution of Paleoarchean dome-and-keel structures – and access the connection between these overturn events and making stable felsic crust – we use an approach integrating zircon and titanite U–Pb and garnet Sm–Nd and Lu–Hf geochronology, Sm–Nd and Lu–Hf isotopic data, and microstructural analyses. Using garnet Lu–Hf and Sm–Nd geochronology, we show that two discrete periods of fabric development related to dome-and-keel formation occurred, at approximately 3.42 to 3.39 Ga and 3.34 to 3.30 Ga. The older population of garnets is mechanically disaggregated, and we interpret that their growth is related to an early event prior to the main phase of dome-and-keel formation. The younger group of garnets, between 3.34 and 3.30 Ga, have microstructures consistent with pre-, syn-, and post-kinematic growth with respect to the development of the dome-and-keel structure. By coupling these microstructures and garnet Lu–Hf ages, we show that the main phase of dome formation is dated by growth of the younger garnet group between 3.33 and 3.30 Ga. The Sm–Nd ages of these garnets are systemically younger than the Lu–Hf ages, consistent with protracted cooling of the system after dome formation until 3.17 Ga. We also focus on the Hf–Nd isotope compositions of the granitic rocks in the Mt. Edgar Granitic Complex, which intruded during these intervals of garnet growth and doming. These rocks crystallized between 3.46 and 3.25 Ga and have well-correlated chondritic initial whole rock Hf-Nd isotopes ($\varepsilon_{Hf(i)}$= +1.5 to -1.8, $\varepsilon_{Nd(i)}$= +2.5 to -1.1) and zircon Hf isotopes ($\varepsilon_{Hf(i)}$= +0.9 to -0.8). Our isotope data, in conjunction with several recently published datasets (Petersson et al., 2020), establishes that the Paleoarchean granitic material in the Pilbara was predominantly juvenile and extracted from a source with broadly chondritic Lu/Hf and Sm/Nd. Together, our dataset illustrates the Pilbara dome-and-keel structures are the cumulative result of multiple events in the Paleoarchean, two of which we date precisely using garnet geochronology. Further, we also show the syn-doming granitic intrusions have juvenile Hf–Nd isotope compositions indicating that dome-and-keel formation, crustal overturn, and juvenile sialic magmatism are all spatially and temporally related.

## References

Collins, WJ, Van Kranendonk, MJ, Teyssier, C 1998,: J. Struct. Geol. 20, 1405–1424.

Petersson, A, Kemp, AIS, Gray, C M, Whitehouse, MJ, 2020, Chem. Geol., 119757.

# Discovery of nearly Hadean zircon in the Ukrainian Shield

**LV Shumlyanskyy[1,2*], GV Artemenko[3], SA Wilde[2], MJ Whitehouse[4], A Bekker[5]**

* corresponding author: Leonid.Shumlyanskyy@curtin.edu.au

1. School of Earth and Planetary Sciences, Curtin University, Perth, Australia
2. Institute of Geological Sciences, Polish Academy of Sciences (ING PAN), Kraków, Poland
3. M.P. Semenenko Institute of Geochemistry, Mineralogy and Ore Formation, Kyiv, Ukraine
4. Swedish Museum of Natural History, Stockholm, Sweden
5. Department of Earth and Planetary Sciences, University of California, Riverside, USA

A small number of Eoarchean zircon grains with ages reaching 3970 Ma (2 grains, SIMS) were recently discovered in the Mesoarchean (c. 2.9 Ga) granites and meta-andesites in the West Azov Domain of the Ukrainian Shield. In total, 17 SIMS and LA-ICP-MS analyses yielded ages over 3700 Ma, and 9 were older than 3900 Ma (Fig. 1). All but one of these zircon grains have negative εHf values, ranging from -1 to -11, and show a tendency towards more negative values in the younger grains. The average minimum MORB-DM model Hf age assuming Lu/Hf = 0 (i.e. Pb-loss in the zircon) is 4.2 Ga. 'Felsic crust' and 'mafic crust' models with Lu/Hf > 0 would result in even older model ages. Grains with the lowest εHf values have older minimum model Hf ages exceeding 4.35 Ga. Therefore, the Hf isotope characteristics of the studied zircon grains are indicative of the presence of Hadean material in the West Azov Domain of the Ukrainian Shield.

On the age vs. εHf diagram, zircon from the West Azov Domain plot within the field defined by the Eoarchean to Hadean detrital zircons from Jack Hills in Western Australia, similar to zircon occasionally found in many other localities worldwide (Fig. 1). Ukrainian zircon thus confirms the well-known phenomenon of the 'evolved' Hf isotope composition of the oldest terrestrial (and lunar) zircons, which might reflect very early development of a thick, long-lived proto crust with a distinct Hf isotope signature. Nearly complete destruction of this early crust in the Eoarchean gave way to the appearance of zircon with juvenile Hf isotope compositions.

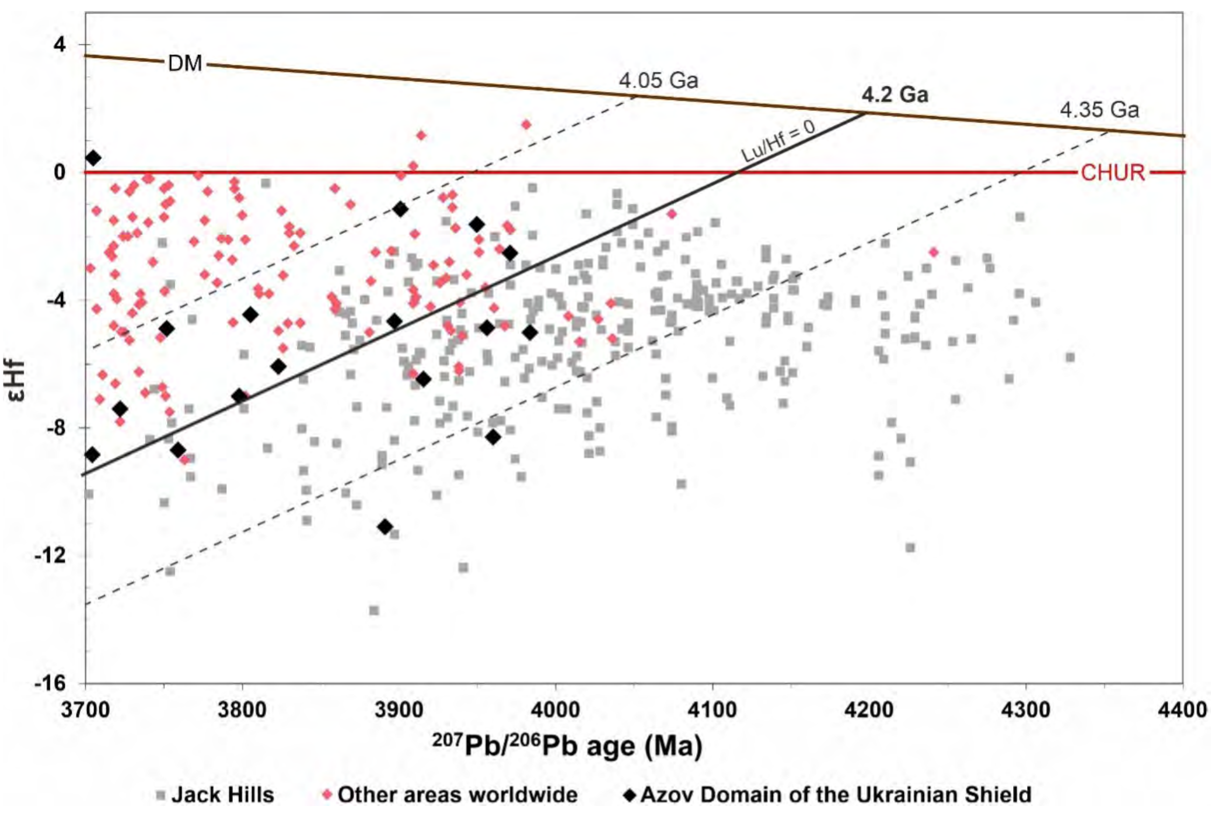



Figure 1. Age vs. εHf diagram for Hadean and Eoarchean zircon from the Azov Domain of the Ukrainian Shield, Jack Hills in Western Australia and other areas worldwide.

# Three episodes of juvenile crustal growth in the Eoarchean Dniester-Bouh Domain, Ukrainian Shield

**LV Shumlyanskyy[1*], SA Wilde[1], AA Nemchin[1]**

* corresponding author: Leonid.Shumlyanskyy@curtin.edu.au

1. School of Earth and Planetary Sciences, Curtin University, Perth, U1987, WA 6845, Australia

We provide combined Lu–Hf and U–Pb isotope data on 14 samples of enderbites and charnockites that constitute a granulite complex in the Dniester-Bouh Domain of the Ukrainian Shield. These rocks have traditionally been regarded as early Archean (c. 3.7–3.6 Ga), while early multigrain zircon dating indicated that many of them crystallized at c. 2.8 and 2.0 Ga. It was believed that these younger ages reflected remelting and remobilization of the early Archean crust.

According to our data, the oldest 3786 ± 32 Ma zircon population defines the primary igneous event in enderbite sample C10-U4. Hafnium $T_{DMmafic}$ and $T_{DMfelsic}$ model ages for these zircons are 4.2 and 4.0 Ga, respectively, whereas $\varepsilon Hf_{(3790)} \approx 1$ and whole-rock $\varepsilon Nd_{(3790)} = 2$. This was followed by an igneous/metamorphic event (possibly involving migmatization) at 3569 ± 22 Ma that closely resembled the initial one with respect to Hf and Nd isotopic systematics.

The next main event took place between c. 3100 and 2800 Ma, and consisted of several phases separated by extended periods of inactivity. Hafnium isotope composition of zircons attained DM values (εHf = 5 to 6), whereas some remobilization of the Eoarchean crust is apparent in negative εHf values that are recorded from several samples. The extended duration of this event and significant input of juvenile material imply large-scale crust-forming processes. Felsic igneous rocks of this age also occur in the Middle Dnieper and Azov domains of the Ukrainian Shield, signifying the importance of this time interval in its geological evolution.

The last major event that affected the early Archean rock assemblage in the Dniester-Bouh Domain took place in the Paleoproterozoic, between c. 2.15 and 1.90 Ga. Hafnium isotope systematics of zircons indicate that significant juvenile input accompanied recrystallization of the rocks formed during the previous events. Several rocks contain zircons with εHf greater than +5. This event resulted in granulite facies metamorphism with emplacement of numerous granitic intrusions, and broadly correlates with the collision of the Sarmatian and Volgo-Uralian segments of Baltica at 2.1–2.05 Ga, with subsequent subduction at the northern margin of Sarmatia. However, timing of the metamorphic and igneous events in the Dniester-Bouh Domain does not match this collision in detail. Moreover, igneous and metamorphic activity was not synchronous in different domains of the Ukrainian Shield and were probably caused by different tectonic events. We interpret that the activity in the Dniester-Bouh Domain was caused by an unknown tectonic event that was happening at the southern margin of Sarmatia during assembly of the Columbia/Nuna supercontinent (collision with Amazonia or West Africa?).

Our U–Pb and Lu–Hf isotope data from granulite-facies rocks of the Dniester-Bouh Domain of the Ukrainian Shield therefore establish three major juvenile crust-forming events, at 3.8–3.6, 3.1–2.8, and 2.15–1.90 Ga respectively, that may extend across the whole of the shield.

# $^{182}W$ isotope evolution from Pilbara Craton, Western Australia

**Y Song[1*], D Stubbs[1], AIS Kemp[2], CD Coath[1], T Elliott[1]**

* corresponding author: ys16618@bristol.ac.uk

1. School of Earth Sciences, University of Bristol, BS8 1RJ, UK

2. School of Earth Sciences, The University of Western Australia, Perth, WA, Australia

The $^{182}Hf$-$^{182}W$ decay system ($t_{1/2}$ = 8.9 Ma) has proven very valuable in understanding the evolutionary history of the early Earth. The parent isotope, $^{182}Hf$, completely decays into $^{182}W$ within the first 50 Ma of the solar system history, so variations in $^{182}W/^{184}W$ are only produced during this period or by later mixing of early-formed reservoirs. Many Archean terrestrial samples have $^{182}W/^{184}W$ about 10 ppm higher than modern crustal values, implying that the mantle source of modern crust has experienced widespread addition of unradigenic material to decrease its $^{182}W/^{184}W$ since the Archean. Several theories have been put forth to explain this decrease in $\Delta^{182}W$, e.g. inmixing of late veneer material (Willbold et al., 2011) or core-mantle interaction (Rizo et al., 2019).

Here we report $\Delta^{182}W$ data of mantle-derived rocks from the Pilbara Craton, Western Australia, focusing on the evolution of W isotopic compositions within this single Archean block through time. The $\Delta^{182}W$ values were measured for a range of lithologies from the Pilbara region including komatiite, basalt and gabbro, with ages ranging from 3.58–2.77 Ga. With an average $\Delta^{182}W$ of +9.7 ± 2.2 ppm, the majority of the examined samples preserved relatively uniform $^{182}W$ excesses. Tungsten has clearly experienced secondary mobility in many samples, yet the W isotopic ratios of samples with magmatic W/Th (0.04–0.24) and disturbed W/Th ratios showed no discernible variations. The secondary tungsten enrichment event has been dated through tungsten-rich rutiles (as high as 13799ppm) found in the 3.5 Ga Mount Webber gabbros. The U–Pb dating of rutiles gave $^{207}Pb/^{206}Pb$ apparent ages at 3.0–2.9 Ga, showing the presence of a tungsten-rich fluid during the metamorphism at the time. Values of $\Delta^{182}W$ = +12 ppm for three Mount Webber samples, which are dominated by W transported by this late metamorphic event, are inconsistent with the theory of a less radiogenic, homogenized $\Delta^{182}W$ crustal fluid proposed by a previous study of the Pilbara Craton (Tusch et al, 2021). No systematic decrease in $\Delta^{182}W$ values with time during Pilbara Craton formation (3.5–2.7 Ga) is observed in our collection of samples. Further younger samples will be investigated, aiming to find the exact timing and style of $\Delta^{182}W$ decrease in the upper mantle from typical Archean values of approximately 10 ppm to the modern composition.

## References

Willbold, M, Elliott, T, and Moorbath, S, 2011, The tungsten isotopic composition of the Earth's mantle before the terminal bombardment, Nature, 477(7363), pp.195-198.

Rizo, H, Andrault, D, Bennett, NR, Humayun, M, Brandon, A, Vlastélic, I, Moine, B, Poirier, A, Bouhifd, MA and Murphy, DT, 2019, 182W evidence for core-mantle interaction in the source of mantle plumes, Geochem. Perspect. Lett., 11, pp.6-11.

Tusch, J, Münker, C, Hasenstab, E, Jansen, M, Marien, CS, Kurzweil, F, Van Kranendonk, MJ, Smithies, H, Maier, W, and Garbe-Schönberg, D, 2021, Convective isolation of Hadean mantle reservoirs through Archean time, Proceedings of the National Academy of Sciences, 118(2).

# Oxygen and silicon isotope systematics of zircons from Izu-Bonin-Mariana arc and the Izu collision zone, a modern analogue of the early evolved crust formation

**T Ushikubo[1*], K Tani[2]**

* corresponding author: ushikubot@jamstec.go.jp

1. Kochi Institute, JAMSTEC, Nankoku Kochi Japan 783-8502
2. Department of Geology and Paleontology, National Museum of Nature and Science, Tsukuba Ibaraki Japan 305-0005

The Izu-Bonin-Mariana (IBM) intra-oceanic arc evolved over approximately 52 million years, where silicic crusts have been generated by subduction zone magmatism [1]. The north end of the IBM arc has been colliding with the Honshu arc at the Izu Collision Zone (ICZ) for approximately 15 million years, and voluminous syn-collision granitic plutons are exposed [2]. Silicic crust formations by intra-oceanic crustal subduction and the following arc-arc collision are probably significant processes of continental crust formation and growth in the early Earth's history. We will report comprehensive oxygen and silicon isotope data of zircons from the IBM arc (approximately 49 Ma to <1 Ma) and the ICZ (15 Ma to 4 Ma).

Oxygen and silicon isotope measurements of zircons were performed with an ion microprobe, Cameca IMS-1280HR of the Kochi Institute, JAMSTEC. The instrumental bias of analyses was corrected based on results of bracketing analyses of the in-house kimberlite zircon standard, KC-KLV-Zrc1 ($d^{18}O$=5.43±0.13‰ and $d^{30}Si$=-0.38±0.19‰ [3,4]). Typical spot-to-spot reproducibility (2SD) of the bracketing standard analyses was ±0.25‰ for $d^{18}O$ and ±0.3‰ for $d^{30}Si$, respectively.

The average $d^{18}O$ values of zircons from individual IBM arc samples (4.9 to 5.3‰) are generally consistent with the mantle zircon value [5]. This is probably because incorporation of sediments into the silicic parent magmas does not occur efficiently. One exception is zircons from diorite of the Omachi Seamount ($d^{18}O$=7.0‰; approximately 38 Ma). Since serpentinite bodies are abundant around this seamount, elevated $d^{18}O$ values of zircons could be a result of assimilation of serpentine during emplacement of the parent magma. On the other hand, zircons from ICZ granitic rocks show wider range $d^{18}O$ values (4.8‰ to 6.4‰), and three samples out of six ICZ samples show $d^{18}O$ values higher than 6.0‰, indicating incorporation of mature sediments from the Honshu arc during the emplacement of the granitic magmas at shallow levels during the arc collision. Contrary to the $d^{18}O$ values, the average $d^{30}Si$ values of zircons from all the studied samples (-0.20±0.37‰ to -0.57±0.34‰) are consistent with the kimberlite zircon data (-0.38±0.19‰) within analytical uncertainty. These results suggest that (1) silicic crusts can be formed by intra-oceanic crustal subduction; however, the $d^{18}O$ values of zircons commonly stay within the range of the mantle value, (2) silicic magmas with elevated $d^{18}O$ values by incorporation of sediments can be effectively formed by arc-arc collisions, (3) assimilation of serpentine is another possibility to form silicic crusts with elevated $d^{18}O$ values [e.g. 6] and (4) $d^{30}Si$ values is much less sensitive to incorporation of mature sediments than $d^{18}O$ values because of smaller isotopic contrast between mantle and mature sediments (larger than 10‰ for $d^{18}O$ vs. a few ‰ for $d^{30}Si$).

## References

1. Ishizuka, O., et al. 2011, EPSL, v.306, p.229-240.
2. Tani, K., et al. 2010, Geology, v.38, 215-218.
3. Ushikubo, T., et al. 2015, Goldschmidt abstract #3214.
4. Ushikubo, T., et al. 2017, GSA abstract #139-8.
5. Valley, J. W., et al. 2005, Contrib. Mineral. Petrol., v.150, p.561-580.
6. Trail, D., et al. 2018, PNAS, v.115, p.10287-10292.

# The identification of the Eoarchean Muzidian Gneiss complex in Central China

D Wang[1,2*], XF Qiu[3], RW Carlson[2]

* corresponding author: da.wang@cdut.edu.cn

1. Research Center for Planetary Science, College of Earth Sciences, Chengdu University of Technology, Chengdu 610059, China

2. Earth and Planets Laboratory, Carnegie Institution for Science, Washington DC, 20015, USA

3. Wuhan Center of China Geological Survey, Wuhan 430205, China

Based on the currently available zircon Hf and bulk-rock $^{142}$Nd isotope data of >3.6 Ga global ancient terranes, only a few of them are derived from pre-existing Hadean crust (e.g. the review of Carlson et al., 2019). These include the Acasta Gneiss complex, the Nuvvuagittuq greenstone belt and a few outcrops in the Napier complex. These terranes share a common feature that their geographic locations are not easily reachable. Here we report a newly identified, Hadean crustal derived, Eoarchean terrane in central China named the Muzidian Gneiss complex. The Eoarchean rocks in the Muzidian Gneiss complex were first reported by Qiu et al. (2021) and then Wang et al. (2023). Unlike those terranes in remote areas of Canada or Antarctica, the Muzidian Gneiss complex is near a town and connected with several highways and freeways. We believe that the convenient location of the Muzidian Gneiss complex will provide new opportunities for the early Earth community to further explore the nature of the first crust on Earth in this new decade.

Our preliminary studies showed that the oldest tonalite–trondhjemite–granodiorite (TTGs) in the Muzidian Gneiss complex have ages ranging from about 3.9 to 3.5 Ga, whose zircon Hf isotope compositions are generally negative and could be projected back to a about 4.3 Ga mafic crustal source. The negative bulk-rock $^{142}$Nd anomalies of these TTGs further confirm that these rocks are most likely reworked pre-existing >4.3 Ga Hadean mafic crust. We also investigated 2.5–2.4 Ga rocks in the same complex to explore their genetic relation to the Eoarchean units and the ultimate Hadean crustal source. These Neoarchean rocks yielded negative $\mu^{142}$Nd values and very negative zircon $\varepsilon$Hf(t) values projectable from the nearby Eoarchean TTGs, which makes them the youngest felsic rocks on Earth with deficits in $^{142}$Nd. This highlights the long-lived nature of the initial Hadean crustal components represented by the Muzidian gneisses that served as the initial nucleus, and the Archean continent was possibly built around it.

## References

Carlson, RW, Garçon, M, O'Neil, J, Reimink, J, Rizo, H, 2019, The nature of Earth's first crust. Chemical Geology 530, 119321.

Qiu, X., Tong, XR, Jiang, T, Khattak, NU, 2021, Reworking of Hadean continental crust in the Dabie orogen: Evidence from the Muzidian granitic gneisses, Gondwana Research 89, 119–130.

Wang, D, Qiu, XF, Carlson, RW, 2023, The Eoarchean Muzidian gneiss complex: Long-lived Hadean crustal components in the building of Archean continents, Earth and Planetary Science Letters 605, 118037.

# Growth, reworking and emergence of continental crust of the Kaapvaal Craton during Paleoarchean

**H Wang[1,2*], JH Yang[1,2]**

* corresponding author: wanghao@mail.iggcas.ac.cn

1. State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing China 100029

2. University of Chinese Academy of Sciences, Beijing China 100049

It is intriguing to speculate on how continental crust evolved and was exposed above the sea level during the Archean, and which tectonic regimes and magmatic mechanisms were responsible for such a process. The continental nucleus of the Kaapvaal Craton, which includes the Barberton granitoid-greenstone terrane (BGGT) in South Africa and the Ancient Gneiss Complex (AGC) in Swaziland, exhibits the best-preserved geological record from 3.6 to 3.0 Ga and thus provides the optimal location to address this issue. In this study, combined U–Pb, O and Lu–Hf isotope and trace element analyses were carried out on detrital zircon grains from two Moodies Group sandstones and three modern river sand samples in the Barberton and Swaziland regions, southern Africa. In addition, the zircon U–Pb ages and O isotopic data were obtained from three metamorphic rocks, one charnockite and two trondhjemites in the AGC. The detrital zircons in the Moodies sandstones had two U–Pb age clusters of 3.25–3.30 Ga and 3.40–3.47 Ga and the oldest age up to 3.57 Ga. This suggests that they were derived from older felsic volcanic rocks of the greenstone belt and the granitoid gneisses in the BGGT and AGC. Using the approach created for Earth's oldest zircons, we inferred that the source magmas of the studied detrital zircons had average arc-like andesitic compositions ($SiO_2$ = 58.0 ± 5.6 wt. %; Th/Nb = 5.0 ± 3.2), similar to those of the Jack Hills detrital zircons. However, these inferred compositions conflict with the source rocks of the detrital zircons, which have high $SiO_2$ contents (average = 70 ± 4.3 wt. %) and moderate Th/Nb ratios (average = 0.76 ± 0.44). These findings suggest that the inferred average andesitic compositions for the Earth's oldest zircons should be re-evaluated. The concordant zircon U–Pb age data reveal four major magmatic episodes for the eastern Kaapvaal Craton at 3.52, 3.46, 3.26 and 3.10 Ga. The first magmatic episode is suggested to dictate crustal growth, whereas the other three magmatic episodes are predominated by crustal reworking. This process is manifested by major positive changes in $\varepsilon_{Hf}(t)$ and $\varepsilon_{Nd}(t)$ values starting at about 3.5 Ga, gradual decreases in $\varepsilon_{Hf}(t)$ and $\varepsilon_{Nd}(t)$ values afterwards, and increases in $\delta^{18}O$ values at about 3.25 Ga. We suggest that modern-style plate tectonic processes may not have been a requirement for crustal growth and reworking in the eastern Kaapvaal Craton during the Paleoarchean. Instead, they could be ascribed to episodic partial convective overturns at different crustal depths. Interestingly, the charnockite and the trondhjemites revealed ultrahigh-temperature melting at low pressure conditions at 3.2 Ga. The three studied metamorphic rocks also record a regional high-T, low-P metamorphic event at 3.2 Ga, and their zircon grains have extremely low $\delta^{18}O$ values (to 0.55 ‰), indicating crystallization from protoliths affected by meteoric fluid interaction. Therefore, some parts of the crust of the Kaapvaal Craton may have exposed above sea level before 3.2 Ga, which may have been induced by an upwelling of mantle hotspot similar to modern Yellowstone.

# Paleoarchean deep mantle heterogeneity recorded by enriched plume remnants

**C Wang[1*], S Song[2*], G Zhao[1,3], C Wei[2], L Su[4], MB Allen[5], Y Niu[4,6,7], XH Li[8], J Dong[2]**

* corresponding authors: daniel.wangchao@gmail.com; sgsong@pku.edu.cn

1. Department of Earth Sciences, The University of Hong Kong, Pokfulam Road, Hong Kong, China
2. MOE Key Laboratory of Orogenic Belts and Crustal Evolution, School of Earth and Space Sciences, Peking University, Beijing 100871, China
3. State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Northern Taibai Streest 229, Xi'an 710069, China
4. School of Scientific Research and State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing 100083, China
5. Department of Earth Sciences, Durham University, Durham DH1 3LE, UK
6. Laoshan Laboratory, Qingdao 266237, China
7. Institute of Oceanology, Qingdao 266071, China
8. State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

Due to the rare occurrences of early Archean deep mantle-sourced magmas, it is unclear whether compositional heterogeneity existed in the early Archean deep mantle, and if it did, how and when this compositional heterogeneity formed. We discovered the oldest mantle plume-related ferropicrite (iron- and magnesium-rich lavas with enriched trace element patterns) on the Earth and associated ultramafic cumulates in Eastern Hebei of the North China Craton (Wang et al., 2019). In situ zircon U–Pb geochronological study on the ultramafic cumulates shows that the ferropicrites were formed in the Paleoarchean (3.45 Ga; Fig. 1a). The detailed geochemical study suggests that the ferropicrites have trace element patterns similar to present-day ocean island basalts (OIB; Fig. 1b), but are more enriched in iron relative to typical mantle plume-related picrites. The Paleoarchean ferropicrites were produced by mantle plume activities from the deep mantle. Their deep mantle source was enriched in iron and incompatible elements, suggesting that deep mantle heterogeneity was present in the Paleoarchean with a partial enrichment of iron and incompatible elements. This research reports the third case of confirmed oldest mantle plume activities with the other two cases of 3.5–3.46 Ga komatiites in South Africa and Australia and the oldest enriched plume remnants, and proves that deep mantle compositional heterogeneity existed in the Paleoarchean, most probably introduced by recycled crustal material.

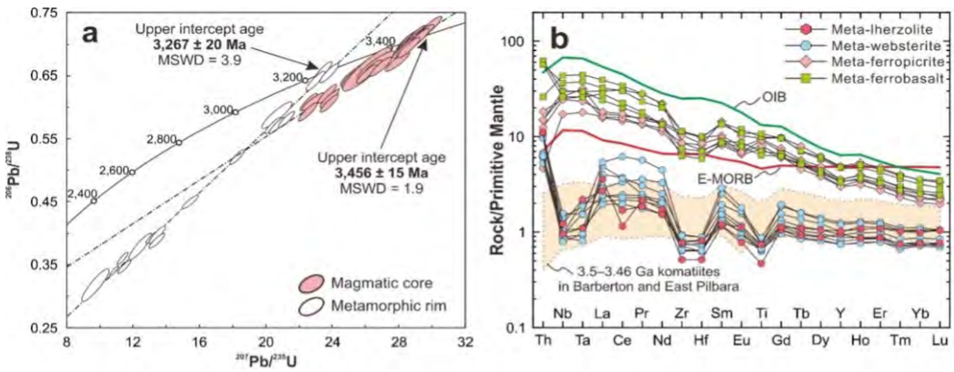



Figure 1. (a) Zircon U-Pb concordia diagram; and (b) trace element diagram for Palaeoarchean ferropicrites and associated ultramafic cumulates in the North China Craton

## Reference

Wang, C, Song, S, Wei, C, Su, L, Allen, MB, Niu, Y, Li, XH and Dong, J 2019, Palaeoarchaean deep mantle heterogeneity recorded by enriched plume remnants: Nature Geoscience, 12(8): 672-678.

# Magmas redox states throughout Earth's history and their potential link to giant impacts and the rise of atmospheric oxygen

**X Wang[1*], M Sun[1], G Zhao[1]**

* corresponding author: u3006391@connect.hku.hk

1. Department of Earth Sciences, The University of Hong Kong, Hong Kong Island, Hong Kong

It is generally believed that the early Earth was remarkably reduced and then transformed into the modern oxidized crust and mantle. However, the origin of the variations in the redox states is still unclear. Here, we investigate the temporal variations of detrital zircon oxygen fugacity (ΔFMQ), which is an igneous oxybarometer, to track magma redox states over Earth's history. Four zircon ΔFMQ increasing trends (i.e. 3.5–3.2 Ga; 2.7–2.5 Ga; 1.9–1.7 Ga; 0.6–0.4 Ga) have been identified throughout the Earth's history. The first increasing trend has the largest increment (2-unit ΔFMQ) and can be attributed to giant impacts that induced charge disproportionation of iron and produced large amounts of ferric iron in melts. The latter three increasing trends overall coincided with the rise of atmospheric oxygen, which resulted in more deposition of oxidized sediments on the seafloor, the subduction of which may significantly increase the redox state of arc igneous rocks. We highlight that the magmas redox states in the pre-plate tectonics regime were strongly controlled by giant impacts, while the magmas redox states show a close link with atmospheric oxygen content in the plate tectonics regime.

**Acknowledgement:** This work was financially supported by NSFC Major Project (41890831) and Hong Kong RGC grants (17307918), and HKU Internal Grants for Member of Chinese Academy of Sciences (102009906) and for Distinguished Research Achievement Award (102010100). This work is a contribution of the Joint Laboratory of Chemical Geodynamics between the University of Hong Kong and Guangzhou Institute of Geochemistry, Chinese Academy of Sciences.

# Earth's evolution – research from surface to the outer core using structural geology dramatically changes plate tectonics

**RB Watchorn**

bobwatchorn123@yahoo.com

Bob Watchorn Research, Mandurah, Western Australia 6210, Australia

With Eagle-Eye (using pattern [structural] recognition and definition software) we can now obtain imaging (similar to magnetic resonance imaging, MRI) of Earth's structural geology from the crustal surface to inner core. The results change the fundamental precepts of plate tectonics. Wherever Eagle-Eye has examined Earth there is evidence of a brittle geological lithospheric environment down to the outer core. There is also abundant evidence of 'continental scale' block movement. This block movement is generated from the core to the surface because the plate margins extend subvertically to the core. There is no evidence of a mobile mantle or 'lava-lamp' type plumes. This new structural geology suggests the current model of 'plate' tectonics is flawed and a new 'block' tectonics model is proposed.

## Earth Evolution

It is suggested that early Earth was much colder (space dust at −100 °C) than the current semi-molten model and re-formed as a solid after the Theia impact at 4.47 Ga spalled off the moon. There is strong evidence of giant impact structures (formed during the Extended Late Heavy Bombardment, ELHB, 4.47–3.6 Ga) penetrating down to the seismic discontinuity at 600 km depth. Many of these ring structures are still undeformed suggesting much of Earth has not undergone major tectonism in the last 3.6 Ga. It is suggested that the base of the giant subductions around the original Theia Impact in the Pacific Ocean are 'scraped off' by the hotter outer core, which is thus pressurized, releasing heat and mass back up the internal plate margins to the surface. It is suggested the first major tectonism occurred at 3–2.6 Ga forming the first worldwide mineralization events.

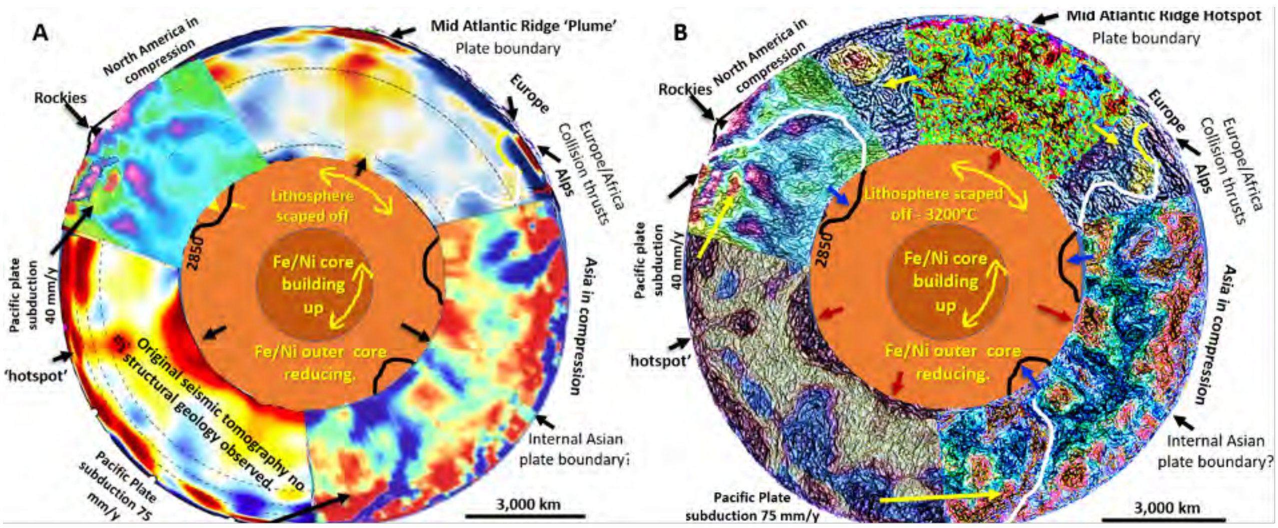



Figure 1. Section through Earth showing A. current plate tectonics data and B. EagleEye structural geology data

# 40 Years of Jack Hills research: global contributions to Zirconology and early Earth Science

**SA Wilde**

s.wilde@curtin.edu.au

School of Earth & Planetary Sciences, Curtin University, GPO Box U1987, Perth, WA, Australia 6845

The year 2023 marks the 40th anniversary of active research in the Jack Hills, Western Australia. It commenced with detailed mapping and preliminary U/Pb zircon geochronology utilizing multigrain techniques, and evolved to ever more detailed work on individual zircon grains at the micro- and nanoscales. When coupled with contemporaneous advances in micro-analysis, this has led to a paradigm shift in how we view the utility of zircon, and also how we envisage the early Earth. Outstanding results include the discovery of the oldest known crystal formed on Earth (Wilde et al., 2001), elevated $d^{18}O$ values indicating early continental crust and oceans and a cool early Earth (Valley et al., 2002), Lu–Hf data establishing the earliest crustal development back to 4.5 Ga (Harrison et al, 2008; Kemp et al., 2010), possible protolith development from a KREEP-like (potassium, rare earth elements and phosphorus) initial source (Kemp et al., 2010), and trace element and Hf data indicating the possibility of plate tectonics in the Hadean (Turner et al., 2020; Mitchell et al., 2022), amongst other advances. Jack Hills is therefore the site that keeps giving, with lead nanospheres recently identified in Hadean and Eoarchean zircon at the 'discovery' site (Kusiak et al., 2023). These, and other 'firsts' for Jack Hills, will be outlined, as too will the potential for further discoveries, including the possibility that discrete periods of activity can be recognized in the Hadean that may be traceable throughout the inner solar system.

## References

Harrison, TM, Schmitt, AK, McCulloch, MT, and Lovera, OM, 2008. Early (>4.5 Ga) formation of terrestrial crust: Lu-Hf, d18O, and Ti thermometry results for Hadean zircons. Earth and Planetary Science Letters, v. 268, p. 476-486.

Kemp, AJA, Wilde, SA, Hawkesworth, CJ, Coath, CD, Nemchin, A, Pidgeon, RT, Vervoort, and JD, DuFrane, SA, 2010. Hadean crustal evolution revisited: New constraints from Pb–Hf isotope systematic of the Jack Hills zircons. Earth and Planetary Science Letters, v. 296, p. 45-56.

Kusiak, MA, Wirth, R, Wilde, SA, and Pidgeon, R.T., 2023. Metallic lead (Pb) nanospheres discovered in Hadean and Eoarchean zircon crystals at Jack Hills. Scientific Reports, 13 (1) (2023), 895. DOI:10.1038/s41598-023-27843-6.

Mitchell, RN, Spencer, CJ, Kirscher, U, and Wilde, SA, 2022. Plate tectonic–like cycles since the Hadean: Initiated or inherited? Geology, v. 50, p. 827-831.

Turner, S, Wilde, S, Worner, G, Schaefer, B, and Lai, Y-L, 2020. An andesitic source for Jack Hills zircon supports onset of plate tectonics in the Hadean. Nature Communications (2020) 11:1241 | https://doi.org/10.1038/s41467-020-14857-1.

Valley, JW, Peck, WH, King, EM and Wilde, SA, 2002. A Cool Early Earth. Geology, v. 30, p. 351-354.

Wilde, SA, Valley, JW, Peck, WH and Graham, CM, 2001. Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4Gyr ago. Nature, v. 409, p. 175-178.

# Jack Hills Zircon hydrogen isotopes: insight for 3.9 Ga late heavy bombardment of Earth

**X-P Xia*, Z Cui, Q Yang, W-F Zhang**

* corresponding author: xpxia@gig.ac.cn

Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, China

Zircon, a widespread accessory mineral in a variety of rocks, can retain its original geochemical information due to exceptionally stable characteristics. When rocks break down, zircon remains as stable detritus in sedimentary rocks, making it a valuable 'time capsule' of early Earth. Hadean zircons have been found in many sedimentary rocks around the world, the most famous being the Jack Hills conglomerate in Australia. The conglomerate contains not only the oldest known zircons on Earth (up to 4.4 billion years old), but also a large number of ancient zircons with ages ranging from 4.4 billion to 3.3 billion years old, providing a rare continuous record of the early evolution of the Earth.

For the first time, the simultaneous analysis of water content and H-O isotopes of these ancient detrital zircons was performed using secondary-ion mass spectrometry (SIMS). The results show that the oxygen isotopes of these zircons are mostly in the range of 5–7‰, consistent with previous studies. The zircons mostly contain hundreds of ppm of water, with a wide range of hydrogen isotopes ranging from -180 to +150‰. What is remarkable that such a large range of hydrogen isotopes occurs only in zircons that are about 3.9 billion years old. The rest of the zircons have significantly smaller ranges of hydrogen isotopes, ranging from -130 to +9‰. Raman spectroscopic analysis of zircons shows that these zircons have been metamict to varied extent, thus it is possible that water may have been altered at a later period, resulting in increased water content in the zircons and affecting hydrogen isotope composition to some extent. However, we believe that the late addition of water is not enough to completely change the hydrogen isotope composition of zircon. This and other studies show that the 3.9-billion-year zircon has a significantly different halogen composition from other zircons, and we believe that the wide range of hydrogen isotope changes in this zircon records a major event in Earth's history, the Late Heavy Bombardment (LHB).

The LHB refers to a high-frequency collision event that affected the inner solar system 4 billion to 3.8 billion years ago. The most direct evidence for the LHB is the widespread impact craters on the surfaces of other planets such as the Moon and Mars during this period and the melting age of meteorite impacts from the asteroid belt. Earth is also thought to have experienced a LHB impact event, but plate tectonic activity has erased most records including the impact craters. The impact was strong enough to melt most of the Earth's crust at the surface, leaving rich magmatic activities, and we think the meteorite impacts carried a wealth of material with distinguishable H isotopic composition from the Earth itself, and is preserved in the Jack Hills detrital zircons.

# Eoarchean crustal evolution of the North China Craton revealed by U–Pb ages, trace elements and Hf–O isotopes of detrital zircons from the Caozhuang quartzite

**JH Yang[1,2*], H Wang[1,2]**

* corresponding author: jinhui@mail.igcas.ac.cn

1. State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
2. University of Chinese Academy of Sciences, Beijing 100049, China

The evolution of early Earth, especially the formation of continental crust and related geodynamics, is still not clear due to the scarcity of ancient rock samples. However, detrital zircon is hosted in younger rocks and to some extent, provides some clues. Zircon has a strong resistance to physical and chemical changes and can survive multiple sedimentary and metamorphic cycles, and record some information of early Earth. Here, we report U–Pb dating, Hf–O isotopes and trace elements of detrital zircon grains in the Caozhuang quartzite from the North China craton (NCC), to constrain the formation and evolution of continental crust. The Caozhuang quartzite has the youngest concordant age cluster for detrital zircons at 3.55 Ga and underwent high-grade metamorphism at 3.50 Ga, which makes the Caozhuang quartzite among the oldest clastic sedimentary rocks around the world. The detrital zircons are euhedral or subhedral in shape, indicating they were of local provenance. The detrital zircon U–Pb age spectra of the Caozhuang quartzite shows continued records from 3.89 Ga to 3.55 Ga with two main peaks at 3.80 and 3.68 Ga, which resemble those of the Anshan gneissic complex. In addition, the concordant detrital zircons in the Caozhuang quartzite show variable $\delta^{18}O$ (mainly from 3.37 to 8.12) and $\varepsilon_{Hf}(t)$ (mainly from -4 to +4) values, which are also comparable with those of the Anshan gneissic complex. Accordingly, the Anshan gneissic complex was the most probable source of rocks for the Eoarchean to early Paleoarchean zircons in the Caozhuang quartzite. Importantly, the Caozhuang detrital zircons show continuous and smooth evolution trends without obvious shift for $\varepsilon_{Hf}(t)$, $\delta^{18}O$, Ti-in-zircon temperatures, oxygen fugacity, Eu/Eu*, Th/Nb, and the inferred $SiO_2$ contents of their host rocks. This indicates the lack of global geodynamic transitions during the Eoarchean, arguing against the onset of modern-style plate tectonics in the NCC during the Eoarchean. The binned averages of $\varepsilon_{Hf}(t)$ values for every 20 Ma interval decrease monotonously from +1 at 3870 Ma to -2 at 3570 Ma, and binned average $\delta^{18}O$ values are elevated in relative to the normal mantle zircon and fall in a narrow range of 6 to 7. The oldest model ages of Hf isotopes are about 4.0 Ga, indicating that the earliest continental crust of the NCC was possibly formed at 4.0 Ga. The isotopic characteristics indicated that the Eoarchean felsic continental crust of the North China Craton formed by partial melting of mafic rocks that underwent low-temperature water-rock interaction after separation from a chondritic mantle source.

# New insights into the oldest crust in the Pilbara Craton

**A Zametzer[1*], CL Kirkland[1], MIH Hartnady[1], S Schorn[2], M Barham[1]**

* corresponding author: andreas.zametzer@postgrad.curtin.edu.au

1. Timescales of Mineral Systems Group, School of Earth and Planetary Sciences (EPS), Curtin University, GPO Box U1987, Perth, WA 6845, Australia

2. Department of Petrology and Geochemistry, NAWI Graz Geocenter, University of Graz, Universitätsplatz 2, 8010 Graz, Austria

Exposures of Archean rocks older than 3.5 Ga are rare, such that investigations of the earliest felsic continental crust are limited to specific regions (e.g. the Acasta Gneiss Complex in the Slave Craton in Canada and the Isua Greenstone Belt in Greenland). In this work, we present new in situ apatite, titanite, and zircon U–Pb data in conjunction with textural observations for comparatively underexplored rocks from the Sylvania Inlier, Pilbara Craton, Western Australia, that provide a window into the timing and processes of early Paleoarchean crust production. The studied rocks are characterized by a mix of felsic domains with quartz–plagioclase assemblages and mafic domains with hornblende–epidote–titanite–ilmenite–plagioclase assemblages. The felsic domains are interpreted to represent leucosomes and have a weighted mean $^{207}Pb/^{206}Pb$ zircon age of approximately 3575 Ma, which necessitates partial melting of an even older mafic protolith. Titanite rims around ilmenite cores yield a weighted mean $^{207}Pb/^{206}Pb$ titanite age of approximately 3540 Ma, suggesting that titanite growth was near coeval with partial melting. Apatite U–Pb data indicate that this rock cooled below the Pb blocking temperature (approximately 450 °C) at approximately 2800 Ma. These new results imply that the Sylvania Inlier is a suitable natural laboratory to examine some of the oldest differentiation processes documented on Earth.

# Theme 2

# Emergence of atmosphere and life on early Earth and other terrestrial planets

Invited Speaker

**Dr Raphael Johannes Baumgartner**

*School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney*
*CSIRO Mineral Resources, Perth, Australia*

Keynote Speaker

**Dr Eva Stüeken**

*School of Earth and Environmental Sciences, University of St Andrews, St Andrews, Scotland*

# Stromatolites from the 3.48 billion-year-old Dresser Formation: crossroads between geology and biology

**RJ Baumgartner[1,2*], MJ Van Kranendonk[2], KA Campbell[3], M Dobson[3], B Teece[2,4], S Caruso[1], M Verrall[1]**

* corresponding author: raphael.baumgartner@csiro.au

1. CSIRO Mineral Resources, Kensington 6151, NSW, Australia
2. The University of New South Wales, Kensington 2033, NSW, Australia
3. University of Auckland, Auckland 1010, New Zealand
4. California Institute of Technology, Pasadena 91109, USA

Stromatolites from the 3.48 Ga Dresser Formation are widely considered as a benchmark for the oldest preserved evidence of life on Earth. However, since their discovery in the 1980s, biogenic interpretations have mostly relied on morphological and textural characteristics. Recent research on pyritized Dresser stromatolites from unweathered drillcores has provided additional evidence for biogenicity through the discovery of putative microbial remains and micromineralogy enriched in organic matter that is consistent with sulfidization of microbial substrates. The research also identified enrichments of transition metals and metalloids – especially nickel, zinc and arsenic – within crinkly stromatolite laminae, consistent with an adsorption of these elements onto microbial substrates (Baumgartner et al., 2019; Baumgartner et al., 2020a,b). In 2019, new wide-diameter cores of the Dresser Formation were obtained under clean drilling conditions to intersect an extensive array of mostly pyritized stromatolites. Here, we expand on previous studies to gain a better understanding of the interplays between geological and biological processes in the formation of morphologically diverse Dresser stromatolites.

Supported by elemental mapping across the wide core sections, microanalytical characterizations aid the documentation of microbial growth structures that are dominated by earliest formed mineral-organic associations. This includes organic matter-rich microspherulitic barite as well as nanoporous pyrite containing convincing microbial remains. Such associations interfere with demonstrably abiotic textures in the dominantly hydrothermally influenced, barite-rich host strata of the stromatolites. Overall, the Dresser stromatolites are believed to have formed in a volcano-sedimentary context in which restricted shallow-water marine regimes were influenced by voluminous hydrothermal exhalations. When our observations are integrated with paleoenvironmental models, it becomes apparent that all stromatolites, though texturally diverse due to growth under contrasting conditions (e.g. proximal versus distal to hydrothermal venting), are dominated by the same mineral-organic biosignature assemblages. Hence, our research represents a critical step forward in demonstrating a biological origin of Dresser stromatolites. Moreover, our data have implications for deciphering microbe-environment interactions and providing a better understanding of the habitability of hydrothermally influenced environments in Paleoarchean times.

## References

Baumgartner RJ, Van Kranendonk MJ, Wacey D, Fiorentini ML, Saunders M, Caruso S, Pages A, Homann M and Guagliardo P 2019, Nano−porous pyrite and organic matter in 3.5-billion-year-old stromatolites record primordial life. Geology, v. 47, p. 1039−1043.

Baumgartner RJ, Van Kranendonk MJ, Fiorentini ML, Pages A, Wacey D, Kong C, Saunders M and Ryan C 2020a, Formation of micro-spherulitic barite in association with organic matter within sulfidized stromatolites of the 3.48 billion-year-old Dresser Formation, Pilbara Craton. Geobiology, v. 18, p. 415-425.

Baumgartner RJ, van Kranendonk MJ, Pagès A, Fiorentini ML, Wacey D and Ryan C 2020b, Accumulation of transition metals and metalloids in sulfidized stromatolites of the 3.48 billion−year−old Dresser Formation, Pilbara Craton. Precambrian Research, v. 337, 105534

# Nitrogen cycling on the Archean Earth: assessing the role of lighting and hydrothermal vents

**EE Stüeken**

ees4@st-andrews.ac.uk

School of Earth and Environmental Sciences, University of St Andrews, KY16 9AJ, UK

Life on the early Earth is often considered to have been more nutrient limited than it is today. In particular, nitrogen is thought to have been less bioavailable, because the enzyme used for biological $N_2$ fixation was suppressed by low solubility of molybdenum in anoxic Precambrian seawater. Furthermore, nutrient recycling in the water column was greatly reduced in the absence of $O_2$ and sulfate. I explore two previously proposed remedies for the Precambrian nitrogen limitation: lightning discharge in the atmosphere and hydrothermal venting in the deep sea. Experimental data suggest that lightning-generated nitrogen oxides were probably not a major contributor to the early biosphere as their isotopic signature is distinct from the sedimentary rock record. In contrast, hydrothermal circulation may have acted as an efficient recycling mechanism that regenerated buried nitrogen back into the open ocean. It is therefore conceivable that volcanically active basins offered attractive refugia for early life.

# Sulfur 4-isotope mass-independent fractionation signature of pyrite in some Isua (Greenland) dolostones: microbial seawater sulfate reduction 3700 million years ago

**JN Ávila[1,2*], AP Nutman[3], VC Bennett[1], CRL Friend[4]**

* corresponding author: j.nunesavila@uq.edu.au

1. Research School of Earth Sciences, Australian National University, Canberra, ACT 2601, Australia
2. School of Earth and Environmental Sciences, University of Queensland, St. Lucia 4072, Queensland, Australia
3. School of Earth, Atmospheric and Life Sciences, University of Wollongong, Wollongong, NSW 2522, Australia
4. Glendale, Tiddington, Oxon, OX9 2LQ, UK

Within the Isua supracrustal belt (Greenland), some <3710 to >3695 Ma dolomitic rocks (with seawater-like rare earth elements (REE)+Y signatures and dolomite marine-like $\delta^{13}C_{PDB}$ = +1‰) containing relicts of stromatolite and sedimentary structures (cross-bedding and tempestite breccias) provide a unique window into Earth's early environment. In situ ion microprobe 4-isotope sulfur analyses (Fig. 1) of rare pyrites in these dolomitic rocks show more dispersion in $\delta^{34}S_{VCDT}$ (total +1 to +8‰) than $\Delta^{33}S_{VCDT}$ (about -1 to -1.8‰ for all but one sample). Signature of Archean atmospheric photolysis with negative $\Delta^{33}S$ is preserved in the measured pyrites but the distinctive $\Delta^{36}S/\Delta^{33}S$ correlation observed in those samples ($\Delta^{36}S_{VCDT}$ about -6.85 $\Delta^{33}S_{VCDT}$) indicates a mass-dependent isotopic fraction effect superimposed on the primary mass-independent sulfur signature. The sulfur isotope data is incompatible with a carbonate metasomatic (non-sedimentary) origin for these rocks. Instead, we explain the observed sulfur isotopic signature as the result of microbial sulfate reduction under low-abundance seawater sulfate (negative $\Delta^{33}S$) in a sedimentary environment, emphasizing that this extends evidence of this metabolic pathway to c. 250 million years earlier than previously thought. In contrast, 3695 Ma banded iron formations stratigraphically succeeding the dolostones (Whitehouse et al., 2005; Papineau and Mojzsis, 2006) and siliceous rocks at a c. 3700 Ma unconformity show a different sulfur isotope signature, with a mixture between volcanic sulfur (no mass-independent fractionation signature) and photolytic elemental sulfur (positive $\Delta^{33}S$). This case demonstrates the retention of different S-isotope signatures through superimposed tectonothermal events.

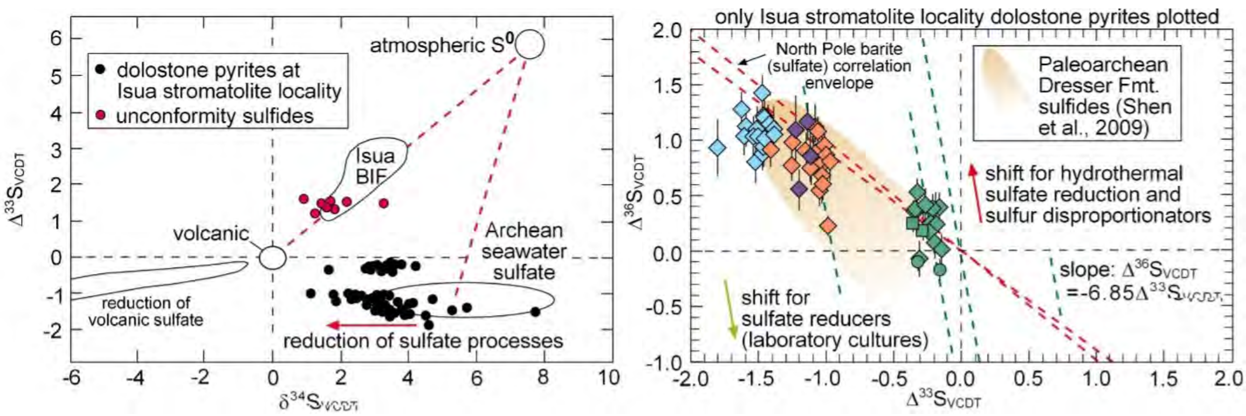



Figure 1. Sulfur isotope signatures of some c. 3700 Ma Isua supracrustal belt rocks

## References

Papineau, D and Mojzsis, SJ 2006, Mass-independent fractionation of sulfur isotopes in sulphides from the pre-3770 Ma Isua Supracrustal Belt, West Greenland: Geobiology, v. 4, p. 227–238.

Whitehouse, MJ, Kamber, BS, Fedo, CM and Lepland, A 2005, The importance of combined Pb and S isotope data from early Archaean rocks, southwest Greenland, for the interpretation of S-isotope signatures: Chemical Geology, v. 222, p. 112–131.

# Atmospheric and hydrothermal sulfur isotope signatures recorded in Archean deep marine sedimentary pyrites from the Yilgarn Craton, Western Australia

**M Chen[1,2*], IH Campbell[2], JN Ávila[3], W Tian[1], PC Hayman[4], RAF Cas[5], TR Ireland[6]**

* corresponding author: mimi.chen@pku.edu.cn

1. Peking University, Beijing 100871, China
2. Australian National University, Canberra, ACT 0200, Australia
3. Griffith University, Nathan, QLD 4111, Australia
4. Queensland University of Technology, Brisbane, QLD 4001, Australia
5. Monash University, Melbourne, VIC 3800, Australia
6. University of Queensland, Brisbane, Queensland 4072, Australia

We report in-situ multiple sulfur isotope analyses for pyrites from deep marine sediments that are interbedded with greenstone lava flows in the c. 2.7 Ga Eastern Goldfields Superterrane and the 2.9 Ga Lake Johnston Greenstone Belt in the Yilgarn Craton, Western Australia. Two endmember sediment types are recognized: shale and chert, with transitional chert as an intermediate. Petrologic studies are consistent with both the pyrite and pyrrhotite having a syngenetic/diagenetic origin. Pyrites from the shales and transitional cherts have positive $\Delta^{33}S$, whereas those from the cherts have $\Delta^{33}S \sim 0$. We suggest that the principal sources of S are atmospheric photolytic $S_8$ ($\Delta^{33}S>0$) and nanoparticulate sulfides from hydrothermal seafloor vents ($\Delta^{33}S=0$). In an anoxic Archean ocean, nanoparticles of sulfides, issuing from black and white smokers, were dispersed through the ocean by currents and slowly accumulated on the sea floor to form shale. During diagenesis, pyrrhotite reacted with available S to form pyrite until all the S was consumed, with unreacted pyrrhotite remaining in the shale. Variations in $\Delta^{33}S$ in the sedimentary pyrites are therefore attributed to variations in the relative proportions of pyrite derived directly from black and white smokers and pyrite formed by the diagenetic reaction between nanoparticulate pyrrhotite and photolytic $S_8$. The cherts are interpreted to have formed close to hydrothermal vents where rapid accumulation of amorphous silica and pyrite from white smokers negated the influence of slow $S_8$ rain.

The $\Delta^{33}S$ isotopic trend across individual sedimentary layers can be explained by variations in the hydrothermal flux as local volcanic activity waxed and waned. The marked global increase in $\Delta^{33}S$ in sedimentary pyrites at c. 2650 Ma is attributed to the emergence of several cratons above sea level at that time, which produced a marked increase in sub-aerial felsic volcanism.

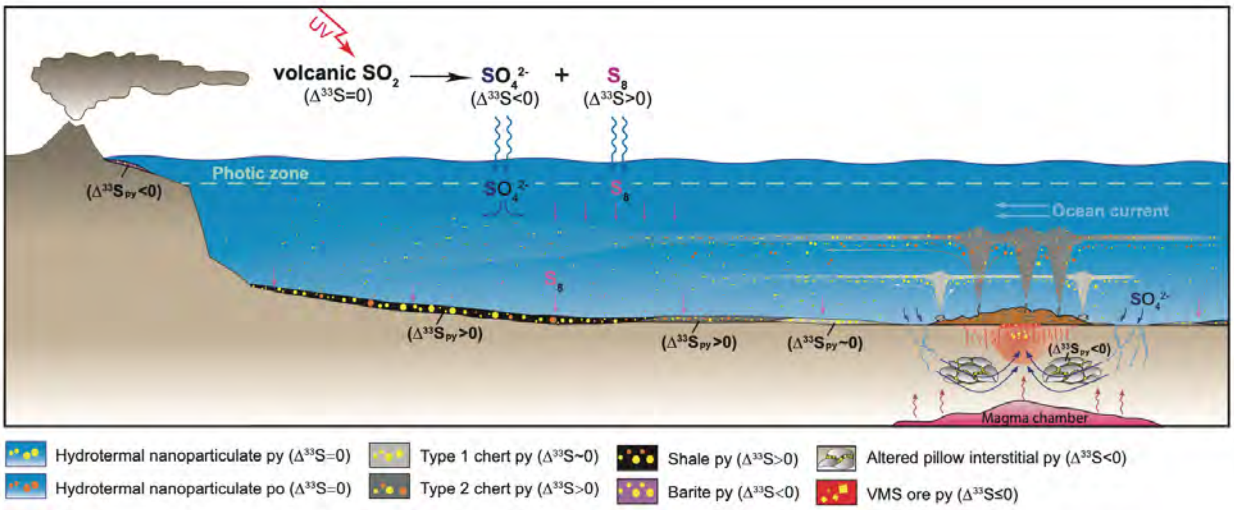



Figure 1. Model sketch of the origin and formation of the Arcehan deep marine sedimentary pyrites

# The effect of the giant 3.26 Ga meteorite impact on early surface environment and life

**N Drabon[1*], DR Lowe[2], AH Knoll[1]**

* corresponding author: ndrabon@fas.harvard.edu

1. Harvard University, 24 Oxford St, Cambridge, MA 02138, USA
2. Stanford University, 450 Serra Mall, Building 320, Stanford, California 94305, USA

Early Earth habitability must have been strongly affected by large meteorite impacts. While the impactor flux gradually decreased from the Hadean to the Archean, at least 16 major impact events (bolide diameter >10 km) are recorded in the Archean rock record. Although it is doubtful that these impacts caused complete ecosystem annihilation, they still had severe consequences for surface conditions. Here we study the sedimentology, petrography and geochemistry of sedimentary rocks across the 3.26 Ga S2 impact event (bolide diameter 37–58 km) in a shelfal and a shallow water section to evaluate the environmental effects of the impact and its possible consequences for early life.

The two sections show similar transitions in sedimentation. Below the S2 spherule layer, black and white banded cherts reflect background sedimentation. A conglomerate containing impact-derived spherules reflects the initial passage of a tsunami. This is overlain by an approximately 1 m-thick, normally graded, black chert bed representing the settling of fine, suspended particles after the tsunami passed. This black chert layer contains euhedral pseudomorphs formed as interstitial evaporates, reflecting partial ocean evaporation. In both sections, the grain size and/or the $Al_2O_3$ (wt%) abruptly increase across the impact event, suggesting an increase in detrital input that continued for some time after the passage of the initial tsunami wave. Additionally the sections show an abrupt (shallow-water section) to more gradual (shelfal) transition to iron-bearing cherts (FeO* up to 7.4 wt%). The increase in FeO* does not correlate with relative deepening or changes in geochemical proxies for provenance, volcanic activity or hydrothermal input. Hence, it is possibly explained by the mixing of a stratified water column by the tsunami, making $Fe^{2+}$-rich deep waters available to otherwise $Fe^{2+}$-poor shallow water environments.

Meteorite impacts are typically seen as agents of mass destruction and extinction. In the short term, the S2 impact certainly would have had disastrous consequences for the early biosphere. However, in the medium term, mixing of the ocean would have made $Fe^{2+}$ available as a potential electron donor to the upper water column (photic zone) and the tsunami-induced erosion and aggressive weathering in a post-impact hothouse may have provided an injection of nutrients, such as P, to the otherwise nutrient starved Archean oceans. Meteorite impacts may thus have had at least transient benefits for the early biosphere.

# Assessing temporal changes in the composition of banded iron formations in the Hamersley Basin

**AJ McCoy-West**

corresponding author: alex.mccoywest@jcu.edu.au

IsoTropics Geochemistry Laboratory, James Cook University, Townsville, QLD, Australia

The banded iron formations (BIF) record underpins our understanding of the global rise in atmospheric oxygen and the geochemical evolution of the oceans. Through the application of geochemical proxies, changes in their chemical, mineralogical and isotopic compositions have provided a record of the physiochemical conditions in the Earth's hydrosphere-atmosphere system at the time of their deposition (Bau and Möller, 1993). Given that their precursor minerals are resistant to diagenetic processes, BIFs are likely to faithfully reflect the chemical composition of seawater (Robbins et al., 2015). In particular, rare earth element (REE) systematics and Nd isotope compositions have been widely used to understand the origin of BIFs and the relative proportions of terrigenous and hydrothermal inputs to the ancient oceans (Alexander et al., 2009).

This contribution will discuss the trace element systematics of a collection of BIFs from the Hamersley Basin, Western Australia. The sample suite includes 40 samples ranging in age from 2.60 to 2.44 Ga and includes samples from the Marra Mamba, Brockman, Weeli Wolli and Boolgeeda Iron Formations. All of the samples come from drill core and have been selected to avoid regions of secondary hypogene enrichment or supergene alteration. However, in an endeavour to eliminate preferential sampling biases, samples were collected at a relatively even spacing throughout the formations. High precision trace element analyses of 45 elements from across the periodic table have been conducted, including quantifying several bioavailable elements (e.g. Cd, Mo, Zn) that will form the foundation of future isotopic studies. Systematic variations in specific trace elements suggest a significant change in the local depositional environment, including increasing terrigenous input during the late Archean in the Hamersley basin. This work will be supplemented by sequential leaching experiments (after Oonk et al., 2017), which will be conducted to separate the carbonate, oxide and silicate phases and interrogate their trace element compositions independently.

## References

Alexander, BW, Bau, M and Andersson, P 2009, Neodymium isotopes in Archean seawater and implications for the marine Nd cycle in Earth's early oceans. Earth and Planetary Science Letters v. 283, p. 144-155.

Bau, M and Möller, P 1993, Rare earth element systematics of the chemically precipitated component in early Precambrian iron formations and the evolution of the terrestrial atmosphere-hydrosphere-lithosphere system. Geochimica et Cosmochimica Acta v. 57, p. 2239-2249.

Oonk, PBH, Tsikos, H, Mason, PRD, Henkel, S, Staubwasser, M, Fryer, L, Poulton, SW and Williams, HM 2017, Fraction-specific controls on the trace element distribution in iron formations: Implications for trace metal stable isotope proxies. Chemical Geology v. 474, p. 17-32

Robbins, LJ, Swanner, ED, Lalonde, SV, Eickhoff, M, Paranich, ML, Reinhard, CT, Peacock, CL, Kappler, A and Konhauser, KO 2015, Limited Zn and Ni mobility during simulated iron formation diagenesis. Chemical Geology v. 402, p. 30-39.

# Quantifying isotopic fractionation of La, Nd and Ce in ancient oceans from ab initio methods and implications for environmental change

**M Nestmeyer*, AJ McCoy-West**

* corresponding author: mark.nestmeyer@my.jcu.edu.au

Isotropics Geochemistry Laboratory, Earth and Environmental Science, James Cook University, Townsville, Qld, Australia

Banded iron formations (BIF) are chemical sediments that can be used to reconstruct ancient seawater chemistry over a huge timespan of Earth's history (3.8–1.5 Ga). Fluctuations in the abundances and isotopic compositions of certain metals in BIF have been widely used to assess changes in the ancient environment through time[1,2]. Specifically, lanthanides are commonly used for geochronology or to assess redox conditions and mixing of isotope reservoirs. To improve our understanding of the mechanisms that fractionate isotopes in oceans during BIF precipitation, we used ab initio methods to calculate reduced partition functions (as 1000 lnβ) for aqueous species of La(III), Nd(III), Ce(III) and Ce(IV). The results are combined with aqueous speciation modelling of a simplified Precambrian seawater that contains the most relevant anions for complexation. Lanthanides show a high affinity for the formation of carbonate complexes in aqueous solution, which is highly pH dependent, leaving a smaller (<1%) and lighter (-0.2‰) proportion of free lanthanides for adsorption onto sediment particles with evolution of the ocean to circumneutral conditions (approximately pH8; Fig. 1). Isotope fractionation between aqueous species shows a typical proportionality to $1/T^2$ [3], which implies that incorporation of lanthanides into BIFs caused a smaller fractionation in the hotter ancient ocean (up to 60 °C)[4]. Therefore, the isotopic composition of lanthanides in BIFs represents a value closer to the seawater than in recent marine sediments. Isotope fractionation between Ce(III) and Ce(IV) species shows $\Delta 1000\ \ln\beta$ (approximately $\Delta^{142}Ce$) values of up to 0.42, indicating a significant fractionation of Ce due to oxidation that is potentially preserved in Precambrian marine sediments. In addition, nuclear field shift effects were calculated for La(III) and Ce(IV). Our results show that mass independent isotope fractionation effects are insignificant between aqueous species.

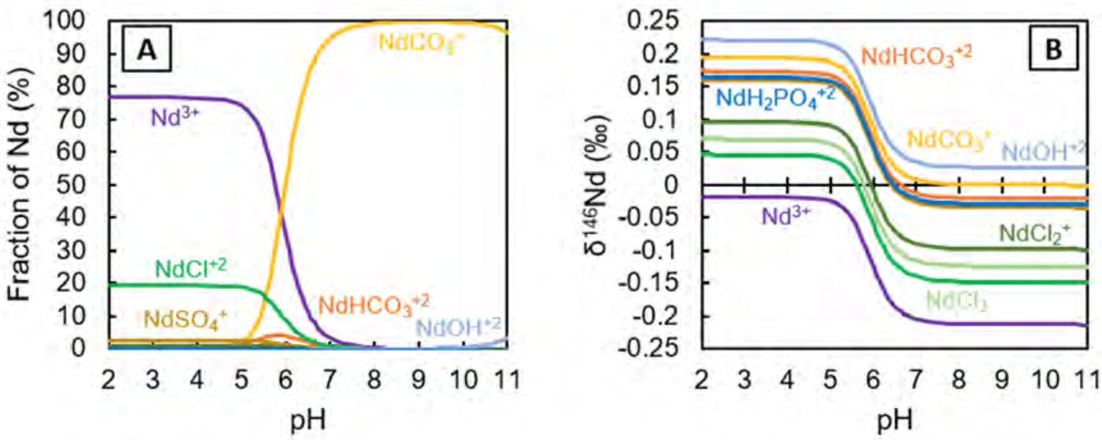



Figure 1. (A) Speciation of Neodymium in a simplified Precambrian seawater. (B) Isotopic composition of the respective Nd aqueous species

## References

1. Pons (2013) Geobiology, 11(3), 201-214
2. Frei (2009) Nature, 461(7261), 250-253
3. O'Neil (1986) Rev. in Min. 16, 1-40
4. Feulner (2012) Rev. of Geophy., 50(2)

# Geochemical constraints on the origin and depositional setting of the Kabirdham banded iron formations, Chilpi Group, India

**PK Mishra[1,2*], SP Mohanty[2]**

* corresponding author: pkmishra.geol@gmail.com

1. Department of Geology, Dharanidhar (Autonomous) College, Keonjhar, Odisha, India 758001
2. Department of Applied Geology, Indian Institute of Technology (Indian School of Mines), Dhanbad, Jharkhand, India, 826004

The Kabirdham iron deposit, a new discovery by the Geological Survey of India in the northern margin of the Bastar Craton, is associated with banded iron formations (BIF) below a dolomite horizon in the lower part of the Chilpi Group (Mishra and Mohanty, 2021). The presence of primary chamosite, greenalite and siderite associated with early magnetite and late hematite has been identified during petrographic, X-ray diffraction analysis and electron probe microanalyzer investigations. The geochemical analysis reveals dominant composition of $SiO_2$ + $Fe_2O_3^{total}$ (average value 85.86 wt%) of BIF bands, which suggests their formation predominantly through chemical precipitation. Major oxides such as $Al_2O_3$ (0.41 to 19.15 wt%) and $K_2O$ (0.004 to 3.56 wt%), and trace elements like Rb (0.35 to 40.20 ppm), Sr (7.75 to 208.96 ppm), Zr (4.2 to 189.4 ppm), Hf (0.09 to 3.84 ppm), Cr (6.64 to 29.86 ppm), Co (2.68 to 35.96 ppm) and Ni (13.09 to 30.20 ppm) show wide variations in the BIF bands. The post-Archean Australian shales (PAAS) normalized rare earth elements and yttrium (REE-Y) pattern shows positive La anomaly, positive Gd anomaly and super chondritic Y/Ho ratio (average 32.15), indicating the preservation of seawater like signatures in the basin of deposition of the BIF. Involvement of hydrothermal fluids is negated from Eu/Sm vs Sm/Yb, and Eu/Sm vs Y/Ho contents. The extremely low $MnO/Fe_2O_3^{total}$ ratio (average 0.001) and redox-sensitive trace element ratios indicate a dysoxic to suboxic-anoxic state of the seawater at the time of deposition. The low positive to transitional negative Ce anomaly, presence of oolitic textures and occurrence of chamosite further strengthen the arguments for the shallow water and anoxic condition in the depositional basin of the Kabirdham BIF. We infer a low atmospheric oxygen content, similar to the reported value from the Archean, during the deposition of these iron-rich rocks. Significance of such a depressed oxygen content in the Paleoproterozoic atmosphere needs further investigation to understand a billion-year delay in biological evolution after the deposition of these rocks.

## References

Mishra, PK and Mohanty, SP 2021, Geochemistry of carbonate rocks of the Chilpi Group, Bastar Craton, India: implications on ocean paleoredox conditions at the late Paleoproterozoic era. Precambrian Research, 353,106023. doi:10.1016/j.precamres.2020.106023.

# Zircon preserving isotopic biosignatures in graphitic inclusions over half-a-billion years

**AK Schmitt[1,2*], M Vogt[1], WH Schwarz[1], J Schmitt[1], M Trieloff[1], TM Harrison[3], EA Bell[3]**

* corresponding author: axel.schmitt@curtin.edu.au

1. John de Later Centre, Building 301, Curtin University, Kent Street, Bentley, WA 6102, Australia
2. Institut für Geowissenschaften, Universität Heidelberg, Im Neuenheimer Feld 234-236, 69120 Heidelberg, Germany
3. Department of Earth, Planetary and Space Sciences, University of California, Los Angeles, 595 Charles Young Drive East, Box 951567, Los Angeles, CA 90095-1567, USA

Biologic activity is interpreted to have exerted control on Earth's surface processes and the rock cycle since at least the early Archean. Evidence for life from this early phase is only preserved as fossils after c. 3.5 Ga due to metamorphic overprint in older rocks. Instead, characteristic depletions in $^{13}C$ relative to $^{12}C$ are recognized as 'chemofossils' provided that subsequent disturbance or exchange can be ruled out. An important part of this record are carbonaceous inclusions armoured by refractory minerals such as apatite or zircon as old as 4.1 Ga. To better constrain how such inclusions form and behave over geological time, we investigated graphite inclusions in zircon from the early Phanerozoic S-type Rumburk granite in the Lusatian complex of eastern central Europe. The zircon host rock is a two-mica, cordierite-bearing peraluminous granite with a highly reduced mineral paragenesis, including wüstite, and it intruded into Neoproterozoic to Paleozoic metagreywacke and graphite-bearing metapelites. Graphite inclusions in zircon are rare: only five inclusions between 8 and 25 μm in diameter were identified in approximately 300 zircon crystals with opaque inclusions (the rest being ilmenite and rutile). Inclusions were trapped at the interface between inherited zircon cores and young overgrowths in voids left behind after metamict detrital zircon dissolved and reprecipitated prior to anatexis. Zircon $fO_2$-barometry and Ti-in zircon thermometry revealed crystallization at FMQ for inherited cores, whereas c. 496 Ma overgrowths indicate low $fO_2$ (FMQ -5) at ~700 °C. Heterogeneous O-isotopic compositions in interiors contrast with homogeneously elevated $\delta^{18}O$ (+7.7‰) in rims, indicating that the granite originated from melting metasediments. Structurally, graphite ranges from well-ordered to significantly disordered, possibly reflecting accumulation of lattice damage due to local irradiation by the zircon host. Carbon isotopic compositions determined by secondary ion mass spectrometry (SIMS) range from -45 to -8‰ ($\delta^{13}C$ relative to Vienna Pee Dee Belemnite), with distributions for individual inclusions peaking at values of -43, -36, -34, -31, and -13‰. Significant heterogeneities over approximately 10–20‰ exist in individual graphite inclusions, typically skewed towards more positive values, in contrast to graphite references analyzed under the same conditions which reproduced within ±2‰. Rayleigh fractionation models between 350 and 600 °C explain this range for graphite precipitation from a mixed $CO_2$>$CH_4$ fluid with an initial bulk value of -32‰, consistent with fluids released from regional metasediments containing carbon of unambiguously biologic origin. Strong isotopic fractionation during graphite-forming reactions involving C-O-H fluids is thus to be expected for graphite in metamorphic and anatectic environments. If $CO_2$ is the dominant C-bearing phase in the fluid, this fractionation leads to increasingly positive values in the residual fluid and graphite precipitating from it, so that the Cisotopic composition of the source reservoir tends to be more negative than that of graphite. With their C-isotopic composition directly traceable to regional organic-rich metasediments, the graphitic inclusions in the Rumburk granite have thus preserved biogenic signatures over nearly 500 Ma.

# A review of the geological setting of the stromatolite-bearing, c. 3.48 Ga Dresser Formation (Pilbara, Australia)

**MJ Van Kranendonk[1*], RJ Baumgartner[2], T Djokic[1], KA Campbell[3]**

* corresponding author: m.vankranendonk@unsw.edu.au

1. The University of New South Wales, Kensington 2032, NSW, Australia
2. CSIRO Mineral Resources, Kensington 6151, NSW, Australia
3. University of Auckland, Auckland 1010, New Zealand

This review presents 30 years of integrated geoscience data and modern analogue studies for the well-preserved, stromatolite-bearing lower chert member of the c. 3.48 Ga Dresser Formation (DF: Pilbara Craton, Australia), widely considered as the best, oldest evidence for life on Earth. Discovered in the late 1970s, subsequent detailed geological and hyperspectral mapping of the entire outcrop area has been augmented by scientific drilling campaigns (2007, 2019) to investigate primary structures and compositions unaffected by surface oxidation. Results from stratigraphic sections integrated with mapping, structural and alteration studies show that sedimentation was contemporaneous with voluminous hydrothermal fluid flow, epithermal-style alteration of footwall basalts and listric growth faulting within an active, gradual volcanic caldera (Nijman et al., 1998; Van Kranendonk et al., 2008, 2019; Tadbiri and Van Kranendonk, 2020; Caruso et al., 2021). The basin evolved from deep to shallow water – including emergent – conditions, then back to deep water, reflecting magmatic inflation and caldera subsidence. Emergence was accompanied by deposition of siliceous hot spring sinter (including geyserite and terracettes), and fluvial and lacustrine facies (Djokic et al., 2017, 2021). Bedded siderite-chert couplets with negative $\delta^{13}C_{carb}$ values, aragonite evaporative crystal splays and Ba-Zn enrichments were deposited from evaporatively-concentrated seawater enriched by hydrothermal fluids during alternating wet and dry seasons in a closed volcanic caldera basin, with analogues in East African rift lakes. Demonstrably biogenic domal, columnar, coniform and stratiform stromatolites flourished on the shoreline of the caldera lake, whereas small bushy microbialites inhabited hot spring deposits (Baumgartner et al., 2019; Van Kranendonk et al., 2019). Repeated, coarse, upward-pointing barite crystals at 20 cm to 6 m thick intervals that cut into overlying, bedded pyrite-dolomite-chert sediment with or without stromatolites are analogous with textures in modern sabkhas where sulfate crystallization via evaporation occurs in unlithified dolomite (+pyrite + organic matter) muds beneath microbial mats (Bontognali et al., 2010).

## References

Baumgartner RJ et al. 2019, Geology 47, 1039–1043.

Bontognali T et al. 2010, Sedimentology 57, 824-844.

Caruso S et al. 2021, Precamb Res 362: 106299.

Djokic T et al. 2017, Nat Comm 8:15263.

Djokic T et al. 2021, Astrobiology 21, 1-38.

Nijman W et al. 1998, Precamb Res 88, 25-52.

Tadbiri S & Van Kranendonk MJ 2020, Precamb Res 347: 105844.

Van Kranendonk MJ et al. 2008, Precamb Res 167, 93-124.

Van Kranendonk MJ et al. 2019, In: Van Kranendonk MJ, Bennett V, Hoffmann E (eds.), Earth's Oldest Rocks, 2nd Ed. Elsevier, USA, p. 985-1006.

# Biomarker imaging by matrix-assisted laser desorption ionization time of flight mass spectrometry: implications for Archean oxygenic photosynthesis and assessment of contamination

**KE Yamaguchi[1*], H Saito[1], K Ishikawa[1], T Okumura[2], A Ijiri[3]**

* corresponding author: kosei@chem.sci.toho-u.ac.jp

1. Department of Chemistry, Toho University, Funabashi, Chiba 274-85110, Japan
2. Centre for Advanced Marine Core Research, Kochi University, Nankoku 783-8502, Japan
3. Faculty and Graduate School of Maritime Sciences, Kobe University, Kobe 658-0022, Japan

Biogenicity of carbonaceous, cyanobacteria-like materials found in the c. 3.5 Ga chert has been challenged, with an opposing interpretation of non-biological, post-depositional origin. Authenticity of 2α-methylhopane, a likely biomarker of oxygenic photosynthesizers cyanobacteria, extracted from the 2.7 Ga black shale has also been challenged (e.g. Brocks et al., 1999, Rasmussen et al., 2008). Therefore, the timing of emergence for oxygenic photosynthesis remains unconstrained. It is important to determine if a biomarker in black shales is indigenous or contamination in later stages by a novel method.

Here we report our development of an analytical method for matrix-assisted laser desorption ionization time of flight mass spectrometry (MALDI-TOF MS) or imaging mass spectrometry (SHIMADZU *iMScope* at the Kochi Core Center, JAMSTEC) to perform in situ mapping of biomarkers in thin sections. Such location information is lost in a traditional method for biomarker extraction from rocks, because powdered samples are used for extraction by organic solvents. For 2D analysis of biomarker distribution, the MALDI-TOFMS method has advantages over the traditional method.

We detected a peak of m/z = 368.4, indicative of hopane, only in the areas where standard material of 2methylhopane had been applied before deposition as matrix of 2,5-dihydroxybenzoic acid. We then showed 2D, sedimentary-structure-dependent distributions of 2-methylhopane in thin sections made from drillcores (WRL1 and RHDH2A) of the black shales in the 2.7 Ga Jeerinah Formation from Pilbara, Western Australia. These drillcores were previously used for detection of 2α-methylhopane by Brocks et al. (1999) and for geochemical and isotopic analyses by Yamaguchi (2002). We also used drillcores (ABDP#10, shallow-facies stromatolitic carbonates) of the 2.7 Ga Tumbiana Formation from the same district. We examined the effects of contaminations of oils after rigorous rinsing by water and organic solvents. We dipped the rock specimens of the Archean black shale and the Cenozoic mudstone, basalt and granite into high and low-viscosity oils. We detected peaks of m/z = 242.3 and 284.1 of the oils, not only for the contaminated parts and irrespective of supersonic rinsing. Sedimentary-structure-dependent distributions of 2-methylhopane in thin sections are the keys for authentic biomarker detection. Firstly, we confirmed syngenicity of hopane in the 2.7 Ga black shales, suggesting operation of oxygenic photosynthesis in the 2.7 Ga shallow ocean. However, we also noted the unexpected survivability of biomarkers during supersonication of the samples. Biomarker mapping by MALDI-TOFMS proved to be a powerful tool for testing its syngenicity. Our results have important implications for the evolution of microbial biosphere and that of redox states in the atmosphere-ocean system in the early Earth.

## Reference

Brocks, JJ, et al. 1999, Archean molecular fossils and the early rise of eukaryotes: Science 285, 1033-1036. Rasmussen, B, et al. 2008, Reassessing the first appearance of eukaryotes: Nature 455, 1101-1104. Yamaguchi, KE 2002, Ph.D. thesis, The Pennsymvania State University, 485p.

# Theme 3

# Early Earth geodynamics: insights from geochemical, isotopic, phase equilibrium, and numerical modelling

Invited Speaker

**Dr Priyadarshi Chowdhury**
*Assistant Professor*
*School of Earth and Planetary Sciences, National Institute of Science Education and Research, Bhubaneswar, India*

Keynote Speaker

**Professor Michael Brown**
*Department of Geology, University of Maryland, College Park, USA*

# Orogenesis on early Earth was controlled by lithospheric peeling

**P Chowdhury[1*], PA Cawood[2]**

* corresponding author: priyadarshi@niser.ac.in

1. School of Earth and Planetary Sciences, National Institute of Science Education and Research, HBNI, Bhubaneswar, Odisha 752050, India
2. School of Earth, Atmosphere and Environment, Monash University, Melbourne, Clayton 3800, Vic., Australia

The late Archean-to-early Paleoproterozoic (about 3–2 Ga) time witnessed major changes in the geological and geochemical makeup of the continental crust in response to the secular cooling of mantle and a concomitant change in the global geodynamics (Cawood et al., 2022). The latter includes the onset of horizontal movement of crustal blocks and the formation of local-scale tectonic cells involving convergent and divergent settings (cf. Gerya et al., 2015). However, whether or not these incipient convergent-divergent settings resemble modern subduction-collision and rift-zones, remains contentious.

Recent numerical modelling shows that the style of lithospheric convergence may have evolved with the secular cooling of mantle since about 3 Ga (Chowdhury et al., 2017, 2020). In particular, the late Archean to early Paleoproterozoic lithospheres with thick and rheologically differentiated crust display evidence of large-scale delamination controlled orogenesis. Referred to as 'peel-back orogenesis' (Chowdhury et al., 2017, 2020), this tectonic process may have been triggered by the short-lived, late Archean subduction/downwelling events that occurred either spontaneously or due to plumes/impacts in the absence of a global mosaic of plates (cf. Sizova et al., 2015; Brown et al., 2020). The peel-back tectonic framework creates asymmetric tectono-thermal settings that can reconcile the secular changes in the about 3–2 Ga-old rock record including: (1) appearance of paired metamorphism; (2) slower cooling of high-grade metamorphic rocks; (3) dominant formation of medium pressure to high pressure tonalite-trondhjemite-granodiorite; and (3) formation of potassic granites and hybrid (high-MgO) granitoids. Thus, we propose that peel-back driven orogenic style dominated the late Archean-early Paleoproterozoic tectonics when the mantle was hotter.

With the further cooling of mantle through the Proterozoic, its viscosity and lithospheric rigidity increased which allowed the isolated tectonic cells to evolve into a globally linked system of plates, i.e. plate tectonics (Cawood et al., 2022). However, the subduction zones and orogens possibly did not show modern, cold subduction or burial of continental crust to coesite forming depths on a global scale until late in the Proterozoic as the mantle was still warm enough to preclude these styles (Stern, 2018; Brown et al., 2020; Cawood et al., 2022). In fact, numerical models show that accretionary orogens may have experienced lithospheric peeling under early-to-mid Proterozoic mantle conditions (Chowdhury et al., 2017; Spencer et al., 2021).

## References

1. Brown, M. et al. 2020. Annu. Rev. Earth Planet. Sci. 48, null.
2. Cawood, P.A. et al. 2022. Rev. Geophys. 60, e2022RG000789.
3. Chowdhury, P. et al. 2020. Earth Planet. Sci. Lett. 538, 116224.
4. Chowdhury, P. et al. 2017. Nat. Geosci. 10, 698–703.
5. Gerya, T.V. et al. 2015. Nature 527, 221–225.
6. Sizova, E. et al. 2015. Precambrian Res. 271, 198–224.
7. Spencer, C.J. et al. 2021. Geophys. Res. Lett. 48, e2021GL093312.
8. Stern, R.J. 2018. Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 376, 20170406.

# Early Earth geodynamics

**M Brown**

mbrown@umd.edu

Laboratory for Crustal Petrology, Department of Geology, University of Maryland, College Park, MD 20742, USA

Mantle convection drives planetary heat loss, as manifest at the surface via one of several potential tectonic modes: stagnant lid (hot or cold), sluggish or squishy lid, and mobile or active lid (<80% of surface behaving as a rigid plate) or plate tectonics (PT; >80% rigid plates). Additionally, an episodic (transient) mode reflects alternating states. The thermal state of the mantle after crystallization of a magma ocean sets the initial conditions for mantle convection. However, because systems with the same physical parameters can exhibit different evolution depending on the initial state, forward modelling of geodynamics is challenging. Thus, how and on what timescale PT emerged after the last magma ocean is unknown, with proposals ranging from the Hadean to the Neoproterozoic. An alternative is to take an inverse approach and test the null hypothesis that Earth has always had PT; accepting the possibility of preservation and survivorship biases, the inverse approach is constrained by geology.

The characteristic features of PT include: large-scale rigidity of lithosphere plates; distinctive tectonic settings for sedimentation (e.g. passive margins, foreland basins); distinctive styles of plate boundary magmatism (mid-ocean ridge and calc-alkaline suite), metamorphism (ocean floor versus subduction- and collision-related), and deformation, with a characteristic spatial asymmetry from trench to hinterland and strong strain localization along lithospheric-scale thrusts formed during collisional orogenesis; and, differential movement between cratons and/or terranes, as evidenced by paleomagnetic data. Many of these features are widespread among cratons since the mid-Paleoproterozoic, and some are recorded in one or more cratons since the Paleoarchean, consistent with a transition from c. 3.2 Ga to c. 2.1 Ga.

The reason why Earth's tectonic mode may have been different in the past relates to secular cooling of the mantle. Currently, Earth generates about half as much heat as it loses, but these processes have changed at different rates through time, such that Earth has been cooling by approximately 100 °C/Ga since 2–3 Ga, but before c. 3 Ga it is unclear whether heat production was in balance with heat loss or whether the mantle was warming to a peak. At present, the variation in potential temperature (TP) of the upper mantle is approximately 120 °C. For an ambient mantle TP >200 °C warmer than at present with a similar variation, widespread stable subduction may not have been possible, but could have occurred where mantle TP was lower. At elevated mantle TP magmatism will be dominant, and a sluggish or squishy lid may have preceded a mobile or active lid.

Subduction initiation is a poorly-understood process, and both endogenic (mantle plume) and exogenic (impact-driven) processes have been suggested as plausible triggers. It is likely that as Earth's mantle began to cool, during the interval 3–2 Ga, stable subduction was able to spread from one or more centres of plate-like behaviour, leading to a connected plate boundary network by the early Paleoproterozoic. Mobility during the Neoarchean enabled the amalgamation of continental crust into several supercratons, but the supercontinent cycle, a probable demonstration of global PT, only began in the Proterozoic.

# Constraining Paleo- to Eoarchean metamorphism using phase equilibrium modelling and in-situ garnet Lu–Hf geochronology in the Itsaq Gneiss Complex, southwest Greenland

**J Alfing[1*], J Kaempf[1], T Johnson[1], C Clark[1], K Rankenburg[2], K Szilas[3]**

* corresponding author: julian.alfing@postgrad.curtin.edu.au

1. School of Earth and Planetary Sciences, Curtin University, Perth, WA, Australia
2. John de Laeter Centre, Curtin University, Perth, WA, Australia
3. Department of Geosciences and Natural Resource Management, Section of Geology, University of Copenhagen, Copenhagen, Denmark

Utilizing the metamorphic pressure–temperature–time (*P–T–t*) record through Earth's history is a proven tool to investigate crustal processes and Earth's evolving tectonic mode(s). In the Archean Eon, a fragmentary rock record before 2.8 Ga hinders our understanding of the early Earth. Here, we investigate well-preserved metabasic rocks from the northern Itsaq Gneiss Complex, southwest Greenland. We examine the *P–T* conditions of metamorphism via phase equilibrium modelling and link the results to geochronological constraints obtained via in-situ garnet Lu–Hf geochronology. The two studied garnet amphibolites record peak assemblages of amphibole + plagioclase + garnet + quartz ± biotite with accesory zircon, apatite ± ilmenite/titanite. Both samples record evidence for incipient partial melting as quartz and plagioclase pseudomorphs replacing former melt films along grain boundaries. Phase equilibrium modelling indicates peak metamorphic *P–T* conditions of approximately 8 kbar and 730–800 ºC. In-situ garnet Lu–Hf dates of 3.6–3.5 Ga are interpreted to reflect cooling ages, given the *P–T* modelling results and closure temperature for Lu–Hf in garnet of c. 650 ºC for the analysed garnet grain sizes. The findings are interpreted to record granulite facies metamorphism attributable to the c. 3.66–3.60 Ga Isukasian orogeny in the Itsaq Gneiss Complex.

# Paleomagnetic records from the East Pilbara Craton of Paleoarchean lithospheric motion and a dipolar geodynamo

AR Brenner[1*], RR Fu[1], ARC Kylander-Clark[2], GJ Hudak[3], BJ Foley[4]

* corresponding author: alecbrenner@g.harvard.edu

1. Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA 02138
2. Department of Earth Science, University of California, Santa Barbara, CA, USA 93106
3. Natural Resources Research Institute, University of Minnesota, Duluth, MN, USA 55812
4. Department of Geosciences, The Pennsylvania State University, State College, PA, USA 16802

Geodynamic and tectonic processes during the Archean remain enigmatic and hotly debated. Paleomagnetism can quantify the rates timing of tectonic processes. We discuss recent paleomagnetic datasets that we have measured from late Paleoarchean rocks in the East Pilbara Craton, Western Australia, which have shown that the East Pilbara experienced substantial surface motions during approximately 3.3–3.2 Ga (Brenner et al., 2020; Brenner et al., 2022). These surface motions occurred at rates of approximately 0.5°/Ma (or about 6 cm/yr) and were sustained for many tens of millions of years, consistent with plate tectonic motions but inconsistent with motions of a stagnant-lid. The data also reveal the oldest documented geomagnetic reversal, indicating that the geodynamo was likely dominantly-dipolar like it is today. Together, these results suggest a geodynamically-mature Paleoarchean Earth from the surface to the core. Importantly, lessons learned from these studies have given us a robust toolkit, including magnetic microscopy and radiometric dating, for understanding the mechanism and timing of magnetizations by tying them to specific mineralization reactions and hydrothermal alteration events. This paves the way for future paleomagnetic work in Archean rocks, in which seafloor hydrothermal systems were especially common. We also discuss ongoing work to refine and extend the geodynamic record further into deep time.

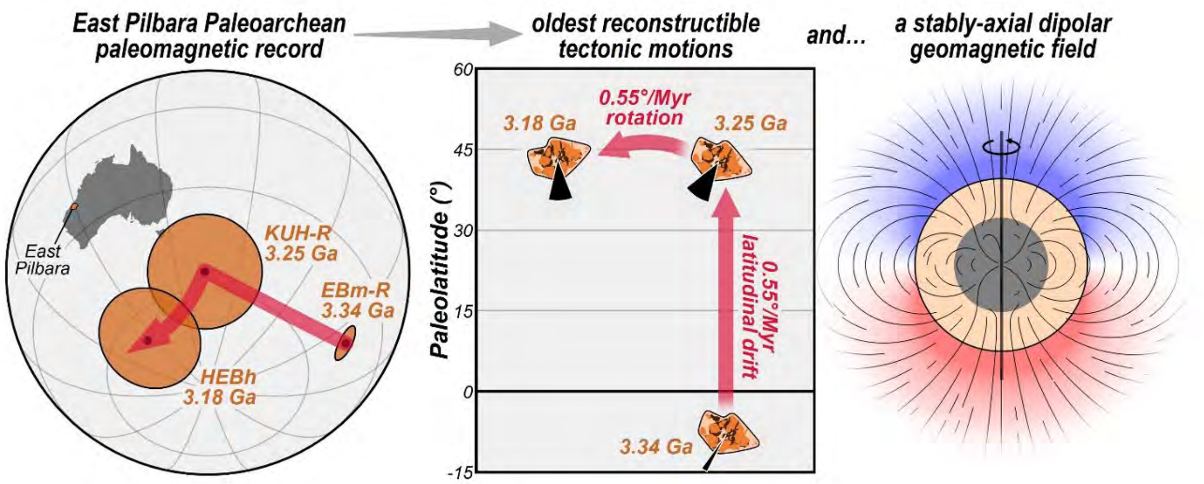



Figure 1. Paleomagnetic data from the East Pilbara Craton have revealed tectonic motions and a reversible, dipolar, core-generated geodynamo in the Paleoarchean

## References

Brenner, AR, Fu, RR, Evans, DAD, Smirnov, AV, Trubko, R and Rose, IR 2020, Paleomagnetic evidence for modern-like plate motion velocities at 3.2 Ga: Science Advances, v. 6.

Brenner, AR, Fu, RR, Kylander-Clark, ARC, Hudak, GJ and Foley, BJ 2022, Plate motion and a dipolar geomagnetic field at 3.25 Ga: PNAS, v. 119, n. 44.

# Tracking Archean continent formation using trace elements in zircon: example of the 3.6–3.2 Ga Barberton Greenstone Belt

**N Drabon[1*], GR Byerly[2], J Wooden[1]**

* corresponding author: ndrabon@fas.harvard.edu

1. Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA

2. Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA, USA

3. Formerly at USGS Menlo Park and Stanford University, Stanford, CA, USA

Zircon trace element geochemistry has become an increasingly popular tool to track crustal evolution through time. This may be especially important in early Earth settings where most of the crust hast been lost, but in some fortuitous instances detrital zircons have been preserved. Here, we use trace elements in combination with hafnium and oxygen isotopes of 3.65–3.22 Ga detrital zircons of the Moodies and Fig Tree Groups from the Barberton Greenstone Belt (BGB), South Africa, to study the evolution of continental crust, and to compare their geochemistry to 4.2–3.3 Ga zircons from the Green Sandstone Bed. Detrital zircons from the Fig Tree and Moodies Groups show major age clusters at 3.55 Ga, 3.45 Ga, 3.29 Ga and 3.26–3.23 Ga. Based on previous work, these zircons have been sourced from within or the vicinity of the BGB, while those of the Green Sandstone Bed were derived from outside the present-day BGB. The zircons trace a crustal evolution from generally more juvenile to more evolved, encompassing two episodes of crustal growth at 3.53 Ga and, previously unrecognized in the felsic igneous record, at 3.29 Ga. Archean BGB zircons show stark differences in their geochemistry to Hadean zircons of the Green Sandstone Bed and are thus not good analogues for Hadean zircon generation. However, similar crustal evolutions between <3.8 Ga Green Sandstone Bed and the BGB zircons suggests that they were neighbouring terranes experiencing similar crustal processes diachronously. Together, they show three phases of continent formation: (1) formation of long-lived protocrust in the Hadean, (2) onset of pervasive hydrous melting and frequent juvenile additions at 3.8 Ga, and (3) transition to crustal processes generating zircon trace element signatures most similar to modern plate-tectonic environments at approximately 3.3 Ga, though other processes such as partial convective overturn cannot be excluded. Hence, detrital zircons from the BGB provide a complex picture of continent evolution in the Archean that would not be accessible from felsic igneous rocks alone.

# No seismic evidence for convective overturn in the East Pilbara Terrane

**K Gessner[1*], MP Doublier[2], AJ Calvert[3]**

* corresponding author: klausgessner@dmirs.wa.gov.au

1. Geological Survey of Western Australia, East Perth, Western Australia, Australia
2. Geoscience Australia, Symonston, Australian Capital Territory, Australia
3. Simon Fraser University, Burnaby, British Columbia, Canada

The East Pilbara Terrane in Western Australia is one of the best exposed examples of early Earth's continents. A widely accepted model for formation of the East Pilbara Terrane is convective overturn, driven by mechanical instability between buoyant granites below volcano-sedimentary greenstone sequences that constituted the uppermost crust. Models of convective Rayleigh-Taylor style crustal overturn predict steeply dipping to subvertical boundaries and compositional zonation of the crust on a comparable scale to the current surface pattern. The first deep seismic reflection survey in the East Pilbara Terrane (Doublier et al., 2020) produced a surprising result, by revealing a stark contrast in structure between what is exposed at Earth's surface and what is imaged at depth. The present day East Pilbara crust is horizontally layered and of predominantly felsic composition, with dense greenstone sequences largely restricted to the top 10 km. There is no geophysical evidence at depth of structural variations similar in shape or scale to the archetypical dome-and-keel geometry exposed at Earth's surface. Instead of being the product of convective overturn, we propose that the defining feature of Earth's early continents was extreme mechanical decoupling during incremental reworking of evolving continental crust. This rheological architecture governed how volcanic basins forming in the brittle-elastic upper crust interacted with flow of highly mobile, viscous mid- to lower crust, and how surface-derived volatiles were introduced to crustal and lithospheric melt sources.

## Reference

Doublier, MP, Johnson, SP, Gessner, K, Howard, H, Chopping, R, Smithies, RH, Martin, DMcB, Kelsey, DE, Haines, PW, Hickman, AH, Czarnota, K, Southby, C, Champion, DC, Huston, DL, Calvert, AJ, Kohanpour, F, Moro, P, Costelloe, R, Fomin, T and Kennett, BLN 2020. Basement architecture from the Pilbara Craton to the Aileron Province: new insights from deep seismic reflection line 18GA-KB1. In: Czarnota, K, Roach, Abbott, S, Haynes, M, Kositcin, N, Ray, A, Slatter, E. (eds.) Exploring for the Future: Extended Abstracts, Geoscience Australia, Canberra, 1–4.

# Implication of the newly discovered ca. 2.7 Ga ultrahigh- temperature metamorphism in northern Labrador, Canada

**M Huang[1,2], S Jiao[1*], Z Lan[1], J O`Neil[3], H Rizo[4], Q Li[1,2]**

* corresponding author: jiaoshujuan0215@126.com

1. State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

2. University of Chinese Academy of Sciences, Beijing 100049, China

3. Department of Earth and Environmental Sciences, University of Ottawa K1N 6N5, Canada

4. Department of Earth Sciences, Carleton University, Ottawa K1S 5B6, Canada

Several lines of evidence suggest that the Earth's tectonic regime might have undergone a significant change in the period of 3.2–2.8 Ga. Investigations of Archean terrains that may have recorded such a shift can help better understand Earth`s tectono-thermal evolution. The Saglek-Hebron complex (SHC) in Northern Labrador, located on the westernmost margin of the North Atlantic Craton, is one of the oldest records of continental crustal rocks with rocks as old as nearly 3.9 Ga. It mainly consists of Archean tonalite–trondhjemite–granodiorite (TTG) gneiss formed within the entire Archean Eon, and includes two supracrustal suites (Eoarchean Nulliak and Paleoarchean Upernavik). It was suggested that the SHC has experienced multiple magmatic-metamorphic events from c. 3.87 Ga to c. 2.5 Ga or even earlier. These tectono-thermal events and associated geodynamic processes are significant for our understanding of the early Earth's lithospheric evolution and the ongoing tectonic mode. Here, we investigate a metasedimentary rock from the Eoarchean Nulliak supracrustal unit. The sample is composed of garnet + orthopyroxene ($Al_2O_3$ of about 8 wt%) + quartz + antiperthite + rutile, and has been interpreted to have formed during the peak metamorphic stage. A combined application of two-feldspar-thermometry, Zr-in-rutile thermometry, as well as mineral mode and chemical composition isopleth by phase equilibria modelling, allowed the identification of ultrahigh-temperature (UHT) metamorphism with a peak temperature above 900 °C and a pressure of 7.4–9 kbar, and post-peak near isobaric cooling (IBC) retrogression evolution characterized by the formation of retrograde biotite and fibrous sillimanite. Secondary Ion Mass Spectroscopy (SIMS) data revealed that detrital zircon grains show a wide range of ages from c. 3.6 Ga to c. 2.9 Ga, while metamorphic zircon grains yield $^{207}Pb/^{206}Pb$ ages ranging from 2705 Ma to 2752 Ma, defining a weighted mean age of 2728 ± 6.3 Ma.

Our study shows that the SHC Nulliak supracrustal assemblage recorded a single episode of Neoarchean UHT metamorphism with a short-lived duration of <40 Myr, combined with the results of Ti-in-zircon thermometry. UHT metamorphism worldwide occurs in clusters at 2800–2500 Ma, 2100–1500 Ma, 1200–1000 Ma, 650–540 Ma and 100–0 Ma, and correlates with the amalgamation of supercratons and supercontinent cycles. Its generation is closely related to the evolution of plate tectonics, especially the convergent margin tectonic processes. Comparing with the other well-studied Archean UHT metamorphic rocks, and as tectonic thickening and radiogenic heating alone are not sufficient to cause such short-lived UHT metamorphism, we conclude that the formation mechanism of UHT metamorphism in the SHC might be caused by the lithospheric thinning and the associated asthenospheric upwelling during the lithospheric peeling in a thinned orogen.

# Continental thermal evolution constrained by secular change of detrital zircon trace elements

**S Jiao*, H Jiang, J Xi, X Zhang**

* corresponding author: jiaoshujuan0215@126.com

State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

Understanding how continental crust formed and evolved is a fundamental geological problem. The secular change of thermal evolution of continental crust was previously estimated using *P–T* conditions of metamorphic rocks, which has revealed that the highest *T/P* occurred in the Mesoproterozoic. It implies that the Mesoproterozoic continental crust is probably the hottest over time, although the thickness during this period is still controversial. Due to the absence of metamorphic rocks before c. 3.5 Ga, the thermal evolution of continental crust before Mesoarchean is ambiguous. Here, we compiled the dataset of temperature- and pressure-indicative trace element concentrations in detrital zircon, a total of over 40 000 data included. Ti-in-zircon contents are temperature dependent at a certain condition, and the secular change in the compiled Ti-in-zircon contents is consistent with the trend in metamorphic *T/P*. On the first-order, Ti-in-zircon contents increase from c. 3.5 Ca to c. 1.3 Ca, and then decrease towards the present- day, confirming a hot Mesoproterozoic crust. Moreover, our results show that the continental crust cooled down from c. 4.3 Ga to c. 3.8 Ga, and the c. 3.8 Ga crust is the coolest in the entire geological time. A second-order metrical change of Ti-in-zircon contents correlates well with the supercraton/supercontinent cycles, with higher values during the supercontinent assembly and lower values during the breakdown.

Eu/Eu* and Gd/Yb of detrital zircons were both regarded as the proxies for the thickness of the continental crust, but the results for these two proxies show absolutely inverse trend. Based on Eu/Eu*, the most thickened crust is in c. 3.5–3.0 Ga, while the hottest Mesoproterozoic crust is the thinnest; based on Gd/Yb, the crustal thickness decreased firstly from c. 4.3 Ga to 3.8 Ga, reach a peak value in c. 2.2–2.1 Ga, then decreased again till c. 0.25 Ga, before a final kick-up towards the present-day. Similar to the Ti- in-zircon trend, the second-order metrical change of Gd/Yb seems to relate to the supercraton/supercontinent cycles, although the peaks of Ti contents are sometimes a bit lagged to that in the Gd/Yb trend. If the thickness proxy of Gd/Yb is preferred, it suggests that the thermal evolution of the continental crust is controlled mainly by tectonic thickening and radiogenic heating, while the peak temperature is reached later than the peak of crustal thickening, implying the effect of mantle heating during the post-thickened lithospheric extension.

This systematic study of temperature- and pressure-indicative trace elements in detrital zircons provides new insights into the continental thermal evolution since the Hadean. It indicates a coolest and thinnest crust at c. 3.8 Ga, which might be related to the Late Heavy Bombardment, especially considering that the oldest (c. 3.5 Ga) komatiites that were regarded as formed by mantle plume occurred slightly later. Our study also shows how both tectonic thickening-thinning due to the supercraton/supercontinent cycle and mantle flux contributed to the evolution of the continental crust.

# A role for impacting in producing crustal nuclei on early Earth

**CL Kirkland[1*], M Brown[2], T Johnson[1], P Sutton[3]**

* corresponding author: c.kirkland@curtin.edu.au

1. Timescales of Mineral Systems Group, School of Earth and Planetary Sciences, Curtin University, Perth, WA, Australia
2. Department of Geology, Laboratory for Crustal Petrology, University of Maryland, Maryland, USA
3. School of Mathematics and Physics, University of Lincoln, Lincoln, UK

The surface of the moon provides a vivid indication of the role of impacting in its evolution. Since Earth's gravity well is 80% greater than our satellites, it will have endured a proportionally higher rate of bombardment. It has been proposed that extra-terrestrial cratering on early Earth was important in crust production, but this proposition has received relatively little attention compared to endogenic (mantle plume or plate tectonic) processes. Isotopic signatures in zircon have been used to address a wide range of questions on the rates, durations, and timing of Earth system processes. Large compilations of time series data from zircon now exist across most continents. Encoded within this time series data are periodicities linked not only to magma production but also, critically, the source of such melts. Hf time series data, reflecting the relative importance of crustal recycling over mantle production, has statistically significant periodicities for the early Earth on 190 $Ma^{-1}$. A similar periodicity is resolved in zircon oxygen isotope data, with bimodality in zircon oxygen isotopes (a function of shallow and deep melting). While each craton has its own tempo of crust production, certain events may be globally synchronous. For example, a peak in the frequency of change points on all cratons at c. 3.3 and c. 2.8 Ga, the former may reflect stabilization of subduction at the beginning of the gradual transition into global plate tectonics, whereas the latter may correspond to changes in the preservation of metamorphic rocks with contrasting thermal gradients. Onto these secular changes a periodic signal of c. 190 $Ma^{-1}$ is evident in zircon oxygen and Hf isotopes, and also in the more recent hypervelocity impact crater record. This frequency correlates with astronomical models of impact flux during Solar System spiral arm passage. In particular, the zircon oxygen isotope time series appears to support secular episodes when shallow melting dominated crust production, implying a surface, not mantle, derived energy input at those times. Based on these data, we posit that the Solar System's entry into and exit out of the galactic spiral arms may have triggered more long period comets to lower their perihelion and enter Earth crossing orbits. While, correlation is not causation, it is relevant to note that early Earth spherule beds also correspond to periods of isotopic deviation and the entry of the solar system into the galactic arms. The favoured model for formation of rocky planets, including Earth, is by collisions, moreover giant impacts are the favoured explanation for the formation of moons, including Earth's, and recent research has highlighted that erosion from impacting is likely key to explaining the composition of our planet. Furthermore, gravitational forces in the spiral arms are seen as driving star formation. Is it then so difficult to expect early Earth crustal nuclei production, to be fundamentally influenced by impacting, as a function of our galactic environment? Given the greater impact flux on our young rocky planet a growing body of research would perhaps suggest not. Geology may benefit from looking outward as well as inward.

# Stable and radiogenic neodymium isotope analyses of TTGs: new insights into crust formation?

**SA Ladwig[1*], AJ McCoy-West[2,1], P Cawood[1]**

* corresponding author: Amrei.ladwig@monash.edu

1. School of Earth, Atmosphere and Environment, Monash University, Melbourne, 3800 Victoria, Australia

2. IsoTropics Geochemistry Laboratory, James Cook University, Townsville, QLD, Australia

Tonalite-trondhjemite-granodiorites (TTGs) are the oldest preserved felsic rocks on Earth and form the backbone of the cratonic cores of the Earths' continents today. The separation of light (L-) and heavy (H-) rare earth elements (REEs) by garnet or amphibole dominated TTG source rocks has been shown to be pressure dependent by multiple previous studies. Thus, investigating the trace element compositions in TTGs has potential for better understanding continent formation. Stable neodymium (Nd) isotopes are a novel geochemical tool that shows promising results as a tracer for a range of time-independent magmatic processes that have previously been applied to a range of igneous rocks. However, no studies have investigated TTGs. Archean granitoids from the Murchison domain of the Yilgarn Craton, Western Australia show that the TTGs sensu stricto (s.st.), ranging between $\delta^{146}$Nd -0.045 to +0.015‰ (average: $\delta^{146}Nd_{TTG\ s.st.}$ of -0.016 ± 0.006‰ [2SD; n=16]), and the TTGs sensu lato (s.l.), ranging between $\delta^{146}$Nd -0.035 to +0.01‰ (average: $\delta^{146}Nd_{TTG\ s.l.}$ of -0.014 ± 0.006‰; 2SD; n=9), are marginally heavier than late stage high potassium granitoids (range: $\delta^{146}$Nd -0.05 to +0.01‰; average: $\delta^{146}Nd_{K-grt}$ of -0.027 ± 0.006‰; 2SD; n=13) or mafic samples (range: $\delta^{146}$Nd -0.04 to 0‰; average: $\delta^{146}Nd_{mafic}$ of -0.028 ± 0.006 ‰; 2SD; n=5). The TTGs s.st. resemble more the bulk silicate Earth value of $\delta^{146}Nd_{BSE}$ = -0.024 ± 0.005‰ (2SD; n=80; ± 0.003‰, 95%se) and TTGs exhibit a greater range than most other measured rock types ($\delta^{146}Nd_{Yilgarn}$ -0.05 to +0.012‰). The heavier $\delta^{146}$Nd of TTGs relative to the BSE implies the occurrence of a fractionation process, and thus stable Nd may serve as a tracer for the evolution of the continental crust. Major and trace element investigations, extended by modelling calculations disprove an effect on $\delta^{146}$Nd by *P–T*-depending compositional changes focused mainly on the relative amounts of garnet and amphibole. But they could constrain minor effects by accessory phases that fractionate the $\delta^{146}$Nd during melting. Our second observation confirms a secular change in the $\delta^{146}$Nd-signal, that is suspected to be the result of magma differentiation. The assessment of an alteration influence on $\delta^{146}$Nd revealed unambiguously no influence, which in turn would exclude the relationship to subduction zone environments. One possible explanation for the variations in $\delta^{146}$Nd is a potentially inherited source signature from mafic precursor rocks that could have overprinted the $\delta^{146}$Nd.

Combing these results with traditional radiogenic Nd data (εNd) confirms an increase in crustal recycling with time along with a greater heterogeneity of $\varepsilon Nd_{(T)}$ in the younger samples. The secular evolution in the εNd-signal is in line with $\lambda_1$, the garnet indicating tracer that describes the slope of the REEs. All three methods, as here presented, $\delta^{146}$Nd, the εNd and the λ-diagrams, combined with previously published work, suggest an evolutionary tectonic change at 2.75 Ga in the Yilgarn Craton, which include proposals for a local rift opening in the Murchison domain, arc accretion and potentially the onset of subduction.

# Neoarchean as a period of transition from vertical to horizontal tectonism: insights from observations in the Superior craton and numerical modelling

**S Lin*, Q Wu**

* corresponding author: shoufa@uwaterloo.ca

1. Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, Canada N2L 3G1

The Superior Craton consists of a series of east-west trending 'subprovinces' or terranes. Many geologists have described evidence that the subprovinces represent a series of microcontinents, remnant arcs, oceanic terranes and accretionary prisms and that the Superior Craton grew by lateral accretion of these elements.

The Superior Craton is also characterized by narrow greenstone belts, surrounded and intruded by voluminous granitoid plutons. The plutons mostly occur in open domes, whereas greenstones generally occur in narrow synclinal keels. Regional scale shear zones are spatially coincident with the greenstone belts.

Two discrete episodes of deformation have been recognized: an earlier recumbent folding and thrusting event and a later upright folding and shearing event. The former was possibly related to terrane accretion and collision, and the latter to the formation of the dome-and-keel structure and the regional scale shear zones. The dome-and-keel structure formed as a result of diapirism and sagduction (vertical tectonism), and the regional scale shear zones have regionally consistent kinematics and were a result of regional horizontal shearing (horizontal tectonism). Results of detailed structural analysis show that diapirism/sagduction and regional horizontal shearing occurred synchronously. The dome-and-keel structures and shear zones overprint and help to obscure earlier accretional/collisional structures, and the shear zones do not necessarily coincide with the terrane boundaries.

To test these interpretations, we developed a three-dimensional numerical modelling scheme so that the information about lithological distribution, flow kinematics and finite deformation pattern is directly available as the numerical model evolves. Utilizing this modelling framework, a numerical model is constructed where a density overturn develops under the backdrop of horizontal shearing. The lithological distribution and structural patterns emerging from the numerical model are similar to what is observed in our synthesis of the geological data. By varying the shear strain rate and the crustal rheology, the numerical model produces a wide range of granitoid-greenstone belt geometry that compares favourably with granitoid-greenstone terranes in the Superior Province and worldwide.

We therefore postulate that the vertical and horizontal tectonics were not mutually exclusive tectonic regimes and that they both contributed to the establishment of crustal architecture in many Neoarchean terranes. The co-existence of both processes in Neoarchean terranes suggests the Neoarchean was the time in the Earth's history when the transition from vertical tectonism to a modern-day-like horizontal tectonics took place.

Furthermore, the curvilinear belts of high accumulated strain developed in our models mimics the characteristics of the major deformation zones in the Superior Province, implying that the nucleation and development of such 'crustal-scale' deformation zones in Neoarchean terranes may be the natural product of strain localization in a synchronous horizontal and vertical tectonic regime, rather than strike-slip shear zones with regionally significant accumulated lateral movements.

# 'High pressure' tonalite–trondhjemite–granodiorite can form at low pressure

**P Liou[1*], ZC Wang[2], RN Mitchell[1], LS Doucet[3], JH Guo[1], MG Zhai[1]**

* corresponding author: liupeng@mail.iggcas.ac.cn

1. Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
2. School of Earth Sciences, China University of Geosciences, Wuhan 430074, China
3. School of Earth and Planetary Sciences, Curtin University, Perth, WA 6102, Australia

Tonalite–trondhjemite–granodiorite (TTG) rocks constitute the majority of preserved Archean crust, but their petrogenesis and geodynamic setting are still matters of great debate. TTGs have been be classified into low-, medium- and high-pressure variants based on their different compositions (e.g. Sr/Y, La/Yb ratios). Among them, the high-pressure type tends to be more trondhjemitic and may indicate the subduction regime. However, the classic model and classification are not consistent with the fact that: (1) for most granitoids, the accessory phases dominate the bulk trace element compositions and have an influence on petrogenetic studies far greater than their abundances might suggest, but have been largely neglected in both geochemical modelling and equilibrium phase modelling; (2) in many terranes, the high-pressure and low-pressure types can be found in the same outcrops and show gradual transitional relationships in mineral assemblages and compositions.

Specifically, for the 2.5 Ga TTGs of the eastern North China Craton, geochemical analyses show that dioritic parental magmas may evolve to trondhjemites through a maximum of 27% fractionation of amphibole and apatite. The cumulate apatite-bearing hornblendites, a predicted solid fractionate and chemical complement to the TTGs, are also identified. They are complementary in major and trace elemental compositions to the TTGs.

In addition, the Fe isotopes provide an alternative tool that eliminates the disturbances caused by accessory mineral phases. Unlike trace elements (e.g. Sr; rare earth elements) that could be disproportionately affected by accessory minerals, the Fe abundances of TTG melts are controlled by mafic rock-forming minerals (e.g. amphibole, pyroxene, and garnet) and Fe-rich oxides. In our analyses, whole-rock $Fe^{3+}/\sum Fe$ and $\delta^{56}Fe$ data support that the 'high-pressure' trondhjemites formed by amphibole-dominated fractionation at low pressure. For the 'high-pressure' tonalites, their light Fe isotopes make them unlikely to be the melting products of mid-ocean ridge basalt-like (MORB) or ocean island basalt-like (OIB) basalts at high pressure within garnet-stability field.

In summary, these 'high-pressure trondhjemites and tonalites can form at low pressure with little involvement of residual garnets. Partial melting is not a unique solution to the problem of how to form the Archean TTGs and how to make an Archean continent. Thick crust or lithosphere (within garnet-stability field) is also not a strict requirement. In fact, the heterogeneity observed in the TTG compositions highlights the diversity of their sources and formation processes.

## References

Liou, P, Wang, Z, Mitchell, RN, Doucet, LS, Li, M, Guo, J and Zhai, M 2022, Fe isotopic evidence that "high pressure" TTGs formed at low pressure. Earth and Planetary Science Letters, v.592, p.117645.

Liou, P and Guo, JH 2019, Generation of Archaean TTG Gneisses Through Amphibole-Dominated Fractionation. Journal of Geophysical Research-Solid Earth, v.124(4): p.3605-3619.

# Vertical tectonics at the Archean–Paleoproterozoic transition: evidence from ultra-high temperature granulites from the North China Craton

**T Liu[1,2,*], C Wei[2,*], TE Johnson[3], E Sizova[4]**

* corresponding author: liuting3624@pku.edu.cn, cjwei@pku.edu.cn

1. College of Earth Sciences, Chengdu University of Technology, Chengdu 610059, China
2. School of Earth and Space Sciences, Peking University, Beijing, 100871, China
3. School of Earth and Planetary Sciences, the Institute for Geoscience Research, Curtin University, Perth, WA 6845, Australia
4. Institute of Earth Sciences, University of Graz, Graz 8010, Austria

Archean supracrustal rocks of ultra-high temperature (UHT) metamorphism, occurring as rafts or enclaves within tonalite–trondhjemite–granodiorite (TTG) gneiss domes, commonly record counterclockwise *P–T* paths. The heat sources and the geodynamic implications behind them are still debated. In the East Hebei terrane of the North China Craton, Archean UHT supracrustal rafts have been reported, but the metamorphic paths and geological settings still need to be investigated. Two pelitic granulites (JD1730 and JD1733), collected from the western margin of Qian'an gneiss dome, are documented for their petrologic observation, mineral chemistry, phase equilibria modelling, Ti-in-zircon temperature calculation and zircon age dating. These two rocks are all metatexite and were divided into cordierite-present melanocratic domains (MDs) and cordierite-absent leucocratic domains (LDs) rich in K-feldspar and quartz. Through the phase equilibria modelling, both of two domains in two rocks record peak condition of 6–8 kbar/980–1060 °C, together with counterclockwise *P–T* path involving a pre-peak up-pressure heating process from approximately 5 kbar/800–900 °C, and a post-peak cooling process to 5–8 kbar/820–850 °C. In JD1730, the peak condition is limited based on the biotite-absent peak assemblages of garnet+K-feldspar+plagioclase+quartz and the $X_{An}$ isopleths (0.05–0.07) of re-integrated K-feldspar in LD, and the inferred peak assemblage of cordierite+sillimanite+orthopyroxene+sapphirine+quartz in MD; the pre-peak up-P process is defined in MD mainly based on the successive growth of sapphirine and orthopyroxene + sillimanite by mainly consuming spinel and cordierite. For JD1733, the peak condition is defined on the plots of the re-integrated $X_{An}$ (0.05–0.06) of perthite in LD, and the inferred peak assemblage involving garnet, plagioclase, cordierite, sillimanite and quartz in the MD; spinel inclusions in garnet are recognized to indicate a pre-peak up-P process in the LD, matching with the path inferred from the MD on the basis of the observations that spinel + corundum (± ilmenite) aggregates were embayed by prismatic sillimanite and then included in garnet. The post-peak cooling processes are all defined from the emergence of biotite in both samples. Besides, the defined UHT peak temperature is supported by the ternary feldspar and Ti-in-zircon thermometers. Geochoronological studies on the zircons show that the UHT metamorphism occurred at approximately 2.50 Ga, with UHT conditions having lasted over 20 Ma and the post-UHT cooling having continued another 20 Ma. The Archean UHT metamorphism is calculated to have extremely high dT/dP of approximately 40 °C/ kbar, being interpreted to related with the vertical tectonics, involving magmatic loading of TTGs and subsequent sinking of supracrustal rocks.

# Paleomagnetism not in favour of a long-lived Archean supercontinent

**Y Liu[1*], RN Mitchell[2,1], Z-X Li[1], U Kirscher[1,3], SA Pisarevsky[1], C Wang[2,1,4]**

* corresponding author: yebo.liu@curtin.edu.au

1. Earth Dynamics Research Group, The Institute for Geoscience Research (TIGeR), School of Earth and Planetary Sciences, Curtin University, Bentley, Western Australia 6102, Australia
2. State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
3. Department of Geosciences, University of Tübingen, Sigwartstrasse 10, 72076 Tübingen, Germany
4. Department of Geosciences and Geography, University of Helsinki, FI-00014 Helsinki, Finland

The existence of Paleoproterozoic rifted margins of many Archean cratons indicates that they were once part of larger land masses. While some suggest that these land masses comprised an Archean supercontinent, contrasting geological records between different clans of cratons have inspired an alternative hypothesis where cratons were clustered in multiple, separate 'supercratons'. Paleomagnetic poles from some Archean cratons including a new c. 2.62 Ga pole from the Yilgarn craton is compatible with either two successive but ephemeral supercontinents or two long-lived supercratons across the Archean-Proterozoic transition (Liu et al., 2021). Neither interpretation supports the existence of a single, long-lived supercontinent, suggesting that Archean geodynamics were fundamentally different from subsequent times (Proterozoic to present), which were influenced largely by supercontinent cycles.

## Reference(s)

Liu, Y, Mitchell, RN, Li, ZX, Kirscher, U, Pisarevsky, SA and Wang, C 2021, Archean geodynamics: Ephemeral supercontinents or long-lived supercratons. Geology, v. 49(7), p.794-798.

# Reappraising the petrogenesis of 2820–2738 Ma magmas of the western Youanmi Terrane, Western Australia

**JR Lowrey[1,2], DA Wyman[2], TJ Ivanic[1], RH Smithies[1]**

* corresponding author: jack.lowrey@dmirs.wa.gov.au

1. Geological Survey of Western Australia, Department of Mines, Industry Regulation and Safety, East Perth WA 6004, Australia

2. School of Geosciences, The University of Sydney, NSW 2006, Australia

The Yilgarn Craton is one of the largest fragments of Archean crust and is critical to understanding the geodynamic processes that operated on early Earth. A study of c. 2820–2738 Ma magmatic rocks in the northwestern Youanmi Terrane of the Yilgarn Craton (Lowrey, 2022) identified several lines of evidence that require a geodynamic reappraisal: (1) the distribution and abundance of komatiites reported in previous studies is grossly overstated and the necessity for anomalously high mantle temperatures of a mantle plume is therefore questionable; (2) volcanic stratigraphy comprises mafic volcanic rocks with boninite-like compositions and mineralogy, mid-ocean ridge basalt-like (MORB) tholeiitic basalts, siliceous high-Mg basalts and high-Mg intermediate–felsic rocks; these lithologies could collectively be considered diagnostic of a subduction setting, if documented in the modern geologic record; (3) Th/Yb–Nb/Yb systematics for volcanic rocks define several distinct trends, parallel to the modern mantle-array, that overlap with trends from modern subduction settings; and (4) coeval mafic–ultramafic sills and granitic rocks that intrude the greenstone sequence contain locally abundant hornblende and indicate widespread hydrous metasomatized mantle sources throughout the northwestern Youanmi Terrane from c. 2810 Ma.

Using new geochemical data and existing geochronological data, Lowrey (2022) defined a chemo-stratigraphic framework with 16 units that can be correlated between structurally separated greenstone belts and, on a regional scale, define discontinuous, broadly north-northeast trends that extend ≤350 km long and ≤50 km wide. Neodymium isotope and trace element systematics of magmatic rocks implicate increasing incorporation of metasomatized mantle from c. 2820 to 2738 Ma and variable recycling of a ≥3050–2920 Ma crustal component. Mantle sources to multiple magmatic units aged c. 2820–2782 Ma are interpreted to have been metasomatized by fluids from hydrous mafic crust whereas mantle sources to c. 2754 Ma shoshonitic rocks (hornblende-biotite rich lamprophyres and granitic plutons) are interpreted to have mixed with and been metasomatized by ancient sedimentary components. A preliminary geodynamic framework is proposed whereby the first magmatic episode from c. 2820–2782 Ma, involving lithospheric thinning and upwelling asthenosphere, as well as depletion and metasomatism of mafic magma sources, is attributed to subduction of relatively isotopically juvenile crust. Following a c. 20 Ma hiatus, the second magmatic episode from c. 2761–2738 Ma, which included crustal-derived transitional tonalite-trondhjemite-granodiorite (TTGs) and mantle-derived shoshonitic and sanukitoid rocks, is interpreted to represent a post-orogenic event related to delamination of arc-crust or slab breakoff.

## References

Lowrey JR 2022, Petrogenesis of c. 2820–2738 Ma magmatism in the northwestern Youanmi Terrane, Yilgarn Craton. Unpublished PhD Thesis, University of Sydney.

# Temporal evolution of $^{182}W$ signatures in the terrestrial mantle: implications for the generation, preservation and destruction of early mantle heterogeneities

**QF Mei[1], JH Yang[1,2*], CF Li[1], XC Wang[3], J Konnunaho[4], YD Wu[1], H Zhong[5], YG Xu[6], H Wang[1]**

* corresponding author: jinhui@mail.igcas.ac.cn

1. State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
2. College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China
3. School of Earth Sciences, Yunnan University, Kunming 650500, China
4. Geological Survey of Finland, P.O. Box 77, 96101 Rovaniemi, Finland
5. State Key Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, China
6. State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China

Komatiites and picrites generated by high degrees of mantle partial melting are proposed to be probes of the Earth's deep mantle. Tungsten isotopes offer a rare chance to ascertain early differentiation, late accretion, core-mantle interaction, and subsequent evolution of the Earth's mantle. Here we present new W isotope data for Archean komatiites and basalts from the Barberton (South Africa) and Suomussalmi (Finland) Greenstone Belts and Permian picrites from the Emeishan large igneous province (China). The Paleoarchean samples from the Barberton Greenstone Belt show $\mu^{182}W$ values ranging from –20.4 to +5.6, whereas the Mesoarchean komatiites from the Suomussalmi Greenstone Belt show $\mu^{182}W$ values of –2.2 to +7.7. The Permian Emeishan picrites give $\mu^{182}W$ values of –7.1 to +3.1. The negative $\mu^{182}W$ values observed in the Paleoarchean samples from the Kaapvaal Craton likely result from either early differentiation or core-mantle interaction. Incorporation of this component into the mantle could lower the average $\mu^{182}W$ value of the silicate Earth, which would explain the lower $\mu^{182}W$ values in some younger granitoids and komatiites relative to most of the Paleoarchean rocks (e.g. Mei et al., 2020; Nakanishi et al., 2023). By combining our results and the published data, the long-term trends in W isotope compositions of mantle-derived rocks provide important insights into the generation, preservation and destruction of early mantle heterogeneities.

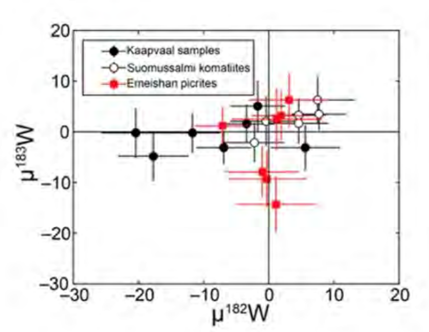



Figure 1. Measured $\mu^{182}W$ and $\mu^{183}W$ values for samples of this study. Error bars represent 2SE

## References

Mei, QF, Yang, JH, Wang, YF, Wang, H and Peng, P 2020, An improved extraction chromatographic purification of tungsten from a silicate matrix for high precision isotopic measurements using MC-ICPMS: Journal of Analytical Atomic Spectrometry, v. 33, p. 569–577.

Nakanishi, N, Puchtel, IS, Walker, RJ and Nabelek, PI 2023, Dissipation of Tungsten-182 Anomalies in the Archean Upper Mantle: Evidence from the Black Hills, South Dakota, USA: Chemical Geology, v. 617, p. 121255.

# *P-T-t* evolution of garnet-bearing migmatites from Karimnagar Granulite Belt and their geodynamic implications

**P Nasipuri[1*], K Satpathi[1], AB Majeed Ganaie[1], L Saha[2], K Yi[3]**

* corresponding author: pritams@iiserb.ac.in

1. Department of Earth and Environmental Sciences, Indian Institute of Science Education and Research Bhopal
2. Department of Earth Sciences, Indian Institute of Technology, Roorkee
3. Korea Basic Science Institute (KBSI), Cheongju city, ChungBuk 28119, South Korea.

The paired metamorphic belts, i.e. coeval high pressure–low temperature rocks (eclogites) and low pressure–(ultra) high temperature rocks (granulite), are the hallmark of modern-day horizontal plate tectonics. At around 3000 Ma, a faster convention mantle formed the earliest continental crust. The gradual cooling of the mantle would ultimately stabilize thick continental plates with deeper mantle convection. Numerical modes also suggest that Mesoarchean to early Paleoproterozoic (3200–2500 Ma) represent a transition period of an early stagnant tectonic model to subduction-driven plate tectonics. Granulite facies represent extreme temperature conditions of lower crustal rocks during crustal assembly and disintegration processes. In the last decade, articles were published from high Mg–Al granulites of twin Karimnagar–Bhopalpatnam Granulite Belts flaking the Eastern Dharwar Craton (EDC) and the Bastar Craton (BC), respectively, to model the Neoarchean crustal amalgamation processes. However, due to limited exposure and prone to retrogression, garnet migmatites, and felsic granulites receive less attention.

The garnet-bearing migmatite and charnockites occur as isolated outcrops in the central part of the Karimnagar Granulite Belt. Orthopyroxene and garnet are the major minerals in the studied samples. Zircon occurs as an accessory mineral. The mineral association implies that garnet stabilized by consuming orthopyroxene, biotite and plagioclase in a prograde reaction path. Phase-diagram modelling implies peak *P-T* conditions, i.e. 900–950 ˚C, 0.7–0.8 GPa for garnet stabilization. The $^{207}Pb/^{206}Pb$ ages of zircon imply the presence of Archean zircon (approximately 2700 Ma) mantled by younger zircons that yield an average age of 2200–2100 Ma. The older zircons preserve magmatic textures and yield an upper intercept age of 2700 Ma when plotting on a U–Pb Concordia diagram.

The 2700 Ma-aged garnets from Karimnagar Granulite Belt, combined with the approximate 2800 Ma high pressure metamorphic events of Bundelkhand Craton (BuC), point towards the existence of a Paleosubduction zone, where the Archean crust of the Bundelkhand Craton was getting subducted below the EDC–BC. We suggest that a probable Archean subduction has produced the high-pressure rocks of the BuC, whereas slab-breakoff and upwelled mantle provided the necessary heat for 2700 Ma aged high temperature granulite facies metamorphism in the EDC just before the Mesoarchean–Paleoproterozioc transition.

# Ultra-high-pressure to low-pressure (<250 to >1000°C/GPa) Eoarchean metamorphisms explained by lateral lithosphere movements

**AP Nutman[1*], VC, Bennett[2], CRL Friend[3]**

* corresponding author: anutman@uow.edu.au

1. School of Earth, Atmospheric and Life Sciences, University of Wollongong, Wollongong, NSW 2522, Australia
2. Research School of Earth Sciences, Australian National University, Canberra, ACT 2601, Australia
3. Glendale, Tiddington, Oxon, OX9 2LQ, UK

Evidence for >3600 Ma low *T/P* metamorphism in Greenland's Itsaq Gneiss Complex (IGC) is: (i) approximately 550 °C ≥2.6 GPa conditions (≤250 °C/GPa) demonstrated by an olivine (high –OH) + antigorite + titano-chondrodite / titano-clinohumite assemblage within low-Ti dunite-harzburgite slivers that were exhumed into the crust by 3717±6 Ma; (ii) Vestiges of 3658±3 Ma high-pressure (garnet + clinopyroxene) mafic granulite; and (iii) Barrovian-style kyanite + staurolite metapelite assemblages (Fig. 1). High *T/P* (≥1000 °C/GPa) metamorphism is shown by 3669±8 Ma trondhjemite melts equilibrated with orthopyroxene that formed coeval to the youngest juvenile tonalitic crust in the complex (latter derived by anatexis under low *T/P* conditions), and a 3660–3570 Ma history of deep crust migmatization under low pressure, garnet-free conditions (Fig. 1). Structural geology indicates the IGC's low *T/P* regimes coincide with (i) crustal imbrication of arc-like tholeiites, boninites, andesites, felsic-intermediate volcano-sedimentary rocks and chemical sedimentary rocks and (ii) thrusting of older rocks over younger ones; whereas subsequent high *T/P* metamorphism was marked by late-orogenic extension/exhumation and deep crustal flow with granitic partial melting and mafic underplating. Thus, the diversity and sequence of Earth's earliest-recorded geodynamic settings resembles more those in modern geodynamics, than the lithological, thermal and structural relationships expected from non-uniformitarian scenarios within a theoretical stagnant lid regime.

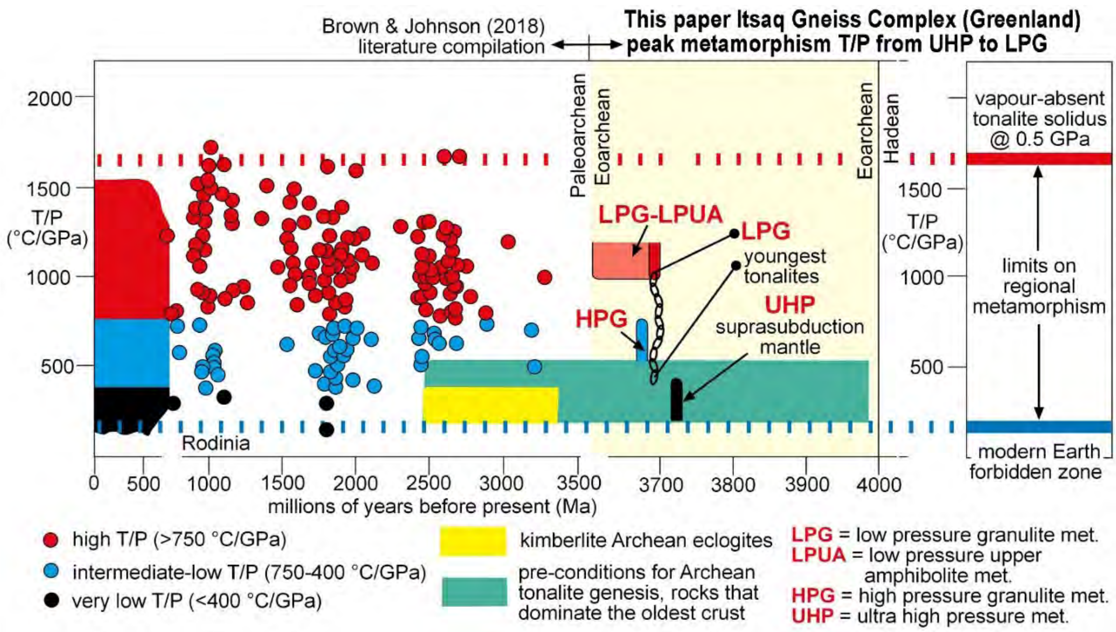



Figure 1. Eoarchean T/P metamorphic conditions in the Itsaq Gneiss Complex

## Reference

Brown, M & Johnson, T 2018, Secular change in metamorphism and the onset of global plate tectonics. American Mineralogist, v. 103, p. 181-196.

# The evolving crustal architecture of the Wawa Subprovince, Superior Craton

**KG Nymoen[1*], DR Mole[2], DK Tinkham[1], PC Thurston[1], RA Stern[3]**

* corresponding author: knymoen@laurentian.ca

1. Mineral Exploration Research Centre, Harquail School of Earth Sciences, Laurentian University, Sudbury, ON P3E 2C6, Canada
2. Geoscience Australia, Canberra, Australian Capital Territory 2609, Australia
3. Canadian Centre for Isotopic Microanalysis, University of Alberta, Edmonton, AB T6G 2R3, Canada

The Superior Craton is Earth's largest relic of Archean crust, thus providing important information on the geology of the early Earth. The craton hosts numerous world-class ore deposits, particularly in the Abitibi-Wawa Terrane, including volcanogenic massive sulfide (VMS), orogenic gold, and lesser komatiite-hosted Ni-Cu-PGE deposits, that are all often clustered spatially and temporally into 'camps'. Controls on the formation of these clusters, the crustal architecture, and geodynamic processes leading to mineralization are yet to be fully resolved. Previous studies used combined U–Pb geochronology, radiogenic (Sm–Nd, Lu–Hf) and stable ($^{18}O/^{16}O$, $\delta^{18}O$) isotopes to map the spatiotemporal evolution of crustal architecture (i.e. the Yilgarn Craton and Abitibi Subprovince, Superior Craton). Our study applies this technique to the less studied eastern Wawa Subprovince along strike of the Abitibi Subprovince and looks to further develop the methodology by integrating whole-rock geochemistry to allow mapping of crustal petrogenetic variations. We integrate multiple analytical datasets from tonalite-trondhjemite-granodiorite (TTG) and felsic volcanic rocks with phase equilibrium modelling to understand crustal architecture, including: 1) zircon trace element, O- and Hf-isotope compositions to identify involvement of low/high-temperature processes and juvenile/ancient crustal input to magmas; 2) whole-rock geochemistry, including Sr/Y ratio, to investigate source characteristics and relative source depth; and 3) whole-rock Nb content and phase-equilibrium modelling of Kapuskasing Structural Zone (KSZ) mafic rocks to establish the depth of source zone melting for Wawa TTG and felsic volcanic rock production. Combining these approaches, we find evidence for a geochemical and isotopic transition around 2695 Ma. Whole-rock geochemistry indicates that pre-2695 Ma rocks are dominated by sodic ($K_2O/Na_2O<0.7$) magmas, and zircon isotopes show mantle-like $\delta^{18}O$ values (4.7–5.9‰) with juvenile εHf values (+2.2–+5.6). Post-2695 Ma potassic ($K_2O/Na_2O>0.7$) rocks are more abundant, showing overall heavier $\delta^{18}O$-isotopes (5.9–7.4‰) and less juvenile εHf values; notably similar to findings from the Abitibi Subprovince. Whole-rock phase equilibrium analysis of Wawa mafic rocks indicates a garnet stability-field >7–8 kbar, suggesting that Wawa TTG source rocks dominated by high Sr/Y were melted predominantly at a crustal depth equivalent to about 26–30 km depth. The felsic volcanic rocks are dominantly sourced from a shallower crustal depth (low Sr/Y) than the TTGs (high Sr/Y). This temporal transition is couped to a spatial change, with the high Sr/Y crust (deep source) trending north to south at >2695 Ma, compared to eat to west at <2695 Ma. Our results demonstrate significant spatial and temporally variability in source characteristics, source depth and hence, crustal architecture across the Wawa Subprovince, features likely to have a significant effect on the formation and localization of mineral systems, with VMS more likely in a more primitive (sodic, mantle-like $\delta^{18}O$ and εHf) and possibly thinner crustal regime. Less primitive crust (potassic, heavy $\delta^{18}O$ and εHf) may reflect a metasomatized component, potentially important for gold mineralization. This study demonstrates that integration of isotopic mapping with whole-rock geochemistry and phase-equilibrium modelling establishes a more robust tool for understanding evolution of crustal architecture.

# Archean garnet-bearing amphibolites in north-eastern Brazil: first constraints on pressure–temperature paths

**CVA Ribeiro*, EL Dantas, RA Fuck**

* corresponding author: carlos.va.ribeiro@gmail.com

Instituto de Geociências, Universidade de Brasília, Campus Universitário Darcy Ribeiro, 70910-900 Brasília, DF, Brazil

The Archean basement of north-eastern Brazil features several Paleo- to Neoarchean plutonic and metasedimentary rocks. Partial melting at high temperatures were previously constrained during the Mesoarchean, Paleoproterozoic and Neoproterozoic. Here we present pressure-temperature paths based on thermodynamic modelling of a garnet-bearing amphibolite that intrudes a 3.35 Ga supracrustal sequence. The sample comprises plagioclase (XAn: 0.88–0.20), pargasitic amphibole, garnet with almandine and pyrope-rich cores (XAlm: 0.60, XPy: 0.15,) and grossular-rich rims (XGrs: 0.40), epidote, quartz, muscovite, titanite, clinopyroxene, K-feldspar (XOr: 0.96), calcite, magnetite, rutile, apatite and zircon. The sample comprises quartz absent domains, where the breakdown of garnet leads to the intergrowth of epidote and amphibole. In quartz-bearing domains, breakdown of garnet leads to symplectites of amphibole and plagioclase (XAn–0.60). Inclusions in garnet comprise amphibole, titanite, ilmenite, magnetite, quartz and calcite. Matrix minerals include amphibole, plagioclase, rutile, calcite, apatite and zircon. Thermodynamic modelling on the NCKFMASHTO system constrained temperatures between 800–850 °C at 8–10 kbar for garnet cores and 750–800 °C for garnet rims. Pressure decrease led to the breakdown of garnet to amphibole + plagioclase ± titanite ± ilmenite at 650 °C and 6 kbar. Recrystallization of matrix amphibole occurred at 600 °C and 4 kbar. The presence of muscovite and rutile suggests possible pressures above 14 kbar at 705 °C. Overall, the P–T path suggest a pressure peak at 14 kbar, followed by peak temperature conditions at 800–850 °C. High-temperature metamorphism overprinting high-pressure metamorphism is a common feature of Archean high-pressure granulites and is predicted by geodynamic modelling as a marker of ancient collisional orogens.

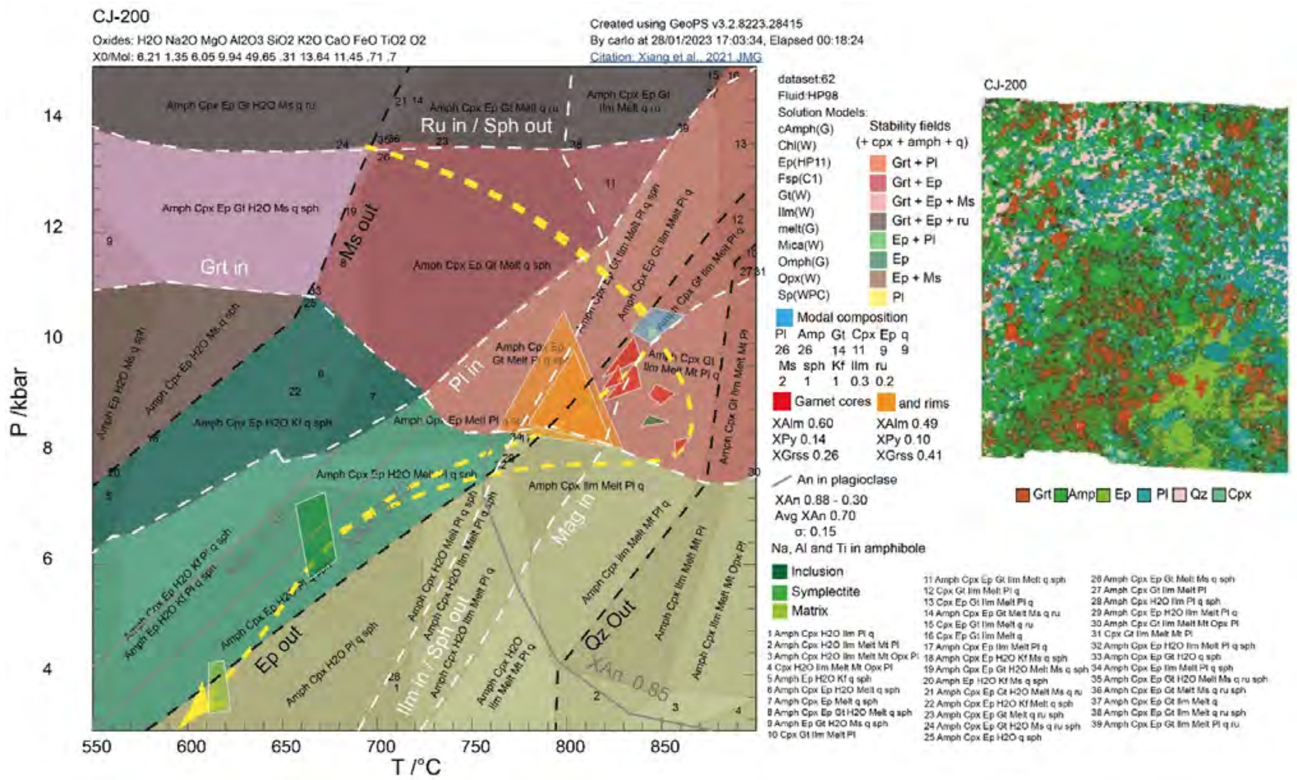



Figure 1. Thermodynamic modelling of sample CJ-200 and QEMSCAN mineral mapping

# Stratigraphy of the Norseman greenstone belt

**J Sapkota*, MC De Paoli, RH Smithies**

* corresponding author: Jyotindra.Sapkota@dmirs.wa.gov.au

Geological Survey of Western Australia, Cnr Hunter and Broadwood Streets, West Kalgoorlie, 6430 WA, Australia

The Yilgarn Craton has been subdivided into seven granite-greenstone terranes — the Narryer, South West and Youanmi Terranes in the west and the Kalgoorlie, Kurnalpi, Burtville and Yamarna Terranes in the east. The eastern terranes collectively comprise the Eastern Goldfields Superterrane. The Kalgoorlie Terrane, which is separated from the Youanmi Terrane by the Ida Fault, typically consists of a 2720–2690 Ma mafic–ultramafic package in greenstone belts, which has been assigned to the Kalgoorlie Group and is overlain by 2690–2665 Ma felsic volcanic and volcaniclastic rocks of the Black Flag Group. The 2665–2655 Ma late basin epiclastic rocks may overlie the Black Flag Group along an angular unconformity. A basement greenstone stratigraphy is identified beneath several succession of the Kalgoorlie Group and in some cases has been confirmed to be older than 2800 Ma, and in this respect similar to units of the Youanmi Terrane to the west and of the Burtville Terrane to the east.

The Norseman greenstone belt, which lies at the southern end of the Kalgoorlie Terrane, consists of the lower, dominantly mafic Penneshaw Formation and the sedimentary Noganyer Formation that consists of banded-iron formation interbedded with silicilastic and volcaniclastic units. A succession of mafic and ultramafic rocks overlying the Noganyer Formation are assigned to the Woolyeenyer and overlying Mount Kirk Formations and have been correlated with the Kalgoorlie Group to the north. An existing 2930 ± 4 Ma age on a felsic volcanic unit interbedded with basalt in the Penneshaw Formation is poorly documented and contentious. The diamond drill hole, PE6, which this sample was sourced from was reinvestigated and the lithology was verified to be felsic volcaniclastic conglomerate. A similar age of 2932 ± 3 Ma was also obtained from a volcaniclastic dacite within the Penneshaw Formation. Mylonitized plagioclase-phyric dacite intrusive into the Penneshaw Formation have given igneous crystallization ages of 2859 ± 3 Ma and 2857 ± 4 Ma.

Two different horizons of volcaniclastic conglomerate interbedded with banded-iron formation in the Noganyer Formation give unimodal age populations of 2938 ± 8 Ma and 2921 ± 7 Ma, interpreted to represent the age of volcaniclastic deposition and of magmatic crystallization. The only geochronological constraint on the Woolyeenyer Formation is from an internally differentiated gabbroic sill that intruded the base of the formation, which has been dated at 2714 ± 5 Ma. The onset of ultramafic volcanism in the Norseman greenstone belt in the Mount Kirk Formation is constrained by a maximum depositional age of an interflow sedimentary unit dated at 2713 ± 8 Ma (single detrital age population).

The current geochronological data shows a >200 Ma time gap between deposition of the Penneshaw–Noganyer Formations and the Woolyeenyer Formation. The Lunnon Basalt that underlies the komatiite horizon in the Kambalda greenstone belt (Kalgoorlie Group) is commonly considered to be a stratigraphic equivalent to the Woolyeenyer Formation. However, our recently acquired data suggests that the Woolyeenyer Formation is geochemically more similar to basement basaltic sequences that underlie the Kalgoorlie Group. Dates from interbedded volcanic and sedimentary rocks within the lower mafic stratigraphy in the Lenora and Menzies greenstone belts suggest that those units were deposited prior to 2800 Ma.

# Titanium isotope insights into the formation and evolution of sanukitoid magmas

**LM Spencer[1*], C Albert[1], HM Williams[2], O Nebel[3], IJ Parkinson[4], RH Smithies[5], H Bruno[6], M Fowler[7], H Moreira[8], CJ Lissenberg[1], MA Millet[1]**

* corresponding author: SpencerLM1@cardiff.ac.uk

1. School of Earth and Environmental Sciences, Cardiff University, Cardiff, UK, CF14 3LD
2. Department of Earth Sciences, University of Cambridge, Cambridge, UK, CB2 3EQ
3. School of Earth, Atmosphere and Environment, Monash University, Clayton, VIC 3800, Australia
4. School of Earth Sciences, University of Bristol, Bristol, UK, BS8 1RL
5. Geological Survey of Western Australia, Department of Mines, Industry Regulation and Safety, Perth, WA 6004, Australia
6. Programa de Pós-Graduação, Faculdade de Geologia (FGEL) – TEKTOS, Rio de Janeiro State University, Rio de Janeiro, 20550-013, Brazil
7. School of Earth and Environmental Sciences, University of Portsmouth, Portsmouth, UK, PO1 3QL
8. Géosciences Montpellier, Université de Montpellier, 34090 Montpellier, France

Sanukitoids are magmas that are both compositionally and temporally transitional between sodic Archean tonalite-trondhjemite-granodiorite (TTG) suites and potassic post-Archean granites. They are generally thought to form by partial melting of mantle peridotite that was metasomatized by an incompatible element-enriched component. The identity of this metasomatic agent and its role in creating compositional diversity among sanukitoids are; however, debated. Additionally, the differentiation of sanukitoid parental magmas to form the more evolved rocks of the 'sanukitoid suite' is poorly constrained. Previous studies of titanium (Ti) stable isotopes have shown that the $\delta^{49/47}$Ti of magmas can be fractionated when they crystallize Fe-Ti oxides (rutile, Ti-magnetite, ilmenite) and silicate minerals such as amphibole, but is not fractionated during partial melting of typical mantle lithologies (Hoare et al., 2022; Millet et al., 2016). Therefore, the $\delta^{49/47}$Ti of sanukitoid magmas can provide new insights into both the nature of the metasomatic agents in their mantle source and the conditions of their differentiation.

Here we present titanium stable isotope data for Mesoarchean sanukitoids from the Pilbara Craton, Neoarchean sanukitoids from the Black Flag Group, Yilgarn Craton, and Paleoproterozoic sanukitoids from the São Francisco Craton. We compare these to 420 Ma high Ba-Sr granites from Scotland, which are considered a Phanerozoic sanukitoid analogue (Fowler and Rollinson, 2012). Primitive sanukitoids and high Ba-Sr granites have significantly heavier $\delta^{49/47}$Ti than the mantle, which may show their mantle source was metasomatized by melts derived from rutile-bearing metabasite and/or sediments. The $\delta^{49/47}$Ti then increases as the magmas become more evolved due to fractional crystallization of amphibole and Fe-Ti oxides. Distinct trends of $\delta^{49/47}$Ti vs indices of differentiation (e.g. $SiO_2$, Mg#) are seen, both within the Black Flag Group and between suites of different ages, which may reflect differences in the $H_2O$ content and/or oxidation state of the parental magmas.

## References

Hoare, L, Klaver, M, Muir, DD, Klemme, S, Barling, J, Parkinson, IJ, Lissenberg, CJ and Millet, M-A 2022, Empirical and experimental constraints on Fe-Ti oxide-melt titanium isotope fractionation factors: Geochimica et Cosmochimica Acta, v. 326, p. 235-272

Fowler, M and Rollinson, H 2012, Phanerozoic sanukitoids from Caledonian Scotland: implications for Archean subduction: Geology, v. 40.12, p. 1079-1082

Millet, M-A, Dauphas, N, Greber, ND, Burton, KW, Dale, CW, Debret, B, Macpherson, CG, Nowell, GM and Williams, HM 2016, Titanium stable isotope investigation of magmatic processes on the Earth and Moon: Earth and Planetary Science Letters, v. 449, p. 197-205

# Contrasting geochemistry of granitoid twins from southern India as a proxy for changeovers of Precambrian geodynamics

**C Sreejith**

sreejithedapal@gmail.com

Department of PG Studies & Research in Geology, MES Ponnani College (University of Calicut), Kerala-679586, India

Variations of geological processes and its products at the end of the Archean are most important in Earth history, since this marks fundamental changes in planetary dynamics. Therefore, recognizing the records of variations in magmatism at Archean–Proterozoic boundary will be much useful to understand the transition from Archean to Proterozoic. This contribution envisages secular variations in geochemistry of granitoids, evolved from a common source with progressive changes in tectonic scenarios as a proxy to establish the time-space relation between Archean and Proterozoic transition.

The lower-crustal section exposed in southernmost part of the southern Indian granulite terrain (SGT) contains granitoid complex of contrasting geochemistry (Sreejith and Ravindra Kumar, 2013). The distinct granitoid groups comprise: (i) metatonalites with characteristic Archean tonalite–trondhjemite–granodiorite (TTG) affinity; and (ii) metagranites showing geochemical patterns archetypal of the post-Archean granites. The metatonalite groups show low-K, magnesian character with moderate to high $SiO_2$ (57–76 wt.%) contents, moderate LREE (average $La_N$ = 154), low HREE (average $Yb_N$ = 6), characteristic high Sr/Y (27–934; average 331) and high $[La/Yb]_N$ (average 39) ratios, and strongly positive and/or no europium (Eu/Eu* = 0.7 to 1.67) anomalies. The geochemical features suggests that protolith for the metatonalites are derived from partial melting of a subducting slab/thickened lower continental crust composed of mafic composite source rocks (eclogitic or basaltic crust) in the Neoarchean (c. 2.73–2.89 Ga). The absence of volcanism associated with the tonalite genesis possibly indicates that the tectonic scenario was flat subduction of an old and cold lithospheric plate. On contrary, the metagranite group show ferroan nature, low to moderate degrees of rare earth elements (REE) fractionation (average $[La/Yb]_N$ = 20), high contents of Y, low Sr/Y ratios with significant negative Eu anomalies (average Eu/Eu* = 0.50). These geochemical features along with high ratios of Rb/Sr, Ba/Sr, and negative anomalies for HFS elements (e.g. Nb and Ti) characterises the metagranite rocks as crustal derivatives formed by remelting and differentiation of arc-accretionary complex crust during the Palaeoproterozoic (c. 1.8 Ga). Thus, the metagranites show orogenic signatures compatible with subduction (continental-arc rocks). This stage indicates a change of style of the down going slab from a flat to subsequently steeper subduction (arc-accretion) during the Palaeoproterozoic producing calc-alkaline high-K granites. The contrasting magmatic episodes of the SGT, therefore, provide evidence for changeover in subduction style from flat to steep during the Archean–Proterozoic transition. This assumption is favoured by the geological records all over the globe with evidence of a plagioclase-rich tonalite-trondhjemite-granodiorite (TTG) dominant crust in the Archean to more or less K-feldspar enriched granite magmatism in the Proterozoic. Thus, these kinds of significant geochemical variations in magmatic records provide opportunities to explore the timing of Archean-Proterozoic transition.

## Reference

Sreejith C and Ravindra Kumar GR 2013, Petrogenesis of high-K metagranites in the Kerala Khondalite Belt, southern India: a possible magmatic-arc link between India, Sri Lanka, and Madagascar. Journal of Geodynamics, v.63, pp. 69–82.

# Primary magnetic remanence from c. 3.47 Ga chert clasts from the Pilbara craton, Western Australia

**Y Usui[1,2*], T Shibuya[2], K Tani[3], M Saitoh[4,2], M Nishizawa[2], T Okumura[5,2], T Kashiwabara[2], T Onoue[6], H Sato[6,2]**

* corresponding author: usui-yoichi@se.kanazawa-u.ac.jp

1. School of Geoscience and Civil Engineering, College of Science and Engineering, Kanazawa University, Kakuma, Kanazawa 920-1192, Japan
2. Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 2-15 Natushima-cho, Yokosuka 237-0061, Japan
3. Department of Geology and Paleontology, National Museum of Nature and Science, 4-1-1, Amakubo, Tsukuba-shi, Ibaraki 305-0005, Japan
4. The University Museum, The University of Tokyo Geology, Isotope geochemistry, and Archaeological science Hongo 7-3-1, Tokyo 113-0033, Japan
5. Center for Advanced Marine Core Research, Kochi University, Kochi 783-8502, Japan
6. Department of Earth and Planetary Sciences, Kyushu University, Fukuoka 819-0355, Japan

The earliest geomagnetic field is important for testing the early plate tectonics, the thermal evolution of the Earth’s interior, and the Sun–Earth space environment. The Pilbara Craton in Western Australia contains one of the least metamorphosed Archean and Proterozoic rocks, and they may preserve paleomagnetic records. However, it has been debated whether the magnetic signals in those rocks are primary or secondary. Here we report the paleomagnetic conglomerate test on Paleoarchean chert clasts. The deposition age of the conglomerate is estimated to be c. 3.47 Ga. The main clast type is moderately rounded grey chert. Stepwise alternating field and thermal demagnetization were performed on chert clasts. Alternating field and thermal demagnetization results indicate that the samples contain two remanence components. One is a low blocking temperature component, and another is a higher blocking temperature component. Preliminary analyses over the high blocking temperature component does not reject the hypothesis that the component is from uniform distribution. In addition, the directions of the low unblocking temperature component were close to either the present geomagnetic field direction or previously reported Proterozoic directions, excluding the possibility of recent, local overprint such as due to lightning strikes. Together, the results suggest that these rocks preserve a magnetic signature of >3.47 Ga, which is one of the oldest records reported so far.

# Archean ultrahigh temperature event in the northwestern Superior Province, Canada

**X Wang[1,2], C Yin[1,2,*], S Lin[3], CG Couëslan[4], CO Böhm[4], J Qian[1,2], J Zhang[1,2], Y Zhang[1,2], Y Xia[1,2], W Li[1,2]**

* corresponding author, Changqing Yin: yinchq@mail.sysu.edu.cn

1. School of Earth Sciences and Engineering, Sun Yat-sen University, Guangzhou, 510275, China
2. Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, 519082, China
3. Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, ON N2L 3G1, Canada
4. Manitoba Geological Survey, 360-1395 Ellice Avenue, Winnipeg, MB R3G 3P2, Canada

Here we report a new occurrence of ultrahigh temperature (UHT) granulites with a peak assemblage of sapphirine + quartz from the Sipiwesk Lake area of the Pikwitonei Granulite Domain (PGD), a Neoarchean high-grade metamorphic domain located at the northwestern margin of the Superior Province, Canada. Petrographic examination reveals that these UHT sapphirine + quartz granulites underwent three metamorphic stages: the prograde metamorphic stage is represented by the early remnant mineral assemblage of garnet, corundum, biotite, sillimanite, and K-feldspar inclusions within sapphirine and/or orthopyroxene; the peak metamorphic stage is marked by the typical UHT mineral assemblages of sapphirine + quartz and sapphirine + orthopyroxene; the retrograde stage is characterized by the matrix minerals of biotite, cordierite and sillimanite. These mineral assemblages and their *P–T* estimates based on phase equilibria modelling constructed in NCKFMASHTO system define a clockwise *P–T* path involving an isobaric cooling process, suggesting a UHT metamorphism at the *P–T* condition of 1035–1110 ºC and 7.9–9.0 kbar. The SHRIMP U–Pb dating on the metamorphic zircons yielded a weighted mean 207Pb/206Pb age at 2681 ± 13 Ma, interpreted to be the timing of the UHT event in the PGD. Combined with *P–T* paths and available metamorphic age data, this UHT event is considered to in connection with collision during the amalgamation of the Superior Province, generating at approximately 2.68 Ga by the upwelling asthenosphere due to slab break-off during this amalgamation.

# Two types of Neoarchean metamorphism and their tectonic implication in East Hebei, North China Craton

**C Wei*, T Liu**

* corresponding author: cjwei@pku.edu.cn

School of Earth and Space Sciences, Peking University, Beijing 100871 China

The East Hebei terrane, located in the northwestern part of the Eastern Block of the North China Craton, is characterized by the dome-and-keel structure, a common feature in most Archean cratons, with supracrustal rocks of granulite-facies to greenschist-facies occurring as rafts or belts within or between the domes consisting of tonalite-trondhjemite-granodiorite (TTG) gneisses. Metasediments of granulite-facies and amphibolite-facies from the western margin of the Qian'an gneiss dome were investigated for their petrography, mineral chemistry, phase equilibria modelling using THERMOCALC and zircon dating.

The granulite-facies metasediments were revealed to show anticlockwise P–T paths involving the pre-peak pressure-increase to the UHT peak and post-peak decompression with cooling. The pre-peak pressure-increase process was constrained on the basis of the spinel and cordierite inclusions in garnet and the outwards increasing grossular (XGrs = 0.03®0.05) in the core of the atoll-like garnet to occur at 6–7 kbar at T = 1000 °C. The peak P–T conditions can be well constrained as 9–10 kbar/>1000 °C according to the maximum XGrs of 0.045–0.050 in garnet together with an average re-integrated anorthite content (XAn = 0.07) in K-feldspar. The peak temperature conditions are consistent with the ternary feldspar thermometer results mostly of 950–1020 °C for antiperthite and perthite, and in accordance with the development of oriented needle-like exsolution of Ti ± Fe oxides in garnet. The post-peak decompression with cooling can be defined, from the stability of final assemblages marked by the later growth of biotite, as 8–9 kbar / 820–880 °C.

The amphibolite-facies metasediments were recognized to show clockwise P–T paths involving the pre-peak isobaric heating to the peak and post-peak isothermal decompression. The peak P–T conditions for a garnet biotite gneiss was constrained as 780–800 °C/10–11 kbar, which corresponds to the medium-P/T type, and the post-peak decompression was defined to 5–6 kbar of the low-P/T type. However, the peak P–T conditions for Mg/Al-rich schists from the same locality show the low P/T conditions of 6–7 kbar / 690–750 °C, similar to that of the decompression stage for the biotite gneiss.

Zircon dating suggests that both the granulite-facies and amphibolite-facies metamorphism occurred at about 2.50 Ga, coeval with TTG magmatic activities. Combining the development of dome-and-keel structures, we prefer a vertical sagduction regime to interpret the tectonic evolution of the East Hebei terrane, which may be also significant for other Archean cratons.

# East Pilbara high heat flow mantle overturns as a record of lithospheric proto-plate formation

**D Wiemer[1*], DT Murphy[2], CE Schrank[2]**

* corresponding author: daniel.wiemer@uwa.edu.au

1. Centre for Exploration Targeting, School of Earth Sciences, University of Western Australia, Crawley WA 6009, Australia
2. School of Earth and Atmospheric Sciences, Queensland University of Technology, Brisbane QLD 4000, Australia

The c. 3.6–3.2 Ga East Pilbara Terrane (EPT) formed by a distinct vertically accretive geodynamic mode during predicted highest planetary heat flow, prior to the onset of Wilson-style plate tectonics at c. 3.2 Ga. Three major greenstone volcanic cycles suggest that mafic proto-crust formed by repeated mantle overturns, which in turn gave rise to the formation of continental crustal material (Wiemer et al., 2018).

However, although generally ascribed to the operation of mantle plumes, the greenstone sequences feature a broad variety of intercalated rock types and emplacement or depositional styles. Thus, source and genetic processes remain debated. Additionally, differences in the compositional range between successive mantle overturns have been attributed to secular changes in the mantle source (Smithies et al., 2007), but may equally reflect variation in lithospheric structure (e.g. Niu, 2021).

We report on the discovery of cumulate-type anorthosite, clinopyroxenite, and olivine-chromite subvolcanic bodies emplaced during the oldest recognized mantle overturn (Warrawoona Group). The finding is exceptional in that these dense ultramafic-mafic rocks have poor preservation potential during dome-keel development that affected the EPT at the end of each mantle overturn. Petrological-geochemical data suggest that these cumulates represent remnants of the magma plumbing system and played a fundamental role in the generation of diverse greenstone compositional types from a common komatiitic parent. Integration of EPT-wide geochemical data and previous petrologic and isotopic constraints indicates that each of the three major mantle overturns was characterized by: (i) a similar source, likely representing small-scale convective ambient upper mantle; and (ii) the re-occurrence of identified main greenstone compositional types, reaffirming the importance of the cumulates. Observed variations in the greenstone compositional range and concomitant decrease in added supracrustal thickness between successive mantle overturns imply a parallel evolution of the lithosphere.

To this end we explore how the range of greenstone compositions, and their temporal variations inform on the lithospheric evolution of the EPT during its development into a mature long-term stable continental lithosphere. We propose that lithospheric thickening and the coeval emergence of continental crust led to the development of a mechanically strong proto-plate that ultimately promoted Wilson-style rifting.

## References

Niu, Y, 2021, Lithosphere thickness controls the extent of mantle melting, depth of melt extraction and basalt compositions in all tectonic settings on Earth – A review and new perspectives: Earth-Science Reviews, v. 217, 10361417.

Smithies, RH, Champion, DC, Van Kranendonk, MJ, and Hickman, AH, 2007, Geochemistry of volcanic rocks of the northern Pilbara Craton, Western Australia: Geological Survey of Western Australia, Report 104, p. 1-47.

Wiemer, D, Schrank, CE, Murphy, DT, Wenham, L, and Allen, CM, 2018, Earth's oldest stable crust in the Pilbara Craton formed by cyclic gravitational overturns: Nature Geoscience, v. 11, p. 357–361.

# Phase equilibria modelling and zircon U–Pb ages of the intermediate to felsic granulites from the Jianping Complex, the North China Craton: implications for the Neoarchean tectonic regime

**N Xu[1], G Zhao [1,2*], HCG Zhang[1]**

* corresponding author: gzhao@hku.hk

1. Department of Earth Sciences, The University of Hong Kong, Pokfulam Road, Hong Kong, China
2. State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Northern Taibai Street 229, Xi'an 710069, China

The Neoarchean tectonic evolution of the North China Craton (NCC) has been a controversial issue, and bears significant implications for the geodynamic changes and cratonization of the NCC. The Jianping Complex (JPC), located at the northwestern margin of the Eastern Block in the North China Craton (NCC), is one of the high-grade complexes that subjected to granulite facies metamorphism. This study focuses on the late Neoarchean to early Paleoproterozoic metamorphic evolution of the felsic and intermediate granulites with 'red-eye socket' texture. Typical peak stage minerals including plagioclase, orthopyroxene, clinopyroxene and quartz, as well as post-peak growth of garnet, clinopyroxene, plagioclase, amphibole and quartz were identified. Phase equilibria modelling for two selected samples was performed using THERMOCALC 3.45. Based on the petrographic observations and the modelling results, anticlockwise *P–T* paths are recovered for the granulites. Peak stage metamorphic *P–T* conditions are constrained to be 940–1000 °C/8.0–8.5 kbar, and the post-peak final solidus assemblages were stable at the conditions of 880–900 °C/9.5–10.5 kbar. U–Pb dating of three granulites yields magmatic ages of approximately 2.50–2.53 Ga and metamorphic ages of approximately 2.49 Ga, suggesting the short interval between the emplacement and the granulite facies metamorphism. Anticlockwise *P–T* paths can result from intrusion and underplating of mantle-derived magmas in several potential tectonic settings, among which scenarios of magmatic arc and mantle plume are both possible for the NCC at approximately 2.5 Ga. Comprehensively considering the lithological, metamorphic, geochronological and structural characteristics of the Neoarchean basement rocks in the NCC, we favour a mantle plume model in this study.

# A Gd/Dy based barometer for the petrogenesis of tonalite-trondhjemite-granodiorite rocks

**R Yao[1*], G Zhao[1,2]**

* corresponding author: geochem@connect.hku.hk

1. Department of Earth Sciences, The University of Hong Kong, Pokfulam Road, Hong Kong, China

2. National Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Xi'an 710069, China

The Archean continental crust is mainly composed of tonalite-trondhjemite-granodiorite (TTG) rocks. Experimental studies have established that these TTG rocks can be generated by partial melting of basaltic rocks. The pressure of partial melting can be linked with tectonic setting. The mostly used approach to constraining the pressure of partial melting is thermodynamic modelling. However, source compositions and partition coefficients used for the modelling are different in different studies, which result in different pressure constraints and tectonic setting interpretations.

In this study, a melt Gd/Dy ratio-based barometer for TTG petrogenesis was established. La/Yb and Gd/Yb were not used because Gd/Dy based barometer is less affected by the uncertainty about the enrichment of the source and the temperature of partial melting. We first developed a model source composition for TTG petrogenesis by analysing experimental data about partial melting of basaltic rocks and differentiation trends about basaltic rocks. Then, thermodynamic modelling was used to obtain the phase proportion of this source composition at various pressure, temperature and water content conditions. Finally, batch partial melting model was used to calculate the Gd/Dy of melt at various conditions. Temperature dependent partition coefficients were used in the calculation. Using the newly established geobarometer, the petrogenesis pressures of most TTG rocks were constrained to be 1.1–1.3 GPa. Therefore, subduction is not needed for the formation of TTG rocks.

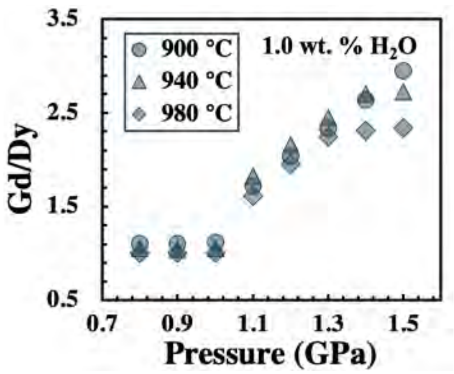



Figure 1. The correlation between the pressure of partial melting and the Gd/Dy ratio of the melt when the water content is 1.0 wt.%.

# Melt inclusions in ultra-high-temperature granulite from Chicheng, northern Trans-North China Orogen and its implication for the initiation of the modern plate tectonics

**D Zhang[1*], PJ O'Brien[2], Y Chen[3], Z Tian[4], M Xudong[5], L Zhao[3], J Guo[3]**

* corresponding author: zhangdingdingx@163.com

1. State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing, China
2. Institut für Geowissenschaften, Universität Potsdam, Karl-Liebknecht Str. 24-25, 14476 Potsdam, Germany
3. State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
4. Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China
5. Key Laboratory of Metallogeny and Mineral Assessment, Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing 100037, China

When did the modern plate tectonics begin and how it evolved is an essential scientific question of Earth Science. Ultra-high-pressure (UHP) metamorphism occurred since 600 Ma during cold subduction, and few Paleoproterozoic eclogites have been reported. The conversion of cold to hot subduction is an important indicator for the initiation of modern plate tectonics. Three narrow ultra-high-temperature (UHT) pelitic granulite interlayers outcropped within high-pressure (HP) mafic granulites in Chicheng, the Trans-North China Orogen. They have the same peak metamorphic age of c. 1910 Ma. Here we report on special melt inclusions in the Chicheng UHT pelitic granulite. Confocal Raman Imaging shows that melt inclusions are composed of kumdykolite, kokchetavite and cristobalite, and they may form at high/ultra-high pressure with eclogite facies. The peak metamorphic temperature of the Chicheng pelitic granulite is 150 °C higher than the mafic granulite. The study shows that the Paleoproterozoic geotherm of the Earth's mantle turned from hot to cold, which implies the operation of modern plate tectonics probably was initiated in c. 1910 Ma.

## References

Ferrero, S, Ziemann, MA, Angel, RJ , O'Brien, PJ, & Wunder B 2016, Kumdykolite, kokchetavite, and cristobalite crystallized in nanogranites from felsic granulites, orlica-snieznik dome (bohemian massif): no evidence for ultrahigh-pressure conditions, Contributions to Mineralogy & Petrology.

Xu, C, Kynický, J, Song, W, Tao, R, Lu, Z, Li, Y, Yang, Y, Pohaka, M, Galiova, MV, Zhang, L & Fei, Y 2018, Cold deep subduction recorded by remnants of a Paleoproterozoic carbonated slab. Nat Commun 9, 2790

# Thick Yangtze continental crust formed in the Mesoarchean

**L Zhang[1,2], S-B Zhang[1,3,4*], Z-X Li[2]**

* corresponding author: sbzhang@ustc.edu.cn

1. CAS Key Laboratory of Crust-Mantle Materials and Environments, School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China

2. Earth Dynamics Research Group, the Institute for Geoscience Research, School of Earth and Planetary Sciences, Curtin University, Perth WA 6845, Australia

3. Center of Excellence for Comparative Planetology, Chinese Academy of Sciences (CAS), Hefei 230026, China

4. Frontiers Science Center for Planetary Exploration and Emerging Technologies, University of Science and Technology of China, Hefei 230026, China

The Mesoarchean era is marked by rapid growth and compositional transition of continental crust. Most studies have shown that felsic plutons became the main component of the upper crust by around 3.0 Ga, although processes related to the generation of the felsic magma remain debated. In particular, the depth of such felsic melt generation is unclear, mainly due to the lack of pressure-sensitive minerals in felsic plutons. However, garnet, stable at great depths and relatively high temperatures, may hold such information.

In this study, Mesoarchean garnet-bearing granites in the Yangtze Craton of South China are investigated. Zircon U–Pb dating results confirm that the host rocks (slightly peraluminous potassic granites) of the garnets were crystallized at 3.0–2.9 Ga. Zircon $\varepsilon_{Hf}(t)$ values range from -7.4 to -3.7, indicating that the host rocks contain reworked old crustal materials. The garnets are pink in colour and mostly euhedral. In backscattered electron images (BSE), garnets are homogeneous without zoning, which is also confirmed by major element results, implying that they crystallized from magmas rather than from metamorphic reactions. Nonetheless, a few large garnet crystals show a core-rim structure with very thin rims, with the latter being sometimes altered by post-magmatic fluids. In addition, almandine and spessartine are the main components of the garnets, which are consistent with the typical compositions of magmatic garnets. Only quartz is found in garnet inclusions, and some garnets occur as inclusions in plagioclase, which argue against a peritectic origin. Different from the major elemental features in individual garnet grains, profiles of heavy rare earth elements (HREEs; Lu and Yb) in many grains show a systematic decrease from cores to rims, which may be caused by continuous growth of garnets. Zr/Hf ratios and Eu/Eu* values in all garnets show a positive correlation, as is observed in zircon, demonstrating that fractional crystallization of zircon and plagioclase occurred during magma evolution. Because high pressure (>0.9 GPa) is generally required to reach the stability field of garnet, the occurrence of Mesoarchean garnet-bearing granites suggests the presence of a mature thick continental crust at c. 2.9 Ga.

# The origin of Archean continental crust: insight from water contents and oxygen isotopes of tonalite–trondhjemite–granodiorite in the Eastern Block, North China Craton

**D Zhao*, M Sun, G Zhao**

* corresponding author: zhaodingyi@connect.hku.hk

Department of Earth Sciences, The University of Hong Kong, Hong Kong Island, Hong Kong

Major advancements in understanding the formation and evolution of early continental crust have been made following the study on origin of tonalite–trondhjemite–granodiorite (TTG) rocks, which dominate in Earth's earliest-formed continental crust. There is a broad consensus that Archean felsic continental crust was derived from the partial melting of mafic crust. However, controversy has long surrounded the issue of whether Archean TTG rocks were sourced from subducted oceanic slabs or oceanic plateau (overthickened crust), corresponding to plate tectonic settings (e.g. island arc) or some pre-plate tectonics (e.g. mantle plume, sagduction, etc.), respectively. In this case, water contents, oxygen isotopes and some other trace elements of the source rocks are regarded as important insights as they should be different between plate tectonic settings and other pre-plate tectonic settings (e.g. mantle plumes). Therefore, we report variations in water contents, oxygen isotopes, hafnium isotopes and trace elements of zircons, associated with whole-rock major and trace elements of the approximately 2.5 Ga Taipingzhai TTG gneisses in the Eastern Block of the North China Craton. Based on these data, we prove that oxygen and water in zircons can be used as a good proxy for primordial oxygen and water in TTG magmas. In this study, zircons from the Taipingzhai TTG gneisses show high oxygen isotopes but relatively low water content, with no or weakly negative correlation between water and oxygen isotopes, indicating that the source rocks of TTG were hybridized hydrated mafic rocks with majority of slightly hydrous oceanic plateau and minority of high-$\delta^{18}O$ supracrustal materials. The low water content is revealed by TTG gneisses in this study, in contrast to high water content of approximately 2.5 Ga TTG gneisses in the Trans-North China Orogen, and as suggested through previous studies formed in subduction zone. Such results indicate a combined two-stage mantle plume-sagduction model, in which minor TTG (mantle-like $\delta^{18}O$, low H2O) and voluminous TTG (high $\delta^{18}O$, low H2O) were formed in the Eastern Block of the North China Craton at approximately 2.7 Ga and approximately 2.5 Ga, respectively. Through our study, Earth's earliest-formed Archean continents are suggested to be most likely originated from oceanic plateaus formed by mantle plumes associated with sagduction, relative to the island arcs via oceanic subduction under a plate tectonics regime.

**Acknowledgement:** This work was financially supported by NSFC Major Project (41890831) and Hong Kong RGC grants (17307918), and HKU Internal Grants for Member of Chinese Academy of Sciences (102009906) and for Distinguished Research Achievement Award (102010100). This work is a contribution of the Joint Laboratory of Chemical Geodynamics between the University of Hong Kong and Guangzhou Institute of Geochemistry, Chinese Academy of Sciences.

# Archean geodynamics: a result of plate tectonics?

**GC Zhao[1,2*], M Sun[1], J Zhang[3], CQ Yin[3]**

* corresponding author: gzhao@hku.hk

1. Department of Earth Sciences, The University of Hong Kong, Pokfulam Road, Hong Kong, China
2. State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, No 229 North Taibai Road, Xi'an 710069, China
3. School of Earth Sciences and Engineering, Sun Yat-sen University, Guangzhou 510275, China

The geodynamic mechanism of Archean cratons is still a controversial topic in modern geology (Arndt, 2013; Condie, 2015; Bédard, 2018). At the centre of the controversy is whether or not Phanerozoic-style plate tectonics can be applied to the Archean. If not, what is the main tectonic mechanism governing crustal formation and growth during Archean time?

A number of lines of evidence seem to support Archean plate tectonics, including tonalite-trondhjemite-granodiorite (TTG) rocks dominant in Archean terrains similar to those in modern subduction zones; some Archean rocks geochemically with arc-affinities, and partial melting of mafic rocks to form TTG requiring $H_2O$, which favours subduction zones (Arndt, 2013). However, plate tectonics cannot sufficiently explain the following lithological, structural and metamorphic features that characterize Archean cratons: (1) dominant bimodal volcanic assemblages in the Archean greenstones; (2) Archean komatiites whose formation needed a melting process that occurred at 1600–1900 °C; (3) nearly coeval emplacement of TTG plutons over a whole craton within a narrow time gap; (4) mass balance problems if Archean TTG rocks were derived from the 10–30% partial melting of either eclogites or garnet amphibolites; (5) dominant domiform structures with vertical lineations; and (6) metamorphism characterized by anticlockwise *P–T* paths involving isobaric cooling following the peak metamorphism, which reflects the origin of the metamorphism related to underplating and intrusion of mantle-derived magmas. Although a continental magmatic arc model can also explain metamorphism involving anticlockwise *P–T* paths, it requires similar-aged relatively high pressure terrains with clockwise *P-T* paths to form paired metamorphic belts like those in current magmatic arcs (Brown, 2006), but such relatively high pressure rocks are absent in most Archean cratons. Considering the above lines of evidence against the Archean plate tectonics, we think that the formation and evolution of Archean continents (cratons) must have been governed by some non-plate tectonics, such as mantle plumes, heat pipes, sagduction, stagnant lids, etc, although none of these non-plate tectonic models can successfully explain all features of Archean cratons.

This research was financially supported by a NSFC project (41890831) and HKU Internal Funds (Project codes: 000250348, 102010100 and 102009906) to GC Zhao.

## References

Arndt, NT, 2013, Formation and Evolution of the Continental Crust. Geochemical Perspectives, v. 2(3), p. 405-533.

Bédard, JH, 2018, Stagnant lids and mantle overturns: Implications for Archaean tectonics, magmagenesis, crustal growth, mantle evolution, and the start of plate tectonics. Geoscience Frontiers, v. 9, p. 19-49.

Brown, B, 2006. Duality of thermal regimes is the distinctive characteristic of plate tectonics since the Neoarchean.Geology, v.34, p. 961-964.

Condie, KC, 2015, Changing tectonic settings through time: indiscriminate use of geochemical discriminant diagrams. Precambrian Research, v. 266, p. 587-591.

# Early Earth tectonic models: tests and (non-)uniqueness

**J Zuo*, AAG Webb**

* corresponding author: jwzuo2@hku.hk

Department of Earth Sciences and Laboratory of Space Research, the University of Hong Kong, Pokfulam Rd., Hong Kong Island, Hong Kong SAR, China, 999077

Whether the earliest records of Earth were formed by plate tectonic or non-plate tectonic processes remains debated. One way to explore this is to investigate the preserved early Earth records and compare them with model predictions. For this purpose, it is crucial to consider plate and non-plate tectonic possibilities for geological records of unknown or controversial origins. However, unlike the plate tectonic processes that predict well-known testable signatures, basic mechanisms and geological predictions of non-plate tectonic models are poorly understood. These knowledge gaps have resulted in improper evaluations of the viability of non-plate tectonic models.

To address these knowledge gaps, we review the kinematics of representative early tectonic models, explore their testable geological predictions, and evaluate the uniqueness of these predictions. We also list key contributions that have provided model tests and highlight predictions that remain to be tested. Models discussed here include (proto-) plate tectonics, heat-pipe tectonics characterized by rapid volcanism and downwards lithospheric advection, partial convective overturn tectonics featured by episodic volcanism and gravity-driven crustal (partial) convection, and sluggish-lid tectonics driven by vigorous mantle convection.

Many geological predictions that are commonly thought to be unique to plate tectonics are non-unique. For example, heat-pipe tectonics and partial convective overturn tectonics also predict material exchanges between the convecting mantle and surface, subduction zone-like geotherms (globally and locally, respectively), as well as volcanic arc-like detrital zircon ages patterns in some basins. Therefore, preservation of such geological records cannot be used to uniquely identify operation of plate tectonics. In contrast, some geology is limited to certain models. Examples include plate drifting that is only compatible with sluggish-lid tectonics and plate tectonics; and thinning of lithosphere over time that is exclusive to heat-pipe tectonics. Our review shows that: (1) plate tectonics predicts diverse crustal settings and is nearly impossible to exclude as a viable early Earth setting; and (2) although non-plate tectonic models predict relatively limited crust-mantle configurations, they remain viable models for Hadean to early Archean time. Additional model tests involving (a) novel analytical methods, (b) new early materials, and/or (c) untested geological predictions are required to narrow the viable range of early Earth tectonic models.

# Theme 4
# The role of Archean lithosphere in the evolution of younger terranes

Invited Speaker
**Dr João Motta**
*University of Campinas, Brazil*
*School of Earth, Atmosphere and Environment, Monash University, Australia*

Keynote Speaker
**Associate Professor Kuo-Lung Wang**
*Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan*
*Department of Geosciences, National Taiwan University in Taipei, Taiwan*

# The extent of Archean lithosphere on Proterozoic terranes from evidence by multiple geoscientific proxies

**JG Motta[1,2*], CR de Souza Filho[1], PG Betts[3]**

* corresponding author: jgmotta@gmail.com

1. Institute of Geosciences, University of Campinas, Campinas, São Paulo, Brazil.
2. Eurasian Resources Group, Dubai, United Arab Emirates.
3. School of Earth, Atmosphere and Environment, Monash University, Clayton Campus, Victoria, Australia.

The construction and preservation of the lithosphere throughout the Archean and Proterozoic eons occurred through geological processes that often obliterate evidence sets for its affiliation and extent, making the record difficult to unfold. Complimentary evidence must be acquired across different spatial and temporal scales from field observations, geochemistry including absolute dating and isotopic studies, and geophysical methods covering different physical properties and depths. We present an overview of recent, large-scale studies employing multiple geoscientific proxies to reveal the evolution of exposed Archean lithosphere and Proterozoic or younger crustal sections related to it.

Multi-proxy studies carried out on Archean-Proterozoic lithosphere identify a recurrent disconnect between the actual exposure of Archean-Proterozoic cratonic crust and the extent of their corresponding lithospheric keels. The combined use of seismology, geochemistry and seismic, magnetotelluric and potential field data shows that Archean substrate often has an extended footprint below Proterozoic to younger successions (e.g. Kalahari and Kaapvaal in Zimbabwe, Amazonian, Gawler, Karelian and São Francisco cratons). In contrast, some cratonic sections have in-depth footprints in seismology and potential field data that are far smaller than the exposed cratonic core crust (e.g. Angola, Tanzania, and Norrbotten cratons). The case for absence of an anticipated Archean framework in the intervening region to the Proterozoic North-, West- and South Australia cratons has been brought up via combined study of the U–Pb–O–Hf isotope systems on zircon and seismic studies. A comprehensive study of the chemical content on ferromagnesian silicates and base metal sulphides – major elements, trace and base metals, Re–Os isotope chemistry – on lithospheric mantle xenoliths hosted on Quaternary volcanics in Central Mexico indicates the presence of a cryptic sublithospheric continental mantle root of Archean-Proterozoic age confined by Paleozoic-Mesozoic sutures. Furthermore, cases exist of key mineral deposit types and their relative abundance being observably limited to either pristine or recycled Archean lithosphere.

The persistence and evolution of Archean lithosphere can be traced through spatial and temporal scales using a range of geoscientific tools to identify the involved geological processes. The presence, absence and recycling of Archean cratonic lithosphere seems to have an important effect on the lithosphere's stability or susceptibility to transformation in subsequent stages, imprinting certain chemical and mechanical characteristics either on their crustal volumes or lithospheric roots. However, no clear picture exists over either the processes that promote cratonic lithospheric growth nor their demise in both the past and present. Viewed holistically, it becomes clear that Archean lithospheric somehow persists in the record although a definitive spatial-temporal blueprint is yet to be defined.

# Archean lithospheric mantle beneath Proterozoic Central Asia Orogenic Belt

**K-L Wang[1,2*], SY O'Reilly[3], VP Kovach[4], S Dril[5], MI Kuzmin[5], V Yarmolyuk[6], V Prikhodko[7], Y Iizuka[1], WL Griffin[3], NJ Pearson[3]**

* corresponding author: kwang@earth.sinica.edu.tw

1. Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan 11529
2. Department of Geosciences, National Taiwan University, Taipei, Taiwan 106
3. GEMOC/CCFS Key Centre, School of Natural Sciences, Macquarie University, Sydney, NSW 2109, Australia
4. Inst. Precambrian Geology & Geochronology, Russian Academy of Sciences, St. Petersburg 199034, Russia
5. Institute of Geochemistry, Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia
6. IGEM, Russian Academy of Sciences, Moscow, Russia
7. Inst. of Tectonics and Geophysics, Far Eastern Branch of Russian Academy of Sciences, Khabarovsk, Russia

The processes causing the vertical accretion of juvenile material from the mantle are thought to have impacted the subcontinental lithospheric mantle (SCLM) beneath the Central Asia Orogenic Belt (CAOB). Cenozoic alkali basalts occur throughout Central and East Asia encompassing southern Siberia, central and southern Mongolia, northeast China and the Russian Far East. Some basalts carry fragments of mantle rocks. These basalts provide direct evidence about the nature and composition of the deep lithosphere and contain a record of mantle processes. In this study, we summarize in situ Os model ages on sulfides in peridotitic xenoliths from off-cratonic settings (in the basalts from Tariat [1.5 Ma], Mongolia; Vitim [14 and 0.65 Ma], Khamar Daban Range [KDR; 17 Ma] and Sviyaginsky volcano [12 Ma], Russia) of the CAOB to examine SCLM formation. Mantle xenoliths collected from these volcanic fields are predominantly spinel lherzolites composed of olivines, orthopyroxenes, clinopyroxenes and spinels, with garnet- and spinel-garnet lherzolites only found in Vitim. Geothermal evidence suggests these lherzolites represent residual SCLM, some of which is quite refractoryand may be ancient. Most of their Os $T_{MA}$ from the least-disturbed sulfides ($^{187}Re/^{188}Os<0.07$), and $T_{RD}$ from higher Re/Os sulfides without later introduction/loss of Os, yield model ages ranging from 0.3 to 3.0 Ga, with peaks around 1.7–1.4, 1.2–0.9 and 0.7–0.5 Ga the CAOB region formed at least by the Proterozoic time, and that some domains are Archean. Younger sulfide Os ages (1.2–0.9 and 0.7–0.5 Ga) may mark the commencement of the Central Asia Orogeny since the Neoproterozoic and involvement of the mantle. These sulfide Os ages, recording formation of the SCLM and subsequent metasomatism by juvenile crustal-growth events, are consistent with the thermotectonic events recorded in the overlying crust of the ancient microcontinents, where the sampled volcanic fields are located. All geochemical characteristics of the Tariat, Vitim, Khamar Daban Range and Sviyaginsky peridotites reveal that ancient, refractory Archean–Proterozoic lithospheric mantle is embedded in the younger, fertile post-Archean lithospheric mantle beneath the CAOB. The ancient Archean–Proterozoic mantle domain has survived, but may have been subjected to metasomatic re-enrichment during Central Asia Orogeny since the Neoproterozoic and the Cenozoic extension with intraplate volcanism in this region. Comparing the lithospheric mantle domains from the above regions as revealed by Os model ages, with ancient microcontinents at least Mesoproterozoic in age and predating formation of the CAOB, significantly diminishes the volume of new juvenile crust generated during the orogeny. Although significant mantle involvement during evolution of the CAOB has been proposed, the extent of ancient continental material may be larger than previously estimated.

# Widespread Archean lithosphere continental foundations – hidden from view?

**GC Begg[1,2], WL Griffin[2], SY O'Reilly[2], L Natapov[2]**

* corresponding author: graham@mineralstargeting.com

1. Minerals Targeting International, West Perth, WA 6005, Australia
2. Australian Research Council Centre of Excellence for Core to Crust Fluid Systems (CCFS) and GEMOC, Macquarie University, NSW, Australia

Multi-disciplinary (geological, petrographic, geochemical, geophysical, geochronological and isotopic) study of both sub-continental lithospheric mantle (SCLM) and overlying crust allows mapping of the architecture and tectonothermal evolution of the entire 60–280 km-thick continental lithosphere. Our 20-year study finds at least 59%, possibly much more of the SCLM to be Archean origin. Outside the cratons this ancient SCLM is subdivided into microcontinental blocks generally bounded by steep trans-lithospheric faults (TLFs). The best preserved, oldest, and generally thickest, SCLM is the most depleted (Mg-rich, Fe-poor, low Al, Ca); the dominant process affecting the SCLM over time is refertilization (including addition of Fe, Ca, Al; Griffin et al., 2009) resulting from the interaction with magmas derived from the convecting mantle, dominantly in magmatic arc settings. Refertilization and associated thinning of the SCLM results in lower seismic velocity, increased density, and lower relative elastic thickness. Isotopic studies of the crust indicate that approximately 60% of today's continental crust is material extracted from the convecting mantle in the Archean (e.g. Belousova et al., 2010). Relatively little of this may still exist as Archean crust – much of it has been repeatedly reworked into successively younger rocks, resulting in a gradual dilution of the old crustal component, or survives at mid- or lower-crust depths. Survival of this large Archean-derived crustal component is consistent with the existence of the ancient SCLM microcontinental blocks that can support and protect it though the eons. Post-Archean SCLM is rarely preserved through an orogenic cycle involving collision of sizable continental blocks. However, the crust may preserve significant volumes of post-Archean juvenile material within specific terranes that are generally smaller than microcontinents. This mapping offers a revolutionary understanding of continental structure and evolution. However, it also requires that large-scale projects in geoscience are strategic and integrative across subdiscipline boundaries and consider all scales from nano to global. Issues that need to be adequately addressed include:

- presence of widespread older deep basement in most arc terranes
- Re-Os model ages for mantle domains that are much older than the overlying crust
- contrasted growth of continents by addition of long-lived volumes of lithosphere hundreds of km across (and deep) rather than accretion of narrow ribbons of juvenile island-arc terranes
- repeated partitioning of deformation such that the margins of such swathes are most intensely deformed and commonly cut by late-tectonic TLFs
- domains of SCLM with anomalously high shear-wave velocity in post-Archean belts
- geodynamic influences on the isotopic characteristics of zircons
- the influence of paleotopography on detrital zircon sources
- the inferred width and lifespan of oceanic plates

## References

Belousova, EA, Kostitsyn, YA, Griffin, WL, Begg, GC, O'Reilly, SY and Pearson, NJ 2010, Lithos 119, p. 457-466.

Griffin, WL, O'Reilly, SY, Afonso, JC and Begg, GC 2009, Journal of Petrology, 50, no.7, p. 1185-1204.

# Widespread Archean lithosphere: implications from a global mantle xenolith Re–Os isotopic database

**J-X Huang[1,2], GC Begg[1,2*], WL Griffin[2], SY O'Reilly[2]**

* corresponding author: graham@mineralstargeting.com

1. Minerals Targeting International PL, West Perth, WA 6005, Australia

2. ARC Centre of Excellence for Core to Crust Fluid Systems, Macquarie University, North Ryde, NSW 2109, Australia

Direct age information on the lithospheric mantle is limited due to difficulty accessing representative samples worldwide and the lack of a suitable dating method. However, the age is a critical element to understanding the formation and evolution of the lithospheric mantle, which further affects our concepts of crustal formation and modification. Grappling with this issue is essential to understand the evolution of continents and their interaction with global geodynamic processes. The Re–Os isotopic system has been proven to be effective in dating mantle peridotites. Combined with detailed petrography and geochemical data, the Os model ages can be interpreted to represent the timing of main melting events, mantle metasomatism or an invalid age because of the mixture of isotopic signals from different events.

We have compiled a comprehensive global Re–Os isotopic database of mantle samples together with other available information to show the valid age information, especially the melt depletion age, on the formation of lithospheric mantle. The data include the in situ analyses of sulphides and alloys by laser ablation multi collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) and the solution analyses of mineral separates and whole rocks measured by multi collector inductively coupled plasma mass spectrometry (MC-ICPMS). We reprocessed the data using consistent parameters of different geological reservoirs to calculate both $T_{RD}$ and $T_{MA}$ ages. Based on 187Re/188Os we evaluated the validity of each model age from in situ analyses. It is rated as: very good, <0.07; good, 0.07–0.12; moderate, 0.12–0.26; poor, >0.26. Both in situ and solution data are judged to have acceptable validity if either 4.0> $T_{MA}$ >=2.8 and $T_{RD}$ >=2.5, or 2.8> $T_{MA}$ >=2.5 and $T_{RD}$ >=1.6, or 2.5> $T_{MA}$ >=1.6 and $T_{RD}$ >=1.0, or 1.6> $T_{MA}$ >=1.0 and $T_{RD}$ >=0.541. $T_{RD}$ provides the minimum age estimate. $T_{MA}$ is presented in this abstract as the majority of the samples do have a certain amount of Re.

$T_{MA}$ between 4.0 and 2.5 Ga with very good to good (in situ) and/or acceptable (solution) validlity are observed in areas of known Archean lithosphere as well as many areas with post-Archean upper crust, most of which have previously been assumed to represent post-Archean lithospheric growth. These latter include: a location 700 km northwest of the Slave Craton, southern USA (Arkansas), central Mexico, southeastern Spain, Cape Verde islands offshore of western Africa, southern Ethiopia, southern Patagonia, Svalbard (Arctic shelf), Central Asian Orogenic Belt (southern Siberia, Mongolia and northeastern China), Tibet, southeastern China, Penghu Islands (Taiwan Strait), southeastern Australia (Mt Gambier), and South Island of New Zealand.

These findings indicate that Archean lithospheric mantle is far more widespread than generally considered and that the upper crust cannot be assumed to be representative of the entire lithosphere. Contrary to models implicitly equating juvenile addition to the crust with an increasing global ratio of continental to oceanic lithosphere with time, these results suggest that tectonothermal reworking of Archean lithosphere is a major factor in the evolution of continents and that net continental growth cannot be assumed.

# Archean to Paleoproterozoic crustal evolution in the Sassandra-Cavally domain (Côte d'Ivoire, West Africa): insights from Hf and U–Pb zircon analyses

**AY Koffi[1*], N Thébaud[2], AN Kouamelan[1], L Baratoux[3,1], O Bruguier[4], O Vanderhaeghe[3], P Pitra[5,6], AIS Kemp[2], N Evans[7]**

* corresponding author: yaoaugustinkoffi@yahoo.fr

1. UFHB Abidjan-Cocody. UFR STRM. 22 BP 582 Abidjan 22. Côte d'Ivoire
2. University Western Australia. School of Earth Sciences, Centre for Exploration Targeting, Crawley, WA6009 Australia
3. GET, Université de Toulouse, CNRS, IRD, UPS, Toulouse, France
4. Géosciences Montpellier, Université Montpellier, CNRS. CC 060, Montpellier Cedex 5, France
5. Université de Rennes, CNRS, Géosciences Rennes, UMR 6118, F-35000 Rennes, France
6. Czech Geological Survey, Klárov 3, CZ-118 21 Praha 1, Czech Republic
7. John DeLaeter Centre, Curtin University, Perth, WA 6845, Australia

Processes leading to the continental crust extraction and its stabilization since the Hadean remain a topic of significant debate (e.g. Spencer et al., 2017). Technical advances in U–Pb and Lu–Hf zircons analysis applied to Precambrian crust have proven to be powerful in constraining the growth and recycling of continental crust (e.g. Petersson et al., 2016). Crustal evolution in the Precambrian south West African Craton is dominated by a significant input of juvenile material into the crust at c. 2.1 Ga. However, it remains unclear how much of the Paleoproterozoic continental mass was influenced by the presence of pre-existing Archean crustal domains. The Sassandra-Cavally (SASCA, Côte d'Ivoire) domain is strategically located east of the Sassandra shear zone at the transition of the Paleoproterozoic and Archean terranes of the Leo-Man Shield. Combined U–Pb and Lu–Hf isotopic analyses by LA-(MC-)ICP-MS were acquired on zircon grains extracted from migmatitic gneisses, metasedimentary rocks and a granitic intrusion. The migmatitic gneisses yield Archean ages between c. 3330 and 2810 Ma with εHf ranging from -9.4 to +3.3 and a metamorphic age at 2076 ± 6 Ma. They are interpreted as orthogneisses extracted from the mantle during the Paleoarchean and reworked substantially in the Mesoarchean. This early period is followed by peaks of zircon dates highlighting crustal extraction during the Eoeburnean (c. 2250 to 2150 Ma) and Eburnean orogenies (c. 2140 to 2100 Ma) with εHf ranging from +0.0 to +5.5, indicating derivation from largely juvenile Paleoproterozoic source rocks. Yet some magmatic sample dated within uncertainty of the metamorphic age at 2084 ± 6 Ma returned two distinct εHf clusters between -4.9 and -8.5, and between +2.2 and +6.5. This result further highlights the local contribution of Archean crustal domains in the foundation of the West African Craton in the Paleoproterozoic (e.g. Petersson et al., 2016).

## References

Petersson, A, Scherstén, A, Kemp, AIS, Kristinsdóttir, B, Kalvig, P, Anum, S 2016, Zircon U–Pb–Hf evidence for subduction related crustal growth and reworking of Archaean crust within the Palaeoproterozoic Birimian terrane, West African Craton, SE Ghana. *Precambrian Research, 275*, p. 286–309.

Spencer, CJ, Roberts, NMW, & Santosh, M 2017, Growth, destruction, and preservation of Earth's continental crust. *Earth-Science Reviews*, *172*, p. 87-106.

# Precambrian dyke swarms of Singhbhum Craton record recycled crustal components in the mantle source

**MPM Prasanth[1*], K-N Pang[1], KR Hari[2], BB Sahoo[2], A Ravindran[3], Y Iizuka[1]**

* corresponding author: manu@earth.sinica.edu.tw

1. Institute of Earth Sciences, Academia Sinica, Taipei 11529, Taiwan
2. School of Studies in Geology and Water Resource Management, Pt. Ravishankar Shukla University, India
3. Institut für Geologie und Mineralogie, Universität zu Köln, 50674 Köln

The Singhbhum Craton records multiple stages of Precambrian dyke swarm emplacements and several petrogenetic models have been proposed for their formation. We document elemental and Sr–Nd isotopic data for three major dyke swarms in the southern part of the craton, including the c. 2.7 Ga Ghatgaon dyke swarm, the Early Proterozoic Keonjhar dyke swarm and the c. 1.76 Ga Pipilia dyke swarm. The dykes exhibit basalt and basaltic andesite with minor andesite compositions and also show trace element signatures typical of continental crustal rocks. Substantial variations can be observed in the age-corrected Nd isotopic data for Ghatgaon (εNdt = -4.8 to +4.6), Keonjhar (εNdt = -11.9 to +3.8), and Pipilia (a single sample with εNdt = 8.85) samples. The ambient mantle-like melting regime is inferred by the lack of magma compositions that could indicate elevated mantle potential temperature. The rare earth elements (REE) systematics of the samples indicate that melting regimes can be constrained between spinel-stable depths and the spinel-garnet transition zone. Ubiquitous continental crust-like trace element and isotopic signatures are best explained by a mantle source with recycled crustal components, probably in the form of pyroxenites. The new Nd isotopic data argue against any simple secular evolution of the mantle source invoked in previous studies. Our data point out that the crustal recycling in the Singhbhum Craton was likely an episodic phenomenon rather than a discrete, single-stage process since the Archean. Geochemical modelling suggests that trace element variations of Ghatgaon, Keonjhar and Pipilia dyke swarms are best explained by a sub-lithospheric mantle source with recycled crustal components (10% or less).

# Archean Nd–Hf isotopic fingerprints in the Rhyacian domains of the southeastern Guiana Shield, northern Brazil

**JM Milhomem Neto[1,2*], JM Lafon[1,2], JAE Pinto[1,2]**

* corresponding author: milhomem@ufpa.br

1. Programa de Pós-Graduação em Geologia e Geoquímica-PPGG, Instituto de Geociências-IG, Universidade Federal do Pará-UFPA, 66075-110, Belém, Pará, Brazil
2. Laboratório de Geologia Isotópica-Pará-Iso, IG-UFPA, 66075-110, Belém, Pará, Brazil

The southeastern Guiana Shield (SGS), northern Amazonian Craton, is part of a large Paleoproterozoic orogenic domain that extends over several countries (Venezuela, Guyana, Suriname, French Guiana, and Brazil). It was built up during the Transamazonian orogenic cycle (2.26–1.95 Ga). It includes extensive segments of Rhyacian juvenile crust and two smaller reworked Archean terranes. The Paleoproterozoic crust consists of granulitic-migmatitic-gneissic complexes, greenstone sequences and granitoids (tonalite–trondhjemite–granodiorite type [TTG] and granitic magmatism) formed during successive stages of subduction of oceanic lithosphere in magmatic arc environments (c. 2.2–2.12 Ga), followed by a collisional stage of tectonic accretion of the magmatic arcs (c. 2.10–2.06 Ga). The available radiometric and isotopic dataset has confirmed the juvenile character of much of this Rhyacian orogenic belt. In the Brazilian territory, the SGS encompasses three tectonic domains: the Archean Amapá Block and the Rhyacian Lourenço and Carecuru domains. The Amapá Block is a continental landmass composed of a Meso–Neoarchean basement (3.19–2.59 Ga), intensely reworked during the Transamazonian orogeny, and a Paleoproterozoic orogenic association of supracrustal sequences and Rhyacian granitoids. To the north and south of the Archean block, the Lourenço and Carecuru domains are Rhyacian terranes where the main magmatic and tectonic-metamorphic episodes (2.26–2.05 Ga) are a result of the geological evolution of the whole Transamazonian belt in the SGS. The influence of the Archean continental crust in these two Rhyacian domains has been investigated using whole-rock Sm–Nd and zircon U–Pb–Hf geochronology of Rhyacian granitoids. For the granitoids of the Carecuru Domain, the Nd–Hf signatures are slightly subchondritic to suprachondritic ($-6.6 < \varepsilon_{Nd(2.2-2.1Ga)} < +1.6$; $-1.0 < \varepsilon_{Hf(2.14\ Ga)} < +3.9$) with Siderian-Neoarchean model ages that confirm they formed in a continental magmatic arc with both Archean reworked and juvenile components in their source. For the central-south portion of the Lourenço Domain at the border with the Amapá Block, assimilation of Archean crust of different ages and proportions in a continental magmatic arc environment accounts for the subchondritic Nd–Hf isotopic signatures ($-6.7 < \varepsilon_{Nd(2.2-2.08Ga)} < -1.51$; $-15.6 < \varepsilon_{Hf(2.2-2.08\ Ga)} < -0.2$) and Meso-Neoarchean model ages of the Rhyacian granitoids. This strong Archean Nd–Hf signature imprinted in all the Rhyacian granitoids, including the less evolved and older ones, suggests a contribution of a metasomatized subcontinental lithospheric mantle, in addition to the Archean crustal assimilation. In the most distant sector of the Lourenço Domain from the Amapá Block, more than 100 km to the north at the French Guiana-Brazil border, the $\varepsilon_{Nd-Hf}$ values are both positive and negative ($-3.6 < \varepsilon_{Nd(2.14-2.09Ga)} < +1.8$; $-2.6 < \varepsilon_{Hf(2.14-2.09\ Ga)} < +2.8$) and the model ages range from the Rhyacian to the Neoarchean. These isotopic signatures indicate lower participation of Archean crustal material, either as restricted continental fragments and/or by incorporation of continental sediments into island arc environments, as has been suggested for some Birimian terranes of the West African Craton in Ghana.

# Cryptic legacy of Archean lithosphere in the Gawler Craton

**AJ Reid[1,2*], GC Begg[3,4]**

* corresponding author: augiteridgeservices@gmail.com

1. Augite Ridge Services, Bridgewater, SA 5155, Australia
2. School of Physical Sciences, University of Adelaide, SA 5005, Australia
3. Minerals Targeting International, Perth, WA 6005, Australia
4. Australian Research Council Centre of Excellence for Core to Crust Fluid Systems (CCFS) and GEMOC, Macquarie University, NSW, Australia

The Gawler Craton hosts one of the world's great iron oxide-copper-gold districts and despite evidence for widespread Archean basement, almost all of the rocks exposed at or near the surface are Proterozoic in age. In particular, the Paleoproterozoic to Mesoproterozoic evolution of the region is increasingly well documented, including major tectonometamorphic and magmatic events that occurred at c. 2440 to 2420 Ma, c. 1730 to 1690 Ma and c. 1630 to 1590 Ma along with significant copper-gold mineralization associated with the c. 1590 Ma events.

However, the possible legacy effects of the widespread Archean basement on the subsequent tectonic/magmatic/thermal systems are perhaps less well considered. We consider several examples across the region, where Archean rocks and indeed possible Archean structures have influenced Proterozoic processes.

In the region with largest exposure of basement rocks, the Eyre Peninsula, Archean rocks have been confirmed in the c. 3150 Ma Cooyerdoo Granite and the c. 2860 Ma Coolanie Gneiss. Using these known exposures and integrating geophysical, inherited zircon and isotopic evidence, studies have shown that a Mesoarchean basement is likely to underlie much of southern Gawler Craton, despite the surface geology being dominated by Paleo- to Mesoproterozoic rock packages.

Key fault zones in the Gawler Craton may also be associated with important boundaries established during the Archean. Faults such as the Elizabeth Creek fault separate late Archean and earliest Paleoproterozoic rock packages, have significant Moho topography and magnetotelluric conductivity anomalies and appear to influence the location of Mesoproterozoic magmatism and mineralization.

Finally, we consider the case of the c. 1620 Ma St Peter Suite, a bimodal igneous complex in the southwest of the region. Based on the (modestly) 'juvenile' Nd isotopic composition, some studies suggest the St Peter Suite is related to a subduction zone process, either continental or even ocean arc setting. However, given the evidence for Archean basement in surrounding areas, and considering c. 1.7 Ga inherited zircon and the enriched nature of the mafic geochemistry, it is equally plausible that it is another example of a typical Australian Proterozoic granite suite that developed as a result of possible back-arc extension of the underlying Archean lithosphere.

In these examples we suggest the Gawler Craton is likely underlain by a lower crust and lithosphere with minimum age of c. 3.1 to 2.8 Ga, which has been rifted, dissected and reworked by intensive Proterozoic activity. Enrichment in heat producing elements that characterizes the eastern Gawler Craton may be indicating something fundamental about the geochemical make up of this 'original' Archean crust, or alternatively, the extent and style of Proterozoic reworking.

The recognition of an Archean lithospheric root in the Gawler Craton conforms to models that suggest many terranes globally are underlain by Archean lithosphere, with variable degrees of reworking. The key implication is that major lithospheric boundaries internal to Proterozoic terranes can be zones of preexisting weakness, being susceptible to reactivation including enhanced magma and fluid flow, which can ultimately be expressed in the upper crust as hydrothermal (or magmatic) mineral deposits.

# Crustal growth and crustal architecture in the southern West African Craton

**N Thébaud[1*], LA Parra-Avilla[1],T Kemp[1], A Eglinger[2], A Koffi[3], M Jessell[1]**

* corresponding author: nicolas.thebaud@uwa.edu.au

1. University Western Australia, School of Earth Sciences, Centre of Exploration Targeting, 35 Stirling Highway, Crawley, Western Australia
2. GeoRessources, Université de Lorraine – CNRS, F-54000 Nancy, France
3. University of Felix Houphouët-Boigny Abidjan, 22 BP 582 Abidjan 22, Ivory Coast

A large number of studies have demonstrated that the combination of in situ U–Pb and Lu–Hf isotope analyses carried out on single zircon grains provides a powerful tool to further understand crust formation and reworking processes through time (e.g. Eglinger et al., 2017). When combined with lithogeochemical data, such analysis may help to fingerprint the different magma sources at play through the crust formation processes and provide an insight into the Precambrian lithospheric architecture (Mole et al., 2015). To further the understanding of the southern West African Craton (SWAC) that includes Paleoproterozoic and Archean domains, zircon grains from felsic intrusions were analyzed for Hf–isotopes over the SWAC. The results of the study suggest the presence of ancient meso- to paleo- Archean lithosphere in Guinea, Liberia and Sierra Leone which appears to have been significantly reworked during the Paleoproterozoic (Eglinger et al., 2017) and also the presence of broadly juvenile Proterozoic domains with localized evidence of Archean crustal reworking (Parra-Avila et al., 2017). Temporally-constrained Lu–Hf analyses enable imaging of the SWAC magmatic evolution in space and time, highlighting a two-step magmatic evolution. From c. 2300 Ma to 2100 Ma, the plutonic activity is associated with input of juvenile material following a north-south corridor running from Burkina Faso to Ghana and further west in the Kédougou-Kéniaba Inlier. Elsewhere in the SWAC, the magmatic signature suggests the reworking of older crustal material as in western Cote D'Ivoire, western Mali but also Ghana and Burkina Faso in the East. (Petersson et al., 2016). The period from c. 2110 Ma to 2080 Ma, which marks the peak of the Eburnean orogeny, is associated with a decrease of juvenile input and progressive reworking of the Eburnean. This second period is also associated with a remarkable shift of magmatism towards the western part of the SWAC that significantly reworks older Archean crustal domains located in southern Guinea (Eglinger et al., 2017). Collectively, the data acquired offer a new perspective on the Archean crustal evolution and associated crustal architecture that punctuated the geodynamic evolution of the SWAC.

## References

Eglinger A, Thébaud N, Zeh A, Davis J, Miller J, Parra-Avila LA, Loucks R, McCuiag C, Belousova E 2017, Precambrian Research 292, p. 258-289

Parra-Avila LA, Belousov E, Fiorentini M, Eglinger A, Blocke S, Miller J 2017, Precambrian Research 306 (2018) p. 174–188

Petersson, A, Scherstén, A, Kemp, AIS, Kristinsdóttir, B, Kalvig, P, Anum, S 2016, Precambrian Research, 275, p. 286–309.

Mole DR, Fiorentini ML, Cassidy KF, Kirkland CL, Thébaud N, McCuaig TC, Doublier MP, Duuring P, Romano SS, Maas R, Belousova EA, Barnes SJ and Miller J 2015, Geological Society, London, Special Publications, 393

# Paleoproterozoic intraplate rifting in the North China Craton: Constraints from geochemistry, zircon Hf–O isotopes of the c. 2.1 Ga A-type granite in the Jiaobei Terrane

**TP Zhao[1*], YY Zhou[2]**

* corresponding author: tpzhao@gig.ac.cn

1. Key Laboratory of Mineralogy and Metallogeny, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China
2. State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

Although the 2.2–2.1 Ga magmatism was extremely active globally, the crust evolutionary scenarios and geodynamic driving mechanisms during this stage are still lacking comprehensive understanding. The present study verifies that the 2.2–2.1 Ga A-type granites are formed in the eastern North China Craton (NCC) and could provide further constraints for revealing the paleoproterozoic tectonic evolutional processes. This study presents geochemistry, U–Pb dating and zircon Hf–O isotopes of the c. 2.1 Ga Atype granites distributed in the Dongbaishi and Gujiacun areas in the Jiaobei Terrane, eastern NCC. The two plutons were metamorphosed at 1.9–1.8 Ga and preserved inherited ages of c. 2.7 Ga. Dongbaishi pluton consists of quartz syenite, monzogranite and syenogranite, and Gujiacun pluton is composed of granodiorite and monzogranite, both of which show metaluminous and calc-alkaline characteristics. They display decreasing $Fe_2O_3^T$, $TiO_2$, $Al_2O_3$, CaO, $Na_2O$ and $P_2O_5$, but increasing $K_2O$, with increasing $SiO_2$ contents, indicating that Fe–Ti oxide, plagioclase and apatite were fractionated during magmatic evolution, which is confirmed by the negative Eu, Sr, P, and Ti anomalies. The high Ga/Al ratios, Zr+Nb+Y+Ce contents and Zr saturation temperatures (850 °C average) of these granites are consistent with the features of A-type granite. Dongbaishi quartz syenite yields zircon $\varepsilon_{Hf}(t)$ values of 0.98 to 6.52 with two-stage Hf model ages ($T_{DM2}$(Hf)) of 2.29–2.65 Ga, along with no obvious $K_2O$ vs MgO correlations, indicating the contribution of mantle-derived materials with potassium-rich minerals in the source. Dongbaishi monzogranite and syenogranite and Gujiacun monzogranite have zircon $\varepsilon_{Hf}(t)$ values of -3.76 to 4.14 with two-stage Hf model ages ($T_{DM2}$(Hf)) of 2.93–2.51Ga. The two plutons have high $K_2O/Na_2O$, low MgO contents (Mg# = 24–33), low CaO/(FeOt + MgO) ratio, low to moderate $Al_2O_3/TiO_2$, Rb/Sr and Rb/Ba ratios, commonly implying metasediments-dominated sources. In situ zircon $\delta^{18}O$ values (5.48–12.2‰, 9.15‰ average) of Dongbaishi and Gujiacun plutons (6.05–7.32‰, 6.77‰ average) are higher than that of the mantle, further confirming the contribution of sedimental materials in the source. Combining the high zircon $\delta^{18}O$ signature, A-type geochemical features and those published for 2.2–2.1 Ga granites and gabbros in eastern NCC, we suggest a thermal anomaly linked to a rift setting could account for the middle to shallower crustal melting. The rifting activity in the NCC during 2.2–2.1 Ga may coincide with the global lithospheric break-up of the supercontinent and the subsequent tectonic transition could correspond to development of the global orogenesis at 2.1–1.8 Ga.

# Theme 5

# Cratons and craton margins: structure, composition and tectonic history

Invited Speaker

**Assistant Professor Ming Tang**

*School of Earth and Space Sciences, Peking University*

Keynote Speaker

**Professor Irina Artemieva**

*SinoProbe National Lab and China University of Geosciences, Wuhan, China*

# Endogenic oxidation and the formation of Archean tonalite–trondhjemite–granodiorite crust

**M Tang[1*], H Chen[1], S Song[1], G Sun[2], C Wang[3]**

* corresponding author: mingtang@pku.edu.cn

1. Key Laboratory of Orogenic Belt and Crustal Evolution, MOE; School of Earth and Space Sciences, Peking University, Beijing 100871, China.

2. Frontiers Science Centre for Deep Ocean Multispheres and Earth System, Key Lab of Submarine Geosciences and Prospecting Techniques, MOE and College of Marine Geosciences, Ocean University of China, Qingdao 266100, China.

3. Department of Earth Sciences, University of Hong Kong, Pokfulam Road, Hong Kong, China.

By the end of the Archean, Earth's surface appears to have formed voluminous felsic crust. However, the nature of this ancient crust remains enigmatic because much of it has been strongly altered and lost its geologic context over Earth's history. Here we use europium systematics recorded by zircon to constrain the minimum melt oxidation state of the Neoarchean granitic rocks. We find that those samples formed at medium to high pressures are oxidized, perhaps as oxidized as those related with porphyry copper deposits in the Phanerozoic. For these oxidized samples, our crystallization modeling places a lower bound on the melt oxygen fugacity at 0–2 log units above the Ni–NiO buffer. The oxidized signatures of these granitic melts are best explained as a consequence of endogenic oxidation due to garnet retention in their sources. Our findings further support that the oxidation state of felsic crustal magmas is connected to crustal thickness, and this connection holds over much of the Earth's crustal differentiation history. In the late Archean, continuous formation of such oxidized crust may have profoundly influenced volatile output from Earth's interior and oxidative weathering processes at the surface.

# Heterogeneous lithospheric mantle and kimberlites sampling

**IM Artemieva**

iatemieva@gmail.com; iartemieva@geomar.de

SinoProbe Laboratory, Chinese Academy of Geological Sciences, Beijing, China
Marine Geodynamics, GEOMAR Helmholtz Center for Ocean Research, Kiel, Germany
School of Earth Sciences, China University of Geosciences, Wuhan, China

Compositional heterogeneity of the cratonic lithospheric mantle is known from samples of kimberlite-type magmatism in Precambrian cratons. Joint analysis of geophysical data demonstrates that magmatism-related thermochemical processes contribute to significant lateral and vertical heterogeneity of the cratonic lithospheric mantle worldwide (the North China, East European, Siberian and Kaapvaal cratons, Greenland and the Canadian Shield), which is reflected in its thermal, density and seismic velocity structure (Artemieva, 2007, 2009, 2011; Artemieva and Vinnik, 2016ab; Cherepanova and Artemieva, 2015; Artemieva et al., 2019; Shulgin and Artemieva, 2019; Xia et al., 2020). This heterogeneity reflects the extent of lithosphere reworking by regional-scale kimberlite-type magmatism and large-scale tectonomagmatic processes associated with large igneous provinces and subduction systems. The results show a strong correlation between the calculated density of the lithospheric mantle, the crustal structure, the spatial pattern of kimberlites and their emplacement ages. In all studied cratons, blocks with the lowest values of mantle density (c. 3.30 g/cm3) are not sampled by kimberlites and may represent the 'pristine' Archean mantle. Diamondiferous kimberlites are typical of a low-density cratonic mantle, while non-diamondiferous kimberlites sample mantle with a broad range of density values. Kimberlite magmatism is restricted to anomalous lithosphere, so that the isopycnicity (equal density condition, when compositional anomalies are compensated by temperature anomalies) is satisfied only in kimberlite provinces. An important conclusion is that the inventory of kimberlite-hosted xenolith samples is biased and therefore not representative of pristine cratonic mantle.

## References

Artemieva IM 2019b, Lithosphere thermal thickness and geothermal heat flux in Greenland from a new thermal isostasy method. Earth Science Rev., 188, 469-481. DOI 10.1016/j.earscirev.2018.10.015

Artemieva IM 2009, The continental lithosphere: Reconciling thermal, seismic, and petrologic data. Lithos, 109, 23-46, doi /10.1016/j.lithos.2008.09.015.

Artemieva IM 2007, Dynamic topography of the East European Craton: Shedding light upon the lithospheric structure, composition and mantle dynamics. Global Planet. Change, 58, 411-434

Artemieva IM, Vinnik LP 2016a, Density structure of the cratonic mantle in southern Africa: 1. Implications for dynamic topography. Gondwana Res., 39, 204-216, doi:/10.1016/j.gr.2016.03.002

Artemieva IM, Vinnik LP 2016b, Density structure of the cratonic mantle in southern Africa: 2. Correlations with kimberlite distribution, seismic velocities and Moho sharpness. Gondwana Res., 36, 14-27, doi: 10.1016/j.gr.2016.05.002

Artemieva IM, Thybo H, Cherepanova Y 2019, Isopycnicity of cratonic mantle restricted to kimberlite provinces. Earth Planet. Sci. Lett., 505, 13-19. DOI 10.1016/j.epsl.2018.09.034

Cherepanova Y and Artemieva IM 2015, Density heterogeneity of cratonic lithospheric mantle: A case study of the Siberian craton. Gondwana Research, 28, 1344-1360, doi: 10.1016/j.gr.2014.10.002.

Shulgin A and Artemieva IM 2019, Thermochemical heterogeneity and density of continental and oceanic upper mantle in the European-North Atlantic region. J. Geophysical Res., 124(8), 9280-9312.

Xia B, Thybo H, Artemieva IM, 2020, Lithosphere mantle density of the North China Craton, J. Geophysical Res., 125(9), e2020JB020296, doi: 10.1029/2020JB020296.

# Proterozoic magmatic destabilization and refertilization of the Yilgarn Craton lithosphere

**ARA Aitken[1*], M Fiorentini[1], M Tesauro[2,3], N Thébaud[1]**

* corresponding author: alan.aitken@uwa.edu.au

1. Centre for Exploration Targeting, School of Earth Sciences, The University of Western Australia, Perth, Western Australia
2. Dipartimento di Matematica e Geoscienze, Università di Trieste, Trieste, Italy
3. Utrecht University, Utrecht, Netherlands

The Yilgarn Craton (hereafter, the craton) is an archetypal Archean craton, with geology characterized by greenstone belts dating from c. 3.7 Ga to c. 2.7 Ga, separated by Neoarchean granite domains dating from 2.68 to 2.62 Ga. The isotopic record of crust forming events defines the growth of a geographically complete craton by the Neoarchean with stable crustal architecture prior to the intrusion of the Widgiemooltha Dolerite at 2.42 Ga. Geophysical studies of the lithospheric mantle resolve regionally variable Mg#. A highly depleted western craton (Mg# >90.5) contrasts with a typically less depleted eastern craton (Mg# <90.5), while the surrounding orogens and basins possess more fertile lithosphere (Mg# <90.0). The lithospheric mantle composition for the eastern craton lies outside the range of xenolith data from Archean regions, suggesting post-Archean refertilization. Refertilization causes increased density associated with locally higher iron content and a higher proportion of clinopyroxene and garnet, with respect to olivine and orthopyroxene. Over the large spatially-averaged volumes to which geophysical data are sensitive, distributed compositional variations generate detectable changes in bulk composition, while a horizontally-layered velocity structure at small scales, consistent with observations in peridotite massifs, may generate radial anisotropy in seismic wave propagation.

As well as the cratons Archean geology, post-Archean igneous and sedimentary rocks record a prolonged lithospheric evolution that is not well resolved in datasets recording bulk crustal isotopic evolution. Reconciling these, we combine interpretation of geological and geophysical data to resolve two phases of lithosphere destabilization driven by major magmatic events at c. 2.06 Ga and at c. 1.08 Ga. In the first stage we suggest that south-east directed mantle flow crosses a lithospheric step between the western and eastern craton, causing shear-induced edge-driven convection and associated sublithospheric melting and magmatism in the lee of this feature. The associated refertilization is proposed to have generated ongoing subsidence and eastwards tilting over the subsequent approximately 250 Ma, with marine sediments deposited as the surface was drawn down through sea level.

Late Mesoproterozoic tectonics led to the exposure of the north-eastern edge of the craton to instability, leading to basin forming and extensional brittle fracturing in the northern craton. We propose that as the 1.08 Ga Giles Event impinged on this lithosphere, a subcrustal extrusion of fertile mantle emanated beneath the craton from a source region to the northeast. Extrusion of fertile mantle was accompanied by magmatism, emplacement of a crustal underplate and the thickening and refertilization of the upper lithospheric mantle. The surface was elevated, supported by a thick and buoyant crust and hot mantle. However, as the lithospheric mantle cooled, subsidence led to the extensive sediment deposition over the north-eastern margin of the craton between 0.85 and 0.70 Ga.

Magmatic destabilization of the mantle and its recratonization are key processes in craton evolution that are not always recognized in datasets recording crustal isotopic evolution. Such events can be detected through geophysical recognition of fertile mantle compositions, spatially associated with magmatic events, and the later formation of broad sedimentary basins over unrifted crust.

# Archean tectonic processes from seismic reflection surveys of the Superior, Yilgarn and Pilbara cratons

**AJ Calvert[1*], MP Doublier[2], K Gessner[3]**

* corresponding author: acalvert@sfu.ca

1. Earth Sciences, Simon Fraser University, Burnaby BC V5A 1S6, Canada
2. Mineral Systems Branch, Geoscience Australia, Symonston, ACT 2601, Australia
3. Geological Survey and Resources Strategy Division, Department of Mines, Industry, Regulation and Safety, Perth WA 6004,Australia

Following deep seismic reflection surveys on the Yilgarn and Pilbara cratons by Geoscience Australia with the Geological Survey of Western Australia and on the Superior Craton by the Canadian Lithoprobe program, these cratons are now some of the best surveyed Archean regions on Earth. We present seismic images that highlight how variations in crustal architecture relate to differences in Archean tectonic processes between cratons. All cratons are characterized by a mostly non-reflective 4–12 km-thick uppermost crust due to the presence of large granitoid plutons and gneissic domains. Localized regions of upper crustal seismic reflectivity are typically interpreted as supracrustal rocks and mafic sills or faults and shear zones. The middle and lower Archean crust contains variably complex geometries of relatively high amplitude reflections, though in some regions, such as the Eastern Goldfields Superterrane and the Abitibi Greenstone Belt, the lower crust appears less reflective than the middle crust. Crustal thicknesses vary from 30 km in the eastern Pilbara to 35–40 km across much of the Yilgarn and Superior, though thicknesses as great as 45–52 km occur locally in the latter two cratons. The characteristics of the Archean crust-mantle boundary, or Moho, which is commonly well-defined, differs between cratons, indicating significant variations in the tectonic processes that have driven the final stages of crustal evolution. Dipping reflections in the uppermost mantle linked to convergent crustal structures are interpreted as relict subduction scars.

In the southern Superior Craton, Moho offsets and north-dipping reflections in the middle and lower crust arose through successive underthrusting of Meso-Neoarchean island arcs, oceanic plateaux and microcontinental fragments, as they accreted against a pre-existing northern nucleus (e.g. North Caribou and Opatica terranes). Seismic reflection lines reveal a doubly vergent orogen above north-dipping mantle reflections that indicate subduction drive accretion. Post-orogenic crustal extension, which is inferred from crustal-scale normal shear zones and dropped greenstone belts, has not erased the original accretionary crustal architecture. In contrast, in the Yilgarn Craton interior, accretionary structures are less clear and there are no prominent offsets in the Moho. In the Youanmi Terrane, which represents the cratonic nucleus, a pervasive fabric of listric east-dipping mid-crustal reflections soles out into the upper part of subhorizontal lower crustal reflections. We interpret this reflective fabric to be the result of widespread crustal collapse during the late stage of craton evolution at c. 2.65–2.6 Ga that also produced subsidence of the upper crust. Though terrane boundaries can be identified in seismic data across the Eastern Goldfields Superterrane, these boundaries have commonly been modified by extension, which also overprinted any accretionary lower crustal structures, perhaps simultaneous with widespread intrusion of post-tectonic melts. Exhumation of moderately reflective, amphibolite to granulite facies crust in the Narryer Terrane above dipping mantle reflectors indicates that shortening along the northwestern edge of the Yilgarn Craton was subduction driven. In the eastern Pilbara Craton, shallowly dipping to subhorizontal reflections in the middle and lower crust preclude crustal-scale vertical tectonic movements and imply that the vertical displacements inferred from surface mapping were largely confined to the upper crust.

# Seismic reflection images of the Superior, Yilgarn and Pilbara cratons

**AJ Calvert[1*], MP Doublier[2], K Gessner[3]**

* corresponding author: acalvert@sfu.ca

1. Earth Sciences, Simon Fraser University, Burnaby BC V5A 1S6, Canada
2. Mineral Systems Branch, Geoscience Australia, Symonston, ACT 2601, Australia
3. Geological Survey and Resources Strategy Division, Department of Mines, Industry, Regulation and Safety, Perth WA 6004, Australia

Following deep seismic reflection surveys on the Yilgarn and Pilbara cratons by Geoscience Australia with the Geological Survey of Western Australia and on the Superior Craton by the Canadian Lithoprobe program, these cratons are now some of the best surveyed Archean regions on Earth. We present seismic images together with derived reflector orientation attributes that highlight both the differences and similarities in crustal architecture between cratons. All cratons are characterized by a mostly non-reflective 4–12 km-thick uppermost crust due to the presence of large granitoid plutons and gneissic domains. Localized regions of upper crustal seismic reflectivity are typically interpreted as supracrustal rocks and mafic sills or faults and shear zones. The middle Archean crust contains variably complex geometries of relatively high amplitude reflections that commonly flatten into the shallowly dipping to subhorizontal reflectors of the lower crust, which in some regions, such as the Eastern Goldfields Superterrane and the Abitibi Greenstone Belt, appear less reflective than the middle crust. Crustal thicknesses vary from 30 km in the eastern Pilbara to 35–40 km across much of the Yilgarn and Superior, though thicknesses as great as 45–52 km occur locally in the latter two cratons. The lateral continuity of the Archean crust-mantle boundary, or Moho, which is commonly well-defined, differs between cratons, indicating significant variations in the tectonic processes that have driven the final stages of crustal evolution. In a small number of locations, Moho offsets or dipping reflections in the uppermost mantle linked to convergent crustal structures are interpreted as relict subduction scars.

In the southern Superior Craton, Moho offsets and north-dipping reflections in the middle and lower crust arose through successive underthrusting of Meso-Neoarchean island arcs, oceanic plateaux and microcontinental fragments, as they accreted against a pre-existing northern nucleus (e.g. North Caribou and Opatica terranes). Seismic reflection lines reveal Moho offsets and a doubly vergent orogen above north-dipping mantle reflections that indicate subduction drive accretion. Post-orogenic crustal extension, which is inferred from crustal-scale normal shear zones and dropped greenstone belts, has not erased the original accretionary crustal architecture. In contrast, in the interior of the Yilgarn Craton, accretionary structures are less clear and there are no prominent offsets in the Moho. In the Youanmi Terrane, which represents the cratonic nucleus, a pervasive fabric of listric east-dipping mid-crustal reflections soles out into the upper part of subhorizontal lower crustal reflections. We interpret this reflective fabric to be the result of widespread crustal collapse during the late stage of craton evolution at c. 2.65–2.6 Ga that also produced subsidence of the upper crust. Exhumation of moderately reflective, amphibolite to granulite facies crust in the Narryer Terrane above dipping mantle reflectors indicates that shortening along the northwestern edge of the Yilgarn Craton was subduction driven. In the eastern Pilbara Craton, shallowly dipping to subhorizontal reflections in the middle and lower crust preclude crustal-scale vertical tectonic movements and imply that the vertical displacements inferred from surface mapping were largely confined to the upper crust.

# Detrital zircon and apatite trace enigmatic Yilgarn Craton rift-magmatism – where did all the 2 Ga grains go?

**AJI Clarke[1*], CL Kirkland[1], S Glorie[2]**

* corresponding author: 20392091@student.curtin.edu.au

1. Timescales of Mineral Systems Group, School of Earth and Planetary Sciences, Curtin University, GPO Box U1987, Perth, WA 6845, Australia.
2. Department of Earth Sciences, University of Adelaide, Adelaide, South Australia, 5000, Australia.

Detrital minerals within Proterozoic basins can be the only extant record of now-denuded crust, thereby giving constraints on paleogeography and subsequent sediment movement. Reconstructing basin histories; however, is critically dependent on identifying potentially exotic far-travelled (allochthonous) versus locally sourced (autochthonous) minerals. Detrital zircon from the Woodline Formation, a component of the Barren Basin, closely match the age and Hf isotopic signatures of the Nornalup, Biranup and Frazer Zone magmatic suites of the Albany Fraser Orogen (AFO), Western Australia. However, the provenance of some Paleoproterozoic (2300–2000 Ma) zircon age maxima remains unresolved. Such ages are not readily accounted for by known tectonomagmatic activity in the AFO or even wider Western Australian Craton. This study presents in situ isotopic data (U–Pb and Lu–Hf) and trace element geochemistry for zircon and U–Pb data for apatite collected from unconsolidated cover and siliciclastic rocks of the Woodline Formation. Paleoproterozoic detritus is absent from the unconsolidated material, demonstrating the substantial Pliocene transport of cover atop the Woodline Formation. This disparity may be important to consider as ongoing exploration efforts in the eastern margin of the Yilgarn Craton often analyze unconsolidated regolith to target mineralization. We present a model of rift architecture during the Mesoproterozoic Biranup Orogeny, whereby an uplifted graben restricted the flow of detritus c. 2 Ga to later basins of the AFO. Based on Hf isotopic signatures, some of our detritus appear to be derived from the recently defined 2030–2010 Ma felsic-igneous Moonyoora Suite; however, time-constrained geochemical data also resolves an earlier c. 2250 Ma episode of enigmatic rift-related magmatism offering an important glimpse into the earliest stages of rifting on the Yilgarn Craton margin.

# Refining key constraints for the tectonometamorphic evolution of the Neoarchean eastern Youanmi margin, Yilgarn Craton

**MC De Paoli*, J Sapkota, FJ Korhonen, DE Kelsey, I Zibra, SR Romano**

* corresponding author: matt.depaoli@dmirs.wa.gov.au

Geological Survey of West ern Australia, 100 Plain Street, East Perth WA 6004, Western Australia

Changes in Earth processes are recorded through petrological, structural, geochemical, lithological and isotopic evidence. These data can be used by Earth scientists to explore fundamental issues such as the global change from pre-tectonic plate geodynamics to the emergence of plate tectonics. The physicochemical properties of rocks play a significant role in determining most geodynamic processes, including orogenesis, and these properties are directly influenced by the chemical reactions that occur during metamorphic evolution. To better understand and decipher orogenesis, it is imperative to understand mineral paragenesis in order to obtain precise estimates on the metamorphic conditions with respect to their temporal (*t*), and pressure (*P*) – temperature (*T*) evolution.

The Geological Survey of Western Australia is presently undertaking in-depth geoscientific studies across the Archean Yilgarn Craton. The focus is on integrating metamorphism, regional deformation and granite emplacement into a holistic model, aided by the newly interpreted regional-scale mapping of the Eastern Goldfields Superterrane and adjacent Youanmi Terrane. The Ballard Shear Zone – Ida Fault system is an exposed crustal-scale structure that separates the two terranes. This structural corridor defines the eastern margin of the Ularring Greenstone Belt (UGB) adjacent to the syntectonic 2680–2660 Ma Riverina Gneiss within the Eastern Goldfields Superterrane. The area of interest forms a high-strain segment of the UGB sandwiched between the Riverina Gneiss to the east and the Copperfield Monzogranite to the west. The mafic–ultramafic greenstone sequence exposed along the UGB likely belongs to the 2720–2690 Ma Kalgoorlie Group. Slices of amphibolite and metasedimentary rocks also occur as km-scale rafts within this structural corridor. Recent reports have described garnet-bearing amphibolite and mica schist within the rocks from the UGB, with *P*–*T* estimates of 7–8 kbar at approximately 600 °C. Given the paucity of documented high-*P* metamorphic assemblages in Archean terrains, a primary objective of this investigation is to assess the prevalence of such high-grade rocks along the Ballard – Ida tectonic zone. A majority of the greenstone present in the UGB consists of metabasites that preserve low- to medium-metamorphic grade assemblages that interfinger with metasedimentary rocks. However, as there is a scarcity of robust *P*–*T* constraints, the significance of the reported *P*–*T* conditions to integrate with tectonic models remains unclear.

In this study, we employ metamorphic petrology techniques to examine metamorphic textures and their significance in determining the *P*–*T*–*t* evolution of a set of layered metamorphosed mafic and sedimentary rocks. This information has direct implications for understanding the larger scale geodynamic processes that were operative during the Mesoarchean – Neoarchean along the Eastern Goldfields Superterrane margin of the Yilgarn Craton, Western Australia.

# Tectonics of the Singhbhum Craton-Rengali Province contact, Eastern Indian Shield: insights into Archean cratonic growth and amalgamation

**A Debnath[1*], A Dutta[2], R Roy[1], S Gupta[1]**

* corresponding author: dnathaishi@gmail.com

1. Department of Geology and Geophysics, IIT Kharagpur, Kharagpur 721302, West Bengal, India
2. Geological Survey of India, Eastern Region, Salt Lake, Kolkata 700091, West Bengal, India

One of the oldest cratonic nuclei in the Eastern Indian Shield is the Singhbhum Craton, the southern part of which comprises Archean greenschist facies rocks that are separated by the Barakot Shear Zone (BSZ) from Archean amphibolite to granulite facies rocks of the Rengali Province. Further south, lithounits of the Rengali Province are separated from Neoproterozoic granulite facies rocks of the Eastern Ghats Province (EGP) by the Kerajang Shear Zone (KSZ). The kinematics of the BSZ is the subject of debate. One school considers the Rengali Province to be a rotated slice of the Bastar Craton that is juxtaposed against the Singhbhum Craton by strike-slip faulting, while the other school believes the Rengali Province is the exhumed root of the Singhbhum Craton, implying that the BSZ is a thrust. Field studies conducted in this region suggest that the BSZ is an eastsoutheast to west-northwest (ESE-WNW) trending contact with no discernible thrust-related signatures but is actually associated with an extensional component. The KSZ that lies to the south of the BSZ has a similar trend (ESE-WNW) and is a predominantly dextral, strike-slip shear zone. Microtextural studies of the thin sections from lithounits from both the BSZ and KSZ indicate a strong dextral shear sense. The KSZ can be traced further to the west into the interior of the Bastar Craton. Along the northwestern margin of the EGP, the sheared contact between the lithounits of the Bastar Craton and the granulite facies lithounits of the EGP, called the Hatibari Shear Zone (HSZ), is mapped to curve into the ESE-WNW trend of the KSZ. This rotation of the HSZ is attributed to shearing along the KSZ, implying that the KSZ postdates the Bastar Craton-EGP contact (HSZ). The continuation of the KSZ into the Bastar Craton, the rotation of the HSZ and the extensional component of the BSZ support the proposition that the Rengali Province is a dilational step-over zone representing a rotated slice of the Bastar Craton, rather than an exhumed root of the Singhbhum Craton. Thus, the much-debated contact between the Singhbhum Craton and the Rengali Province is an intracontinental, strike-slip shear zone.

# Archean and Paleoproterozoic evolution of the In Ouzzal granulitic terrane (Western Hoggar, Algeria)

**S Djemai*, K Ouzegane, A Bendaoud**

* corresponding author: safouane.djemai@usthb.edu.dz

Laboratoire de Géodynamique, Géologie de l'Ingénieur et de Planétologie, Faculté des Sciences de la Terre, de Géographie et de l'Aménagement du Territoire, U.S.T.H.B., Algiers, 16111, Algeria

The In Ouzzal terrane (Western Hoggar) is an example of Archean crust remobilized during a very hightemperature metamorphism related to the Paleoproterozoic orogeny (2.04–1.9 Ga). Pan-African events (c. 0.6 Ga) are localized and generally of low intensity. The In Ouzzal terrane is composed of two Archean units: a lower crustal unit made up essentially of enderbites and charnockites and a supracrustal unit of quartzites, banded iron formations, marbles, Al–Mg and Al–Fe granulites commonly associated with mafic (metanorites and garnet pyroxenites) and ultramafic (pyroxenites, lherzolites and harzburgites) lenses. Cordierite-bearing monzogranitic gneisses and anorthosites also occur in this unit. In Ouzzal terrane is exceptional due to numerous carbonatite complexes systematically associated to syenites. They constitute one of the oldest carbonatite emplaced at 2.04 Ga coeval with ultra-high-temperature metamorphism. The continental crust represented by the granulitic unit of In Ouzzal was formed during various orogenic reworking events spread between 3200 and 2000 Ma. The formation of a continental crust made up of tonalites and trondhjemites took place between ≥ 3200 and 2700 Ma. Towards 2650 Ma, extension-related alkali-granites were emplaced. The deposition of the metasedimentary protoliths between 2700 and 2650 Ma was coeval with rifting. The metasedimentary rocks such as quartzites and Al–Mg pelites anomalously rich in Cr and Ni are interpreted as a mixture between an immature component resulting from the erosion and hydrothermal alteration of mafic to ultramafic materials and a granitic mature component. The youngest Archean igneous event at 2500 Ma includes calc-alkaline granites resulting from partial melting of a predominantly tonalitic continental crust. These granites were subsequently converted into charnockitic orthogneisses. This indicates crustal thickening or heating and probably late Archean high-grade metamorphism coeval with the development of domes and basins. The Paleoproterozoic deformation consists essentially of a reactivation of the pre-existing Archean structures. The structural features observed at the base of the crust argue in favour of deformation under granulite facies. These features are compatible with homogeneous horizontal shortening of an overall northwest– southeast trend that accentuated the vertical stretching and flattening of old structures in the form of basins and domes. This shortening was accommodated by horizontal displacements along transpressive shear corridors. Reactional textures and the development of parageneses during the Paleoproterozoic (c. 2 Ga) suggest a clockwise pressure–temperature (*P*–*T*) path characterized by prograde evolution at high pressures (800–1050° C at 10–11 kbar), leading to the appearance of exceptional parageneses with corundum–quartz, sapphirine–quartz and sapphirine–spinel–quartz. This was followed by an isothermal decompression (9–5 kbar). The *P*–*T* path followed by the granulites is compatible with a continental collision, followed by delamination of the lithosphere and uprise of the asthenosphere.

# A Cratonic scale early Ensialic successor basin in the Superior Province

**H Gibson, PC Thurston, J Ayer, J Simmons**

* corresponding author: hgibson@laurentian.ca

Harquail School of Earth Sciences, Laurentian University, Sudbury ON, Canada P3E2C6

The Superior Province contains east-west striking successor basin siliciclastics. These sediments have maximum depositional ages (MDA) of 2704 to 2682 Ma, and comprise the English River (Quetico and Pontiac subprovinces) and smaller coeval occurrences, in turn succeeded by Temiskaming type fluvial-alluvial to marine successor basins (c. 2672 Ma) unconformably overlying older supracrustal sequences.

Traditionally, the Superior Province is considered an accretionary orogeny, the early successor basins viewed as separate events, assembled through successive accretionary or collisional events, yielding east–west alignment of granite-greenstone and sedimentary subprovinces. In this model, the sediments are foreland basins and/or accretionary prisms along volcanic arcs.

We challenge these interpretations, hypothesizing that these sediments are not multiple events within isolated basins, but rather a product of a southward younging and prograding single event covering the Superior Province south of a Mesoarchean core, now preserved in separate basins that extend over an approximately 1400 km by 450 km area and four subprovinces. Comparable turbiditic sediments of the c. 2680 Ma Burwash group cover much of the eastern Slave craton (400 x 800 km basin).

Supporting features include:

- similarity of sedimentary lithofacies throughout and between 'basins'
- detrital zircons indicating local volcanic provenance and a distal, northern provenance for older zircons
- the narrow MDA range for the sedimentary units across the southern Superior indicating a single widespread basin, preserved as separate remnants
- previous correlations are based on similar MDA ranges for detrital zircons between individual basins (e.g. Pontiac with Quetico) but not all sedimentary basins as herein
- their occurrence in narrow, east-west trending linear belts paralleling trans-crustal structures dissecting the Abitibi and Wabigoon subprovinces
- the higher metamorphic grade of the older sediments within the more extensive English River, Quetico and Pontiac subprovinces attributed to accretionary processes could equally indicate preservation within early extensional basins
- the occurrence of volcanism within the sedimentary basins, particularly syn-sedimentary komatiites and lamprophyres (e.g. Pontiac, Porcupine and Hurst) suggest extension, crustal thinning and high-heat flow.

Implications include:

- sediment production is late following amalgamation of the Abitibi-Wawa subprovince and involved uplift and erosion of a northern Superior provenance following collision of the 3.5 Ga Minnesota River Valley terrane with the Superior Province c. 2685
- the location of Timiskaming sediments suggests preservation in second order basins within larger basins defined by the older sediments
- synorogenic structures, partly responsible for local younger zircons within the older sediments, and subsequent preservation of the older sediments and younger Temiskaming sediments between and overlying greenstone belts, may represent reactivated ancestral faults operative during greenstone belt volcanism. Evidence includes the localization of volcanic assemblages, volcanic centres, VMS deposits (particularly Au-rich VMS deposits) and gold deposits along these structures. Testing will continue within the Metal Earth project.

# Unravelling Archean continental evolution: insights from the boundary between the Youanmi and South West terranes, Yilgarn Craton (Western Australia)

**C Gill[1*], N Thébaud[1], N Tucker[1], R Quentin de Gromard[2], T Ivanic[2], C Fisher[1], T Kemp[1]**

* corresponding author: cat.gill@research.uwa.edu.au

1. School of Earth Sciences, Centre for Exploration Targeting, University of Western Australia, Perth WA, Australia
2. Geological Survey of Western Australia, Perth WA, Australia

Archean continental evolution is still poorly understood due to the poor preservation and overprinted nature of many Archean-age terranes. The southwest Yilgarn Craton is a well-preserved and relatively well-exposed portion of Archean crust, which forms an ideal natural laboratory to test tectonic models for Archean continental evolution. In this area, the boundary between the South West and Youanmi Terranes was recently shifted to be congruent with extensive geological and geophysical data that indicate that a large portion of the old South West Terrane is in fact a high-grade equivalent to the rest of the Youanmi Terrane. The data also show that the two terranes were juxtaposed along a major crustal discontinuity, possibly during the 2665–2635 Ma granulite-facies tectonomagmatic event that formed most of the structures of the sinistral transpressive Corrigin Tectonic Zone (Quentin de Gromard et al., 2021). In this study, we combine field based structural and lithostratigraphic investigations with metamorphic petrology and geochronology in order to develop a tectonomagmatic framework for the region and the influence of these processes in the wider Yilgarn Craton.

Preliminary field observations of the South West Terrane directly west of the terrane boundary reveal wellpreserved meta-sedimentary outcrops that retain their original depositional features such as ripples, crossbedding and, in one case, an angular unconformity, giving important way-up information. Structural investigation shows a complex polyphase deformation history with at least three phases of folding. This interpretation allows the stratigraphy to be simplified and the characteristic quartzite in the area to be considered as one unit rather than multiple units juxtaposed with each other, as was previously thought (Nieuwland, 1979). Towards the Youanmi–South West Terrane boundary, strain is observed to increase and the adjacent stratigraphy is rotated 90° to become parallel with it. The presence of alumina-rich metamorphic minerals such as sillimanite and andalusite indicate that this folding is associated with at least one episode of metamorphism and a high thermal gradient.

When integrated with geochronological analysis the new structural data from this previously understudied area provides new insights into the assembly of the southwestern portion of the Yilgarn Craton. In addition to testing the validity of the new terrane boundary, our findings have broad implications for our understanding the timeline of tectonic events across the wider Yilgarn Craton and regional exploration strategies based upon reconstructing the large-scale processes behind mineral enrichment.

## References

Nieuwland, DA 1979, Structural geology and geochronology of the Toodyay district, Western Australia: Australian National University, PhD thesis (unpublished).

Quentin de Gromard, R, Ivanic, TJ and Zibra, I 2021, Pre-Mesozoic interpreted bedrock geology of the southwest Yilgarn, Accelerated Geoscience Program extended abstracts: Geological Survey of Western Australia, Record 2021/4, p. 122–144.

# Plate tectonic limits on the assembly of cratonic Australia

**W Gorczyk[1*], A Aitken[1], I Tyler[1,2], P Betts[3], F Kohanpour[1,2]**

* corresponding author: weronika.gorczyk@uwa.edu.au

1. Centre for Exploration Targeting, University of Western Australia, Perth, WA 6009, Australia
2. CSIRO Mineral Resources, Australian Resources Research Centre, Kensington, WA 6000, Australia
3. School of Earth, Atmosphere and Environment, Monash University, Melbourne, Victoria 3800, Australia

Since at least the Neoarchean, the development of Earth's continents has occurred within a global system of tectonic plates. For a better understanding, it is necessary to mesh detailed analyses of component terranes within the broader spatio-temporal framework of the tectonic plate system. Although several reviews of Proterozoic tectonic events are available for the Australian continent and their links to events on other continents, there is no generally accepted model of cratonic assembly. Since the 1980s, it is clear that prior to the Nuna (Columbia) supercontinent, several disparate Archean cratons and supercratons were formed that, by the time of the supercontinent Rodinia, were brought to coherency along several major orogenic belts. However, the details of the major events, and in particular the timing of convergence and the configuration of plate margins, have remained elusive due to the major orogenic belts being largely unexposed and heavily reworked during later intraplate orogenesis. For each scenario tested, we reconcile geological evidence, recording tectonic events within a geodynamically sound plate reconstruction.

Two continuous tectonic scenarios for the Paleo- to Mesoproterozoic assembly of the cratonic lithosphere of Australia are presented here. The scenarios are founded on those tectonic events that are relatively well established and well supported by data. For the intervening periods and areas that are disputed, mostly due to scarcity of data, we test geodynamic criteria to explore which possibilities are better supported by our geodynamic criteria and the implications of those models for the larger-scale plate tectonic setting.

The geodynamic criteria considered here are:

- The lifespan of oceanic crust.
- It takes 6–10 Myr from the onset of subduction to establishment of a magmatic arc above the subducting slab.
- Termination of subduction by a) collision, b) soft docking or c) clogging.
- 3D slab orientations at depth.
- Long-lived systems lend preference to elongated subduction systems like the Andean, with the interaction of several large plates, rather than the congested Caribbean-style systems with many small microplates.

In the models we are presenting, non-preserved intra-oceanic subductions are not included as the geological record is predominantly available at the edges of the cratons. The time frame we are considering in this set of models includes the assembly of two super continents: Nuna (1900–1800 Ma) and Rodinia (1300–900 Ma), and the processes of the transition between them.

# The extent of the Kalahari Craton

**GH Grantham[*1], PH Macey[2], P le Roux[2], B Eglington[3], L Iaccheri[4], H Ueckermann[1]**

* corresponding author: ghgrantham@uj.ac.za

1. Department/ of Geology, University of Johannesburg, Johannesburg, 2006, South Africa

2. Department of Geosciences, University of Cape Town, Rondebosch, 7700, South Africa

3. Department of Geological Sciences, University of Saskatchewan, Saskatoon, SK S7N 5E2, Canada

The combined extent of the Kalahari Craton in southern Africa and Grunehogna Craton in Dronning Maud Land, Antarctica (DML), as defined by surface exposures, is well established and comprises c. 1 518 300 $km^2$. Two small exposures recently recognized at Brekkerista, Sverdrupfjella with an age of c. 2850 Ma confirm Archeanean crust underlying the Maud Belt. Archeanean crust underlying the Maud Belt was previously inferred from xenocrysts and $Nd_{TDM}$ data from Cambrian to Neoproterozoic granites and Mesoproterozoic gneisses in western DML. Neoproterozoic-Cambrian granites with highly evolved Nd characteristics have been reported as far east as the Conrad Mountains, central Dronning Maud Land (CDML) suggesting that much of western CDML is similarly underlain by Archeanean crust at depth. Similarly Cambrian minettes at Schirmacher oasis have $Nd_{Tdm}$ ages >2.0 Ga.

In central Mozambique, Mesoproterozoic gneisses underlying the Barue Complex along the eastern margin of the Kalahari Craton similarly have $Nd_{Tdm}$ signatures indicating probable Archean basement at depth. In the Nampula Complex, Neoproterozoic to Cambrian age granites, east of the Namama shear zone have relatively juvenile characteristics whereas those west of the shear zone have evolved characteristics.

On reconstruction of Gondwana, these data suggest that the Archeanean crust extends at depth at least up to the Orvinfjella Shearzone and east of Schirmacher Oasis in CDML and up to the Namama shear zone in northern Mozambique. The extent of the revised distribution of exposed and subcrustal Archeanean crust in southern Africa and Antarctica suggests an area of 1 731 000 $km^2$, an increase in area of 14%.

The recognition of extensive Archeanean crust underlying DML, particularly that underlying the Maud Belt and CDML, provides insight to the nature of thickened crust indicated by aero-gravity, satellite gravity and seismic tomography data (Grantham et al., 2019). The thick crust in this area has been interpreted as resulting from the Kuunga Orogeny, a Neoproterozoic-Cambrian continent-continent collision between north and south Gondwana from c. 570 Ma to c. 480 Ma (Grantham et al., 2013, 2008)Antarctica (DML. Crustal thickness estimates suggest that the thickened crust extends at least to the Gamburtsev Mountains, underlying much of east Antarctica.

## References

Grantham, GH, Kramers, JD, Eglington, B, Burger, EP 2019, Precambrian Research 333. https://doi.org/10.1016/j.precamres.2019.105444

Grantham, GH, Macey, PH, Horie, K, Kawakami, T, Ishikawa, M, Satish-Kumar, M, Tsuchiya, N, Graser, P, Azevedo, S 2013, Precambrian Research 234, p. 85–135. https://doi.org/10.1016/j.precamres.2012.11.012

Grantham, GH, Macey, PH, Ingram, BA, Roberts, MP, Armstrong, RA, Hokada, T, Shiraishi, K, Jackson, C, Bisnath, A, Manhica, V 2008, Geological Society, London, Special Publications 308, p. 91–119. https://doi.org/10.1144/SP308.4.

# Archean gneiss complexes in Finnish Lapland, northern Fennoscandia

**J Halla**

jaana.halla@helsinki.fi

Finnish Museum of Natural History, University of Helsinki, Finland 00014

In the Archean, the first basaltic crust of the Earth turned into a thickening continental tonalite-trondhjemite-granodiorite (TTG) crust. Despite many decades of TTG investigations, the researchers have not yet agreed upon the tectonics behind the conversion and several scenarios such as stagnant lid, plume and arc tectonics are under debate. However, there has been limited research focused on the migmatitic nature of the TTG-amphibolite associations that often form an essential part of the TTG crust. Understanding the origin of this association is an important factor in understanding the formation of the early protocontinents. This ongoing project will provide structural, geochemical and geochronological results from two less-studied TTG-amphibolite complexes in Finnish Lapland: the Mesoarchean Rommaeno complex (3.2 Ga) of the Norrbotten Province and Neoarchean Lake Inari Complex of the Kola Province. Both complexes consist of folded and banded TTG gneisses with abundant amphibolite enclaves. Amphibolites show in situ melting structures and metatexite-diatexite transitions forming a boundless interconnected network. The geochemical results from Lake Inari confirm the bimodality of the tonalitebasalt association as well as the intermingled combination of low and high heavy rare earth elements (HREE) TTGs. Variable HREE content is a typical feature for TTGs. The amphibolites are basalts in total alkali-silica classifications and show flattish REE patterns. Two geochemical endmembers of TTGs can be identified within the Lake Inari area, one with depleted HREE and low Mg content and the other with high HREE and elevated Mg content. Both these types seem to be coeval and intermingling, which could be explained by mixing of local metatexite melts with diatexite melts from garnet-bearing granulite facies layers. The amphibolites represent oceanic plateau type basalts. The most likely explanation for the origin of the TTG gneiss complexes in Finnish Lapland is in situ and in-source partial melting of basalts in the deep parts of a thick oceanic plateau.

# Lower Fortescue-aged A-Type magmas in the East Pilbara Craton mark one of Earth's oldest rifts

**HM Howard[1*], RH Smithies[1]**

* corresponding author: heather.howard@dmirs.wa.gov.au

1. Geological Survey of Western Australia, 100 Plain Street, East Perth, WA 6004, Australia

The 2766–2749 Ma Hardey Formation is a voluminous and widespread lower stratigraphic unit of the Fortescue Basin of the Pilbara region. It shows significant regional variation both in terms of the proportion of clastic and volcaniclastic rocks and in the prevailing composition of magmatic units. In the central and western parts of the basin, siliciclastic rocks including sandstone, siltstone and conglomerate dominate the formation; igneous units are restricted to the upper part and comprise the mafic–ultramafic Coolajacka Member, Cooya Pooya Dolerite and the overlying volcanoclastic Lyre Creek Member. The latter comprises relatively primitive (Mg# = 55 to 71) mafic to intermediate deposits, including ignimbrites, and shows early Fe-depletion trends reminiscent of calc-alkaline magmatism, a common feature of magmatic rocks of the Hardey and Kylena Formations in the western Pilbara. The Cooya Pooya Dolerite is geochemically extremely similar to the Coolajacka Member, suggesting the units might be genetically related.

In the northeast of the basin, at Gregory Range, the Hardey Formation is dominated by felsic volcanic rocks. Comagmatic and cogenetic intrusions form the locally syn-deformational granites marking the northnorthwest trending structure that now forms the boundary with Proterozoic and younger sedimentary basins. Magmatic units include the 2763–2757 Ma Gregory Range Suite (granites), dacites and rhyolites of the 2764 Ma Koongaling Volcanic Member and in the upper part of the formation, mafic and felsic magmas of the 2766–2749 Ma Tanguin Member. Only mafic magmas of the Tanguin Member have equivalents in the western exposures of the Hardey Formation, being geochemically very similar to the Lyre Creek Member.

The Gregory Range Suite, Koongaling Volcanic Member and felsic magmas of the Tanguin Member have the ferroan and incompatible trace element-enriched characteristics of hot, dry, A-type magmas. Incompatible trace element patterns for the Tanguin Member and the overlying Kylena Basalt suggest they may be end products of a similar source. However the Gregory Range Suite and Koongaling Volcanic Member were most likely derived from a slightly different mafic parental magma and this raises the question of it perhaps being related to the earlier Mount Roe Basalt. The rhyolites and dacites of the 2766–2755 Ma Bamboo Creek Member lie to the west of Gregory Range. These are compositionally variable, with three regionally distinct groups, likely reflecting variation in bulk source. All have compositional attributes transitional to A-type magmas.

Thus, A-type magmatism dominates the Hardey stratigraphy in the Gregory Range region and extends to the west and south in the form of the Bamboo Creek magmas. Elsewhere, clastic rocks dominate the Hardey Formation; previously mapped felsic volcanic rocks are probably weakly fractionated eruptions from mafic sills. The structural and magmatic characteristics of the Gregory Range support a long-lived, northnorthwest trending, magma-related rift. It reflects one of the oldest preserved rift structures on Earth and was fundamental to the development of later Proterozoic basins.

# Formation of the Yilgarn protocraton by rift-related magmatism from 3.01 to 2.92 Ga

**TJ Ivanic, JR Lowrey, MTD Wingate, Y Lu**

Geological Survey of Western Australia (GSWA), Mineral House, 100 Plain St, East Perth, WA 6004, Australia

Interpreted ages from new geochronology have allowed the definition of ten stratigraphic, volcano-sedimentary associations (Fig. 1) and their grouping into the Southern Cross Supergroup. These associations yield magmatic crystallization ages between 3.01 and 2.92 Ga and are mapped in several belts along a 750 km corridor within the Youanmi Terrane,Yilgarn Craton. These associations comprise six named formations and four other greenstone successions, which we combine into the Southern Cross Supergroup. The formations are locally well preserved in the stratigraphically lower portions of greenstone belts and are interpreted to unconformably underlie the c. 2.8 Ga Murchison Supergroup. The Southern Cross Supergroup consists of equal parts of metabasaltic and meta-andesite–dacite–rhyolite rocks and variable proportions of metasedimentary rocks. In many areas, there are spatially associated synvolcanic tonalite–trondhjemite–granodiorite (TTG) plutons. Whole-rock geochemistry of felsic volcanic rocks indicates multiple source depths and locally highly fractionated compositions. More widely distributed TTG gneisses in the Youanmi Terrane, with magmatic crystallization ages between 3.05 and 2.99 Ga, may have formed basement to the 3.01–2.91 Ga volcano-sedimentary rocks, as their chemical compositions are consistent with melting of lower-crustal sources. After deposition of the Southern Cross Supergroup, a magmatic hiatus occurred between 2.91 and 2.82 Ga. Zircon Lu–Hf data for two of the formations of the Southern Cross Supergroup and their proximal, synvolcanic TTGs yield a unimodal peak in εHf values spread over 40 Ma, with εHf indistinguishable from chondritic uniform reservoir (CHUR) and with no indication of significant crustal contamination. Distal to the volcanic rocks of the Southern Cross Supergroup, TTG gneisses of the Thundelarra Supersuite are slightly more evolved, with εHf(i) between 0 and -2, indicating minor contributions from a >3.3 Ga crustal component. We consider the geometry of these formations, their homogeneous mantle source and the punctuated chronology over 100 Ma to be consistent with a rift setting, in which the rift axis was coincident with the juvenile Cue Isotopic Zone (Sm–Nd $T_{DM}^2$ = 2.95 Ga) immediately to the east. Additional data may be needed to rule out other tectonic processes during this time interval. We consider the wide distribution of supracrustal rocks and TTGs from 3.01–2.91 Ga to represent a significant building block and a protocratonic stage of the Yilgarn Craton.

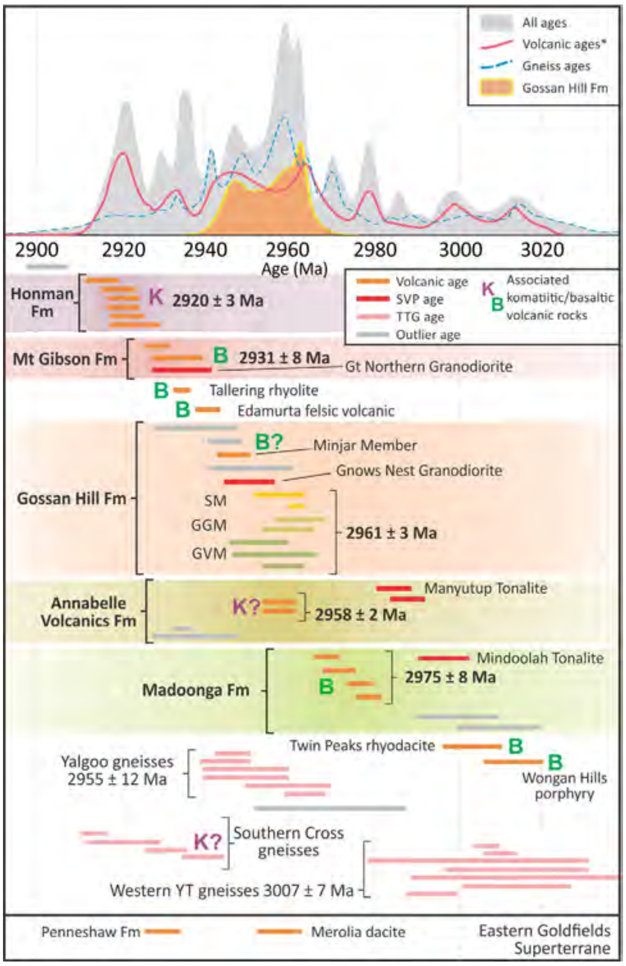



Figure 1. Summary of magmatic crystallization ages from the Youanmi Terrane between 3.04 and 2.90 Ga (horizontal bars indicate ±95% confidence intervals) arranged from the oldest ages in named and unnamed greenstones to the youngest. SVP = subvolcanic pluton, SM = Scuddles Member, GGM = Golden Grove Member, GVM = Gossan Valley Member, YT = Youanmi Terrane.

# Campaign-style in situ Lu–Hf garnet geochronology to constrain the timing of early Archean metamorphism in the Western Dharwar Craton

**J Kaempf[1*], J Alfing[1], C Clark[1], TE Johnson[1], M Jayananda[3], KR Aadiseshan[3], K Rankenburg[2], SV Balaji Manasa Rao[3]**

* corresponding author: jonas.kampf@postgrad.curtin.edu.au

1. School of Earth and Planetary Sciences, Curtin University, Perth, WA, Australia
2. John de Laeter Centre, Curtin University, Perth, WA, Australia
3. Centre for Earth, Ocean and Atmospheric Sciences, University of Hyderabad, Hyderabad, India

Traditional geochronological methods targeting accessory phases such as zircon and monazite to date high-grade metamorphic events commonly fail to directly link metamorphic ages to the respective pressure–temperature (*P–T*) conditions of formation. Recent developments in laser-ablation inductively coupled plasma-tandem mass spectrometry (LA-ICP-MS/MS) have made it possible to obtain in situ Lu–Hf ages in garnet (Simpson et al., 2021), a mineral that is common in most high-grade metamorphic rocks and widely utilized in thermobarometric studies. The combination of high spatial resolution and preservation of textural relationships makes the method a valuable tool in unravelling complex metamorphic histories of polymetamorphic terranes and constraining *P–T* time paths. Here, we apply campaign-style in situ LAICPMS/MS Lu–Hf garnet geochronology to a variety of high-grade metamorphic rocks from across the Western and Central Dharwar Craton, as well as parts of the Mesoarchean Coorg block and Mercara shear zone, to constrain the timing of Archean metamorphism. Our results show a wide distribution of Neoarchean to early Paleoproterozoic ages (2.6–2.4 Ga) along the eastern and southern margin of the Western Dharwar Craton, reflecting its accretion with the Central Dharwar Craton and other crustal blocks. Records of a potentially older metamorphic event (3.2–3.0 Ga) that did not experience widespread Neoarchean overprinting are mainly preserved in the Coorg block and the cratonic cores of the Western and Central Dharwar blocks and may help to explain their crustal evolution prior to Neoarchean accretion. Finally, this study outlines the advantage of in situ Lu–Hf garnet dating over conventional (time and resource intensive) isotope dilution dating, along with its pitfalls and limitations.

## Reference

Simpson, A, Gilbert, S, Tamblyn, R, Hand, M, Spandler, C, Gillespie, J, Nixon, A and Glorie, S 2021, In situ Lu–Hf geochronology of garnet, apatite and xenotime by LA ICP MS/MS: Chemical Geology, v.577, p. 120299.

# Elevated radiogenic heat production as a thermal driver for Neoarchean metamorphism in the southwest Yilgarn Craton, Australia

**FJ Korhonen*, DE Kelsey, IOH Fielding, ER Blereau, MC De Paoli, SR Romano**

* corresponding author: fawna.korhonen@dmirs.wa.gov.au

Geological Survey of Western Australia, 100 Plain Street, East Perth WA 6004, Australia

The thermal structure of the lithosphere has a first-order control on continental growth and the stabilization of cratons. Metamorphic rocks record pressure (*P*)–temperature (*T*)–time (*t*) information that can provide essential constraints on a wide range of geological processes leading to cratonization, such as changes in the thermal environment over time. The Geological Survey of Western Australia is currently undertaking detailed geoscientific studies across the Yilgarn Craton, including forward modelled phase equilibria calculations integrated with in situ geochronology and thermochronology to constrain *P*–*T*–*t* conditions of metamorphism. These datasets are being used to better understand the protracted evolution of the Yilgarn Craton, but may also be applicable to other Archean terranes worldwide.

The metamorphic database currently contains more than 40 data points across the Yilgarn, representing one of the most well-characterized quantitative metamorphic datasets worldwide. The data show that granulite and amphibolite facies conditions dominate the southwest Yilgarn, with apparent thermal gradients ranging between 65 and 225 °C/kbar at 2665–2635 Ma. Much of the current dataset is from the northwest-trending Corrigin Tectonic Zone (CTZ), a major sinistral transpressive shear zone system comprising granulite-grade, mid-crustal meta-igneous and metasedimentary rocks. East of the CTZ, within the southern Youanmi Terrane, the data suggests that *P*–*T* conditions are broadly similar to the conditions recorded in the CTZ. West of the CTZ, within the South West Terrane, there is a scarcity of exposed metamorphic rocks, but field observations are suggestive of a lower metamorphic grade.

Elevated apparent thermal gradients seem to correspond to elevated crustal radiogenic heat production. The crustal evolution of the southwest Yilgarn is characterized by voluminous granite magmatism between 3010 and 2610 Ma. A compilation of all inferred Archean rock types sampled in the southwest Yilgarn shows that the crustal rocks are elevated in radiogenic heat production with an average value in the dataset of 7.1 $\mu Wm^{-3}$ (*n*=1260) at 2640 Ma, compared to the global crustal average of 2.78 $\mu Wm^{-3}$ (calculated at 2640 Ma). A long history of elevated heat production in the crust is implied by the calculated heat production of granitic rocks that make up a significant portion of the southwest Yilgarn crust, which were emplaced prior to, synchronous with and following the 2665–2635 Ma metamorphism. In addition, amphibolite to granulite facies supracrustal rocks in the southwest Yilgarn have elevated radiogenic heat production values (on average 3.3 $\mu Wm^{-3}$, *n*=27). Together these imply that at the time of 2665–2635 Ma high-*T* metamorphism, and at the depth where amphibolite to granulite facies metamorphism was occurring, the crust was also strongly enriched in heat-producing elements, and that contemporaneous magmatism was sourced from crust with elevated radiogenic heat production. The thermal structure of the crust during Neoarchean metamorphism was likely a combination of elevated crustal heat production, the effects of regional-scale granite magmatism and a juvenile mantle contribution at depth.

# Multiple seismic constraints on Precambrian continental fragments of the northern West Australia Craton

**T Li[1], L Zhao[1], H Yuan[2,3,4], RE Murdie[2], K Gessner[2]**

1. State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
2. Geological Survey of Western Australia, Mineral House, East Perth, Western Australia 6004, Australia
3. Centre for Exploration Targeting, University of Western Australia, Perth, Western Australia 6009, Australia
4. School of Natural Sciences, Macquarie University, NSW 2109, Australia

It is challenging to understand the evolution and dynamics of the Precambrian continent due to lack of sufficient observations. The West Australia Craton (WAC) has a prolonged history of multiple terranes formation and accretion in the Archean and Paleoproterozoic. It therefore provides an ideal laboratory to study how Precambrian continental fragments amalgamate to form stable continents. However, some questions remain unclear, including how many terranes were assembled and where the collisional boundaries are. These tectonic events have probably left unique imprints in the lithosphere, which can be detected by seismic signal. Here we target the northern WAC, including the Pilbara Craton, the Canning Basin and the Kimberley Craton, using a passive source array. We show multiple crustal models imaged by shear wave velocity, radial anisotropy and $V_p/V_s$ ratio with a cutting-edge transdimensional inversion method. Combining our models and evidence from other disciplines, we discuss the possible role of internal continental fragments in the regional assembly processes. Integrated with results from other Archean and Paleoproterozoic cratons, our study offers direct shallow lithospheric constraints to better understand the formation and evolution of Precambrian continents.

# Linking the Paleoproterozoic tectonomagmatic lull with Archean supercraton: a geochemical study on the early Paleoproterozoic rocks in the North China Craton

**Z-X Li[1], S-B Zhang[1,2,3], Y-F Zheng[1,2,3], K Su[1], L Zhang[1]**

1. CAS Key Laboratory of Crust-Mantle Materials and Environments, School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China

2. Center of Excellence for Comparative Planetology, Chinese Academy of Sciences (CAS), Hefei 230026, China

3. Frontiers Science Center for Planetary Exploration and Emerging Technologies, University of Science and Technology of China, Hefei 230026, China

A tectonomagmatic lull (TML) at 2.4–2.2 Ga in the early Paleoproterozoic is indicated by the global geological record. However, the origin of the TML remains unclear. This study addresses the TML from the perspective of supercontinents and supercratons. A suite of amphibolites, dioritic dykes and granitoids within this age range were reported in the Taihua Complex in the southern margin of the North China Craton. The amphibolites with protolith ages of c. 2.34 Ga show arc-like trace element distribution patterns, depleted whole-rock Nd–Hf, zircon Hf isotope compositions and high U/Th ratios. All these geochemical features suggest that the amphibolite protoliths were produced by partial melting of enriched mantle generated through fluid metasomatism. The c. 2.27 Ga dioritic dykes show arc-like trace element patterns, enriched zircon Hf isotope compositions and high Th/Yb ratios. These observations indicate that the dioritic dykes were derived from partial melting of enriched mantle metasomatized by terrigenous sediment-derived melts. Compared to earlier mafic rocks, the Paleoproterozoic mafic magmas have lower melting temperatures and pressures, but higher T/P ratios, suggesting thinning of the lithospheric mantle. The c. 2.33 Ga granites have chondritic whole-rock Hf–Nd isotopes, neutral zircon εHf(t) values, high zircon saturation and Ti-in-zircon temperatures, indicating that they were formed by remelting of early Archean crust under high temperatures. Altogether these rocks record a continental rifting event during the TML. Combined with the reworked detrital zircon Hf isotope composition, the high T/P metamorphism and lower rates of plate motion during the TML, we propose that the extension regime was globally dominant during the TML. The decrease in global zircon numbers during the TML is similar to the troughs after the assembly of Nuna/Columbia and Rodinia. The cratons with magmatism during the TML belong to the Sclavia or Nunavutia supercraton, which broke in the Paleoproterozoic, whereas those without magmatism during the TML belong to the Supervaalbara supercarton, which remained stable during the lull. In this regard, the intrinsic cause of the TML is the limited magmatism in response to the breakup of one supercraton and the stability of other supercratons.

# High-pressure felsic granulites of the North China Craton at the late Archean transition to plate tectonics

**P-H Liu, Z-H Tian, W Zhang**

* corresponding author: lph1213@126.com

Institute of Geology, Chinese Academy of Geological Sciences, Beijing, 100037, China

Converging lines of evidence suggest that, during the late Archean, Earth completed its transition from a stagnant-lid to a plate tectonics regime, although how and when this transition occurred is debated. Here, we present Neoarchean high-pressure Kyanite-garnet-bearing felsic granulites of the Yinshan Block, North China Craton, which equilibrated at approximately 1.32–1.42 GPa and 855–905 °C (Fig.1). Laser ablation-inductively coupled plasma-mass spectrometry U–Pb zircon geochronology indicate that these assemblages grew c. 2483 Ma. The thermal regimes required to generate these metamorphic conditions are typical of collisional orogenesis and suggest that the continental lithosphere was capable of supporting crustal thickening to 45–50 km. Such crustal thickening provides supporting evidence that tectonic regimes similar to modern Earth–style tectonics were in operation at the Archean-Proterozoic transition.

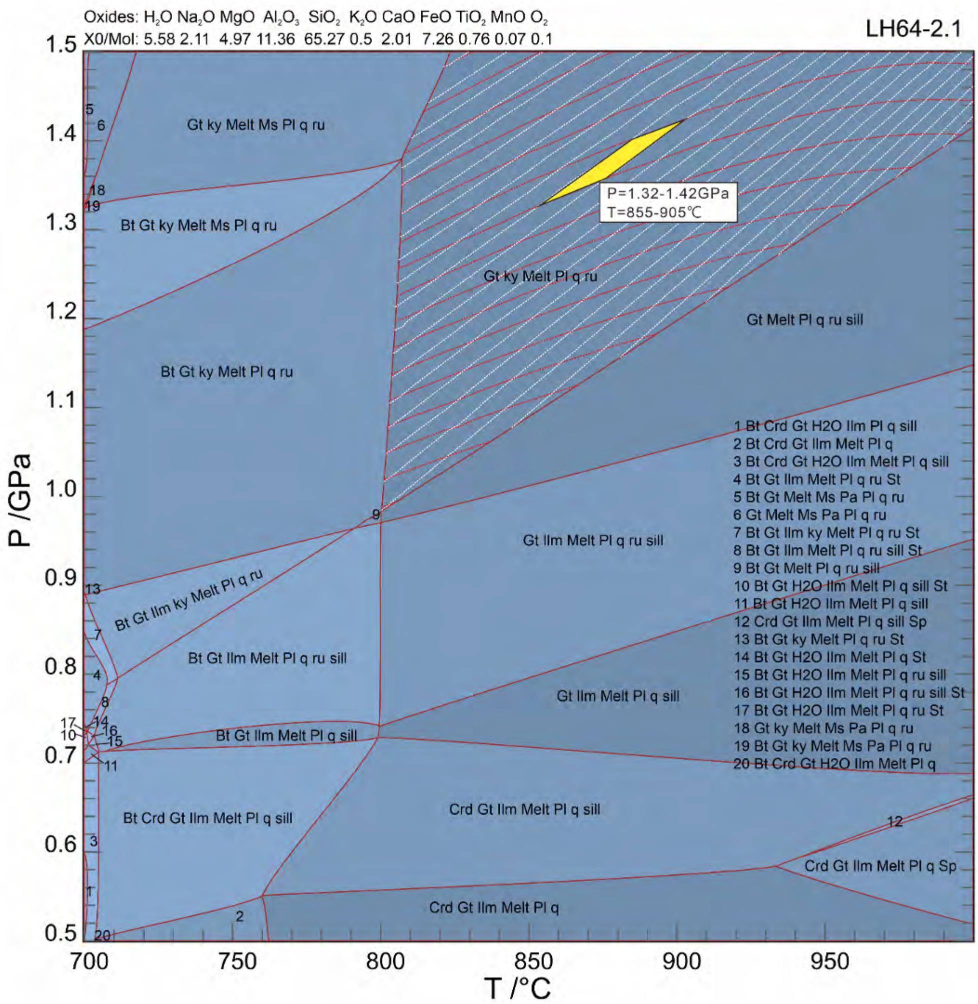



Figure.1. *P–T* pseudosection with the proposed *P–T* path for high-pressure felsic granulite sample LH64-2.1

# Insights from the c. 1.8 Ga Bridget Suite: unveiling the youngest felsic magmatism in the Pilbara Craton

**Y Lu[1*], RH Smithies[1], K Gessner[1], SP Johnson[1], IOH Fielding[1], J Lowrey[1], PA Morris[2]**

* corresponding author: yongjun.lu@dmirs.wa.gov.au

1. Geological Survey of Western Australia, 100 Plain Street, East Perth, WA 6004, Australia
2. Ganseki Geoscience, Ardross, Perth, Western Australia 6153, Australia

The Bridget Suite is a series of undeformed, hornblende-bearing intrusions forming an approximately 150 km-long northwest trend within the northeastern Pilbara Craton. The trend is parallel to the c. 2.76 Ga Gregory Range Suite, which has A-type magmatic affinity and to the Paleoproterozoic suture zone between the Percival Lakes Province and the Rudall Province. The Bridget Suite comprises numerous small plutons, stocks and dykes of hornblende- and clinopyroxene-bearing monzodiorite, monzonite, and monzogranite, commonly with trachytic textures. The intrusions are highly magnetic and can be identified readily in aeromagnetic images. However, the genesis of this distinct magmatic suite is poorly understood. Here we report new geochronology and geochemistry to better constrain the timing, petrogenesis, metallogenic fertility and geodynamic setting of the Bridget Suite.

The sensitive high-resolution ion microprobe (SHRIMP) U–Pb zircon dating of a quartz monzonite collected from the largest Bridget Suite intrusion, in the Mosquito Creek Basin, yielded an igneous crystallization age of 1790 ± 7 Ma. The sample also contains xenocrystic zircon cores dated at 3352–3162 Ma and 2879–2688 Ma, which are similar to ages of exposed igneous rocks in the East Pilbara Terrane, including the Emu Pool, Cleland and Split Rock Supersuites as well as the Bamboo Creek Member of the Hardey Formation in the overlying Fortescue Basin. The abundant xenocrystic zircon cores are consistent with the hydrous nature of the Bridget Suite, as indicated by the presence of ubiquitous hornblende phenocrysts and low zircon saturation temperature of 700–740 °C.

The crystallization age of 1790 ± 7 Ma indicates that the Bridget Suite is the youngest felsic magmatism in the Pilbara Craton. This suite is contemporaneous with the Yapungku Orogeny and emplacement of the 1804–1762 Ma Kalkan Supersuite in the Rudall Province, the main phase of the Capricorn Orogeny and emplacement of the Moorarie Supersuite in the Gascoyne Province and deposition of the Ashburton Basin along the northern margin of the Capricorn Orogen.

Based on the new geochemical data, the Bridget Suite appears to be an evolved, hydrous, and oxidized magmatic suite ranging from monzodiorite, monzonite to quartz monzonite. The suite is more alkaline and has higher Sr, Ba and Rb concentrations than all Archean granitic rocks in the Pilbara Craton. It is also metaluminous, belongs to the high-K to shoshonite series and has high Sr/Y (35–83) and Eu/Eu* (0.85–0.97), both of which increase with increasing $SiO_2$. The magmatic evolution of the suite is interpreted to involve suppression of plagioclase crystallization and promotion of hornblende crystallization in hydrous magma. The Bridget Suite may have originated from a mantle source, as indicated by higher Mg# (>50) and Cr (>25 ppm) in the most primitive samples, compared with partial melts of mafic lower crust. The suite is geochemically similar to K-rich porphyries at the Ok Tedi and Northparkes porphyry Cu-Au deposits, two well-known porphyry deposits in post-collisional setting and likewise may be prospective for Cu-Au.

We propose that the Bridget Suite was derived from metasomatized mantle beneath the eastern Pilbara Craton in an intraplate setting and that the trigger for melting was likely related to Paleoproterozoic accretion of Percival Lakes Province onto the eastern Pilbara Craton. The suite was likely emplaced along a preexisting crustal-scale structure initiated during the c. 2.76 Ga east-west rifting of the Pilbara Craton, as marked by the Gregory Range Suite.

# New geophysical, geologic and geochemical data from the western Wabigoon and Winnipeg River terranes: implications for Neoarchean geodynamics in the western Superior Craton

**C Ma[1,*], AQ Adetunji[1], J Marsh[1], M Naghizadeh[1], RWD Lodge[2], D Snyder[1], R Sherlock[1], B Lafrance[1], P Thurston[1], J Ayer[1]**

* corresponding author: macmachong@gmail.com

1. Mineral Exploration Research Centre, Harquail School of Earth Sciences, Laurentian University, Sudbury, Ontario, P3E2C6, Canada
2. Department of Geology, University of Wisconsin-Eau Claire, Eau Claire, Wisconsin, 54702, USA

The Archean is considered a pivotal era during Earth's evolution and the geodynamic processes in this eon are critical for understanding Earth's early history. This study, as part of the Metal Earth project, focuses on the greenstone-dominated western Wabigoon terrane (WWT) and the tonalite-trondhjemite-granodiorite-dominated Winnipeg River terrane (WRT) of the western Superior Craton. New seismic, magnetotelluric and geologic data, along with previously published seismic reflections, revealed the 3D crustal structures underlying the region. Whole-rock geochemistry and in situ U–Pb, Lu–Hf and trace elements of zircon reveal episodic magmatic events associated with crustal growth or reworking in the WRT and broadly continuous volcanism related to formation of oceanic crust in the WWT. The crustal structures are consistent with a c. 2700 Ma convergent belt characterized by an allochthonous greenstone belt forming a thrust sheet in the upper crust, a collision zone in the mid- to lower-crust, an apparent crustal root of 3 - 5 km relief and subcreted crustal rocks beneath a mantle wedge. This model is supported by c. 2700 Ma transcrustal magmatism in the WRT and c. 2707–2703 Ma volcanism along the WRT–WWT boundary. The WRT data reveal magmatic reworking at c. 3060 and c. 2930–2920 Ma of the isotopically evolved components of the incipient WRT. Magmatism at c. 2910 Ma recorded juvenile magmas and reworking at c. 2830–2800, 2735–2730 and c. 2700 Ma that largely reflects reworking of the juvenile components of the incipient WRT. The WWT data represents prolonged bimodal volcanism from c. 2780 to 2725 Ma. The felsic/intermediate volcanic rocks are characterized by variable Th/Nb and highly depleted Hf compositions, likely derived from mantle sources ranging from those of normal mid-ocean ridge basalts (N-MORB) to those of enriched MORB (E-MORB), many of which assimilated various felsic crustal components. The mafic volcanic rocks are commonly dominated by low La/Sm basalts with negligible Nb, Ta anomalies and limited range of Th/Nb, forming a mantle array on the Th/Yb–Nb/Yb plot and consistent with oceanic crust of N-MORB to enriched N-MORB affinities. Some basalts from the c. 2738–2725 Ma assemblages, however, yielded high La/Sm, negative Nb and Ta anomalies, and limited range of Th/Nb. This might be associated with passive subcretion and rollback of oceanic crust of the stagnant-lid model or subduction of oceanic lithosphere, both of which are supported by zircon trace element compositions that indicate hydrous, oxidized, large-ion lithophile element-enriched, medium- to high-pressure magmas. This study suggests that the western Superior Craton underwent significant mantle depletion at c. 2910 Ma beneath the WRT and that crustal growth and mantle depletion bracketed by prolonged, episodic crustal reworking may be a fundamental characteristic of cratonization. Moreover, identification of three magma-series requires assemblage-scale analysis. Our detailed approach of distinguishing rock types and assemblages of a greenstone belt offers a practical solution to more accurately characterize Archean volcanic rocks and to better understand the early Earth.

# Testing early Earth deformation models in the Archean East Pilbara Craton, Western Australia

**AJ Okayli Masaryk*[1], AC Robinson[1], A Yin[2]**

* corresponding author: ajokaylimasaryk@uh.edu

1. Department of Earth and Atmospheric Sciences, College of Natural Sciences and Mathematics, University of Houston, Houston, Texas, 77004, USA
2. Department of Earth, Planetary, and Space Sciences, College of Letters and Science, University of California, Los Angeles, California, 90095, USA

The Pilbara (northwest Australia) and Kaapvaal (Africa) cratons exhibit pristine 3.6–2.7 Ga crust; as such, they provide a critical window in the mechanical behaviour of the early Earth's lithosphere. The fundamental characteristics of these terranes are deformed, steeply dipping greenstone synclines (i.e. keels) folded between massive tonalite–trondhjemite–granodiorite (TTG) domes. An ongoing debate is whether the terranes' current dome-and-keel geometries and structural fabrics represent a different crustal deformation mechanism in the early Earth or typical plate tectonic related structures heavily modified by subsequent deformation. We focus on two observations of current map patterns within the greenstone belts along the margins of the Shaw dome that we suggest may be the result of modern thrust sheet-style structures that were subsequently folded into their current geometry. Firstly, map patterns of complexly faulted and folded strata in the Lallah Rookh-Western Shaw (LRWS) corridor are like cross-section patterns of antiformal stacks in thrust sheet hanging walls. We suggest that the complexly folded and imbricated strata in the greenstone keels may represent tilted antiformal duplexes in the hanging wall of a regionally extensive thrust sheet. Secondly, the elongated Shaw dome in the south-centre East Pilbara granite-greenstone terrane (EPGGT) is bound by the Mulgandinnah shear zone (MSZ) to the west and the Split-Rock shear zone (SRSZ) to the east. Our initial explorations back-rotating the mylonitic foliation and lineation data of these shear zones from previously published data (Zegers et al., 1998) onto a continuous planar structure displays a primarily northeast-southwest trending, top-to-the-southwest linear fabric from both the SRSZ and MSZ, with a possible northwest-southeast overprinting fabric in the MSZ. While more detailed structural investigations of the shear zones bounding the Shaw dome are necessary to assess the viability of this reconstruction, we suggest that the shear zones may represent an initial sub-planar shear zone along the base of a regional thrust that was folded into its current geometry by subsequent deformation. Our model for the tectonic history of the EPGGT involves a modern-style structural evolution, where the current structural geometries are formed by the development of a greenstone basin; southwest-directed thinskinned emplacement and thrust stacking over a granitic terrane and cross-folding of the ductile crust via a younger tectonic event(s) causing the older shear zones to appear parabolic in map view. This hypothesis predicts that the shear zones, which form contacts between the granites and greenstones, are a continuous folded detachment fault that should show similar trends in kinematic data (e.g. lineation direction, shear sense) when unfolded, and that complexly folded and faulted geometries in greenstone belts with near vertical bedding may be rotated thrust belt structures.

## References

Zegers, TE, de Keijzer, M, Passchier, CW and White, SH 1998, The Mulgandinnah Shear Zone; an Archean crustal scale strike-slip zone, eastern Pilbara, Western Australia: *Precambrian Research*, v. *88*, p. 233–247.

# Using stable and radiogenic Nd isotopes to trace secular evolution of the Archean crust

**AJ McCoy-West[1*], A Ladwig[2], JF Moyen[3], MA Millet[4], E Bruand[5], O Nebel[2], P Cawood[2]**

* corresponding author: alex.mccoywest@jcu.edu.au

1. IsoTropics Geochemistry Laboratory, James Cook University, Townsville, QLD, Australia
2. Department of Earth, Atmosphere and Environment, Monash University, Clayton, VIC, Australia
3. Université de Lyon, Laboratoire Magmas et Volcans, Saint Etienne, France
4. School of Earth and Ocean Sciences, Cardiff University, Park Place, Cardiff CF10 3AT, UK
5. Laboratoire Magmas et Volcans, CNRS, Université Clermont Auvergne, Clermont-Ferrand, France

For decades radiogenic Nd isotopes have formed a cornerstone of studies seeking to understand crustal growth and evolution (Allègre and Rousseau, 1984; DePaolo, 1980). Recent analytical advances mean we can now simultaneously obtain radiogenic and stable Nd isotope compositions (McCoy-West et al., 2017; McCoy-West et al., 2020), allowing us to reconstruct not just the temporal history of a magmatic rock, but also the processes involved in its formation. Studies of the chemical and isotopic composition of the Archean crust remain hindered by sampling biases and the lack of reference suites that have been systematically measured for multiple geochemical tracers. To this end, we gathered a large collection of 154 samples of various lithologies (but with a strong emphasis on granitoids) ranging in age from c. 3.6 Ga to 2.7 Ga from across the Kaapvaal craton and Limpopo belt in southern Africa (the SWASA collection). The wide range of crystallisation ages and the progressive stages of craton assembly recorded make this an ideal sample set for accessing temporal changes in magmatic compositions related to crustal evolution.

Here we present Nd isotope data for 67 of these samples from across the region and age spectrum. The radiogenic Nd compositions are consistent with previous determinations with depleted mantle model ages mostly ranging from 3.0 to 3.7 Ga and crustal residence times of up to 0.5 Ga. Stable Nd isotope compositions ($\delta^{146/144}$Nd) range from -0.11‰ to +0.12‰, which is three times more variability than seen in modern basalts (McCoy-West et al., 2021). Above 70 wt% $SiO_2$, the proportion of samples with $\delta^{146/144}$Nd resolvable heavier than the bulk silicate Earth increases substantially. After 2.8 Ga, post tectonic high-K granites with heavier $\delta^{146/144}$Nd dominate the sample suite. This is distinguishable from the older trondhjemitetonalite-granodiorite samples which possess more normal $\delta^{146/144}$Nd and consistent with a temporal change in the source compositions of the granitoids.

## References

Allègre, CJ and Rousseau, D 1984, The growth of the continent through geological time studied by Nd isotope analysis of shales. Earth and Planetary Science Letters v. 67, p. 19-34.

DePaolo, DJ 1980, Crustal growth and mantle evolution: inferences from models of element transport and Nd and Sr isotopes. Geochimica et Cosmochimica Acta v. 44, p. 1185-1196.

McCoy-West, AJ, Burton, KW, Millet, M-A and Cawood, PA 2021, The chondritic neodymium stable isotope composition of the Earth inferred from mid-ocean ridge, ocean island and arc basalts. Geochimica et Cosmochimica Acta v. 293, v. 575-597.

McCoy-West, AJ, Millet, M-A and Burton, KW 2017, The neodymium stable isotope composition of the silicate Earth and chondrites. Earth and Planetary Science Letters v. 480, p. 121-132.

McCoy-West, AJ, Millet, M-A, Nowell, GM, Nebel, O and Burton, KW 2020, Simultaneous measurement of neodymium stable and radiogenic isotopes from a single aliquot using a double spike. Journal of Analytical Atomic Spectrometry v. 35, p. 388-402.

# Crustal evolution of the southeastern Superior Craton and insights into Archean geodynamics

**DR Mole[1,2,*], JH Marsh[2], PC Thurston[2], RA Stern[3]**

* corresponding author: david.mole@ga.gov.au

1. Geoscience Australia, Canberra, Australian Capital Territory, Australia
2. Mineral Exploration Research Centre (MERC), Harquail School of Earth Sciences and Goodman School of Mines, Laurentian University, Sudbury, Ontario P3E 2C6, Canada
3. Canadian Centre for Isotopic Microanalysis, University of Alberta, T6G 2E3, Canada

Archean crustal evolution and its tectonic paradigm can be directly linked to the evolution of the mantle, the hydrosphere-atmosphere, oxygenation of the Earth and the formation and storage of ore deposits. Hence, it is vital to understand the evolution of the early crust if we are to understand our planet's evolution as well as transformational events in its history.

During the last 30 years, the collection of vast amounts of isotopic data, especially U–Pb, Sm–Nd, Lu–Hf, and $\delta^{18}O$, has significantly advanced our understanding of crustal processes and their timing. However, we rarely look at these data in a spatial context. This study aims to constrain the time-space evolution of the southeastern Superior Craton, Canada, by mapping the zircon Hf–O isotopes and trace element data from 148 Archean magmatic rocks (6340 total analyses).

In Lu–Hf space, the dataset demonstrates the highly juvenile nature of this region, with the majority of values between $\varepsilon Hf_i$ +6 and +2. When plotted spatially, the most juvenile data (+4 to +6 $\varepsilon Hf_i$) delineate an east-west oriented zone, broadly inline and subparallel to the Cadillac-Larder Lake and Porcupine-Destor structures. Surrounding this juvenile region is less juvenile crust (0 to +3 εHf). Corresponding $\delta^{18}O$ values show that light to mantle-like data (3.0–5.6‰) correlate with the most juvenile crust imaged by the εHf, with heavier $\delta^{18}O$ (5.8–7.5‰) plotting to the south, east and west of this zone. Zircon trace element proxies for hydration (Eu/Eu*), oxidation (ΔFMQ using Ti, Ce, U), and continental vs oceanic origin ($U_i$ [initial U] /Yb) replicate the pattern observed in the Lu–Hf and $\delta^{18}O$. This suggests that, broadly, the southeastern Superior consists of a central east-west orientated juvenile zone consisting of the most reduced, least hydrated, least continental, and most high-temperature hydrothermally altered crust. This zone is surrounded by crust, which is more hydrated, oxidised, has a greater supracrustal $\delta^{18}O$ component and is slightly less juvenile. The major ore systems of the Abitibi subprovince, including volcanogenic massive sulfide, gold and komatiite-hosted Ni–Cu–PGE systems, fall within the east-west highly juvenile zone.

Current tectonic models for this region of the Superior Craton range from long-lived Neoarchean subduction across the whole Abitibi tectonothermal 'event' (2750–<2695 Ma), known as 'horizontal' tectonics, to a variety of non-arc processes including plume-related crustal overthickening (i.e. oceanic plateau), sagduction/drip tectonics and subcretion, known as 'vertical' tectonics. Models combining arc and non-arc processes have also been suggested (i.e. plume-arc interaction) and our data broadly support a combined model. We propose the east-west zone delineated by the various geochemical data represents a paleo-rift zone, driven by ambient mantle or mantle plume processes. The dry, reduced, oceanic character of the zone appears to preclude an arc or back-arc setting prior to c. 2.7 Ga. However, temporal changes in hydration, oxidation and the increased heavy $\delta^{18}O$ component at c. 2.7 Ga suggest a major geodynamic shift, potentially marking the onset of subduction and associated compression. This is contribution 2020050 of the Mineral Exploration Research Centre (MERC) Metal Earth project.

# Low $\delta^{18}O$ volcanism in the Neoarchean Fortescue Group, Pilbara Craton

**DR Mole[1,2,*], HM Howard[3], RH Smithies[3], CL Kirkland[4], ML Fiorentini[5], LAJ Martin[6], RA Stern[7], LA Parra-Avila[8]**

* corresponding author: david.mole@ga.gov.au

1. Geoscience Australia, Canberra, Australian Capital Territory, Australia
2. Mineral Exploration Research Centre (MERC), Laurentian University, Sudbury, Ontario P3E 2C6, Canada
3. Geological Survey of Western Australia, Plain Street, East Perth, WA, Australia
4. Centre for Exploration Targeting (Curtin node), Curtin University, Kent Street, Perth, WA, Australia
5. Centre for Exploration Targeting, University of Western Australia, 35 Stirling Hwy, Perth, WA, Australia
6. Centre for Micro-characterization and Microanalysis, University of Western Australia, Perth, WA, Australia
7. Canadian Centre for Isotopic Microanalysis, University of Alberta, T6G 2E3, Canada
8. School of Earth Sciences, University of Western Australia, 35 Stirling Hwy, Perth, WA, Australia

Archean greenstone belts are a vital window into the tectonostratigraphic processes that operated in the early Earth and the geodynamics that drove them. However, the majority of greenstone belts worldwide are highly-deformed, complicating geodynamic interpretations. The volcano-sedimentary sequence of the 2775–2690 Ma Fortescue Group is different as it is largely undeformed, offering a unique insight into the architecture of greenstone sequences. In the Fortescue magmatic rocks, geochemical signatures, that in deformed belts in the Superior or Yilgarn Cratons might have been interpreted as arc-like, are explained by contamination of rift-related mantle and plume-derived magmas with Pilbara basement crust; understanding the wider geological and structural setting allows a more complete interpretation. However, contamination of Fortescue magmas by an enriched subcontinental mantle lithosphere (SCLM) is an alternative hypothesis to the crustal contamination model. If demonstrated, the addition of sediments and fluids to the SCLM, required to form enriched/metasomatized SCLM, would suggest active subduction prior to the Neoarchean. To test this hypothesis, we collected Hf–O isotopic data on zircons from felsic volcanic rocks throughout the Fortescue Group; if the contamination had a subducted sedimentary component ($\delta^{18}O$>20‰), then the O-isotopes should record a heavy signature. The results show that the c. 2775 Ma Mt Roe Formation has $\varepsilon Hf_i$ from 0 to -5.6, and $\delta^{18}O_{VSMOW}$ of +4.8 to +0.3‰, with the majority of values <+3‰. The c. 2765 Ma Hardey Formation (mostly sediments) has highly unradiogenic $\varepsilon Hf_i$ of -5 to -9.4, and $\delta^{18}O$ of +7.8 to +6.6‰. The c. 2730 Ma Boongal Formation displays similar values as for Mt Roe, with $\varepsilon Hf_i$ +1.9 to -5.5 and $\delta^{18}O$ +3.0 to -0.6‰. The c. 2720 Ma Tumbiana Formation shows the greatest range in $\varepsilon Hf_i$ from +4.9 to -4.6, with $\delta^{18}O$ +7.1 to +0.7‰, with the majority between +4.5 and +2.5‰. Data from the 2715 Ma Maddina Formation are more restricted, with $\varepsilon Hf_i$ between +4.0 and -0.1, and $\delta^{18}O$ +5.0 to +3.8‰. The youngest formation, the 2680 Ma Jeerinah Formation, has $\varepsilon Hf_i$ +2.3 to -6.2, and $\delta^{18}O$ +5.1 to -2.1‰. Importantly, these data provide little evidence of a cryptic enriched SCLM source in the Fortescue magmas. Furthermore, the dataset contains some of the lightest $\delta^{18}O$ data known for Archean zircon, highlighting a c. 100 Myr period of high-temperature magma-water interaction, with long-term continental emergence implied by the trend to meteoric $\delta^{18}O$ compositions. The exception to this is the Hardey Formation, which may have formed via crustal anatexis in a period of reduced heat-flow between the 2775–2665 and 2730–2680 Ma events. Data from the other formations show a broad trend of increasing $\delta^{18}O$ and εHf from 2775 to 2680 Ma. We suggest this represents the effects of progressive cratonic rifting, allowing mantle-derived magmas to reach the surface less impeded and also a decreasing role of meteoric water in the rift zone as the sea invades. As a result, the εHf and $\delta^{18}O$ data from the Fortescue Group represent the evolving nature of an Archean rift zone, from an emergent volcanic centre to a submarine environment.

# Construction of the Yilgarn Craton over 1.5 billion years

**DR Mole[1,*], CL Kirkland[2], ML Fiorentini[3], SJ Barnes[4], KF Cassidy[3], EA Belousova[5], M Hartnady[2], N Thebaud[3]**

* corresponding author: david.mole@ga.gov.au

1. Geoscience Australia, Canberra, Australian Capital Territory, Australia
2. Centre for Exploration Targeting (Curtin node), Curtin University, Kent Street, Perth, WA, Australia
3. Centre for Exploration Targeting, University of Western Australia, 35 Stirling Hwy, Perth, WA, Australia
4. Mineral Resources, CSIRO, 26 Dick Perry Avenue, Kensington, Perth, WA, Australia
5. Geochemical Evolution and Metallogeny of Continents (GEMOC), Macquarie University, NSW, Australia

The Yilgarn Craton of Western Australia represents one of the largest pieces of Precambrian crust on Earth and a key repository of information on the Meso–Neoarchean period. Understanding the crustal, tectonic, thermal and chemical evolution of the craton is critical in placing these events into an accurate geological context, as well as developing holistic tectonic models for the Archean Earth. In this study, we collected a large U–Pb (420 collated samples) and Hf isotopic (2163 analyses) dataset on zircon to investigate the evolution of the craton. These data provide strong evidence for a Hadean–Eoarchean origin for the Yilgarn Craton from mafic crust at c. 4000 Ma. This ancient cratonic nucleus was subsequently rifted, expanded and reworked by successive crustal growth events at c. 3700 Ma, c. 3300 Ma, 3000–2900 Ma, 2825–2800 Ma and c. 2730–2620 Ma. The <3050 Ma crustal growth events correlate broadly with known komatiite events, and patterns of craton evolution, as revealed by Hf isotope time-slice mapping (Fig. 1), and image the periodic break-up of the Yilgarn protocontinent and the formation of rift zones between the older crustal blocks. Crustal growth and new magmatic pulses were focused into these zones and at craton margins, resulting in continent growth via internal (rift-enabled) expansion and peripheral (crustal extraction at craton margins) magmatism. Consequently, we interpret these major geodynamic processes to be analogous to plume-lid tectonics, where the majority of tonalite-trondhjemite-granodiorite (TTG) felsic crust, and later granitic crust, was formed by reworking of hydrated mafic rocks and TTGs respectively, via a combination of infracrustal and/or drip-tectonic settings. While this process of crust formation and evolution is not necessarily restricted to a specific geodynamic system, we find limited direct evidence that subduction-like processes formed a major tectonic component, aside from redocking the Narryer Terrane to the craton at c. 2740 Ma. Overall, these 'rift-expansion' and 'craton margin' crustal growth processes led to an intracratonic architecture of younger, juvenile terranes located internally and externally to older, long-lived, reworked crustal blocks. This framework provided pathways that localized later magmas and fluids, driving the exceptional mineral endowment of the Yilgarn Craton.

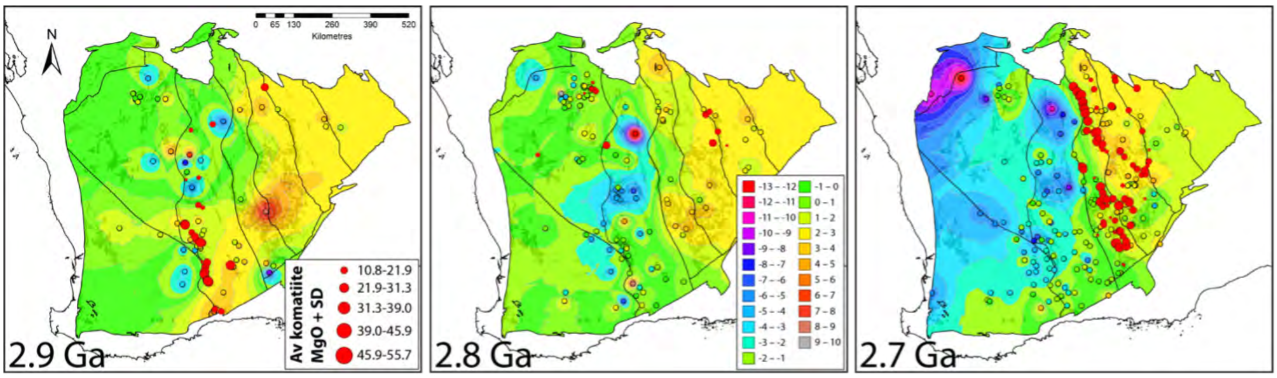



Figure 1. Lu–Hf isotope time-slice maps of the Yilgarn Craton, at c. 2.9 (3050-2820 Ma), 2.8 (2820-2720 Ma) and 2.7 (2720-2600 Ma) Ga

# Crustal growth and tectonometamorphic evolution of the La Grande, Nemiscau and Opatica subprovinces (Superior Province, Canada): a long-lasting history

**RP Pérez[1], A Tremblay[1], Y Daoudene[2], R Stevenson[1], J David[2], G Ruffet[3], D Bandyayera[2]**

*corresponding author: pedreira_perez.rocio@courrier.uqam.ca

1. GEOTOP-Département des Sciences de la Terre et de l'Atmosphère, Université du Québec à Montréal, Montreal, Quebec, H3C 3P8, Canada

2. Bureau de la Connaissance Géoscientifique du Québec, Ministère de l'Énergie et des Ressources Naturelles, Quebec City, Quebec, G1H 6R1, Canada

3. CNRS (CNRS/INSU), Université de Rennes 1, Géosciences (UMR6118), 35042 Rennes, France

The metasedimentary Nemiscau subprovince is an east–west-trending belt separating the volcano-plutonic La Grande and Opatica subprovinces of the Superior Province. The Nemiscau is interpreted as the remnant of a subduction-related accretionary complex or turbiditic synorogenic basin. The integration of structural and geochronological data indicates long-lasting polyphase deformation and metamorphism in the eastern Superior Province. Two discrete tectonometamorphic events, known as pre-$D_1$ (2815–2804 Ma) and $D_1$ (2756–2736 Ma), may record mid-crustal decoupling between a rigid upper crust and hotter, middle-to-lower crustal plutonic rocks (tonalite–trondhjemite–granodiorite TTGs) prior to the Kenorean orogeny (2720–2680 Ma). Maximum depositional ages (<2724 Ma) for the Nemiscau indicates sedimentation during at least the early stages of the Kenorean orogeny. This was followed by $D_2$ (2704–2677 Ma) dip-slip deformation coeval with granulite facies metamorphism and anatexis in the Nemiscau subprovince (2697–2685 Ma). A $D_3$ dextral strike-slip deformation event at 2658–2621 Ma was accompanied by amphibolite facies metamorphism. A $D_4$ deformation event, associated with localized brittle-to-ductile conjugated shear zones and decreasing crustal cooling from amphibolite to greenschist facies conditions, occurred at ≤2598 Ma. $^{40}Ar/^{39}Ar$ step-heating ages of hornblende grains suggest slow cooling following $D_3$, between c. 2625 and 2590 Ma. The 2590–2555 Ma ages of a second population of hornblende grains may imply crustal cooling following the emplacement of late-stage granitic intrusions, whereas $^{40}Ar/^{39}Ar$ muscovite ages suggest retrogression into greenschist facies at c. 2535 Ma. Nd isotopic data (εNd -3.55, +1.61) and U–Pb ages of inherited zircons (2.91–3.46 Ga) argue for recycling of Paleo- to Mesoarchean continental crust during genesis of TTG suites (≥2800 Ma) in the La Grande ($T_{DM}$ 3.52–3.08 Ga) and Opatica ($T_{DM}$ <3.07 Ga) subprovinces. The isotopic composition (εNd -1.12, +0.24) of younger TTGs (<2755 Ma) and syn- to late-tectonic intrusions (<2646 Ma) in the Nemiscau and Opatica subprovinces is consistent with the crustal evolutionary trend of the older Opatica TTG suites, suggesting that they originated by partial melting of these latter 'basement' rocks. The emplacement of sanukitoid suites at 2704–2693 Ma in the La Grande and Opatica subprovinces is contemporaneous with the partial melting episode in the Nemiscau. εNd values (-0.61, +1.64) of these sanukitoids, suggesting a renewed mantle source ($T_{DM}$ 3.02–2.85 Ga) slightly perturbed by the incorporation of older crustal material. Mafic–ultramafic rocks of the greenstone belts have juvenile signatures that are consistent with depleted mantle sources. The associated intermediate and felsic volcanic rocks exhibit a wide range of εNd values (-1.87, +2.01), likely reflecting mixing of c. 3.0 Ga mantle and >3.0 Ga crustal components.

Our field and isotopic data show more similarities than differences between the La Grande, Nemiscau and Opatica subprovinces. This result suggests that they most likely represent a single composite terrane instead of distinct crustal blocks or microcontinents. The overall structural characteristics of the region are consistent with the evolution of a 'hot' orogen, in which contemporaneous gravity processes and lateral extrusion of high-temperature crustal material affected the middle and lower crust.

# Inter-dome sedimentary response to vertical tectonics in the pre-orogenic Yilgarn Craton

**C Phillips[1], TJ Ivanic[1]**

* corresponding author: Christopher.Phillips@dmirs.wa.gov.au

1. Geological Survey of Western Australia (GSWA), Mineral House, 100 Plain St, East Perth, WA 6004, Australia

The early Neoarchean Mougooderra Formation preserves chemical sedimentation in a quiescent lacustrine or submarine shelf setting, which differs in style and age to other 'late basins' within the Yilgarn Craton. Localized reworked granite–greenstone units are deposited from sediment-gravity flows in response to uplift and erosion associated with vertical tectonic doming. The formation is primarily exposed in a narrow north–south-trending corridor on the east flank of the Yalgoo dome in the Youanmi Terrane. Sedimentology of the Mougooderra Formation was investigated from seven traverses along a strike length of approximately 150 km.

The Mougooderra Formation is metamorphosed at greenschist facies but preserves fine-grained siliciclastic material deposited from suspension settling after turbidity current events interbedded with variably ferruginous or jaspilitic banded chert or banded iron-formation. Beds of chert or magnetiterich banded iron-formation have been measured up to 5 m thick and can be traced on magnetic imagery for 5 to 10 km along strike. These lithofacies provide evidence for very limited to no terrigenous sedimentation and the prevalence of a quiescent depositional setting. Fine-grained and chemical units are punctuated by deposition from sediment-gravity flows including turbidity currents and debris flows in a likely middle to outer fan setting. Pebble to boulder conglomerate beds are abundant at the base of normal graded packages becoming massive to cross-bedded lithic sandstone. These lithofacies are interpreted as channel fill deposits either in the main turbidity current channel or smaller distributary channels spread across the outer fan. Conglomerate–sandstone units are overlain, and lateral to, aggradational sandstone units or heterolithic sandstone–siltstone lithofacies. These units represent deposition on the outer fan from a series of waning turbidity currents interbedded with, and lateral to, deposits from suspension settling and chemical precipitation of chert and banded iron-formation.

The composition of conglomerate clasts and sandstone units, in conjunction with detrital zircon geochronology, indicate a significant proportion of the Mougooderra Formation was derived from directly underlying greenstone units. Sources include the 2800–2735 Ma Polelle Group and 2825–2800 Ma Norie Group (Murchison Supergroup) as well as rocks of the intrusive 2825–2733 Ma Annean Supersuite. However, significant age components from c. 2767 to 2746 Ma are within error of the Goonetarra Granodiorite, a late phase of the magmatism within the Yalgoo dome, and are likely sourced from this younger component of the Annean Supersuite. These ages constrain portions of the Mougooderra Formation to be deposited from high-density sediment-gravity flows responding to local tectonic drivers (i.e. broadly coeval with intrusion, uplift and erosion of the Yalgoo dome from c. 2746 Ma).

Folding of the formation indicates that deposition of the Mougooderra Formation must have been completed before east–west shortening and associated orogenic events accompanying the c. 2730 Ma Yilgarn orogeny. We interpret the Mougooderra Formation as a series of rapidly deposited sediment gravity flows from c. 2746 to 2730 Ma during the latter stages of local doming into an otherwise quiescent chemical paleoenvironment.

# Early earth surface processes, paleoclimate, and crust-mantle interactions: insights from Dharwar craton, India

**PVS Raju**

perumala.raju@gmail.com

CSIR- National Geophysical Research Institute, Uppal Rod, Hyderabad, Telangana, 500007, India

As the Sedimentological and stratigraphic analyses of these oldest sedimentary successions on earth is inadequate, the sedimentary environmental conditions under which life evolved on early earth is purely a matter of speculation and highly ambiguous (Mazumder and Chaudhuri, 2021). Consequently, the co- evolution of life and environment on early earth is poorly constrained. It is extremely important to study this coevolution of life and environment as this is the key to the search for life in terrestrial planets as they share similar early history. India has perhaps the richest Paleoarchean to Paleoproterozoic crustal components on Earth (in the Singhbhum, Dharwar and Bastar cratons; see Mazumder et al., 2019; Mazumder and Choudhury, 2021). Researchers have reported 4.2-4.0 Ga xenocrystic zircons from Gneissic rocks of eastern India and have pointed out the antiquity of the Indian rock associations (Chaudhuri et al., 2018). The Sedimentological and stratigraphic aspects of Paleoarchean- Mesoarchean successions of the Singhbhum craton has been studied in recent years (summarized by Mazumder et al. 2019). In contrast, the sedimentological analyses of the Paleoarchean successions of the Dharwar craton (the Sargur Group, which is of similar age to the Moodies Group in the Barberton Greenstone Belt, South Africa), is under focused. The 3.3-3.2 Ga Sargur Group of the Dharwar craton have siliciclastic deposits but sedimentological investigation of these rocks are inadequate. It hosts barite deposits which is interbedded with quartzite's speculated part of the succession formed under subaerial condition but no sedimentological verification has yet been made (Mazumder et al., 2019; Sunder Raju and Mazumder, 2020). Researchers have identified a Mesoarchean paleosol but geochemical and sedimentological verifications are yet to be made (Eriksson and Mazumder, 2020; Sunder Raju and Mazumder, 2020). The extant surface environmental conditions and its shift in terms of sea level change and tectonics are yet to be inferred (see Sunder Raju and Mazumder, 2020). Unlike the Moodies, the paleobiological inventory of the Paleoarchean successions of the Dharwar craton (the Sargur Group) is poor. The depositional environments of the Paleoarchean sedimentary rocks and tectonic settings have been constrained by geochemical characterization of the associated volcanic rocks without undertaking any sedimentary facies analysis (see Sunder Raju and Mazumder, 2020 for discussion). The paleo weathering and provenance characteristics of the Paleoarchean sedimentary rocks are unknown. The interaction between surface and internal processes is largely unknown. To fill in the prodigious gap in knowledge base on early earth surface environment and crust-mantle interactions, a thorough and in-depth sedimentological (sedimentary facies analysis and provenance studies), paleoclimatic and stratigraphic analyses of the Paleo- Mesoarchean stratigraphic successions of the Dharwar craton has such footprints. The geochemical data from volcanics interbedded with sediments to constrain the tectono-sedimentary model and global correlation with the Kaapval and Pilbara cratons will be presented.

## References

Mazumder, R., and Choudhuri, T. 2021. Paleoarchean terrestrial to shallow marine sedimentation on Singhbhum Craton, eastern India (the Western Iron Ore Group). Precambrian Research, 354, article No. 106071.

Sunder Raju, P.V. and Mazumder, R. 2020. Archean sedimentation in Dharwar Craton, India and its implications. Earth Science Reviews, 202, article no 102999.

Eriksson, P.G. and Mazumder, R. 2020. Archean Earth Processes (Preface), Earth Science Reviews, 202, article no. 103058.

Mazumder, R., Chaudhuri, T., Biswas, S. 2019. Palaeoarchaean sedimentation and magmatic processes in the eastern Iron Ore Group, eastern India: A commentary. Geological Journal, 54 (5), 3078-3087.

Mazumder, R., De, S. and Sunder Raju. 2019. Archean-Proterozoic transition: the Indian Perspective. Earth Science Reviews. 188, 427-440.

Mazumder, R., 2019. A Paleoproterozoic Aeolianite (the Nummana Member) from the Lower Wyloo Group, Pilbara Craton, Western Australia, and Its Implication," The Journal of Geology 127, 109-118.

Chaudhuri, T., Yusheng, W., Mazumder, R., Mingzhu M. and Dunyi L 2018. Evidence of Enriched, Hadean Mantle Reservoir from 4.2-4.0 Ga zircon xenocrysts from Paleoarchean TTGs of the Singhbhum Craton, Eastern India. Scientific Reports, 8: Article number: 7069.

# Internal structures and flow patterns of the Mt Edgar dome, East Pilbara Terrane using anisotropy of magnetic susceptibility

**NM Roberts[1*], B Tikoff[2], RA Salerno[3], JD Vervoort[3]**

* corresponding author: nmrobert@hamilton.edu

1. Department of Geosciences, Hamilton College, Clinton NY 13323, USA
2. Department of Geoscience, University of Wisconsin-Madison, Madison WI 53705, USA
3. School of the Environment, Washington State, Pullman WA 99164, USA

Large, ovoid structural domes – cored by voluminous granitic batholiths and surrounded by supracrustal rocks – are a hallmark of Early Archean crust. The East Pilbara Terrane displays this 'dome-and-keel' architecture, although the internal structures remain poorly defined because of difficulties in identifying fabric orientations (foliation and lineation) and fabric geometries (L-tectonites to S-tectonites) in the field.

We present anisotropy of magnetic susceptibility (AMS) data from the Mt Edgar dome and the northern Corunna Downs dome. AMS measures the bulk orientation and distribution of magnetic minerals within a 1inch core specimen. The resultant magnetic fabric is an ellipsoidal description that provides both foliation and lineation, fabric geometry (L vs S tectonite) and degree of fabric development (magnitude of anisotropy). Data were collected on over 1000 oriented specimens collected from 150 stations spread throughout the Mt Edgar dome. The AMS data reveal that the Mt Edgar dome has a coherent internal structure across the entire dome. Magnetic lineations show a radiating pattern that emanate from a zone of vertical lineation within the c. 3.2 Ga Emu Pool Supersuite. Magnetic foliations are preferentially oriented in a subvertical northwest–southeast striking orientation. The southwest margin of the dome preserves large scale fold structures within the c. 3.4 Ga Tambina Supersuite orthogneisses. AMS ellipsoids exhibit oblate (flattening) shapes on the southwest half of the dome and prolate (constrictional) shapes in the central part of the dome that has steeply plunging radiating lineations.

The AMS data are interpreted in the context of microstructural observations and geochronological data. Granitic rocks exhibit primarily high-temperature microstructures with significant evidence for the presence of partial melt during deformation in some areas. The presence of a coherent structure across granitic units of vastly different ages suggest that the present granitic dome structure continued to deform until at least 3.2 Ga. Recent Sm–Nd isochron ages of garnets at the margin of the Mt Edgar dome are consistent with continued deformation at elevated temperature during the emplacement of the c. 3.2 Ga Cleland Supersuite, the youngest of the Paleoarchean granitic supersuites in the East Pilbara.

These internal structures provide significant constraints on the crustal processes that led to the development of coherent structural domes in some of Earth's earliest preserved continental crust. In particular, these data document the presence of highly mobile crust in the late Paleoarchean. Dome structures represent the focusing of multi-age granitic crust into structural domes. The highly uniform northwest–southeast striking sub-vertical foliation suggests that doming did not proceed in a radially symmetrical way, which may imply that crustal flow occurred in response to northeast–southwest shortening. At the same time, the radiating lineations suggest significant vertical flow from a central region within the core of the dome.

# New workflow for the spatial prediction of isotopic data: example from the Neoarchean Yilgarn Craton

**A Rossalim[1,2*], ARA Aitken[1,2], CM Fisher[1,2], N Thébaud[1,2], MW Jessell[1,2], R Schreefel[1,2]**

* corresponding author: azim.binrossalim@research.uwa.edu.au

1. School of Earth Science, The University of Western Australia, Crawley WA, 6009, Australia

2. Centre for Exploration Targeting, The University of Western Australia, Crawley WA, 6009, Australia

Geologists have been using isotopic and other geochemical data as proxies to map the evolution of craton. The different in Sm/Nd and Lu/Hf ratios in rocks and minerals resulting from radioactive decay can image the juvenile mantle input in the continental crust and/or reworking of crustal components. Such data had revealed useful constraints regarding the continental crust formation and evolution with time. Moreover, the spatial interpolation of model age data has gained popularity over the past decade to document the crustal and associated lithospheric architecture. However, previous isotope studies used simpler interpolation methods that lack careful data structure analysis and prediction error quantification. In this study, we present a large Hafnium (n=233) and Neodymium (n=551) dataset collected over the Neoarchean Yilgarn Craton. We utilize the isotopic datasets to develop an alternative method for predicting the data using geostatistical approach, kriging and cokriging. Spatial contouring that we obtained with this method may then be used to image the tectonic evolution of the craton. The samples are mapped at 39 different time slices, from 2.98 to 2.6Ga for every 10 million years interval to produce a continuous, 3D isotopic evolution model. For each time slice, we generate variogram models to show the spatial dependence degree among samples within the determined space and time. From the models, we map the Hf and Nd values at each time slice together with the prediction error maps. We then focus on analysing three time slices with a varying number of samples (2.9, 2.7 and 2.6Ga) that represent the major tectonic event in Yilgarn Craton. The Hf and Nd maps show a different block of juvenile and reworked crust that changes over space and time. The kriging and cokriging approach can generate a measure of uncertainty, thus helping to avoid misinterpretation on the results. We suggest that our approach can help to delineate the juvenile vs reworked crustal block boundaries with a higher level of confidence. Furthermore, our approach allows continuous analysis of isotopic changes in space and time, rather than limited to 'time-slices', which enables the study of isotopic pattern behaviour in response to the tectonic event in the craton.

# Crustal growth in the Archean: insights from zircon petrochronology of the far-eastern Yilgarn Craton

**R Schreefel[1*], CM Fisher[1], AIS Kemp[1], SG Hagemann[1], Q Masurel[1], N Thébaud[1], C Davies, LAJ Martin[3], JR Lowrey[4], Y Lu[1,4], KF Cassidy[1,5]**

* corresponding author: ravi.schreefel@research.uwa.edu.au

1. Centre for Exploration Targeting, School of Earth Sciences, The University of Western Australia, Perth, Australia
2. Hamelin Gold Ltd, Perth, Australia
3. Centre for Microscopy, Characterisation and Analysis, The University of Western Australia, Perth, Australia
4. Geological Survey of Western Australia, Department of Mines, Industry Regulation and Safety, Perth, Australia
5. Bare Rock Geological Services Pty Ltd, Perth, Australia

The Archean Yilgarn Craton in Western Australia represents one of the key pieces for investigating the mechanisms of crustal growth during Earth's infancy. However, the far eastern margin of the Yilgarn Craton has received comparably limited scientific scrutiny. In this study, in situ zircon petrochronology (U/Pb, O, and Hf isotopes) is used to constrain the formation and evolution of the easternmost Yamarna and Burtville regions of the Yilgarn Craton. The new data highlights the unequivocal existence of relatively old (c. 2840–2777 Ma and c. 2726–2652 Ma), compared to the Eastern Goldfields Terrane, and isotopically mantle-like crust (zircon εHf: +2.1 to +3.5; $\delta^{18}O$: 5.0 to 5.9‰) at the eastern edge of the exposed craton. We refer to this crust as the 'Dorothy Hills Block'. The Dorothy Hills Block shows geochronological and isotopic similarities with the adjacent 'Burtville Block' and Youanmi Terrane, >400 km further west, which suggest at a shared history subsequent to c. 2970 Ma. In addition, linear greenstone belts characterized by younger magmatism (c. 2720–2660 Ma) with a constant, mildly super-chondritic Hf isotope composition (εHf: 0.0 to +3.5) are identified between the Burtville and Dorothy Hills blocks. We refer to this region as the 'Yamarna Rift', by analogy to the better-understood 'Kalgoorlie-Kurnalpi Rift'. It is inferred that crust in the Burtville and Dorothy Hills blocks formed via pericratonic magmatism (c. <2970 Ma), associated with mantle upwelling focused along the eastern edge of the c. >3300 Ma Yilgarn proto-craton. The Yamarna and Kalgoorlie-Kurnalpi intracratonic (failed) rift basins (c. 2720–2630 Ma) are interpreted to have formed via a major mantle upwelling event, potentially contemporaneous with a west-dipping subduction zone east–northeast of the preserved Yilgarn Craton. The revised crustal evolution model for the Eastern Goldfields Terrane, including petrochronological data from the far-eastern region and new nomenclature, suggests both pericratonic and intracratonic, sustained, and autochthonous geological development during the Neoarchean. Similar crustal evolutionary trends are recorded in other Archean cratons (e.g. Superior Craton), which suggests that similar geodynamic regimes operated on a global scale in the Archean.

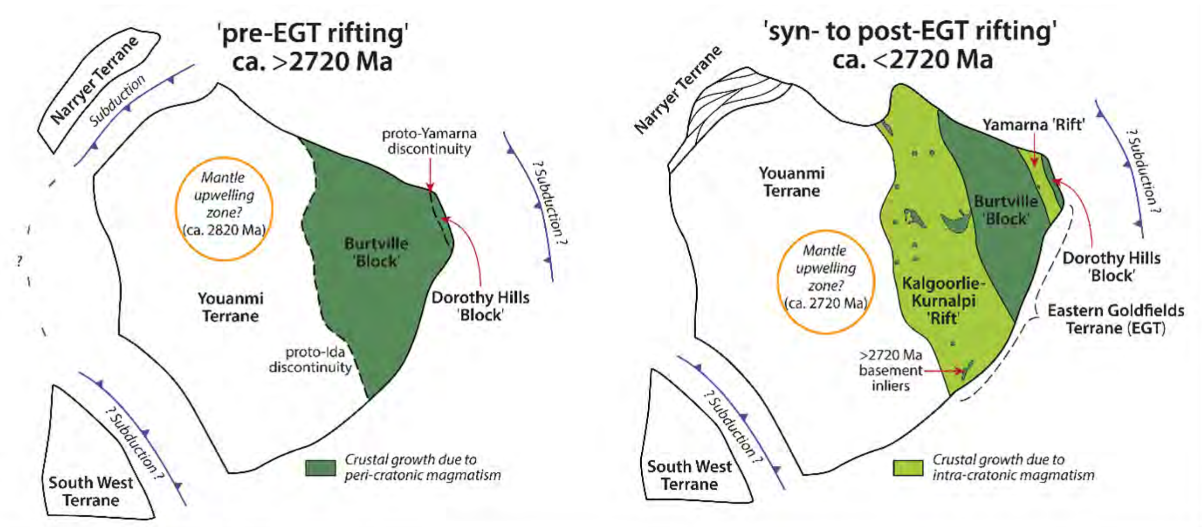



Figure 1. Revised Neoarchean crustal evolution of the Yilgarn Craton including the newly proposed subdivision of the Eastern Goldfields Terrane

# Paleo-Mesoproterozoic tectonics along the margins of Archean Bundelkhand Craton north-central India: constraints from U–Pb sensitive high-resolution ion microprobe zircon ages and supercontinent connections

**AK Shrivastava[1], MB Raza[2], L Saha[1*], K Yi[3], P Nasipuri[2], JK Pati[4]**

* corresponding author: saha.lopamudra@gmail.com

1. Department of Earth Sciences, Indian Institute of Technology, Roorkee, 247667, India
2. Department of Earth and Environmental Sciences, Indian Institute of Science Education and Research, Bhopal, 462066, India
3. Korea Basic Science Institute, Korea Basic Science Institute (KBSI), 162 Yeon Gu DanJi-ro, Ochang, Cheongjucity, ChungBuk, 28119, South Korea.
4. Department of Earth & Planetary Sciences, Nehru Science Centre, University of Allahabad, Prayagraj, UP 211002, India

U–Pb sensitive high-resolution ion microprobe (SHRIMP) ages have been determined from the sandstone of Par Formation of Gwalior Basin having conformable contact with the basement granite and sandstone unit of the Bhopal Basin. These basins respectively occur along the north-western and south-eastern margins of the Bundelkhand Craton in north-central India. Based on the geochemistry and discrimination diagrams, the basement rocks of the Gwalior basin are classified as A2-type granites. Rift-induced passive margin settings are determined for the deposition of the sandstones of Gwalior and Bhopal Basins.

The magmatic zircon grains from the basement granite of the Gwalior Basin yield a $^{207}Pb/^{206}Pb$ average age of 2538±2 Ma (MSWD = 1.44). The detrital zircons from the sandstone of Par Formation yielded two distinct age groups at c. 2564±24 Ma and c. 2044±2 Ma. In contrast, the detrital zircons from the Bhopal basin yield three distinct populations with a weighted average mean ages of 2511±5 Ma, 1694±6 Ma and 1355±9 Ma respectively. These three zircon populations also yield concordia ages of 2541±5 Ma, 1675±8 Ma and 1384±7 Ma respectively.

Presence of c. 2564 Ma detrital zircons with magmatic features in the sandstone of Gwalior Basin determines the maximum deposition age (MDA) of the clastic rocks and initiation of Gwalior Basin due to rifting. Prevalence of extensional tectonics during the same period is also evidenced from emplacement of A2-type basement granite in the basin and additionally in the Bundelkhand Craton. The younger weighted mean age c. 2044 Ma obtained from the rims of zircons from the sandstone sample of the Gwalior Basin constrain the second phase of zircon growth. This event is correlated with the intrusions of mafic dykes along the northern margin of the Bundelkhand Craton between 2100 and 2000 Ma.

Similarly, the youngest age population of c. 1384–1355 Ma from the sandstone of Bhopal Basin constrains the MDA for the unit. This event is correlated with extensional tectonics leading to emplacement of A-type granitoids along the Chotanagpur Gneissic Complex in the eastern segment of Central Indian Tectonic Zone along the southern margin of Bundelkhand Craton.

The 2500 Ma ages from the Gwalior granites are thus linked to global magmatic activity leading to the stabilization of extended Ur at c. 2500 Ma. The 2048 Ma and 1355 Ma ages from the Gwalior and Bhopal Basins respectively are correlated with the breakup of extended Ur and Columbia respectively.

# Interdisciplinary analysis of mantle structure suggests a North Caribou superterrane in the Superior craton, North America

**DB Snyder*, PC Thurston**

* corresponding author: dbsnyder1867@gmail.com

Metal Earth: Mineral Exploration Research Centre (MERC), Laurentian University, Sudbury Ontario, P3E2C6, Canada

Multiple blocks of crust >2.7 Ga in age or with older model ages appear throughout the Superior craton as isolated fragments. These terranes are today distributed radially, based on their oldest rock age, from old marginal terranes (Northern Superior and the Minnesota River Valley) through those with significant crustal gneiss blocks (North Caribou, Winnipeg River, Marmion, and Opinaca) or rare indicators such as 3.5–3.1 Ga model ages in northern Wabigoon, to younger central terranes (Abitibi, Pontiac and Wawa). This distribution is not typical of modern accreted continental margins that exhibit a consistent younging direction. Component terranes play a pivotal role in reconstructions of Archean tectonic histories that must consider the entire subcontinental lithosphere by using relevant observations of structures within both the crust and mantle. Multi-azimuthal receiver function analysis identified a regional Ps seismic discontinuity striking 065 and dipping at 7 degrees to the east–southeast within the mantle of the Superior craton. This strike roughly parallels that of: a previously recognized regional extensional fault striking 057º and dipping 18º within the western Superior crust; the axis of the turbititic Quetico Basin and an apparent Moho keel. Here we jointly interpret these seismic features as a detachment or décollement with characteristics of an unconformity, low-angle thrust and normal faults. An unconformity with quartz arenites characterizes the top of 2.9 Ga gneissic basement within the North Caribou terrane. Thrusting probably relates to the dominant phase of folding and horizontal shortening strain, mineralization and peak metamorphism that all occurred during the Kenoran (D2) crustal deformation at 2.72–2.66 Ga. Here we suggest that this shortening occurred when the distal margin of a composite North Caribou superterrane obliquely underthrust the entire lithosphere of the converging thinner, juvenile Abitibi-Wawa terrane along a low-angle, so-called 'flat slab' subduction trajectory.

Sulphide- and carbon-rich metasediments make good conductors. Conductivity patterns widely typical of the Superior craton suggest a whole lithosphere mineralizing system similar to that proposed beneath the Olympic Dam mine camp in the Gawler craton of southern Australia. Broad (100 km) mantle conductors at 90–110 km depth beneath the southern Abitibi underlie strong conductors within the mid-crust observed amid a generally conductive zone at 15–30 km depth. Historical 'breaks' represent steep, isoclinal folds or thrust faults within upper crustal greenstones that detach within mid-crustal gneisses and some older through-going steep crustal structures. Isolated conductors core these isoclinal fold or fault zones and thus connect the mid-crustal conductive zone to the near-surface along mapped high-strain zones. We propose metal-rich turbiditic sediments on top of the North Caribou superterrane margins were underthrust to 80–120 km depths, melted and rose within the Abitibi lithosphere as carbonatitic fluids, concentrating and depositing gold and other economically important metals where conductors occurred.

# A modern analogue for partial convective overturn basins: provenance and sedimentology of the Parriott salt mini-basin

**EJ Stoll*, N Drabon**

* corresponding author: estoll@fas.harvard.edu

Earth and Planetary Science Department, Harvard University, Cambridge, MA 02138, USA

The tectonic environment of the early Earth is a key issue in Precambrian geology (e.g. Palin and Santosh, 2021). One proposed setting to exist before modern plate tectonics is partial convective overturn (PCO) driven by a density instability between light felsic plutonic rock emplaced beneath dense mafic and ultramafic volcanic deposits (Van Kranendonk et al., 2007). However, what the basinal record would look like is not understood due to the lack of a modern analogue. A potential, if imperfect, model exists in modern salt basins. They form through similar gravitational instabilities, causing diapirism of underlying salt and accommodation developed through sagging of the overlying sediments. In this project we study the sedimentology and provenance of the Parriott salt mini-basin of the Paradox Basin, United States, as a potential analogue for PCO settings.

Results highlight the impact of salt diapirism on the basin infill, sedimentology and structure. Clast counts of conglomerates deposited during diapirism show an unroofing sequence: initial reworking of immediately underlying siliciclastics, followed by older fossiliferous limestone and lastly erosion into the salt diapirs. The basin evolution shows a shift from a braided channel complex into a lacustrine environment as accommodation increases with diapirism. Paleoflow indicates an initial shedding of sediment off the rising diapirs followed by a more mixed signal, including longitudinal transport and breaching of the salt walls during slower rates of salt diapir growth (Trudgill, 2011). The basin is symmetric, with uplift occurring on both sides of the sinking crust, despite a potentially different rate and height of uplift of each diapir (Trudgill, 2011). Angular unconformities during times of an increased rate of diapirism are present adjacent to the salt diapirs, but diminish to conformable surfaces towards the centre of the basin.

Based on these results, an unroofing sequence and symmetric geometry may be key indicators of a PCO basin. Sedimentology would be dictated by the rate of diapirism and thus accommodation, and paleoflow should come from the uplifted domes formed by diapirism during times of rapid uplift. Additionally, an angular unconformity close to the basin margins would be consistent with PCO. Thus, identifying these features in an Archean basin would suggest it formed under non-uniformitarian tectonics and provide support for the existence of PCO in the early Earth.

## References

Palin, RM, & Santosh, M 2021, Plate tectonics: What, where, why, and when? Gondwana Research, 100, p. 3–24.

Trudgill, BD 2011, Evolution of salt structures in the northern Paradox Basin: Controls on evaporite deposition, salt wall growth and supra-salt stratigraphic architecture. Basin Research, 23(2), p. 208–238.

Van Kranendonk, MJ, Smithies, HR, Hickman, AH, Champion, DC 2007, Review: Secular tectonic evolution of Archean continental crust: interplay between horizontal and vertical processes in the formation of the Pilbara Craton, Australia. Terra Nova, 19(1), p. 1–38.

# Xenolith constraints on the lithospheric architecture and mantle geochemistry of the South Australian Craton

**ZJ Sudholz*, GM Yaxley, AL Jaques**

* corresponding author: zachary.sudholz@ANU.edu.au

Research School of Earth Sciences, The Australian National University, Canberra, ACT 0200, Australia

The lithology, geochemistry and architecture of the subcontinental lithospheric mantle (SCLM) underlying the South Australia Craton has been constrained using pressure (*P*) and temperature (*T*) estimates and mineral compositions for >4000 garnet and diopside mantle xenocrysts from >10 Jurassic kimberlites. We show that lithospheric thickness is greatest (>200 km) beneath the central Gawler Craton, whereas thinner lithosphere occurs beneath the eastern Nackara Arc (Adelaide Fold Belt). Xenocryst compositions define two lithochemical domains within the shallow and deep SCLM that are separated by a mid-lithosphere discontinuity (MLD). The shallow SCLM (60–130 km) comprises low $Cr_2O_3$ lherzolite and wehrlite, with depleted and refertilized compositions enriched in light rare earth elements. The mid-lithosphere (130–160 km) is depleted in garnet and Cr diopside and has strong-negative seismic receiver functions calculated from nearby permanent seismic stations. We interpret these properties to reflect minor amounts of pargasitic amphibole in highly refertilized lherzolite. The deep SCLM (>160 km) comprises high $Cr_2O_3$ lherzolite with elevated $TiO_2$ and FeO, and depleted (0.91–0.93), which relate to previous melt extraction events and prolonged high-T melt metasomatism along the lithosphere base. We interpret the lithochemical stratification of the SCLM to reflect a multi-stage top-down growth (Fig. 1). The shallow SCLM reflects an amalgamation of Precambrian cratonic nuclei characterized by heterogeneity in geochemical enrichment and depletion. Interaction of the shallow SCLM with mantle plumes accreted melts along the paleo-lithosphere–asthenosphere boundary, which now occurs as a MLD. The deep SCLM represents depleted mantle residue formed during mantle plume impingement and thickened during orogenesis.

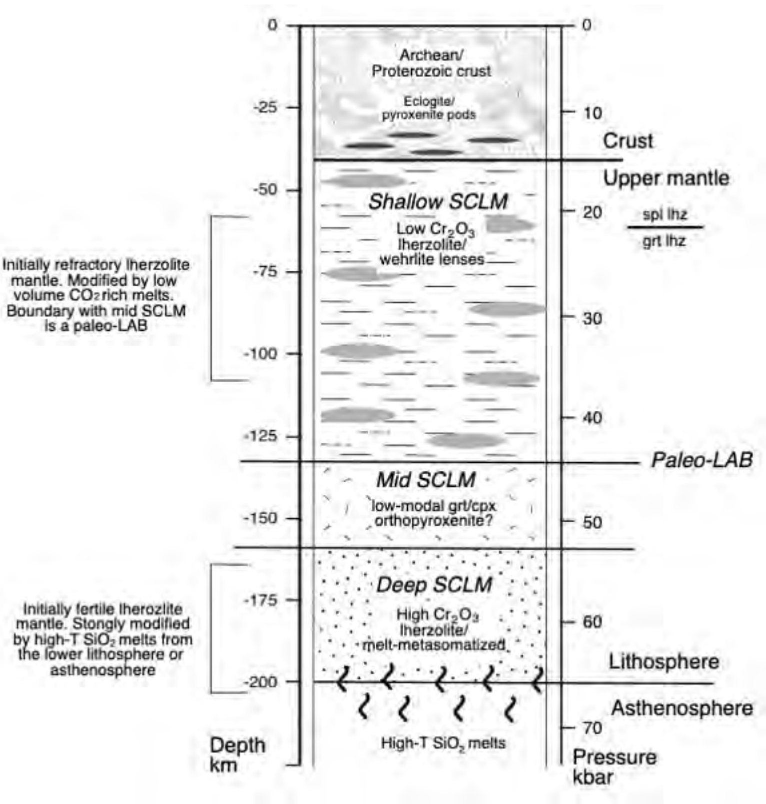



Figure 1. Lithochemical stratigraphy of the South Australian Craton SCLM

# Structural and lithostratigraphic record of the Agnew-Wiluna Belt: tectonic implications for the Yilgarn Craton

**N Thébaud[1*], Q Masurel[1,2]**

* corresponding author: nicolas.thebaud@uwa.edu.au

1. School of Earth Sciences, Centre for Exploration Targeting, University of Western Australia unit, Crawley WA, Australia
2. Minerals Targeting International Pty Ltd, West Perth, WA, Australia

Over the last couple of decades, structural schemes proposed for the Yilgarn Craton largely derived from the structural record acquired in gold and nickel deposits. Such structural schemes present complex deformation paragenetic tables (i.e. local paleo-stress history tables) pointing towards with 4 to 10-stage structural schemes (e.g. Duuring et al., 2012). The problems associated with such an approach is that it commonly ignores the partitioning of protracted, convergent deformation that generated large-scale (10–100 km) finite strain patterns; the importance of critically defining regional deformation phases with respect to major tectonic events and/or significant changes in tectonic conditions and the fact that the first-order geometric and kinematic characteristics of upper-crustal deformation in wide, hot orogens, can be explained by orogen-parallel gradients in crustal strength.

In this contribution we focus on the tectonomagmatic evolution of the Agnew-Wiluna Greenstone Belt (AWB) in the Yilgarn Craton. We present a coherent structural history for the AWB constructed using regional geophysical data, seismic reflection data, lithostratigraphic compilation and structural data from surface exposures. We propose that the feedback between inhomogeneous, east-west-directed bulk crustal shortening and magmatism in a transpressive deformation regime induced cyclic weakeningthenhardening of the continental crust between c. 2680 and 2630 Ma, ultimately resulting in the observed finite strain pattern. Collectively the body of data collected in the Agnew-Wiluna Belt (AWB) depict a tectonic evolution similar to that documented in other geological domains and terranes across the Yilgarn Craton (e.g. Zibra, 2020).

## References

Duuring, P, Bleeker, W, Beresford, SW, Fiorentini, ML, Rosengren, NM 2012. Structural evolution of the Agnew–Wiluna greenstone belt, Eastern Yilgarn Craton and implications for komatiite-hosted Ni sulphide exploration: Australian Journal of Earth Sciences, v. 59, p. 765–791.

Zibra, I 2020. Nearchean structural evolution of the Murchison Domain (Yilgarn Craton): Precambrian Research 343:105719.

# Craton modification as identified from geophysical observation

**H Thybo**

h.thybo@gmail.com

SinoProbe laboratory, Chinese Academy of Geological Sciences, China
China University of Geological Sciences, Wuhan, China
Eurasia Institute of Earth Sciences, Istanbul Technical University, Turkey

Abundant evidence shows that 'stable' cratons are modified during their existence, as illustrated in several cases.

The Baltic Shield formed during the Svecofennian orogeny c. 1.7 Ga and its western parts were reworked by the Sveconorwegian/Grenvillian orogeny. Recent geophysical interpretations image a large body of crustal material in eclogite facies beneath the present Moho in the central shield. This body probably formed after the initial cratonization (Buntin et al., 2021).

The isopycnicity hypothesis proposes that a trade-off between composition and temperature of the lithospheric mantle maintains constant topography in cratons (Jordan, 1978) based on kimberlite data from South Africa. However, gravity data from Siberia shows that kimberlite pipes solely modify cratons in isostatic equilibrium (Artemieva et al., 2019). Therefore, kimberlite sampling is non-representative, and the real composition of most cratonic mantle lithosphere is unknown.

Strong seismic anisotropy is observed in many cratons and is commonly attributed to the mantle due to frozen-in lithospheric features or asthenospheric flow. Recently it was demonstrated that a major part of the anisotropy resides in the crust of the Kalahara craton and that the fast axes are parallel to the strike of major dyke swarms and orogenic fabric (Thybo et al., 2019). This finding indicates significant craton modification by magmatic intrusion.

Modification by external stresses and induced magmatism may even split existing cratons. Integrated interpretation of existing data and geodynamic modelling show that a linear sequence of volcanic harrats in the Arabian craton potentially represents the formation of a new plate boundary (Artemieva et al., 2022). It is probable that the extension in the northern Red Sea rift will jump to the volcanic lineament, which eventually will develop into new ocean spreading and effectively split the existing craton.

## References

Artemieva, I.M.. Lithosphere structure in Europe from thermal isostasy. Earth Sci. Rev. 188, 454–468 (2019).

Artemieva, I.M., Yang, H., Thybo, H. Incipient ocean spreading beneath the Arabian shield, Earth-Science Reviews, 226, 103955 (2022)

Buntin, S., Artemieva, I.M., Malehmir, A. et al. Long-lived Paleoproterozoic eclogitic lower crust. Nat Commun 12, 6553 (2021).

Jordan, T. Composition and development of the continental tectosphere. Nature 274, 544–548 (1978)

Thybo, H., Youssof, M. & Artemieva, I.M. Southern Africa crustal anisotropy reveals coupled crust-mantle evolution for over 2 billion years. Nat Commun 10, 5445 (2019)

# Ultra-high thermal gradient granulites in the Narryer Terrane, Yilgarn Craton, Western Australia, provide a window into the composition and formation of Archean lower crust

**NM Tucker[1*], J Hammerli[2], AIS Kemp[1], ML Rowe[1], CM Gray[1], H Jeon[3], MJ Whitehouse[3], MP Roberts[4]**

* corresponding author: naomi.tucker@uwa.edu.au

1. School of Earth Sciences, University of Western Australia, Perth, Australia
2. School of the Environment, Washington State University, Pullman, USA
3. Swedish Museum of Natural History, Box 50 007, SE-104 05, Stockholm, Sweden
4. Centre for Microscopy, Characterisation and Analysis, University of Western Australia, Perth, Australia

Granulites from the Narryer Terrane in the northern Yilgarn Craton, Australia, record evidence for high to ultrahigh thermal gradients during the Meso–Neoarchean. U–Pb zircon ages reflect a complex history of high-grade, prolonged and poly-phase metamorphism, with evidence for several thermal pulses at c. 2745–2725 Ma, c. 2690–2665 Ma and c. 2650–2610 Ma (Fig. 1). Forward phase equilibria modelling on rocks with varying bulk compositions and mineral assemblages suggest that peak temperatures reached 880–920 °C at pressures of 5.5–6 kbar at c. 2690–2665 Ma, followed by near-isobaric cooling. These new pressure–temperature results also indicate that these rocks underwent some of the hottest thermal gradient regimes in the metamorphic record (≥150 °C/kbar; Fig. 1). Previous models have inferred that ultrahigh thermal gradients and coeval large-scale anatectic melting in the Narryer Terrane were primarily generated by mantle-driven processes, despite most of the lithological, isotopic and geochemical observations being at odds with the expected geological expression of large-scale mantle upwelling. We re-evaluate the mechanisms responsible for generating extreme thermal gradients in the Narryer Terrane and propose that long-lived high crustal temperatures between c. 2690 Ma and 2610 Ma were instead facilitated by elevated radiogenic heat production in thickened, highly differentiated ancient crust. Our findings suggest that mantle-derived magma input and new crustal addition may not be the only drivers for high- to ultrahightemperature metamorphism and cratonization of ancient crustal blocks.

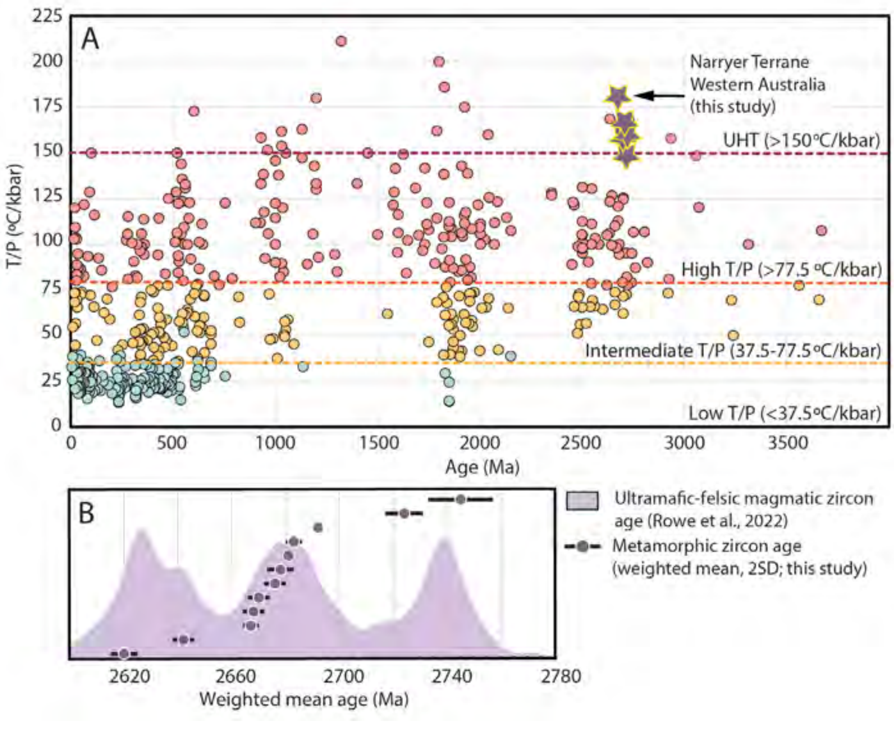



Figure 1. Metamorphic ages and thermal gradients of Narryer Terrane granulites compared with a global metamorphic dataset (A) and regional magmatism (B)

## Reference

Rowe, ML Kemp, AIS, Wingate, MTD, Petersson, A, Whitehouse, MJ & van der Riet, C 2022, Precambrian Research, v. 372, 106609

# Lithospheric architecture and evolution of the Archean northeast Congo craton revealed by O–Hf isotopes in zircon

**RE Turnbull[1,2*], AH Allibone[3], CM Fanning[4], F Matheys[5], E. Kasereka[3], J Kabete[6], NJ McNaughton[7], R Jongens[1], E Mwandale[3], J Holliday[3]**

* corresponding author: ret26ster@gmail.com

1. Anatoki Geoscience Ltd, 25 Jackson Street, Te Anau 9600, New Zealand
2. GNS Science, Dunedin Research Centre, Private Bag 1930, Dunedin 9054, New Zealand
3. Barrick Gold Corporation, 3700-161 Bay St., Toronto, Ontario MSJ 2S1, Canada
4. Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
5. Loncor Resources Inc, 1 First Canadian Place, Suite 7070, 100 King Street West, Toronto, Canada
6. Mazoka Resources Limited, 11 Usutu Avenue, Sandton, Johannesburg, South Africa
7. John de Laeter Centre, Curtin University, Perth, WA 6845, Australia

Neoarchean terranes formed during one of the principal phases of crustal growth in Earth history and host some of the world's most significant mineral resources. Understanding the lithospheric architecture and tectonomagmatic evolution of Neoarchean terranes is therefore fundamental to understanding their potential mineral endowment. Archean rocks in the northeast Democratic Republic of Congo (DRC) underlie approximately 80,000 $km^2$ of the Congo Craton and are one of the least studied Archean terranes in the world. Here we report 74 laser ablation inductively coupled plasma mass spectroscopy Lu–Hf and 49 sensitive high-resolution ion microprobe oxygen isotope determinations on zircon from 69 granitoid and five siliciclastic sedimentary rocks from the northeast DRC. These data form part of the first regional-scale study of the geochronology and isotopic character of Archean rocks in the northeast DRC.

Felsic–intermediate magmatism across the northeast DRC occurred between c. 3200 and 2530 Ma with the principal episode of plutonism and crustal growth occurring between c. 2670 and 2530 Ma. This plutonism included three geochemically distinct suites. Firstly, an earlier sodic-calcic suite with high Sr/Y ratios, with a second broadly coeval calc-alkaline to high-K suite with low Sr/Y ratios emplaced between c. 2670 and 2600 Ma and thirdly, a largely younger ferroan, high-K calc-alkaline suite with elevated high field strength elements (HFSE) that were mostly emplaced between c. 2600 and 2550 Ma. A minor but distinct shift in zircon O–Hf isotopic values is observed between these two broad episodes of magmatism, with the two earlier magmatic suites characterized by more 'mantle-like' isotopic values ($\delta^{18}O$ = +4.5‰ to +7.0‰; $\varepsilon Hf_{(t)}$ = 0 to +4), and the younger HFSE-elevated suite characterized by 'crustal' evolved values (range of $\delta^{18}O$ = +5.0‰ to +7.7‰; $\varepsilon Hf_{(t)}$ = -1 to +2). This isotopic shift at c. 2600 Ma may reflect a minor increased contribution from recycled older supracrustal material. Alternatively, it could reflect input of hot, enriched asthenospheric mantle coupled with closed system fractionation that would also result in granitoids with these Hf and O isotopic characteristics. The ferroan, HFSE-elevated chemistry and lack of inherited zircon in the younger suite supports the latter interpretation.

Distribution maps of the Lu–Hf isotopic data highlight a clear isotopic boundary in the eastern part of the northeast DRC that coincides with the contact between Neoarchean plutons and the composite West Nile Gneiss which includes Mesoarchean granitoids emplaced as early as c. 3200 Ma. Zircon from the West Nile Gneiss have strongly negative $\varepsilon Hf_{(t)}$ values (range -8.6 to +2.0) which contrast with those of the more primitive Neoarchean plutons to the west. The range of U–Pb ages (3.2–2.6 Ga) and strongly evolved isotopic composition of granitoids from the West Nile Gneiss suggest that it is underlain by an ancient Meso–Paleoarchean lithosphere, some of which may have been in place as early as c. 3.8–4.0 Ga whereas lithosphere under the rest of the northeast DRC is Neoarchean in age. The boundary between the West Nile Gneiss and the Neoarchean granitoid terrane to the west is therefore likely a major trans-lithospheric structure whose scale and isotopic character are comparable with similar boundaries in the Archean Yilgarn and Superior cratons.

# Late Archean accretion of continental crust through oceanic subduction in the North China Craton

**X Wang[1*], SZ Li[1], YF Zheng[2]**

* corresponding author: wangx@ouc.edu.cn

1. Key Lab of Submarine Geosciences and Prospecting Techniques MOE, Ocean University of China, Qingdao, 266100, China
2. CAS Key Laboratory of Crust-Mantle Materials and Environments, University of Science and Technology of China, Hefei, 230026, China

The North China Craton (NCC) contains at least three continental nuclei, namely Jiaoliao, Xuhuai and eastern Alxa, two of which include ancient rocks as old as 3.8 Ga. It is distinguished from the majority of Archean cratons by its extensive records of 2.6–2.5 Ga mafic magmatism but rare records of 2.8–2.7 Ga magmatism. It is unknown which role this late-formed craton played in the Archean global tectonics. We present an integrated study of 845 suites of whole-rock major-trace element data and their associated zircon Hf and whole-rock Nd isotope compositions for three episodes of basaltic–andesitic magmatism at c. 2.88–2.73 Ga, 2.65–2.60 Ga and 2.56-2.50 Ga respectively from the whole NCC. The first two episodes of rocks are mostly distributed close to the three continental nuclei, whereas the 2.56–2.50 Ga rocks are widespread in the craton. These rocks were divided into light rare earth elements (LREE)-depleted tholeiitic basalt, LREE-enriched tholeiitic basalt, tholeiitic andesite, calc-alkaline andesite and sanukitoids mainly based on their $SiO_2$ contents, $(La/Sm)_N$ ratios, La/Yb and Sr/Y ratios and Sr-Ba concentrations. These five groups generally have arc-like trace element distribution patterns, with variable enrichments in fluid-mobile incompatible trace elements, which are consistent with their water contents calculated by their Mg–Fe variations. Such coupling features suggest that their mantle sources were enriched by subducting oceanic slab-derived fluids in the forms of aqueous solutions and hydrous melts. Compared to the other Archean cratons elsewhere on Earth, the NCC is significantly deficient in komatiites and komatiite-related rocks, but contains much higher proportions of the LREE-enriched basalts and calc-alkaline andesites. This difference suggests that plate tectonics gradually replaced mantle plume in dominating the continental growth during the late Archean. Such reasoning was further strengthened by the formation of 2.75 Ga metavolcanic rocks from the Alxa block in the westernmost NCC. The felsic volcanics show tonalite–trondhjemite–granodiorite (TTG)-like geochemical compositions, with variable zircon Hf–O isotope compositions that can be categorized into three groups. Group1 has high $\varepsilon Hf_{(t)}$ values of 8.5 ± 0.3 at t=2750 Ma and low $\delta^{18}O$ values of 4.3–5.6‰; group 2 exhibits $\varepsilon Hf_{(t)}$ values of 1.8 ± 0.3 and elevated $\delta^{18}O$ values of 5.7–7.0‰, and group 3 shows moderately high $\varepsilon Hf_{(t)}$ values of 3.9 ± 0.4 but the highest $\delta^{18}O$ values of 5.6–7.9‰. Their magma sources would be the overthickened oceanic crust that was generated through seafloor spreading at different ages and underwent seawater hydrothermal alteration at different temperatures. Several failed subductions caused these oceanic crusts to collide with the continental nucleus, which was finally replaced by a successful subduction leading to both partial melting of the thickened crusts and the metasomatized mantle wedge.

# Exhumation of an Archean granulite terrane by paleoproterozoic orogenesis: evidence from the North China Craton

**D Wang[1*], RN Mitchell[2,3], JH Guo[2,3], FL Liu[1]**

* corresponding author: wangd221@gmail.com

1. Key Laboratory of Deep-Earth Dynamics of Ministry of Natural Resources, Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China
2. State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
3. Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China

Granulites represent high-grade metamorphic rocks of the deep continental crust. The metamorphism and exhumation of granulites from Archean terranes provide insights into the crustal evolution of Archean cratons and shed light on the formation and reactivation of cratons. We present petrology, U–Pb geochronology (zircon, rutile and titanite) and pressure-temperature (*P–T*) paths for metadiabase dykes in a deep-seated Archean granulite terrane of the North China Craton. Garnet (Grt) coronae in the metadiabase dykes are developed between plagioclase (Pl) and clinopyroxene (Cpx) via the reaction Pligneous + Cpx → $Pl_1$ + Grt ± quartz. The reaction proceeds inward within the plagioclase, progressively consuming Pligneous ($X_{An}$ = 0.65–0.69) and leaving Ca-poor Pl1 ($X_{An}$ = 0.46–0.53) as the residue. Geothermobarometry and *P–T* pseudosections suggest peak conditions for garnet formation at 800–850 °C and 10–12.5 kbar. During retrograde metamorphism, Grt broke down to Ca-rich $Pl_2$ ($X_{An}$ = 0.73–0.74), and ilmenite replaced rutile. Geothermobarometry suggests the *P–T* conditions of retrograde metamorphism as 700–750 °C and 4.5–7.5 kbar. Zircon and titanite U–Pb geochronology shows that the protolith of metadiabase dyke was formed at 2.4 Ga and underwent granulite-facies metamorphism at 1.86 Ga. The intrusion of mafic dykes into the Archean granulite terrane indicates that the Archean basement was also heated and buried in Paleoproterozoic. The metadiabase dykes and the hosting Archean basement underwent Paleoproterozoic granulite-facies metamorphism at a depth of approximately 40 km, followed by near-isothermal decompression and subsequent near-isobaric cooling at depths of 15–25 km. Crustal shortening and thickening may have been caused by the underplating of the Khondalite series beneath the Archean basement during the amalgamation of supercontinent Columbia. The Paleoproterozoic orogeny induced a second-generation metamorphism of the Archean basement along the margin of the craton and drove the exhumation of the Archean granulite terranes to the middle crust.

# A multi-layer isotopic approach to explore the crustal basement of Australia

**B Ware[1*], A Zametzer[2], J Liebmann[2], CL Kirkland[2]**

* corresponding author: bryant.ware@curtin.edu.au

1. John de Laeter Centre, Curtin University, Perth, WA 6845, Australia

2. Timescales of Mineral Systems Group, School of Earth and Planetary Sciences, Curtin University, Perth, WA 6845, Australia

The advent of neodymium (Nd) isotope maps of selected terranes in Australia, more recently complemented by zircon hafnium (Hf) and whole rock / ore lead (Pb) isotope maps (e.g. Geoscience Australia's 'Isotopic Atlas of Australia'), allows a powerful image of the (covered) crystalline basement to be resolved. These individual radiogenic isotope systems provide distinct (often complementary) constraints on geological processes, geological reservoirs and rock types (Champion and Huston, 2016). Furthermore, identifying isotopic signatures from different material scales (e.g. single mineral, mineral populations to whole rock) can further elucidate geologic processes from mineralization to global secular changes in crustal evolution. Taking a multi-layered approach extended to isotopic systems at different analytical scales, may allow different fractionation processes to be tracked and inform on the extent of secondary alteration. For example, hydrothermal alteration may greatly affect the Rubidium (Rb) – Strontium (Sr) system when investigating the whole rock yet initial compositions may be retained within either specific minerals (e.g. apatite) unaffected by alteration or recrystallization (e.g. Creaser and Gray, 1993); or where a different isotopic system may remain undisturbed (e.g. Sm–Nd). Furthermore, different isotopic systems within different minerals will also have dissimilar detection limits permitting a more complete spatial coverage. Here we compile literature and newly acquired isotopic data from a variety of radiogenic isotope systems determined at the crystal to whole rock scale to identify inconsistencies or differences in isotopic behaviour at the terrane scale. Specifically, we present the results of a case study from a suite of granitic samples across the Ida Fault in the Yilgarn Craton, Western Australia. Utilizing the power intrinsic to differing sensitivities of isotopic systems to geologic processes, we aim to derive cumulative maps that provide new insights into crustal evolution and thus inform on the mechanisms that control mineralization. Comparison of isotopic tracer maps with geochronology layers (e.g. uranium–lead) provides the framework for the 4D understanding of a wide range of natural processes.

## Reference

Champion, DC and Huston, DL 2016, Radiogenic isotopes, ore deposits and metallogenic terranes: Novel approaches based on regional isotopic maps and the mineral systems concept. Ore Geology Reviews v.76, p.229–256, https://doi.org/10.1016/j.oregeorev.2015.09.025

Creaser, RA and Gray, CM 1993, Preserved initial 87Sr/86Sr in apatite from altered felsic igneous rocks: A case study from the Middle Proterozoic of South Australia. Geochimica et Cosmochimica Acta v.56, p.2789-2195, https://doi.org/10.1016/0016-7037(92)90359-Q

# Continental growth at Neoarchean cratonic margins

**DA Wyman[1*], PN Hollings[2]**

* corresponding author: derekwyman@sydney.edu.au

1. School of Geological Sciences, University of Sydney, Sydney NSW 2006, Australia
2. Lakehead University, Thunder Bay ON P7B 5E1, Canada

Studies of c. 2.72 Ga mafic–ultramafic volcanic sequences from the Lake of the Woods belt in the Wabigoon subprovince and the Shebandowan belt of the Wawa Abitibi subprovince provide new context for the Neoarchean evolution of the Superior Province Craton's southern margin. For clarity, we refer to rock types here in the framework provided by Pearce and Reagan (2019).

In the Lake of the Woods area, sampled outcrops were part of the c. 2720 Ma 'Upper Keewatin' assemblage where the ultramafic-bearing sequences occur conformably within dominantly calc-alkaline sequences. Well-preserved primary textures are found in intermediate and mafic rocks in the Lake of the Woods volcanic, including pillows and bedding. Ultramafic rocks, however, are generally schists consisting mainly of talc, tremolite and chlorite and no spinifex textures were observed. Possible spinifex texture has previously been reported but only in samples with less than 16% MgO. Two chemically distinct ultramafic groups (MgO >22 wt%) are recognized. One is boninitic with $Al_2O_3/TiO_2 \approx 25$, while the other displays $Al_2O_3/TiO_2 \approx 21$. Picrites are common Mg-rich rock types in the region but siliceous high Mg basalt (SHMB) and boninites also occur. Gaps on the trends observed on element–element plots between the ultramafic and mafic rocks indicate the various rock types do not represent crystal fraction of komatiite magmas. Instead, the ultramafic rocks likely contain accumulated olivine.

In the Shebandowan area, mafic–ultramafic intrusions occur in broadly contemporaneous 2720 Ma tholeiitic and calc-alkaline volcanic sequences. The intrusions may contain locally well-preserved olivine and pyroxene cumulates. Pillowed flows are commonly preserved in the mafic rocks but most ultramafic rocks are strongly recrystallized. No differentiated komatiite flow structures have been observed and spinifex textures are not observed in ultramafic rocks, although random acicular secondary amphibole may occur. Genuine clinopyroxene spinifex and randomly distributed clinopyroxene locally consist of partially preserved elongate, zoned blades. The textures may be present in a variety of non-komatiitic rocks (e.g. MgO = 11.5 wt%) including SHMB, picrites, low-Ti basalts, and boninites.

The c. 2720 Ma volcanic sequences of the southwestern Superior Craton document the repetition and close association of tholeiite, calc-alkaline and rifted margin – proto-arc volcanism along the craton's margin. Collectively, the evidence from along the southern Superior Craton suggests crustal growth near the temporal transition to modern-style plate tectonics involved episodic subduction at rifted cratonic margins. The occurrence of plume(s) near the margin, as recorded near the top of the Abitibi belt's Pacaud assemblage and in younger assemblages, points to comparatively small mantle upwellings that were intrinsically linked to active tectonics in the crust and upper mantle.

## Reference

Pearce, JA and Reagan, MK 2019, Identification, classification and interpretation of boninites from Anthropocene to Eaoarchean using Si–Mh–Ti systematics: Geosphere, v. 15, p. 1008-1037.

# A Greater Australia juxtaposed with the Greater India along northern East Gondwana

X Zhang[1,2*], J Xi[1,2]

* corresponding author: zxr@mail.iggcas.ac.cn; zxr627@163.com

1. State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China

2. College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing, China

A fundamental but challenging task in geology is the paleogeographic configuration of peripheral terranes (especially those in Asia) in Phanerozoic supercontinents or megacontinents, primarily owing to the paucity of high-quality paleomagnetic data and geologic records. In this study, we synthesized available detrital zircon data from relevant regions in South Asia to better reconstruct northern East Gondwana. Nearly identical Precambrian detrital zircon age patterns, characterized by predominant c. 1300–1000 Ma and 600–500 Ma age populations, are observed in the Lhasa, West Burma, East and West Sumatra, and East and West Java terranes, further comparable to those of the Collie, Perth, and Carnarvon basins along Western Australia. In addition, Precambrian detrital zircons from western and southwestern Borneo are dominated by c. 1870 Ma and 2520 Ma age populations, resembling those of Timor, Tanimbar, and Babar offshore Northern Australia (Kimberley to Pine Creek). Detrital zircons from southeastern Borneo, West Sulawesi, central Sulawesi metamorphic belt, and two microcontinents of Tukang Besi-Buton and Banggai-Sula define consistent major age populations of c. 1950–1800 Ma, 1450–1350 Ma and 440–200 Ma that are almost indistinguishable from those of Bird's Head, New Guinea. By contrast, age populations of c. 1000–850 Ma and 600–450 Ma prevail in detrital zircons from Sibusima (Sibumasu excluding East Sumatra) and South Qiangtang, further similar to those of Tethyan and High Himalayas of northern India. Based on the above observations, we put forward an innovative term, namely Greater Australia (approximately 2000 km by 2000 km), consisting of Precambrian–Mesozoic basement rocks of Sumatra, Lhasa, West Burma, Java, Borneo, and Sulawesi, and propose a new paleogeographic reconstruction of northern East Gondwana involving a Greater Australia lying side by side with the Greater India that was once situated between South Qiangtang and Sibusima to the north and Tethyan and High Himalayas to the south. The Greater Australia underwent a long-lasting fragmentation into smaller continental blocks or terranes during the successive opening of the Tethyan and Indian oceans in the Paleozoic to Cretaceous, contrasting to the Greater India that vanished during India–Asia collision in the Cenozoic. Our new tectonic reconstruction challenges current understanding of Gondwana dispersion and Asian accretion.

# Interrogating the record of Archean tectonics from metamorphism in the Minnesota River Valley, USA (Superior Province)

**Y Xu[1], RM Holder[1], DR Viete[2]**

* corresponding author: xyiruo@umich.edu

1. University of Michigan, Ann Arbor MI 48109-1005, USA
2. Johns Hopkins University, Baltimore, MD 21218, USA

If and how plate tectonics operated in the Archean remains a controversial topic. The Minnesota River Valley (MRV) gneiss terrane in the southernmost part of the Superior Province contains a variety of tectonic 'blocks' with diverse igneous and metamorphic rocks dating back to over 3.5 Ga. Therefore, its geologic history provides valuable insights into the tectonic processes that shaped the early continents. This study focuses on the granulite-facies Montevideo and amphibolite-facies Morton blocks of MRV, which are separated by the east-trending Yellow Medicine shear zone. We combined inverse thermobarometry calculations and phase-equilibrium modelling to constrain the pressure (*P*) and temperature (*T*) of peak metamorphism in the two blocks. The Morton amphibolite-facies metamorphic conditions are inferred to be 610–760 °C and 3.8–6.3 kbar, and the Montevideo granulite facies to be 800–860 °C and 4.4–7.0 kbar. The two blocks are likely metamorphosed together by advective heating due to plutonism at c. 2.6 Ga. We also performed zircon and monazite U–Pb geochronology and garnet diffusion chronometry to obtain ages and duration of metamorphism. The *P–T–t* data is used to determine the tectonic and thermal conditions of Archean metamorphism in the two blocks and whether significant lateral translation of the blocks — akin to modern plate tectonics — could have caused their juxtaposition.

# New seismic observations of the West Australian Craton from dense array deployments

**H Yuan[1,2,3], X Xu[4], T Li[5], K Wang[5], M Dentith[2], S Johnson[1], R Murdie[1], K Gessner[1], L Zhao[5]**

* corresponding author: huaiyu.yuan@dmirs.wa.gov.au

1. Geological Survey of Western Australia, East Perth, WA 6004, Australia
2. Centre for Exploration Targeting, University of Western Australia, Perth, WA 6009, Australia
3. ARC Centre of Excellence for Core to Crust Fluid Systems, Macquarie University, Macquarie Park NSW 2109, Australia
4. Tsinghua University, Haidian, Beijing 100190, China
5. Institute of Geology and Geophysics, Chinese Academy of Sciences, Chaoyang, Beijing 100029, China

The West Australian Craton (WAC) includes the Archean Pilbara and Yilgarn Cratonic nuclei, which were sutured and partially reworked by Proterozoic orogens and affected by Mesozoic rifting during the breakup of Gondwana. Recent dense seismic arrays have greatly improved the seismic coverage in Western Australia, particularly in the WAC. Here we present some provisional findings and discuss their potential tectonic implications for craton assembly and modification processes, with an emphasis on the craton margins.

- With decreasing age of formation and reworking the crust generally becomes thicker, more mafic and its Moho less well defined. This is interpreted as a change in the effectiveness of lower crustal removal and implies that overall the lithosphere became progressively stronger, making discrete mechanical failure more likely.
- The craton margins, repeatedly altered by pre- and post-cratonization deformation, have much thicker crust that often includes a high-velocity lower portion and a buckled (or imbricated) and dipping Moho.
- The northwestern part of the Yilgarn Craton, the Narryer Terrane, which contains the WAC's oldest, Paleo–Archean rocks and c. 4.4 Ga detrital zircon grains within younger metasedimentary rocks, has the thickest crust of the craton, but lacks its characteristic thick lithospheric keel.
- Fragments of Archean crust have been imaged within the Paleoproterozoic orogens, possibly representing former microcontinents.
- The WAC lithosphere is internally heterogeneous, with large velocity variations across terrane boundaries and a high-velocity dipping structure at its northern boundary.
- Along terrane boundaries, high-velocity mid- to lower crustal structures, sometimes abrupt crustal velocity domain changes, are often present beneath surface mineral deposits.

These new seismic observations are consistent with dominantly vertical and a distributed viscous deformation in the Archean nuclei, whereas the craton margins more commonly show localized, planar and shallow dipping structures. Our new seismic results support a transition from vertical to horizontal tectonics broadly across the Archean–Proterozoic transition. The spatial correlation with deposits with crustal-scale velocity anomalies suggests a deep origin of the surface mineral systems.

# Neoarchean vertical tectonism in eastern North China Craton: structure, metamorphism and numerical modelling

**J Zhang[1, 2*], C Zhao[2], CY Yu[2], T Yang[3], G Zhao[1], PA Cawood[4], C Yin[2]**

* corresponding author: jian@hku.hk

1. Department of Earth Sciences, The University of Hong Kong, Hong Kong
2. School of Earth Sciences and Engineering, Sun Yat-sen University, Guangzhou, China
3. Department of Earth and Space Sciences, Southern University of Science and Technology, Shenzhen, China
4. School of Earth, Atmosphere and Environment, Monash University, Clayton, Australia

The debate on the role of vertical versus horizontal tectonism in Archean cratons is intimately linked to the initiation time and mechanism of plate tectonics. The dome-and-keel architecture preserved in some Mesoarchean and older cratons, such as the Kaapvaal and Pilbara cratons, has an intrinsic relationship with vertical tectonism. Whether such a structural pattern also occurs widely in Neoarchean cratons remains poorly constrained. Determining the kinematics, geometry, structural evolution and the timing of these structures is crucial to understanding the tectonic regime of the early Earth. Our detailed mapping and structural analysis revealed that the eastern North China Craton preserves Neoarchean greenstone–granite rock association with typical dome-and-keel structures. Metamorphic data for these rock assemblages record both anticlockwise *P–T* paths involving near-isobaric cooling (IBC) and clockwise paths with nearly isothermal decompression (ITD) from nearby locations, leading to controversial and contradictory interpretations. To resolve the geodynamic process of such a dome-and-keel architecture and the presence of coexisting diverse *P–T* paths and to place them within a viable geodynamic regime, we conducted 2D thermomechanical numerical models with the initial and boundary conditions similar to that of the Neoarchean eastern North China Craton. Our model results reveal that heat transferred from the high-temperature lower boundary and crustal density inversion led to crustal-scale sagduction that generated the observed dome-and-keel architecture, resulting in four major types of *P–T–t* paths. Firstly, an anticlockwise IBC-type *P–T–t* path in which the supracrustal rocks progressively sink to a deep crustal level through sagduction and experience a long-lived residence followed by ambient mantle cooling without significant exhumation. Secondly, a clockwise ITD-type *P–T–t* path where the supracrustal rocks sink to the deep crust and are partly captured by upwelling felsic magmas, resulting in rapid exhumation to a middle crustal level. Thirdly, a newly identified crescent-type *P–T–t* path that reveals an integrated burial–exhumation cycle characterized by an initial high dT/dP burial stage, followed by the rapid exhumation to the upper crust and extensive low dT/dP cooling Lastly, a hairpin-type *P–T–t* path in which deeply buried supracrustal rocks experience a slow exhumation rate. The dome-and-keel architecture and *P–T–t* paths produced by the numerical model conform to the structural, metamorphic and geochronological data of the Eastern Block. We propose that the geological complexity of eastern China and temporally coexisting diverse *P–T–t* paths most likely developed under a mantle plume-related crustal-scale sagduction geodynamic regime in Neoarchean.

**Acknowledgement:** This study was financially supported by the NSFC (42025204, 41890831), The University of Hong Kong Seed Fund for Basic Research (201811159089), and the Australian Research Council (FL160100168).

# Tectonic setting of the Paleoproterozoic Inglefield mobile belt, North Greenland: zircon Hf–O isotopic constraints

**Q Zhang[1*], AP Nutman[2], X-H Li[1,3]**

* corresponding author: zqing0101@gmail.com

1. State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
2. GeoQuEST Research Centre, School of Earth, Atmospheric and Life Sciences, University of Wollongong, Wollongong 2522, NSW, Australia
3. College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China

This study focuses on the Paleoproterozoic Inglefield mobile belt, North Greenland, to investigate its evolution and lower crust architecture. By integrating the published zircon U–Pb data and new zircon Hf–O isotopic data, we answer the following questions. Firstly, for the arc magmatic rocks within the belt, what is the mix of those produced by entirely intra-oceanic arcs vs those formed in Andean-like marginal continental arcs? Secondly, within the Paleoproterozoic orogen–arc system, there are post-arc, syn- to late granite intrusions. These commonly carry inherited Archean zircons, indicating that there are allochthons of Archean rocks hidden in the deep crust. From the Hf isotopic signatures of these zircons, can they be matched with neighbouring Archean terranes or are there hitherto unrecognized buried exotic terranes beneath Paleoproterozoic arc rocks? Thirdly, the Inglefield mobile belt has within it metamorphosed clastic sedimentary rocks. For those with unimodal Paleoproterozoic detrital zircon populations, does the isotopic signature match that of coeval igneous arc-related rocks in the same orogen? For the sedimentary rocks with complex detrital zircon spectra, how well do the U–Pb–Hf signatures match those of adjacent Archean terranes or are they evidence of exotic cryptic terranes as thin slices along orogen margins? These questions will help to constrain the evolution of this early Precambrian mobile belt and therefore help answer whether the 'modern' plate tectonics exist in Early Precambrian in Greenland.

# Reworking of Eoarchean to Mesoarchean continental crust in the Anshan–Benxi area, North China Craton: evidence from the Lianshanguan potassic granitoids

**W Zhang*, P-H Liu**

* corresponding author: wzhan7@126.com

Institute of Geology, Chinese Academy of Geological Sciences, Beijing, 100037, China

The Anshan-Benxi area, one of the most important early Precambrian basements in China, is located in the northeast of the North China Craton. The area has not only the oldest rocks (c. 3.8 Ga) of China but also 3.8–2.5 Ga differently original granitoids (e.g. trondhjemite, syenogranite or monzogranite). The Lianshanguan batholith extends in an east–west direction with an area of approximately 250 $km^2$. Xenoliths in it are mainly from the Anshan Group, including magnetite quartzite, plagioclase-amphibolite and gneiss. The Lianshanguan granitoids are mainly composed of syenogranites ($K_2O$ > 4 wt% and $K_2O/Na_2O$ ratios >1.3) with some other granitoids such as monzogranite and potassium-rich granite. Laser ablation inductively coupled plasma mass spectrometry (LA–ICP–MS) U–Pb analyses of two syenogranites yielded concordant ages of 2541 ± 22 Ma and 2512 ± 13 Ma respectively. The features of strongly peraluminous compositions, Zr saturation temperatures (809 C on average), low 1000*Ga/Al ratios and Zr+Nb+Ce+Y contents, the existence of Al-rich minerals (e.g. muscovite) and high normative contents of CIPW corundum (mostly >1%), suggest that they are similar to S-type granites derived from partial melting of metasediments. In the 1/VSr/V diagram, the Lianshanguan syenogranites define a line with positive slope, suggesting that their compositional variation was mainly resulted from the mixing process. The syenogranites have zircon $\varepsilon Hf_{(t)}$ values of -20.19 to +4.9 with two-stage Hf model ages ($T_{DM2}$(Hf)) of 3.90–2.70 Ga and the $T_{DM2}$(Hf) age spectra show dominant peaks at 3.54 Ga, 3.45 Ga and 2.89 Ga and subordinate age peaks at 3.79 Ga, 3.74 Ga, 3.34 Ga and 3.02 Ga. Based on petrologic, geochemical and isotopic characteristics, we infer that the Lianshanguan syenogranites mainly resulted from reworking of complicated Eochean–Mesoarchean crustal materials with possibly a small portion of c. 2.7 Ga juvenile crustal materials and are extensively derived from the mixing of different melt end-members in various proportions. The $T_{DM2}$(Hf) ages of c. 2.5 Ga syenogranites from the Anshan–Benxi area are much more complicated than that of coeval syenogranites (two peaks at c. 2.8 Ga and c. 3.1 Ga) from the northern Liaoning and western Liaoning – eastern Hebei areas, indicating the late Neoarchean reworking of Eoarchean to Mesoarchean continental crust (including metasedimentary sources) in the Anshan–Benxi area, North China Craton.

# Seismic imaging of the southwest Yilgarn Craton with ambient noise tomography

**P Zhang[1*], H Yuan[2], MS Miller[1], R Pickle[1], R Murdie[2], K Gessner[2]**

* corresponding author: ping.zhang@anu.edu.au

1. Research School of Earth Sciences, Australian National University, Canberra ACT 2601, Australia
2. Geological Survey of Western Australia, Perth WA 6004, Australia

The geological structure of southwest Australia is complex and has a rich history of Precambrian cratonization and Phanerozoic continental breakup. This region is dominated by the Archean Yilgarn Craton, but its tectonic evolution has been a subject of controversy for over a century. Recent work by the Geological Survey of Western Australia has refined the terrane boundary between the South West Terrane and the Youanmi Terrane and has added geological context to mineral deposits in the southwest Yilgarn Craton. The Southwest Australia Seismic Network (SWAN) is a new temporary broadband network of 27 stations that has been deployed since July 2020 to record earthquakes for seismic hazard applications and to improve the rendering of 3D seismic structure in the crust and mantle lithosphere of southwest Australia (Miller et al., 2023). Using continuous data recorded by the SWAN and nearby stations, this study has produced a new 3D shear wave velocity model in the crust and uppermost mantle, using ambient noise tomography. Preliminary images show relatively high-velocity anomalies in the crust of the Yilgarn Craton and distinct low-velocity anomalies beneath the Perth Basin in the west, separated by the strong velocity contrast along the north–south trending Darling Fault. In the southwest Yilgarn Craton, we detect a prominent velocity contrast between the South West Terrane and the Youanmi Terrane in the lower crust to the uppermost mantle, which roughly coincides with the refined terrane boundary. These initial results are being integrated with other geophysical, geochemical and geological information to improve understanding of the unusual intraplate seismic activity and the geological history of the Archean Yilgarn Craton.

## Reference

Miller, M. S., Pickle, R., Murdie, R., Yuan, H., Allen, T. I., Gessner, K., ... & Whitney, J. (2023). Southwest Australia Seismic Network (SWAN): Recording Earthquakes in Australia's Most Active Seismic Zone. Seismological Research Letters.

# Reactivation of craton margins: insight from seismic images

**L Zhao[1*], K Wang[1], H Yuan[2,3,4], T Li[1], X Xu[1]**

* corresponding author: zhaoliang@mail.iggcas.ac.cn

1. State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
2. Geological Survey of Western Australia, Mineral House, 100 Plain Street, East Perth, Western Australia 6004, Australia
3. ARC Centre of Excellence for Core to Crust Fluid Systems, Department of Earth and Planetary Sciences, Macquarie University, New South Wales 2109, Australia
4. Centre for Exploration Targeting, University of Western Australia, 35 Stirling Highway, Crawley, Perth, Western Australia 6009, Australia

Characterized with positive buoyancy and high viscosity, Archean cratons are relatively flat, stable regions of the crust that have remained undeformed even though their margins may have suffered intermittent tectonic events. Inducing stress concentrations with strain localized at the boundaries, the margins help the craton to avoid destruction. Therefore, the knowledge of reactivation of craton margins plays an important role in our understanding of craton evolution.

The results from multidisciplinary studies, including geophysical, geological, and geochemical observations, suggest that the lithosphere of the North China Craton (NCC) has been extensively reactivated during the Late Mesozoic to Cenozoic. In contrast to the long-term stability of the western NCC, the eastern part has experienced a significant thinning from a thick (approximately 200 km) Archean or Proterozoic lithosphere to its current approximately 80 km-thick lithosphere. Almost all the boundaries of the NCC went through diverse deformations due to multiphase tectonic events surrounding it, including extensions and compressions. The NCC is therefore an ideal place to investigate the reactivation of craton lithosphere responding to different styles of tectonics.

In this study, we revisit seismic datasets collected from portable arrays crossing the boundary between the eastern and western NCC. We implement a cutting-edge trans-dimensional Bayesian tomographic inversion technique to invert ambient noise dispersion and surface wave dispersion data for shallow lithospheric shear wave velocity structure. By comparison with the interior structures across the boundary, we discuss the reactivation of craton margins in response to compression and extension deformations exerted by the mantle flow triggered by the Pacific Plate subduction and its implications for the secular change in the rheology of craton lithosphere.

# Neoarchean tectonic evolution of the Yilgarn Craton, Western Australia

**I Zibra**

ivan.zibra@dmirs.wa.gov.au

Geological Survey of Western Australia, East Perth, WA 6004, Australia

Structural studies are a significant but frequently neglected tool to improve our understanding of early Earth tectonic processes and geodynamic settings. Two end-member styles of Archean crustal deformation are generally termed 'dome-and-keel' and 'transpressional belts' (Choukroune et al., 1997). Dome-and-keel domains were shaped by the juxtaposition of rising granite batholiths and sinking denser greenstones, with a tectonic style dominated by gravitational instabilities and body forces. In contrast, transpressional belts are generally interpreted to reflect accretionary processes associated with production of juvenile crust along ancient crustal boundaries.

The Yilgarn Craton mostly exposes Meso- to Neoarchean granite–greenstone terranes that preserve evidence of large-scale tectonomagmatic events of Neoarchean age. In this context, recent structural studies suggest that large-scale structures that can be related to the two end-member tectonic styles outlined above are preserved in distinct parts of the craton. Dome-and-keel domains are exposed in the Yalgoo area, near the western end of the craton, reflecting periods of granitic diapirism that took place during pre-orogenic periods of prevailing lithospheric extension and tectonic quiescence (Zibra et al., 2020).

In contrast, the rest of the craton exposes a network of dominantly north-striking and steeply dipping shear zones that developed during the 2730–2660 Ma Yilgarn Orogeny (Zibra, 2020). The onset of the orogeny reflects the collision between the westernmost Narryer Terrane with the rest of the craton, post-dating a long period of lithospheric convergence and associated subduction episodes that are recorded in the structural, geochemical, geophysical and metamorphic record (Zibra et al., 2022).

Although several of the orogenic high-strain zones have been the subject of publications, a craton-wide perspective on the dominant tectonic style is currently missing and represents one of the main goals of this contribution. Here, I present a statistical evaluation of craton-wide structural data (n=1590) collected during the last 15 years. Furthermore, I combine this extensive structural dataset with stratigraphic and geochemical data, in order to gain fundamental insights into the tectonomagmatic evolution of the Yilgarn Craton and into Archean tectonics in general.

## References

Zibra, I 2020, Neoarchean structural evolution of the Murchison Domain (Yilgarn Craton). Precambrian Research, 343, 105719. https://doi.org/10.1016/j.precamres.2020.105719

Zibra, I, Kemp, AIS, Smithies, RH, Rubatto, D, Korhonen, F, Hammerli, J, Johnson, TE, Gessner, K, Weinberg, RF, Vervoort, JD, Martin, L and Romano, SS 2022, Greenstone burial–exhumation cycles at the late Archean transition to plate tectonics. Nature Communications, 13(1). https://doi.org/10.1038/s41467-022-35208-2

Zibra, I, Lu, Y, Clos, F, Weinberg, RF, Peternell, M, Wingate, MTD, Prause, M, Schiller, M and Tilhac, R 2020, Regional-scale polydiapirism predating the Neoarchean Yilgarn Orogeny. Tectonophysics, 779, 228375. https://doi.org/10.1016/j.tecto.2020.228375

# Theme 6
# Defining the Archean to Proterozoic transition

Invited Speaker
**Dr Indrani Mukherjee**
*Lecturer in Earth Sciences, University of New South Wales*

Keynote Speaker
**Associate Professor Andrey Bekker**
*Department of Earth and Planetary Sciences, University of California, Riverside, USA*

# Life on the edge of the Archean–Proterozoic transition

**I Mukherjee[1], R Large[2]**

* corresponding author: indrani.mukherjee@unsw.edu.au

1. University of New South Wales, Sydney NSW 2052 Australia
2. University of Tasmania, Hobart TAS 7001. Australia

The Archean–Proterozoic (AP) transition is marked by remarkable changes in Earth system processes including plate tectonics, glaciations and geochemical conditions of Earth's ocean-atmosphere system. Evidently, life navigated its way through these major fluctuations into the Proterozoic, towards greater complexity and diversity. This presentation will discuss major changes in Earth system processes and the biosphere, including the reciprocal nature of their interactions, during the AP transition. Several geochemical proxies have provided useful insights into this transitional period. While not all geochemical proxies are in agreement with one another, they do provide a unique perspective on different aspects of Earth system processes such as redox conditions, nutrient supply, biological evolution and economic mineralization. This presentation will focus on the chemistry of pyrite in marine black shales (approximately 2500 pyrite analyses) alongside other existing geochemical proxies, with an aim to highlight major controversies surrounding this transition period. For instance, whether the Great Oxidation Event was a sharp event at 2.33 Ga or a more prolonged event, beginning much earlier (c. 2.7 Ga). Geochemical trends (bio-essential trace metal archives) will also be discussed in light of biological evolution during the AP transition. While organisms of definite eukaryotic origins have been recorded in the Mesoproterozoic rock record, can we reconcile geochemical conditions of the AP transition with the evolution of proto-eukaryotes or eukaryotic cellular machinery?

# In search of the event-based definition for the Archean-Proterozoic boundary

**A Bekker**

andrey.bekker@ucr.edu

Department of Earth & Planetary Sciences, University of California, Riverside CA 92521 USA

There is growing interest to define the Archean–Proterozoic boundary as a synchronous and potentially global surface event. The rise of atmospheric oxygen in the early Paleoproterozoic, closely followed by the assembly and emergence of large landmasses and associated emplacement of Large Igneous Provinces (LIPs), was bracketed by three to four Snowball Earth events and led to the largest and longest positive carbon isotope excursion in seawater composition in Earth's history, the Lomagundi Event (LE). Since each of these events could be globally synchronous and widespread, they hold an eminent potential to define a Global Boundary Stratotype Section and Point (GSSP) that deserves to be considered.

Assembly of the supercraton Superia occurred over a protracted period that started in the late Neoarchean and continued to the early Paleoproterozoic, potentially ending at c. 2.3 Ga with the Arrowsmith orogeny in northwest Canada. Associated emplacement of LIPs affected all landmasses, but their ages cluster into several discrete groups that individually are not expressed on all continents. The initiation of the Great Oxidation Event (GOE), as defined by the disappearance of mass-independently fractionated sulphur (MIF-S) from sedimentary records, has been constrained between c. 2.45 and 2.43 Ga. However, the long-term disappearance of MIF-S has been recently considered to be either globally asynchronous or to correspond to a series of rises and falls in atmospheric oxygen in association with global glaciations. The Paleoproterozoic glaciations are generally imagined to have a global extent since there is strong evidence for glaciation at sea level near the paleoequator. However, diamictites in the Boolgeeda Iron Formation and the Koegas Subgroup, if indeed glacial, would correspond to regional-scale glaciations leading to the Snowball Earth events. Although three stratigraphic horizons with glacial diamictites are recorded in the Huronian and Snowy Pass supergroups of Ontario and Wyoming respectively, other Paleoproterozoic successions bear evidence for two, one or zero glaciations. Furthermore, synchronicity of Paleoproterozoic ice ages, in contrast to the Neoproterozoic glaciations, has to be tested with high-precision geochronology. Finally, the LE that was inferred to last between c. 2.22 and 2.06 Ga, might be mistaken for shorter-lived but similar magnitude excursions leading to the LE and occurring in its aftermath, before c. 2.0 Ga.

Pending future work to test synchronicity of the early Paleoproterozoic events with high-precision geochronology, it seems premature at this stage to define the GSSP based on any of these events that could be multiple and asynchronous worldwide. In contrast, the conventional approach based on the numerical value for the Archean–Proterozoic boundary avoids potential confusion and provides an independent framework to test the synchronicity and global extent of the early Paleoproterozoic events.

# The provenance of siliclastic sedimentary rocks of the Archean–Paleoproterozoic transition drilled in the FARDEEP project in Fennoscandia

**C Gärtner*, H Bahlburg**

* corresponding author: claudiagaertner@uni-muenster.de

Institut für Geologie und Paläontologie, Westfälische Wilhelms-Universität, Münster, Germany

The formation of siliciclastic sedimentary rocks during the Archean–Paleoproterozoic transition was governed by weathering processes under an oxygen-free atmosphere in tectonic settings linked very likely to hot and shallow subduction processes. The detritus contained in lowermost Paleoproterozoic sedimentary rocks should reflect the Archean evolution of its sources in general and the Neoarchean evolution in particular.

We report on a provenance study of Paleoproterozoic siliciclastic, partly volcanoclastic sandstones and greywackes and the matrix of diamictites (2.5–1.9 Ga) from the Pechenga and Imandra-Varzuga greenstone belts of Fennoscandia, based on a combination of single grain heavy mineral analysis, whole rock geochemistry and U–Pb and Hf isotope systematics of detrital zircons. The rocks contain up to 40% pseudomatrix but still preserve a highly variable spectrum of stable and labile heavy minerals, including rutile, zircon and tourmaline but also amphibole, garnet, titanite, spinel, pyroxene and epidote. Nb/Cr ratios in rutile indicate that minerals had been derived from mafic and predominantly felsic rocks. These data reflect the presence of mafic and evolved felsic lithologies in the source areas. Th/Sc ratios in strata deposited between 2.5 and 2.0 Ga are mostly between 0.1 and 0.6, typical of the sourcing (Neo) Archean crust. Detrital zircon ages range from 3.7 Ga to c. 1.9 Ga with most samples yielding a prominent population of Archean ages between 2.9 and 2.6 Ma. The youngest detrital zircon age populations from the glaciogenic Neverskrukk and Polisarka formations constrain the Huronian glaciation in Fennoscandia to c. 2.41 Ma. The overlying Kolosjoki and Kuetsjärvi formations deposited between c. 2.1 and 1.9 Ga have additional age distribution maxima between 2.1 and 1.9 Ga and give further evidence in support of syndepositional magmatism.

Initial εHf isotope values of Archean-aged zircons range between +7 and -12 and are mostly moderately juvenile to juvenile. Values decrease from juvenile to slightly negative εHf values with age, conforming to isotopic crustal evolution paths, having originated at 3.3 and 3.0–2.9 Ga. $Hf_{TDM}$ model ages range between 4.1 and 2.2 Ga with abundant model ages between 3.5 and 3.0 Ga. Initial εHf values of Paleoproterozoic rocks deposited between 2.5 and 2.4 Ga are between +1 and -11, while those at 2.0 Ga are between +6 and -10. Values form vertical arrays at 2.4 Ga and 2.0 Ga, potentially indicating significant crustal recycling of c. 3.0 Ga and younger Archean crust.

Our results constrain the provenance areas for the Archean detrital zircons in the lower Paleoproterozoic siliciclastic rocks of the Pechenga and Imandra-Varzuga greenstone belts of Fennoscandia to the surrounding cratonic domains like the Kola and Karelian provinces, as well as the Murmansk and Belomorian provinces. The zircon age distributions trace the assembly and dispersal of the Kenorland supercontinent and probably also the Paleoproterozoic accretion of microcontinents to Fennoscandia. The mineralogically diverse detritus constituting the studied rocks and the detrital zircon age distributions attest to the presence of a (Neo)Archean mafic and evolved felsic upper crust having sourced the studied sedimentary rocks.

# Phase relations and monazite geochronology of mafic granulites from the Karimnagar Granulite Belt and their bearing in Archean–Paleoproterozoic tectonics

**K Satpathi*, P Nasipuri, AM Ganaie**

* corresponding author: kausik20@iiserb.ac.in

Department of Earth and Environmental Sciences, Indian Institute of Science Education and Research, Bhopal, India

This study reports phase relations and U–Th–$Pb_{total}$ in situ monazite geochronology of newly discovered mafic granulites from the Karimnagar Granulite Belt, Eastern Dharwar Craton, India. Orthopyroxene, garnet, Fe–Ti oxides, spinel and subordinate plagioclase constitute the mineralogy of studied samples. Detailed petrographic examination indicates two distinct mineralogical domains defined by garnet–orthopyroxene–plagioclase–quartz and hercynite–magnetite–ilmenite–corundum assemblages. The mineral assemblages suggest the following reaction:

1. $Fe_2TiO_4 + O_2 \rightarrow (FeTiO_3 + Fe_2O_3)_{ss} + Fe_3O_4$ ,
   $FeAl_2O_4 + O_2 \rightarrow Fe_3O_4 + Al_2O_3$

2. $3\ Fe_2SiO_6 + 3\ CaAl_2Si_2O_8 \rightarrow Ca_3Al_2Si_3O_{12} + 2\ Fe_3Al_2Si_3O_{12} + 3\ SiO_2$

Phase equilibria modeling of hercynite–magnetite–ilmenite–corundum assemblages indicates hematite–ilmenite–corundum stabilized from ulvospinel (as a lower lithosphere mantle lithology component) at a temperature of approximately 1000  and pressure of approximately 1.2 GPa. The phase diagrams also predict garnet stabilization at approximately 800 , 0.7 GPa by consuming plagioclase and orthopyroxene. The U–Th–$Pb_{total}$ in situ monazite dating indicates the presence of three distinct populations with weighted mean ages of 2586 ± 24 Ma, 2446 ± 12 Ma and 2091 ± 24 Ma respectively. The Neoarchean 2586 ± 24 Ma age is retrieved from a high-$ThO_2$ monazite core. The slightly younger Plaeoproterozoic 2446 ± 12 Ma age is retrieved from relatively low-$ThO_2$ rims that laced the high-$ThO_2$ core. The youngest 2091 ± 24 Ma age is retrieved from irregular outer domains of monazite grains. When normalized with CI–Chondrite rare earth element contents, the Neoarchean monazite exhibit nearly flat to negative Eu anomaly. In contrast, the Early Paleoproterozoic monazites show flat to positive Eu anomaly.

Compared with the global tectonics, the Neoarchean 2586 ± 24 Ma ages are correlated with the accretion of the Eastern Dharwar Craton and Bastar Craton as a part of the extended Ur assembly (Santosh et al., 2004). The low-$ThO_2$ monazite rims indicate intrusion and cooling of mafic dykes at 2446 ± 12 Ma. As mafic dyke intrusions are generally associated with rifting, we suggest the Eastern Dharwar Craton – Bastar Craton block rifted apart during c. 2446 Ma (Meshram et al., 2021)which marks the contact between the Bastar and Eastern Dharwar cratons in peninsular India. In this study, we attempt to constrain the petrogenesis of granulites from Gondpipri, Bhopalpatnam on the northern flank and Karimnagar on the southern flank of the Pranhita-Godavari valley using petrography, mineral and whole-rock geochemistry, fluid inclusion studies, and UPb zircon geochronology. The presence of relict magmatic textures and orthopyroxene chemistry is suggestive of an igneous protolith while CO2-rich fluid inclusions in quartz correspond to subsequent granulite-facies overprint. Geochemically, charnockites from both granulite belts are metaluminous, magnesian, and calc-alkaline, having similar Sr and Y concentrations, Rb/Sr, Sr/Y, LaN/SmN, GdN/YbN, and Eu/Eu* ratios, and positive BaPb and negative Nb-Ta-Ti anomalies. Zircons in charnockites from both granulite belts furnish magmatic crystallization ages of $\\sim$2.5 Ga (UPb isotope. The c. 2100 Ma ages from the monazite rims probably represent the thermal effect of a younger mafic dyke intrusion in the Dharwar and Bastar Craton (Satpathi et al., 2022).

## References

Tushar Meshram, M Lachhana Dora, Srinivasa R Baswani, Dewashish Upadhyay, Rajkumar Meshram, Kirtikumar Randive, Sameer Ranjan, and Jayanta K Nanda 2021, Petrogenesis and UPb Geochronology of Charnockites Flanking the Pranhita Godavari Rift in Peninsular India-Link between the Bastar and Eastern Dharwar Cratons, Gondwana Research 92: p. 113–32.

M. Santosh, K Yokoyama, SK Acharyya 2004, Geochronology and Tectonic Evolution of Karimnagar and Bhopalpatnam Granulite Belts, Central India Gondwana Research, Volume 7, Issue 2, , p. 501-518, ISSN 1342-937X.

Kausik Satpathi, Hifzurrahman, Xie Hang-Qiang, AB Majeed Ganaie, Sagar Misra, Pritam Nasipuri 2022, A2-Type Granites from the Bastar Craton, South-Central India, and their Implication in Archean-Paleoproterozoic Tectonics in Indian Peninsula. *Lithosphere* 2022 (Special 8): 7938481.

# The Australian record of Huronian glaciation and the Great Oxidation Event – towards a Proterozoic Global Boundary Stratotype Section and Point

**D McB Martin**

david.martin@dmirs.wa.gov.au

Department of Mines, Industry Regulation and Safety, Geological Survey of Western Australia, 100 Plain Street, East Perth WA 6004, Australia

The Mount Bruce Supergroup of Western Australia records an almost uninterrupted stratigraphic succession from c. 2780 Ma to ≥2208 Ma that includes Huronian-aged diamictites in its upper part, as well as physical and geochemical proxy records of the closely associated Great Oxidation Event (GOE). Until recently, this succession was considered to contain a single glacigenic horizon of uncertain absolute age. Global correlation with the Huronian Glacial Event (HGE) is complicated by the existence of three to four glacigenic horizons in the type area in North America, and in Southern Africa. The accuracy of such correlations is critical to establishing a Proterozoic chronostratigraphic Global Boundary Stratotype Section and Point (GSSP), based on the first appearance of glacial deposits (Van Kranendonk et al., 2012; Shields et al., 2022). The Mount Bruce Supergroup also contains a well-known proxy record of the ocean-atmosphere system prior to the GOE, as preserved in the banded iron formations (BIFs) and shales of the Hamersley Group, as well as the current chronometric Archean–Proterozoic boundary. It is therefore of global significance to the definition of this boundary and associated chronostratigraphic units. This poster summarizes recent work aimed at refining and formalizing the stratigraphy of intervals likely to contain Paleoproterozoic GSSP candidates. Significant new observations include basal Boolgeeda Iron Formation and Turee Creek Group disconformities, as well as eight unconformity-bound depositional units in the revised Turee Creek Basin, identification and naming of four diamictites of interpreted glacigenic origin, revision of the stratigraphic nomenclature of the Wyloo Group and confirmation of the genetic relationship between the Cheela Springs Basalt and the newly named c. 2208 Ma Balgara Dolerite. These new observations and geochronological constraints are particularly helpful in constraining correlations to Southern Africa. A significant advantage of the relatively continuous Australian stratigraphic record of the Archean–Proterozoic transition, over that of North America or Southern Africa, is that it is preserved in a coherent geographical area without uncertainties in regional correlation. However, more work on geochronological constraints and the geochemical proxy record is required within this succession in order to better constrain potential GSSPs.

## References

Shields, GA, Strachan, RA, Porter, SM, Halverson, GP, Macdonald, FA, Plumb, KA, Alvarenga, CJ de, Banerjee, DM, Bekker, A, Bleeker, W, Brasier, A, Chakraborty, PP, Collins, AS, Condie, K, Das, K, Evans, DAD, Ernst, R, Fallick, AE, Frimmel, H, Fuck, R, Hoffman, PF, Kamber, BS, Kuznetsov, AB, Mitchell, RN, Poiré, DG, Poulton, SW, Riding, R, Sharma, M, Storey, C, Stueeken, E, Tostevin, R, Turner, E, Xiao, S, Zhang, S, Zhou, Y and Zhu, M 2022, A template for an improved rock-based subdivision of the pre-Cryogenian timescale: Journal of the Geological Society, v. 179, no. 1, article no. jgs2020-222, doi:10.1144/jgs2020-222.

Van Kranendonk, MJ, Altermann, W, Beard, BL, Hoffman, PF, Johnson, CM, Kasting, JF, Melezhik Victor A, Nutman, AP, Papineau, D and Pirajno, F 2012, Chapter 16 - A chronostratigraphic division of the Precambrian: Possibilities and challenges, *in* The geologic time scale *edited by* FM Gradstein, JG Ogg, MD Schmitz and GM Ogg: Elsevier 16, p. 299-392.

# Microbial mat textures and associated microfossils from the Mesoproterozoic Gaoyuzhuang Formation in North China

**Q Ouyang[1*], C Zhou[1], Y Sun[1,2]**

* corresponding author: qouyang@nigpas.ac.cn

1. State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing 210008, China
2. University of Chinese Academy of Sciences, Beijing 100049, China

Fossilized microbial mats, including stromatolites, are useful indicators of microbial life and their inhabiting environment, especially in the study of Precambrian shallow marine habitat. Despite the abundant records of stromatolitic structures and mat-building microfossils, reports of microfossils associated with stromatolites are relatively rare. We report silicified microfossils preserved together with laminated microbial mats from chert bands in lower part of the c. 1.4 Ga Gaoyuzhuang Formation in the North China craton. Three different silicified microbial mat textures are recognized: 1) typical stromatolitic texture, with alternating dark laminae rich in dispersed kerogen and trapped particles that vary in grain sizes and roundness and light laminae consisting mainly of micrites; 2) laminated microbial mats, with alternating dark laminae consisting of pustular mats formed by 2–5 µm-sized coccoidal microfossils and light laminae being mainly composed of silicified crystal fans; 3) alternating dark and light micro-quartz laminae, with dark laminae composed of either simple filamentous microfossils (mainly *Siphonophycus*) or dispersed kerogen, and grains (siliciclastic grains, silicified intraclasts, various microfossils) which occur both within and out of the dark laminae. The three mat textures also differ significantly in microfossil compositions: no microfossil is found in the type 1 texture; type 2 texture contains abundant coccoidal microfossils dominated by *Coccostratus* and *Eoentophysalis*, with rare occurrence of non-septate filaments *Siphonophycus* and coccoidal forms <2 µm in size scattered between the coccoidal colony laminae. Most coccoidal microfossil cells are delicately preserved, with the topmost cell layers being best preserved and darkest in colour in each mat lamina and some cells are preserved in division state. These structures indicate that *Coccostratus* and *Eoentophysalis* are likely builders of the type 2 mats and these mats were silicified in a stage earlier than those in type 1. Type 3 texture contains diverse filamentous microfossils, including many large and septate forms, such as *Oscillatoriopsis* and *Palaeolyngbya*, but coccoidal forms are rare. The micron-thick crystal fan laminae in the type 2 texture represents cemented substrates that were sporadically formed in suprasaturated water conditions and the dominance of coccoidal microfossils is consistent with their preference for colonization on firm substrates, which has also been reported from many late Mesoproterozoic rock units, such as the Angmaat Formation. The occurrence of three microfossil-mat texture associations in one stratigraphic succession may suggest strong reliance of benthic microfossil composition on sedimentary and preservational conditions.

# Marine redox state during early Tonian: evidence from Huainan and Feishui groups of North China craton

**Y Sun[1,2], Q Ouyang[1], W Wang[1], C Guan[1], C Zhou[1*]**

* corresponding author: cmzhou@nigpas.ac.cn

1. State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing 210008, China

2. University of Chinese Academy of Sciences, Beijing 100049, China

The Tonian Period (1000–720 Ma) witnessed the transition from a prokaryote-dominated marine ecosystem to one that was characterized by proliferation of eukaryotes and this fundamental shift has been interpreted as reflecting the rise of eukaryotic algae driven by increasing nutrient availability (e.g. phosphate and nitrate) in the mid-Tonian. Uranium isotope measurements from carbonate rocks indicate an extensive shallow water anoxia in the early Tonian oceans, just prior to or coincident with this marine ecosystem transition in the Tonian. The Huainan and Feishui groups' crop in the southeastern margin of the North China craton, detrital zircon ages and biostratigraphic data indicate that they are early Tonian in age and thus provide suitable material for revealing this marine ecosystem transition and associated paleoenvironmental changes. We carried out iron speciation, inorganic and organic carbon isotope and sulfur isotope analyses for the Huainan and Feishui groups in Huainan area of northern Anhui Province. The carbon isotope profile provides additional chemostratigraphic evidence for early Tonian age of the Liulaobei Formation of the Huainan group. Iron speciation data, with most of the $Fe_{HR}/Fe_T$ values less than 0.2, reveal persistent oxic bottom water conditions, apparently inconsistent with an extensive shallow water anoxia scenario indicated by uranium isotope data. The present study may suggest a heterogeneous ocean redox state in the early Tonian and indicates that availability of nitrate and phosphate may have already started to increase in the early Tonian, which led to diversification of eukaryotes.

# Late Archean to early Paleoproterozoic regional stress field transfer and its tectonic implication in the Eastern Block of the North China Craton

**Z Tian*, P Liu**

* corresponding author: tianzhonghua@cags.ac.cn

Institute of Geology, Chinese Academy of Geological Sciences, Beijing, 100037, China

The initiation of plate tectonics on Earth is significant for early tectonic evolution, crustal growth and paleo-environment. The North China Craton is one of the ideal places for studying this topic. However, because of Mesozoic craton destruction, the Archean rocks within the North China Craton were split into many small pieces by later strike-slip faults and extensional fault systems. Therefore, structural restoration of the original position of the Archean rocks in this Eo–Neoarchean (3.8–2.5 Ga) terrane is the first step in our Precambrian research work. After detailed structural deciphering and restoration, Tian et al. (2022) discovered that the tectonic units and banded iron formations (BIF) in Archean supracrustal rocks cropping out in the Eastern Block of the North China Craton are arranged in line with the north northwestern–south southeastern strike, which is consistent with their oriented gneissic foliations. Combined with its Archean deformational age, the regional stress field in the Eastern Block was inferred as an approximate east–west direction. The Jiao-Liao-Ji back-arc basin was presented as a depositional central for the Paleoproterozoic sediments in the Eastern Block. The Liaohe Group is typical of sediments in this basin, from the bottom to top; the Langzishan Formation was deposited in a passive margin; the volcanic sediments in the Li'eryu Formation were related to an active tectonic setting; the Gaojiayu Formation was presented as a Paleoprotezrozoic turbidite that deposited in a deep-sea setting (Tian et al., 2021) and the Dashiqiao carbonate rocks associated with mafic rock including pillow lava was presented depositing in a seamount nearby the extensional ridge. Early Paleoproterozoic orogenesis deeply affected these sediments and a north–south direction orogenic contraction was presented by Tian et al. (2020) according to detailed geological mapping and structural deciphering. Therefore, from the late Archean to the early Paleoproterozoic, the regional stress field in the Eastern Blocks of the North China Craton was transferred from the approximate east–west direction to the north–south direction. Modern subduction belt migration and evolution often result in regional stress field transformation, therefore, we suggest that regional stress field transfer in late Archean to early Plaeoproterozoic is a significant indicator for the initiation of plate tectonics.

## References

Tian ZH, Nutman AP 2022, Structural restoration of an Eo-Mesoarchean (3.8–2.9 Ga) terrane, Eastern China, dissected by the Tanlu fault zone: Journal of Structural Geology. 2022;161:104629.

Tian, ZH, Liu, F, Yan, Z, Liu, P, Xu, W, Liu, L, Wen, F and Xiao, W 2021, Paleoproterozoic turbidite deposition in the Liaodong Peninsula, northeastern North China Craton: Constraints from the Gaojiayu formation of the Liaohe Group: Precambrian Research, 352:106008.

Tian, ZH, Liu, F, Liu, P, Wen, F and Xiao, W 2020, A Paleoproterozoic nappe on Meso-Archean gneisses exhumed by a Cretaceous metamorphic core complex in northeastern North China Craton: International Journal of Earth Sciences, 109 (4): 1403-1420.

# Redox state of the 2.2 Ga Deep Ocean: Geochemical Evidence from the Birimian Greenstone Belt, Ghana

**KE Yamaguchi1[*], H Hayama[1], M Ikehara[2], S Kiyokawa[3], T Ito[4], T Onoue[3], GM Tetteh[5], F Nyame[6]**

* corresponding author: [kosei@chem.sci.toho-u.ac.jp]

1. Department of Chemistry, Toho University, Funabashi, Chiba, Japan
2. Centre for Advanced Marine Core Studies, Kochi University, Nankoku, Japan
3. Department of Earth and Planetary Science, Kyushu University, Fukuoka, Japan
4. Department of Education, Ibaraki University, Mito, Japan
5. Department of Geological Engineering, University of Mines and Technology, Tarkwa, Ghana
6. Department of Earth Science, University of Ghana, Legon, Ghana

The Paleoproterozoic Era has been characterized by an inferred rapid rise of atmospheric oxygen (Great Oxidation Event or GOE) at ~2.4-2.2 Ga. Oxygenation of the surface environment of the Earth was most likely to have been heterogeneous; molecular $O_2$ produced by oxygenic photosynthesis first oxygenated the surface ocean after oxidizing dissolved reduced species such as Fe and S, then excess oxygen was liberated into the atmosphere and transported to deep ocean by ocean circulation. Although the timing of GOE has long been debated, such stepwise oxygenation itself appears to have been widely accepted.

Geological and geochemical evidence to support such Paleoproterozoic GOE is largely based on characteristics of sedimentary rocks that formed in rather shallower environments, such as shallow marine or continental settings, namely carbonates, shallow-facies shales, and paleosols. Since there is a general lack of least-metamorphosed deep-facies siliceous sedimentary rocks that were deposited right after the inferred GOE, studies that geochemically constrain the degree of oxygenation of the deep ocean are hampered.

We drilled to obtain 2.2 Ga least-metamorphosed deep-facies sedimentary rocks from the Birimian Greenstone Belt, southwest Ghana. The 196m-long core at low-grade metamorphism (upto greenschist facies) comprise of basaltic volcanic rocks and fine-grained sedimentary rocks. Here we report results of major element analysis by XRF, trace and rare earth element analysis by ICP-MS, Fe-speciation analysis, S-speciation analysis, $C_{org}$ and $C_{carb}$ analysis, and $C_{org}$ and $S_{py}$ isotope analysis for 25 samples selected from 20m-long sedimentary unit of the core (Hayama, 2019).

We estimated the origin of Fe in the samples using mass balance calculation with PAAS to suggest that Fe in the lower part of the core was continental and hydrothermal in origin, while that in the upper part was mostly continental. In a plot of DOP (degree of pyritization) vs. $Fe_{HR}/Fe_T$, 16 samples with positive Ce anomalies fall within the “oxic” domain, and 8 samples without any Ce anomaly fall within the “euxinic” domain. Trace elements such as redox-sensitive Mo, Cu, Ni, and Zn are neither enriched (EF ≤ 1) nor associated with $S_{py}$ content, but the “euxinic” samples have mild positive correlation with $Al_2O_3$ content. The $C_{org}$ isotope compositions are near −25‰, independent of stratigraphic height.

The data set consistently suggests that redox state in the 2.2 Ga deep ocean was essentially oxic, with temporal anoxic/euxinic transitions. Enhanced continental weathering under an oxic atmosphere would have increased nutrient input into the ocean, primary productivity, consumption of dissolved $O_2$, and sporadic emergence of euxinic conditions.

Redox state of the deep ocean right after the inferred GOE at around 2.4 Ga would place important constraints on the co-evolution of the atmosphere, ocean, and biosphere.

## Reference

Hayama, H 2019, Redox state of the deep ocean 2.2 billion years ago: Constraints from geochemistry of shales, southwest Ghana: MSc Thesis, Toho University, Japan.

# Authigenic carbonate precipitation associated with anaerobic oxidation of methane in Ediacaran of South China

**C Zhou[1*], C Guan[1], W Wang[1], Q Ouyang[1], H Shi[1,2], Y Sun[1,2]**

* corresponding author: cmzhou@nigpas.ac.cn

1. State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing 210008, China

2. University of Chinese Academy of Sciences, Beijing 100049, China

The origin and evolution of microbial methane metabolism have been closely linked to the global carbon and sulfur biogeochemical cycles and the evolution of the Earth's surface system. Exploring geological records of methanogenesis and methane oxidation is the basis and prerequisite for revealing these relationships. The occurrence of highly $^{13}$C-depleted organic carbon in the Neoarchean rocks has been interpreted as results of methanogenesis and anaerobic methanotrophy. Some distinctive sedimentary structures, such as the molar-tooth structure in the Proterozoic carbonate rocks, have been proposed to be related to methane release in carbonate sediments, though direct evidence is lacking. The geological records of methane metabolism in Precambrian, however, are generally scarce. Authigenic carbonates have been discovered from the Ediacaran (c. 635–539 Ma) succession in South China. They are mainly composed of calcite and occur as either nodules and lenses that are generally aligned with sedimentary laminations, or cements in dolomicrite. Field investigations have confirmed their occurrence in multiple horizons of the Ediacaran Doushantuo and Dengying formations. The $^{87}$Sr/$^{86}$Sr values of calcite nodules ranging from 0.7080 to 0.7085, resembling that of contemporaneous seawater, suggest that seawater is the main source of sediment pore water. Calcite nodules and cements generally have pronounced negative $\delta^{13}$C values (as low as –38‰) compared to surrounding dolomite, indicating that carbon source of calcite nodules and cements may be partially derived from methane oxidation. It has been proposed that the formation of calcite nodules and cements is related to anaerobic methane oxidation (AOM) driven by microbial sulfate reduction (MSR), which occurs in the sulfate methane transition zone (SMTZ) below the sediment–water interface. The presence of SMTZ in the superficial layer of sediments below the sediment–water interface requires a higher concentration of seawater sulfate (approximately 10 mM) in Ediacaran, indicating that the concentration of seawater sulfate increased significantly after the Neoproterozoic global glaciation, which is consistent with the increase in atmospheric oxygen content and the corresponding increase in oceanic sulfate input flux during the Neoproterozoic Oxygenation Event (GOE).

# Low $\delta^{18}O$ and $\delta^{30}Si$ 2.3 billion-year-old tonalite–trondhjemite–granodiorites within-plate hint at onset of Paleoproterozoic supercontinent cycle

**YY Zhou [1*], MG ZHai[1,2], TP Zhao[3]**

* corresponding author: zhouyanyan@mail.iggcas.ac.cn

1. State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
2. College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China
3. Key Laboratory of Mineralogy and Metallogeny, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China

The backbone-like tonalite-trondhjemite-granodiorite (TTG) in the Archean cratons is a crucial probe to trace the regime of the continental evolution. However, marked decreases of TTG and other magmatism occurred across the Archean–Paleoproterozoic transition, along with atmospheric oxygenation and glaciations. Here we report the c. 2.3 Ga TTG in the North China Craton (NCC), which may represent the last major global pulse of TTG. The c. 2.3 Ga TTGs were derived from partial melting of the Archean basaltic crust under low-medium pressure and high thermal gradients (up to 900 °C/GPa) in an intraplate setting. The crustal thickness during this time is estimated at 32–38 km, strikingly thinner than the prior Neoarchean crust of the NCC. The rocks contain the lowest-known zircon $\delta^{18}O$ (1.24–4.39‰) and bulk-rock $\delta^{30}Si$ values (-0.41–0.13‰) in contrast to global TTGs through time, implying high-temperature (*T*) hydrothermal interaction between the Archean protolith sources and meteoric water. Combing the published coeval komatiitic–gabbroic rocks, low-$\delta^{18}O$ A-type granites and thinning lithosphere since 2.50 Ga, we suggest initial rifting within-plate. The c. 2.3 Ga low-$\delta^{18}O$ igneous rocks and coeval magmatism in the NCC may reveal a consistent early Paleoproterozoic interval of low-$\delta^{18}O$ magmatism and coincided with intraplate rifting prior to the breakup of Archean cratons or supercratons, plausibly hinting at the onset of the Paleoproterozoic supercontinent cycle. The low-$\delta^{18}O$ magmatism coincident with the Huronian glaciation could represent positive feedback loops for paleoclimate changes.

# Theme 7

# Mineral systems of Archean terranes and their margins

Invited Speaker

**Dr Patricia Durance**

*Chief Geologist, SensOre Ltd*

Keynote Speaker

**Dr Patrick Mercier-Langevin**

*Research Scientist, Geological Survey of Canada (GSC), Canada*

# Big data and machine learning are impacting our understanding of Archean mineral systems: targeting Li-bearing pegmatites

**PD Durance*, M Rowe, J Chen, A Eggo, D Burkett, R Rowe, J Potter**

* corresponding author: patricia.durance@sensore.com.au

SensOre Ltd, Perth, WA 615 , Australia

Lithium–caesium–tantalum (LCT) pegmatites are one endmember of the rare earth element (REE) pegmatite family, capable of hosting economically significant concentrations of Li. There is a strong record in the literature documenting the petrogenesis, metallogeny, geodynamic and tectonic settings of granite-related mineralization systems including pegmatites. Lithium–caesium–tantalum pegmatites occur on all continents, most frequently associated with Archean cratons. These pegmatites formed in pulses that coincide with periodicity of orogenic granite and detrital zircons during times of supercontinent assembly and major collisional orogenic events (Duuring, 2020 and references therein). The granitic parental magmas of LCT pegmatites are dominantly peraluminous and inferred to be derived from melting continental crust at depth (Cerny et al., 2005). Enrichment in lithium is attributed to extensive fractional crystallization of compositionally evolved granitic magmas.

Archean cratons in Western Australia are highly prospective and host some the of world's largest LCT pegmatite deposits. Recently we have seen attempts to translate this knowledge of world-class examples into a mineral systems framework for REE pegmatites that would enable a more systematic targeting approach for mineral exploration (Sweetapple, 2017; Duuring, 2020 and Turnbull et al., 2018). At the same time, the application of machine learning on big data is being used to generate targets for Li-bearing pegmatites in a computing environment that is agnostic of empirical knowledge presented above and independent of any conceptual framework of the mineralizing system. Accurate predictions in lithium exploration can be achieved through machine learning techniques applied to lithogeochemistry, mineral chemistry and geophysics data, with extensive data cleaning and pre-processing as the crucial foundation. This keynote will present our findings for targeting Li-bearing pegmatites, illustrating how this work is impacting concepts embedded in a mineral systems framework.

## References

Černý P, Ercit, TS 2005, The Classification of Granitic Pegmatites Revisited: The Canadian Mineralogist, vol. 43, p. 2005-2026

Duuring P 2020, Rare-Element Pegmatites: A Mineral Systems Analysis: Record 2020/7, Geological Survey of Western Australia, 13p.

Sweetapple, MT 2017, Granitic pegmatites as mineral systems: Examples from the Archaean. NGF Abstr. Proc. 2017, 2, 139–142.

Turnbull RE, Morgenstern R, Hill MP, Durance PMJ, Rattenbury MS 2018, Lithium Mineral Potential in New Zealand. Lower Hutt (NZ): GNS Science. 210 p. (GNS Science consultancy report; 2018/63).

# Convergent margin metallogenic cycling during the Archean: insights from the Abitibi and other Archean terranes

P Mercier-Langevin[1*], B Dubé[2], DL Huston[3], MP Doublier[3]

* corresponding author: patrick.mercier-langevin@nrcan-rncan.gc.ca

1. Geological Survey of Canada, Quebec City, Quebec, Canada
2. Independent, Quebec City, Quebec, Canada
3. Geoscience Australia, Symonston ACT, 2609, Australia

The Abitibi greenstone belt (AGB), in the Superior Craton of Canada, is one of the best exposed, preserved, and mineralized Archean greenstone belts on Earth. It has a very well constrained metallogenic history with world-class volcanic-hosted massive sulphide (VHMS) and orogenic gold deposits, along with many other deposit types. The AGB consists of east-trending successions of volcanic, sedimentary and intervening intrusive rocks. The volcanic construction, comprising seven assemblages, started at 2790 Ma and ended at 2695 Ma. Each assemblage consists of varying abundance of mafic (±ultramafic), intermediate and felsic submarine volcanic and volcaniclastic rocks. Tonalite-trondhjemite-granodiorite (TTG-type) magmatism at about 2750–2695 Ma accompanied volcanism. These rocks may have formed via plume, volcanic plateau, and arc/back-arc style magmatic activity. Turbiditic deep-marine sedimentation at c. ≤2700–2685 Ma followed the main phases of volcanic construction, coeval with a transition from TTG-type magmatism to sanukitoïd-style magmatism. This deep-marine sedimentation is associated with early thin-skin folding and thrusting (imbrication) and uplift ($D_1$ and $D_2$: about 2685–2679 Ma in the southern Abitibi). This was followed by extension and uplift, and by basin deepening and syn-orogenic sedimentation over an angular unconformity (c. ≤2679–≤2669 Ma Timiskaming Group alluvial-fluviatile deposits) and early- to syn-Timiskaming, sub-alkalic to alkalic/shoshonitic magmatism at about 2683–2670 Ma in the southern part of the belt. A switch to compression ($D_3$, thick-skin thrusting) followed at <2670 Ma and is responsible for the development of the east-trending, crustal-scale and/or first-order structures. Regional metamorphism is coeval with $D_3$ and bracketed at about 2660–2640 Ma.

Metallogenesis in the AGB began with VHMS deposits at about 2760 Ma, with most deposits formed between 2730 and 2695 Ma. Komatiite- and intrusion-hosted Ni-Cu-(PGE) deposits at about 2740–2700 Ma overlapped VHMS formation as did porphyry-like Au±Cu and Cu±Mo-Au deposits hosted by polyphase TTG intrusive complexes. This was followed by major gold mineralization, starting with early (pre-Timiskaming) intrusion-associated deposits at about 2700–2686 Ma associated with early $D_1$-$D_2$ deformation. A few syn-Timiskaming intrusion-associated gold and porphyry-style Cu-Mo-Au systems formed at about 2683–2670 Ma, coeval with calc-alkalic to alkalic intrusive rocks. Gold metallogenesis gradually transitioned to the classic, and dominant, syn-$D_3$ orogenic (quartz-carbonate vein-style) gold systems at about 2670 Ma along the major east-west fault zones, peaking at about 2660–2640 Ma in the southern Abitibi. Late- to post-tectonic S-type intrusive complexes host about 2650–2745 Ma Mo-Bi deposits and about 2639–2637 Ma LCT-type Li pegmatites.

A similar progression from VHMS, Ni-Cu-(PGE) and calc-alkalic porphyry Cu-Au deposits to orogenic gold to granite-related and pegmatite deposits is present in other Archean terranes such as the Slave and Yilgarn. This reasonably consistent temporal pattern is also characteristic, albeit longer-lived, of younger convergent margins and defines what is now referred to as the convergent margin metallogenic cycle (CMMC: cf. Doublier et al., 'Convergent margin metallogenesis constrains onset of subduction on Earth', this volume). The AGB represents one of the oldest CMMC, with a comparatively short, single cycle that lasted ≤125 Ma, typical of shorter-lived metallogenic histories during the Archean in response to secular changes in tectonic processes and the onset of subduction (shallow break-off subduction).

# Rhyacian gold of the Guiana Shield

**M Bardoux**

mbardoux@barrick.com

Barrick Gold Corporation

Rhyacian rocks of the Guiana Shield are bounded by Archean crust. Rhyacian gold is the prime commodity of the Cuyuni and Marowijne megabasins (respectively CMB in Guyana and MMB in Suriname and French Guiana) where three principal gold deposit types have been roughly defined to date and only briefly documented (eight theses in the last 20 years). Well-endowed vein hosted deposits of the MMB are somewhat exclusive to this basin for which a new classification terminology is proposed as Orogenic Clastic Sediment Hosted (OCSH). This emphasizes that auriferous sulphidic veins are nearly exclusively hosted in moderately strained, coarse clastic sediments (conglomerate to sandstone) where veins are most related to very discrete (metric) high strain zones. Fluids in OCSH veins are likely to be predominantly of metamorphic origin. Tungsten anomalism is commonly related to altered rutile (not plutonic related). Arsenic anomalism is mainly related to black shales. Vein gold deposits of the CMB are generally hosted inside or on the immediate edges of felsic plutonic bodies of varied sizes (plugs to batholiths) where edge strain is amongst the highest encountered in the Rhyacian realm. A large variety of vein orientations and types occur in each of these IH deposits. Many IH veins are polymetallic and commonly yield telluride pathfinders confirming their subcontinental lithospheric mantle (SCLM) sourcing. Strain regimes of most deposits vary from pure shear (coaxial, elongated) to simple shear (non-coaxial, no length change, rotational) states, which produce different vein networks that need to be discerned to optimize targeting in 3D. Thus, a new terminology is also proposed for these orogenic gold deposit types as pure shear orogenic (PSO) and simple shear orogenic (SSO). Their determination relies principally on the final shape of strain markers and the finite orientation of mineral stretching lineations.

There are clearly multiple gold events spread over nearly 80 Ma across the Guiana Shield (starting with comagmatic settings c. 2160 Ma at Yaou, Las Christinas and Camp Caiman, and ending with late tectonic phases c. 2080 Ma at Karouni) supporting the concept that much Rhyacian gold started mobilizing in a magmatic (polymetallic) state and (additional?) gold ended up in mesothermal vein states (and confined sodic, potassic and calcic orogenic style alteration halos). Sparse geochronology suggests that tectonic regimes affecting the CMB deposits may have terminated 20 Ma later than in the MMB. This may relate to tectonic partitioning between the two megabasins around a giant metamorphic/ultra-high temperature/ tonalite–trondhjemite–granodiorite landmass that separates the two basins. The partitioning may be defined by the Bartica Gneiss Complex and the Bakhuis Horst (separated by the Mesozoic Takutu Grabben) which are two very prominent lithospheric highs that may have caused tectonic partitioning on their respective boundaries. Several differences are noted with the making of Archean gold deposits.

# Does the underlying Archean always influence the development of Proterozoic mineralization?

**SA Occhipinti*, CV Spaggiari**

* corresponding author: sandra.occhipinti@csiro.au

Commonwealth Scientific and Industrial Organisation, 26 Dick Perry Avenue, Kensington, WA 6151, Australia

In this contribution we review some examples of Proterozoic mineral systems that developed close to the edge and within a few kilometres of uncovered Archean basement by drawing on mineral potential mapping data, extensive geophysical surveys and geological mapping in these regions. Mineral systems formed during compressional or extensional episodes are sometimes thought to be influenced by the geometry and composition of underlying Archean crust, ancient deep crustal-scale structures or even metal-enriched subcontinental lithospheric mantle of Archean age. However, tracing their influence into mineralized zones within Proterozoic basins or orogenic belts is often enigmatic.

The Yilgarn Craton is surrounded by Proterozoic margins that, as far as is known, all differ in terms of mineral deposits. Within the craton itself, Au and Ni–Cu–PGE deposits (particularly komatiite-hosted) are relatively abundant and in some cases fairly evenly spaced. Around the margins of the craton, however, these types of deposits (including intrusive magmatic Ni–Cu–PGE) are less common and not predictably spatially distributed. For example, the large Tropicana Au deposit hosted in high-temperature Archean gneiss in the north-eastern part of the Albany–Fraser Orogen on the south-eastern margin of the craton is an isolated Archean Au deposit and no similar deposits have been found within the orogen. In comparison, gold deposits in the Yerrida Basin of the Capricorn Orogen on the north-eastern craton margin are relatively small and associated with specific geological units and structural zones. In northern Australia, the Kimberley Basin developed above an unexposed Archean basement and its east and west margins contain Proterozoic to Phanerozoic mineralization including valuable critical mineral deposits such as Ni–Cu–PGEs, V–Ti, orogenic Au and gems such as diamonds. Archean structure and fertility may have influenced some regions of Ni–Cu–PGE and Au mineral systems development. For example, emplacement of mafic–ultramafic bodies containing Ni–Cu–PGE mineralization in the Kimberley and Albany–Fraser regions and lamprophyre dykes in the Kimberley may have been channelled through deep-seated orogen perpendicular structures, over which transcurrent movement occurred during subsequent basin development or inversion along the craton margin. Intrusive magmatic Ni–Cu–PGE deposits typically form in small conduits with high magma volumes and it is likely that perpendicular structures facilitate this. The Yilgarn Craton is dominated by a north-westerly structural trend, although recent investigations of granite geochemistry suggest early east–west trends, similar to those of the 2.4 Ga Widgiemooltha dyke suite. Ni mineralization has recently been identified within a Widgiemooltha sill adjacent to the Ida Fault, a terrane boundary. The Mesoproterozoic Nova-Bollinger intrusive magmatic Ni–Cu–PGE deposit occurs adjacent to northeast-trending crustal-scale structures within the Albany–Fraser Orogen and was likely structurally controlled at depth as it was emplaced during reworking of the craton margin.

One factor that may influence the role of underlying Archean basement is whether remobilization of metals is important to form deposits. For magmatic Ni–Cu–PGE deposits, remobilization is typically destructive so craton edges with well-preserved Archean architecture and intersecting structures hosting intrusions may be more favourable. Alternatively, gold and base metals may benefit from reactivation and the influence of fluid flow, particularly during basin formation above craton margins.

# Hematite ore formation in the Vermilion district of Minnesota

**ZP Allerton[1*], G Hudak[1,2], C Teyssier[1]**

* corresponding author: puszt002@umn.edu

1. Department of Earth and Environmental Sciences, University of Minnesota, Minneapolis, MN 55455, USA
2. Natural Resources Research Institute, Duluth, MN 55811, USA

The Vermilion district of northern Minnesota, USA, hosts hematite iron ore in the Lake Vermilion-Soudan State Park. The lens-shaped massive hematite ore bodies are enclosed within protore Algoma-type magnetite-chert banded iron formations (BIFs) (Hudak et al., 2016). The BIFs are folded ($D_1$) and the ore is hypothesized to have formed synkinematically during regional shearing ($D_2$), which activated fluid migration and resulted in hypogene hydrothermal alteration of BIFs to hematite ore (Klinger, 1960; Thompson, 2015). These ore units are nested in $D_2$ shear zones, but field observations and hand sample analyses suggest the ore is devoid of both $D_1$ and $D_2$ deformation, indicating post-kinematic ore formation. The ore samples display distinctive textures, suggestive of several stages of alteration, but the timing of ore mineralization is unknown and the different stages of alteration processes are poorly understood. An early study (Symons, 1967) proposed a possible association between hematite ore mineralization and emplacement of the Mesoproterozoic Duluth Complex, a layered mafic intrusion within the Midcontinent Rift system. The hypothesis was based on magnetic paleopoles in the ore having similar remanence directions to the Duluth Complex and dissimilar to all adjacent and proximal units. This study aims to investigate if the intrusion could have initiated ore formation.

The project utilizes standard petrography, electron microprobe analysis (EMPA) and a relatively new combined geo- and thermochronology technique to better understand ore formation and genesis. Petrographic analysis confirms at least two different ore textures. Firstly, fine-grained massive ore with microcrystalline specular hematite devoid of original banding of the protore, including chlorite- or quartz-filled vugs. Secondly, massive ore displaying more than one generation of hematite, comprising microcrystalline hematite that makes up the matrix with subhedral bladed specular hematite aggregates. Mineral separation did not yield datable accessory minerals (apatite or monazite) and other studies revealed trace amounts of monazite that are too small for radiometric dating (Thompson, 2015). In the absence of conventional accessory minerals, direct U–Pb geochronology coupled with (U–Th)/He thermochronology of hematite (Courtney-Davies et al., 2022) is being applied to obtain hematite iron ore ages.

## References

Courtney-Davies, L, et al. 2022, Hematite geochronology reveals a tectonic trigger for iron ore mineralization during Nuna breakup: Geology, v. 50, p. 1318-1323,https://doi.org/10.1130/G50374.1.

Hudak, GJ, et al. 2016, Bedrock geologic map of Lake Vermilion/Soudan Underground Mine State Park – Report to the Minnesota Department of Natural Resources: Natural Resources Research Institute, University of Minnesota Duluth, Technical Report NRRI/TR-2016/20, 23 p.

Klinger, FL1960, Geology and ore deposits of the Soudan mine, St. Louis County, Minnesota [thesis].

Symons, DT 1967, Paleomagnetic evidence on the genesis of the hard hematite ore deposits of the Vermilion Range, Minnesota. Canadian Journal of Earth Sciences, 4(3), 449–460. https://doi.org/10.1139/e67-023.

Thompson, A 2015, A hydrothermal model for metasomatism of Neoarchean Algoma-type banded iron formation to massive hematite ore at the Soudan Mine, Ne Minnesota [thesis].

# Radioactive mineral detection through hydrothermal alteration mapping using Advanced Spaceborne Thermal Emission and Reflection Radiometer and airborne geophysical data: preliminary results on Central Hoggar (Algeria)

**B Ayad[1*], T Lamri[2], N Imessaoudene[2]**

* corresponding author: bayad@usthb.dz or bayad.edu.usthb@gmail.com

1. Laboratoire de Géodynamique, Géologie de l'Ingénieur et de Planétologie, FSTGAT, USTHB. B.P 32 EL ALIA, Bab Ezzouar, Algeria - 16000
2. Institut d'Architecture et des Sciences de la Terre , Université Ferhat Abbes Sétif -1- Campus El Bez, Sétif, Algeria - 19000
3. Centre de Recherche en Astronomie Astrophysique et Géophysique, BP - 63 Rte de l'Observatoire, Bouzareah, Algeria - 16000

The Hoggar region, belonging to the Tuareg Shield, represents one of the most economic regions in Algeria. In Central Hoggar, the Proterozoic terranes of Serouenout and Azrou N'Fad are characterized by the pronounced hydrothermal alteration of their basement/cover rocks. These latter constitute potential hosts for rare earth elements (REE) and other economic minerals.

In our study, we focus on radioactive elements and their associated alteration minerals. From this perspective and from previous field observations, we propose to map a portion of the Serouenout terrane lying between two major faults that had supposedly played an important role in accommodating mineral deposits.

Our methodology consists of using combined remote sensing data from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images and airborne radiometric surveys in order to detect anomalies of radioactive minerals corresponding to K, Th and U surface concentrations and to map the related potential economic ore bodies.

The preliminary results from the conversion of airborne radiometric data, showing anomalies of radioactive element concentrations (specifically percentages of eU, eTh, K), are consistent with some of the remotely sensed and field observed hydrothermal alteration minerals, mostly associated to granites, which are known concentrate such elements. U/Th and U/K ratios permitted delineating tracts for potential ore bodies with the highest anomalies of uranium concentrations and which might be of a significant economic interest.

Pairing airborne radiometric data with hydrothermal alteration maps from ASTER images provides valuable information for radioactive mineral detection. This combination method is particularly time efficient as it helps avoid other – more likely sterile – hydrothermal alteration locations during field investigations.

# Structural evolution of the Nyanzaga and Kilimani gold deposits, Sukumaland Greenstone Belt, Tanzania Craton

**C Berthier[1,2,3*], A Chauvet[3], J Feneyrol[1], A-S André-Mayer[2], A Eglinger[2], J Brigden[4], J McIntyre[4], N Thébaud[5], R Bosc[1]**

* corresponding author: celestine.berthier@univ-lorraine.fr

1. Arethuse Geology SARL, Fuveau 13710, France
2. GeoRessources, Université de Lorraine, CNRS, Nancy 54000, France
3. Géoscience Montpellier, Université de Montpellier, CNRS, Montpellier 34095, France
4. OreCorp Limited, Subiaco WA 6008, Perth, Australia
5. Centre for Exploration Targeting, University of Western Australia, Crawley, WA 6009, Australia

The tectonic Neoarchean evolution that resulted in refolded folds and overprinting planar fabrics affected one of the world's giant gold provinces, the Lake Victoria Goldfield, in which lies the Sukumaland Greenstone Belt (SGB; Henkel et al., 2016), Tanzania Craton, and was of major importance in focusing gold mineralization. This multiphase and/or progressive deformation history led to a complex structural pattern and heterogenous gold distributions, as expressed in the two greenstone-hosted gold deposits of Nyanzaga and Kilimani located less than a kilometre apart, in the heart of the SGB. We conducted extensive field work at the deposit scale and a detailed petro-structural-textural study at core to microscopic scales on sulphide and silicate minerals, in order to determine the controls of deformation and hydrothermal events on gold mineralization. Early $D_1$ shortening under ductile conditions resulted in kilometric asymmetrical folds showing various geometries and orientations, from open to isoclinal and cylindrical to sheath geometries, with northwest- to northeast-oriented axial planes and moderately plunging to the northwest through to northeast. A discrete $S_1$ cleavage is expressed within the finest sedimentary layers, parallel to the $D_1$-related fold axial plane. Strong carbonatization and silicification developed alongside dolomite-quartz veins, either crustiform when parallel to the bedding or comb when perpendicular to it, typical of synfolding veins (Druguet, 2019). The second stage consists of progressive deformation with subhorizontal north shortening and a progressive shift from ductile $D_{2a}$ to brittle $D_{2b}$ events. The $D_{2a}$ stage is characterized by east- to east-northeast-striking folds with subvertical plunge that refolded the $D_1$-related folds, attested by the major variations in their geometries and orientations. A discrete $S_{2a}$ cleavage overprinted the $S_1$ fabric. Disseminated pyrite grains crosscut the $D_1$related veins and are affected by the $D_{2a}$-related folds. The two-stage folding led to overturned anticlines with northwest-oriented subvertical limbs at the Kilimani deposit and a subvertical east limb shifting from northwest- to northeast-oriented at the Nyanzaga deposit. Finally, major subvertical faults developed during the $D_{2b}$ stage, preferentially along the vertical lithological contacts that constitute weak planes favourable for fracturing, focusing the ore-bearing fluid(s) and depositing gold. It resulted in mineralized northwest-trending dextral strike-slip faults in both deposits and highly mineralized north-oriented dilatational jogs constrained by the strike-slip faults at the Nyanzaga gold deposit, where the stratigraphy was north–south reoriented during the $D_{2a}$-related folding. Jogs are expressed by electrum- and As–Sb–Pb–Cu–Ni-rich sulphide-bearing north–south normal faults and extensional veins. Therefore, if Kilimani and Nyanzaga deposits show similar volcano-sedimentary sequences and underwent the same history of deformation and hydrothermal alteration, the geometry of their folded lithologies did not allow similar fracturing and faulting, explaining the higher mineralization rate of the Nyanzaga deposit.

## References

Druguet, E 2019, Deciphering the presence of axial-planar veins in tectonites: Geoscience Frontiers, v. 10, p. 2101-2115.

Henkel J, Poulsen KH, Sharp T, Spora P 2016, Lake Victoria Goldfields: Episodes, v. 39, p 135-154.

# The origin of volatiles in the Ni–Cu–Co Ovoid deposit of the Voisey's Bay complex: new insights on the role of accessory minerals in tracing ore-forming processes

**S Caruso[1,2*], M Le Vaillant[1,2], SJ Barnes[1]**

* corresponding author: stefano.caruso@csiro.au

1. Mineral Resources, Commonwealth Scientific and Industrial Research Organisation, Kensington 6151, WA, Australia
2. Centre for Exploration Targeting, University of Western Australia, Crawley 6009, WA, Australia

The 1.34 Ga-old Voisey's Bay Complex is a troctolite–anorthosite–diorite suite located at the western margin of the Archean Nain Province, Labrador, northern Canada. Magmatic sulfide deposits occur in the two tabular magma chambers (Eastern Deeps and Western Deeps) as well as in the magma conduits (Ovoid, Mini-Ovoid conduits, Eastern Deeps feeder; Li and Naldrett, 1999). Nickel–copper sulfides have disseminated to semi-massive textures at the base of the Eastern Deeps chamber, whereas sulfides are only disseminated in the Western Deeps chamber. In the conduits, sulfide textures range from disseminated to massive and develop sulfide-matrix breccia textures along the footwall contacts. Fragment in the sulfide-matrix breccias comprises endogenously-derived troctolite, olivine gabbro and peridotite as well as paragneiss and orthogneiss xenoliths. These sulfide-rich clast-supported breccias are interpreted to have formed through the downward percolation of sulfide melt, which displaced the interstitial silicate melt between the endogenous fragments and the xenoliths (Barnes et al., 2017). Continuous biotite–hornblende reaction rims are often present at the interface between the silicate clasts and the sulfide. Detailed textural analysis suggests that these hydrous silicates formed through reactions between the breccia fragments and volatile component derived from the sulfide liquid. Experimental and field evidence support this hypothesis, as the sulfide melt is able to host minor amounts of water and halogens (Mungall and Brenan, 2003; Wykes and Mavrogenes, 2005). However, the origin of K required for the formation of biotite is yet to be fully understood. Furthermore, the occurrence of accessory minerals such as apatite and ilmenite, which are commonly regarded as residual, within the sulfide-matrix breccias is at odds with conventional genetic models of magmatic Ni–Cu–Co sulfide deposits.

In this study we characterize the trace element composition of apatite, biotite and Fe-oxides in barren troctolite, sulfide-rich and sulfide-poor breccia samples to trace the origin of the volatile component in the Ni–Cu–Co Ovoid deposit. Furthermore, we explore the ability of these accessory phases to record the effects of ore-forming processes and their potential as vectors toward mineralization.

## References

Barnes, SJ, Le Vaillant, M and Lightfoot, PC 2017, Textural development in sulfide-matrix ore breccias in the Voisey's Bay Ni–Cu–Co deposit, Labrador, Canada: Ore Geology Reviews, v. 90, p. 414–438

Li, C and Naldrett, AJ 1999, Geology and petrology of the Voisey's Bay intrusion: reaction of olivine with sulfide and silicate liquids: Lithos, v. 47, p. 1–31

Mungall, JE and Brenan, JM 2003, Experimental evidence for the chalcophile behavior of the halogens: The Canadian Mineralogist, v. 41, p. 207–220

Wykes, JL, and Mavrogenes, JA 2005, Hydrous sulfide melting: Experimental evidence for the solubility of $H_2O$ in sulfide melts: Economic Geology, v. 100, p. 157–164

# Gold mineralization and remobilization in metamorphosed and polydeformed Archean rocks of the Superior Province, Québec: insights from the Cheechoo deposit and its auriferous pegmatites

**S De Souza[1*], M Perrot[1], F Turlin[1,2], P-A Groulier[1,3], M Jébrak[1], J Turcotte[4]**

* corresponding author: de_souza.stephane@uqam.ca

1. Université du Québec à Montréal, Montreal, Quebec, Canada H2X 3Y7
2. Université de Genève, Geneva, Switzerland
3. Troilus Gold, Montreal, Quebec, Canada H2Y 2H7
4. Sirios Resources, Montreal, Quebec, Canada H3C 3R7

Archean gold deposits in amphibolite facies rocks commonly have complex parageneses, in part due to superimposed deformation and metamorphism. In these conditions, gold may also be remobilized with other low melting point chalcophile metals (e.g. Bi, Ag, As, Sb), thus leading to equivocal deposit models. The Eeyou Istchee James-Bay area (Québec), in the southeastern Superior Province of Canada, hosts several gold deposits in amphibolite facies supracrustal rocks and intrusions. Many of these deposits, such as the Cheechoo deposit, are located in the La Grande subprovince, close to the contact with amphibolite to granulite facies metasedimentary rocks and migmatites of the Opinaca subprovince. The Cheechoo deposit (resources: 1.5 Moz @ 0.94 g/t Au indicated and 0.5 Moz @ 0.73 g/t Au inferredis partially hosted by disseminated sulfide zones in granodiorite. However, most of the resources are associated with auriferous granitic pegmatites, an uncommon feature to most Archean gold deposits. A detailed mineralogical, structural and U–Pb geochronological laser ablation inductively coupled plasma mass spectroscopy (LA-ICP-MS) study was initiated to constrain the genesis of this unusual deposit. The gold zones and the pegmatites are hosted by hornblende–biotite-bearing granodiorite, biotite–plagioclase–quartz±garnet metawacke, and biotite–sillimanite–plagioclase paragneiss. Preliminary metamorphic modeling on metasedimentary rocks indicates minimum temperature conditions in the upper amphibolite facies (approximately 600 °C). The granodiorite was hydrothermally altered prior to the main phase of compressive $D_2$ deformation and late-kinematic peak metamorphism. Its chemical composition is similar to that of 2671–2636 Ma anatectic leucogranites in the adjacent Opinaca subprovince. It includes three main metamorphosed alteration types that do not show systematic association with gold-rich zones: albitization, calc-silicate (actinolite–plagioclase–diopside±garnet) and biotitization, with trace amounts of disseminated sulfides (arsenopyrite–pyrrhotite–lollingite). The disseminated mineralization is associated with quartz–plagioclase–diopside±scheelite veinlets, which are cut by later quartz±gold–scheelite veinlets. The mineralized pegmatites contain biotite, tourmaline, apatite and muscovite. They intruded the metasedimentary rocks and granodiorite after peak metamorphism, as suggested by mineralized tourmaline selvages replacing aluminosilicate porphyroblasts and their emplacement along the axial planes of $P_3$ folds and $D_3$ dextral shear zones. They are in textural continuity with mineralized quartz–feldspar and quartz–tourmaline veinlets. They also contain maldonite ($Au_2Bi$), native bismuth and gold, electrum, lollingite, arsenopyrite and pyrrhotite, which occur as melt inclusions in plagioclase and quartz, as interstitial grains, and in microscopic k–feldspar veinlets that cut across plagioclase crystals. The granodiorite yielded a zircon crystallization of c. 2640 Ma, whereas metamorphic monazite from the metasedimentary rocks was dated at c. 2609 Ma. Two pegmatite dykes yielded ages of c. 2570 and 2566 Ma on U-rich zircon rims, which are considered minimum estimates because of possible lead loss due to radiation damage. These data indicate that the granodiorite was hydrothermally altered and mineralized between 2640 and 2609 Ma. Prograde metamorphism peaked at upper amphibolite facies, possibly resulting in Au–Ag–As–Bi remobilization, consistent with the localized and variable Au concentration in the disseminated mineralization. The subsequent emplacement of auriferous pegmatites and associated veinlets between 2609 and 2570 Ma contributed to Au scavenging and to its concentration in melts and hydrothermal fluids within late structural sites in a dextral shear regime.

# Convergent margin metallogenesis constrains onset of subduction on Earth

**MP Doublier[1*], DL Huston[1], B Eglington[2], S Pehrsson[3], P Mercier-Langevin[4], S Piercey[5]**

* corresponding author: michael.doublier@ga.gov.au

1. Mineral Systems Branch, Geoscience Australia, Symonston ACT, 2609, Australia
2. University of Saskatchewan, Saskatoon, Saskatchewan, Canada
3. Geological Survey of Canada, Ottawa, Ontario, Canada
4. Geological Survey of Canada, Quebec City, Quebec, Canada
5. Memorial University, St. John, Newfoundland and Labrador, Canada

Convergent margins are a hallmark feature of modern style plate tectonics. One expression of their operation is metallogenesis, which therefore may yield important insights into secular changes in styles of convergence and subduction. A global comparison of metallogenesis along convergent margins of over 20 well-endowed provinces indicates a consistent and systematic progression of mineral deposit types. We term this progression the convergent margin metallogenic cycle (CMMC).

This CMMC mirrors convergent margin evolution. Each metallogenic cycle begins with the formation of porphyry copper deposits and/or volcanic-hosted massive sulphide deposits, associated with arc construction and back-arc basin formation respectively. When the convergent margin transitions into contraction/orogenesis due to processes such as accretion, flattening of subduction or continent–continent collision, mineral deposits that form include orogenic gold and structurally hosted base metal deposits. Post-contractional extension is marked by the formation of intrusion related rare metal (tin, tungsten, molybdenum) and gold deposits, pegmatites and alkaline porphyry copper deposits, closing the CMMC.

Our analysis of the metallogenic record reveals that prior to c. 3 Ga, metallogenesis is episodic and non-systematic, with CMMCs not recognized. From the mid- to late Mesoarchean onwards, CMMCs are observed in all provinces analyzed and display systematic trends through time: the mid-Meso- to Neoarchean metallogenic provinces are characterized by a single metallogenic cycle, whereas in the Paleo- to Mesoproterozoic provinces, both single and multiple metallogenic cycles occur. From the middle Neoproterozoic onwards, multiple metallogenic cycles are the rule. This evolution is accompanied by an increase in the duration of metallogenesis, ranging from about 100 to 180 million years in the Meso- to Neoarchean and 220 to more than 400 million years since the late Proterozoic.

We interpret these trends to reflect secular changes in tectonic processes and Earth evolution. The emergence of CMMCs from c. 3 Ga provides independent evidence for the operation of some early form of subduction since this time. The fact that CMMCs are recognized in all provinces of mid-Meso- to Neoarchean age suggests that subduction was the common modus operandi rather than an exception. The first appearance of multiple metallogenic cycles in the Paleoproterozoic may reflect the strengthening of cratonic margins by tectonothermal maturation since formation in the Archean. Long-lived metallogenesis and multiple metallogenic cycles in the Neoproterozoic and Phanerozoic are linked to deep-slab break-off, or modern subduction in which the internal strength of the subducting slab allows maintenance of slab coherency.

# Structural controls on giant spodumene pegmatite deposits of the northern Pilbara Craton, Western Australia

**JL Grigson[1*], MW Grigson[2], AIS Kemp[1], SG Hagemann[1], MT Sweetapple[1]**

* corresponding author: john.grigson@research.uwa.edu.au

1. School of Earth Sciences, The University of Western Australia, Crawley WA 6009, Australia

2. Arc Minerals Consultants, Gidgegannup WA 6083, Australia

Giant spodumene pegmatite deposits at Pilgangoora and Wodgina are part of an extensive lithium-rich pegmatite district on the western margin of the East Pilbara Terrane, within the northern Pilbara Craton. Here, regional deformation is manifested by faults, folds and shear zones within c. 3.18 Ga greenstone belts with mylonite and gneissic foliation in the surrounding c. 2.95–2.85 Ga granitic complexes. A four-fold deformation scheme is developed from regional mapping (see Figure 1) and the study of pegmatites and wall rocks at individual deposits. D4 controlled the location of c. 2.85 Ga spodumene pegmatite intrusions. D4 was progressive and comprises: a) macroscopic F4a subvertical folds and D4a fault arrays, and; b) D4b ductile shear zones with upright S and L–S fabrics that transpose D4a structures. Regionally, S4b is inclined steeply towards the west-northwest and L4b plunge obliquely towards either the north or south. However, D4b shear zones at Pilgangoora and Wodgina are distinct (Fig. 1), wherein there are two S4b fabrics present, namely main fabric domains inclined steeply towards the west-northwest and subsidiary fabric domains locally aligned with oblique D4a faults. L4b in both fabric domains are colinear and plunge steeply. Such strain compatibility indicates synchronous ductile flow to form the main and subsidiary S4b fabric domains. Spodumene pegmatite intrusions at Pilgangoora and Wodgina are mostly en echelon sheets inclined gently towards the east-southeast, opposite to the inclination of the main fabric domains. The sheets are up to 1000 m-long and 100 m-thick, and terminate laterally by tapering or by pinching out against subsidiary fabric domains. Sheet formation reflects tensile shear failure and magmatic inflation in a coaxial brittle–ductile regime. Closely spaced D4a faults acted as passive attractors of coaxial strain and the subsidiary and main S4b fabric domains record strong subvertical extrusion of fault blocks during constriction. Localized constriction at Pilgangoora and Wodgina contrasts starkly with the regional D4b strain pattern, which reflects oblique extrusion during transpression. Spodumene pegmatite intrusions exhibit remarkable structural controls and structural mapping and analysis is a critical step for locating new deposits in Archean terranes.

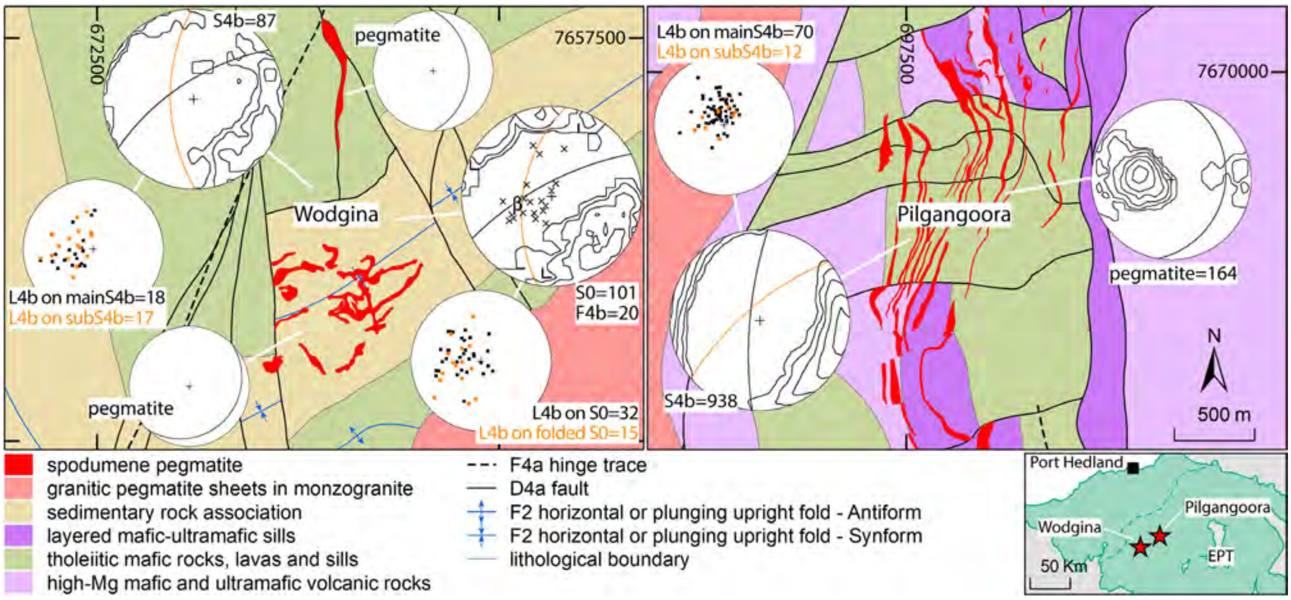



Figure 1. Geological maps and equal-area stereonets of structural elements at the Wodgina and Pilgangoora deposits

# Early Earth's oxygenation: insights from Archean manganese formations of Dharwar Craton, India

**GH Reddy, C Manikyamba***

* corresponding author: cmaningri@gmail.com

CSIR-National Geophysical Research Institute, Uppal Road, Hyderabad 500 007, India

The Archean eon marking the beginning of the Earth's rock record corresponds to about 40% of the global mineral resources with most iron and a part of manganese derived from such ancient sedimentary host rocks. The Archean manganese formations of Dharwar Craton are confined to the western sector in the three greenstone belts of Sandur, Shimoga and Chitradurga greenstone belts, and associated with banded iron formations (BIFs) and stromatolitic carbonates. They provide an opportunity to probe into the early Earth's oceanic hydrosphere and in turn the pre-Great Oxygenation Event (GOE) early oxyatmoversion along with the primitive biosphere evolution. In the Dharwar Craton, the Mn-ore occurs as supergene colloform, nodular, botryoidal segregations within the clay and phyllitic sediments, whereas the primary ore is confined as dendritic, rhythmically banded, or laminated forms in the proto-ore, that is banded manganese quartzite and shale retaining their banded nature. Mineralogically, they are composed of secondary manganese minerals, namely pyrolusite, cryptomelane, goethite, hematite and jouravskite. Their composition, namely Mn/Fe ratios between 4–6, variable Ce anomalies (Ce/Ce* = 0.01–5.39), ∑REE/Fe average 16 x $10^{-4}$, $(Sm/Yb)_N$ >1 and $(Eu/Sm)_N$<1, suggest a paleoridge hydrothermal source of Mn and its cycling across a Mn–paleoredoxcline. The Mn deposition is suggested to be under fluctuating oxic–anoxic conditions in a shallow shelf with the mixing of low-T hydrothermal fluids (<250 °C) and seawater. The Mn-rich arenaceous and argillaceous sediments dated at the maxima of 3.4 Ga (detrital zircon U–Pb ages) suggest the contribution of oldest crust during the deposition of manganese in the Dharwar Craton within a passive margin environment in the Archean Sea. Although the initial oxygenation of the atmo–hydrosphere is an enigma, studies on stromatolitic carbonates, banded iron formations and carbonaceous phyllites from the Dharwar Craton with negative $\delta^{13}C$ (-2.53‰ to 0.01 ‰, -28.5‰, -38.5‰ to -1.8‰ respectively) suggest the formation of oases of biogenic $O_2$ in the surface oceans of the Archean. Therefore, the Archean Mn-formations of Dharwar Craton associated with the above lithounits clearly endorse the biogenically mediated oxygen input that led to redox stratification in the Archean proto-ocean which facilitated Mn (II) oxidation. The comprehensive geochemical, stable isotopic evidences combined with the detrital U–Pb zircon ages of the associated lithologies and the manganese formations of the Archean Dharwar Craton provide new insights on the prevalence of ocean oxygenation prior to the GOE at the passive margins of Archean oceans.

## References

Manikyamba, C, Sindhuja, CS, Khelen, AC, Pahari, A 2022, Archean Biogeochemical Cognizance from Dharwar Craton, India – A Review: Journal of Geological Society of India, v.98, p. 74-78.

Ostander, CM, Nielsen, SG, Owens, JD, Kendall, B, Gordon, GW, Romaniello, SJ and Anbar AD 2019, Fully oxygenated water columns over continental shelves before the Great Oxidation Event: Nature Geoscience, v. 12, p. 186.191.

# Illuminating transcrustal upflow zones with implications for ore localization and reuse of crustal architecture

**TRC Jørgensen[1*], HL Gibson[1], EA Roots[1,2], V Rajesh[1], GJ Hill[3], DB Snyder[1,2], M Naghizadeh[1]**

* corresponding author: trc.joergensen@gmail.com

1. Mineral Exploration Research Centre, Harquail School of Earth Sciences, Laurentian University, Sudbury, Canada

2. Geological Survey of Canada, Ottawa, Canada

3. Institute of Geophysics, Czech Academy of Science, Prague, Czech Republic

The integration of geological and geophysical (seismic, gravity, and magnetotelluric) datasets along a approximately 50 km transect through the world-class Noranda District in the Neoarchean Abitibi greenstone belt, Superior Province, Canada, identifies crustal-scale features and architecture that might explain the clustering and relative location of conventional and Au-rich volcanogenic massive sulfide (VMS) deposits. Furthermore, these same crustal-scale features may have played a role in focusing younger orogenic-style Au mineralization. The Abitibi greenstone belt is considered one of the most highly endowed greenstone belts in the world and its VMS endowment has in part been explained by its extensive juvenile crust that would facilitate high level magmatism, high heat flow, and extension-related structures. However, the processes and geological features responsible for the differential metal endowment and occurrence of deposit clusters within the Abitibi greenstone belt are less clear. The Noranda District is host to approximately 20 VMS, approximately 19 smaller orogenic Au, and minor synvolcanic intrusion-hosted Cu-Mo ±Au ±Ag mineralization, with a large proportion of the metal budget (17 VMS deposits accounting for 104 Mt of 130 Mt VMS ore) restricted to a smaller area coinciding with a magmatic centre characterized by the greatest combined surface area of synvolcanic plutons and intrusions, felsic volcanic rocks and the highest density of synvolcanic structures. A whole-of-crust integration of seismic, gravity, and magnetotelluric imaging with surface geology shows the subsurface in the endowed area is characterized by a deeper extending low seismic reflectivity zone, the largest low-density volume, and the presence of subvertical low resistivity (≤50 Ωm) pipe-like features that connect to a relatively low resistivity (approximately 50–100 Ωm) middle-lower crust, itself potentially extending into the upper mantle. The results imply that clustering of ore deposits in the Noranda District was controlled by ancestral transcrustal structures that localized, optimized, and sustained magmatic and ore-forming processes. The largest and most Au-rich VMS deposits are located where three major synvolcanic faults coincide with one of the most prominent subvertical low resistivity corridors at the locus of the magmatic centre and an optimal location for a magmatic contribution of metal, in particularly Au, to the VMS system. The spatial association with overprinting c. 30 Ma younger orogenic Au deposits suggest that the primary crustal architecture responsible for focusing VMS deposits may have played a role in localizing later Au mineralization.

# Hydrothermal alteration zones at the Montague gold deposit, Gum Creek greenstone belt, Southern Cross Province, Yilgarn Craton, Western Australia

**MJ Kasten*, D Wiemer, SG Hagemann**

* corresponding author: mitchkasten@me.com

Centre for Exploration Targeting, School of Earth Sciences, University of Western Australia, Crawley WA 6009, Australia

The Montague gold deposit, located in the Gum Creek greenstone belt within the Youanmi Terrane of the Southern Cross Province, Western Australia, is hosted in greenschist facies, metamorphosed basalts and granodiorites. The deposits are spatially associated with the $D_3$ northwest striking Caledonian shear zone, which is a subsidiary shear zone off the regional-scale Victory Well shear zone. Despite over 100 years of exploration for gold (and other metals) in the Gum Creek greenstone belt, detailed geological studies only started in the 1990s. Beeson et al. (1993) provide the only regional scale investigation of the lithostratigraphic and structural framework of the Gum Creek greenstone belt. Hence, the overall economic potential and characteristics of gold mineralization in the Gum Creek greenstone belt remain poorly investigated.

New whole rock geochemistry of both pristine and hydrothermally altered rocks from the metabasalts and the granodiorites that form the host rocks to the Montague gold deposit indicate that hydrothermally altered rocks experienced loss in silica content with varying $K_2O$, compared to least altered samples. Supported by petrological observations, chloritization, sericitization and K-metasomatism affected the rocks during hydrothermal alteration. Indeed, mass balance calculations (Gresens, 1967) reveal that significant gains in CaO, total C, S and $H_2O$ resulted from hydrothermal alteration. Furthermore, chlorite geothermometry from distal and proximal alteration zones in both the metabasalt and granodiorite host rocks yield temperatures of 301 ± 12 °C (distal) and 336 ± 6 °C (proximal) respectively.

Our new chemical–petrological data suggest that the Montague deposit of the Gum Creek greenstone belt is best classified as an Archean orogenic (mesozonal) gold system. The characteristic features include: structural control on the localization of the ore bodies in second-order brittle–ductile shear zones adjacent to first order fault zones; distinct hydrothermal alteration zoning surrounding the controlling structures and estimated hydrothermal alteration temperatures of about 301 ± 50 °C indicating mesozonal crustal level emplacement and development of the ore-bearing system.

## References

Beeson, J, Groves, D and Ridley, JR 1993, Controls on mineralization and tectonic development of the central part of the northern Yilgarn Craton. Minerals and Energy Research Institute of Western Australia, Report 109.

Gresens, RL 1967, Composition-volume relationships of metasomatism. Chemical Geology, v. 2, p. 47-65.

# The Carr Boyd intrusive complex: new insights on the sole mineralized intrusion-hosted Ni system within the Eastern Goldfields Superterrane, Yilgarn Craton, Western Australia

**M Le Vaillant*[1], L Schoneveld[1], C Siegel[1], C Spaggiari[1], SJ Barnes[1], S Warriner[2]**

* corresponding author: margaux.levaillant@csiro.au

1. CSIRO, Mineral Resources BU, Discovery Program, Kensington WA 6151 Australia
2. Estrella Resources Ltd, Perth WA 6000 Australia

The Carr Boyd Rocks historic mine is located 80 km northeast of Kalgoorlie in Western Australia and was actively mined for its Ni-Cu resource until 1977. Mineralization was described as hosted within 'sulfide breccia pipes' (Purvis et al. 1972), although their formation was poorly understood. The abandoned pit and surrounding prospects occur within a mafic-ultramafic layered intrusion informally known as the Carr Boyd intrusive complex (CBIC), with a surface expression of approx. 78 km$^2$ and compositions ranging from peridotite to leucogabbro (Purvis et al. 1972, Hayden 2008). Recently, a massive sulfide accumulation was discovered at the contact between the intrusive complex and the country rocks at the T5 prospect. This project investigated the generation and emplacement of the CBIC and its contained sulfide mineralization, the 3D geometry of the intrusive complex, identification of potential ore genesis processes at play and evaluated prospective areas within the complex. A detailed geochemical study was completed using company assays, resulting in a new lithogeochemical classification of the mafic-ultramafic rock types within the complex. 3D visualization confirmed the company's current interpretation of the geometry of the CBIC. Primary sub-horizontal igneous layering has been rotated and is now steeply dipping to the WSW. And the SW edge of the intrusive complex is interpreted as potentially representing the original floor of the CBIC (or basal contact). Representative samples of the two distinct sulfide occurrences, the Carr Boyd 'sulfide breccia pipes' and the T5 sulfide intersection both appear to have been shielded from deformation and display classic magmatic textures (pentlandite loop textures) and no clear evidence of sulfide remobilization. Interestingly, sulfide compositions show clear differences with more elevated Ni tenors but lower Pd and Pt tenors for the Carr Boyd 'sulfide breccia pipes,' compared to T5 sulfides. The sulfides are interpreted as products of two distinct magma batches with varying metal compositions, suggesting two separate mineralizing events within the CBIC. Olivine compositions (laser ablation ICP-MS) are clearly different between the Carr Boyd pipes and T5, which supports the interpretation of two separate magma pulses. Interestingly, a linear correlation between Co and Ni is observed in sulfide-bearing samples, which might represent a good indicator of sulfide presence. Within the CBIC spinel has Al-poor chemistry, interpreted as primary, and there appears to be a depletion of Ni content that can be correlated with the presence of sulfide. Finally, apatite from the Carr Boyd pipes yielded an age of 2694 ± 42 Ma and T5 apatite yielded an age of 2687 ± 56 Ma, both within uncertainty of each other. The CBIC mineralized complex is the first known example of a mineralized Archean intrusion-hosted nickel sulfide system in the Eastern Goldfields Superterrane of the Yilgarn Craton, opening a new search space. The CBIC is underexplored and still holds potential for both internal sulfide breccias resembling the Carr Boyd breccia pipes as well as basal contact massive sulfide occurrences like T5.

## References

Purvis AC, Nesbit RW, and Hallberg JA 1972, Economic geology, v. 67, p. 1093-1113.

Hayden P, 2008, GSWA, Statutory mineral exploration report A078186, 21p

# Tracking gold (re)mobilisation and (re)precipitation during ductile-brittle microscale deformation, Copenhagen gold deposit, East Pilbara terrane, Australia

**L Marulier[1*], A Eglinger[1], J Perret[1,2], N Mériaud[3], AS André-Mayer[1], C Berthier[1], S Sheppard[3]**

* corresponding author: lucas.marulier@univ-lorraine.fr

1. Université de Lorraine, UMR 7359 GeoRessources, CNRS, 54000 Nancy, France
2. Centre for Exploration and Targeting, 35 Stirling Highway, M006 Crawley WA 6009, Australia
3. Calidus Resources Ltd, Perth, West Perth WA 6005, Australia

Gold can have different forms when examined at a microscopic scale, such as being embedded within the crystal lattice of gold-bearing minerals like pyrite and arsenopyrite (known as refractory gold) or present as micro-inclusions of native gold or electrum. The way it is accommodated depends on intrinsic and extrinsic characteristics of the mineral. Intrinsic characteristics describe the in-situ properties such as geochemistry, kinetic, growth rate or crystallography. In contrast, extrinsic characteristics define external mechanisms operating from outside like deformation rate or fluid flow. Constraining these processes and their interactions is therefore critical to understand the timing and the conditions of the mineralization. In this study, we focus on the Copenhagen gold deposit located in the c. 3.51–3.31 Ga Warrawoona greenstone belt in the East Pilbara Terrane, which consists of a syncline bounded by two felsic granitic domes (Hickman, 2021). We integrated petrographic, micro-structural and -textural observations with geochemical in-situ analyses and quantitative mapping of sulphides using an electron microprobe, scanning electron microscopy and laser-ablation inductively coupled plasma mass-spectroscopy. A statistical approach using principal component analysis of minor and trace element concentrations of pyrite highlights the elemental signature of generations distinguished from micro-structural and -textural observations and therefore provides insights into their mobility from one generation to another. Our findings show that the Copenhagen deposit underwent two hydrothermal pulses and deformation phases with a D2-related gold enrichment. The mineralization is hosted in a several-metre thick, sulphide-rich high-strain corridor showing a progressive ductile-brittle strain evolution, and overprinting a cryptic D1-related mineralization hydrothermal alteration and veining stage. The heterogeneous textures and geochemical signatures of pyrite and arsenopyrite with their associated polycrystalline strain fringes allow for splitting the D2 event into two stages. Firstly, a ductile-dominated non-coaxial strain shown by sigmoidal sericite strain fringes, C-S structure and dissolution texture within pyrite. The deformation induces As-rich fluid flow that triggers geochemical processes such as dissolution-reprecipitation and/or Au-chemisorption allowing for the precipitation of electrum within pores and the incorporation of Au within pyrite and arsenopyrite lattice. Secondly, a ductile-brittle coaxial strain illustrated by alternating quartz-carbonate-chlorite strain fringes and oscillatory zoning in both pyrite and arsenopyrite. This ductile-brittle stage is responsible for the remobilization of refractory gold contained within existing sulphides and its reprecipitation as electrum micro-inclusions within fractures affecting pyrite and arsenopyrite grains. Therefore, this study provides insights concerning the readjustment of intrinsic and extrinsic properties of gold-bearing minerals and their environment to trigger gold enrichment. Moreover, it put forward the progressive aspect and the close link between deformation history and geochemical processes in orogenic gold deposits at the microscale. Coupled with observations at larger scales, the highlighted conclusions can provide clues for better targeting in mineral exploration.

## Reference

Hickman, AH 2021, East Pilbara Craton: a record of one billion years in the growth of Archean continental crust: Geological Survey of Western Australia, Report 143, 187p.

# Deep crustal architecture of the Archean Yilgarn Craton: insights from multidisciplinary data integration, geological validation and implications for gold exploration targeting

**Q Masurel[1,2], N Thébaud[1], A Aitken[1], H Smithies[3], K Gessner[3], C Fisher[1], J Lowrey[3], Y Lu[3]**

* corresponding author: quentin@mineralstargeting.com

1. School of Earth Sciences, Centre for Exploration Targeting, The University of Western Australia, Perth, WA, Australia
2. Minerals Targeting International Pty Ltd, West Perth, WA, Australia
3. Geological Survey of Western Australia, Department of Mines, East Perth, WA, Australia

Many, if not all, gold systems are spatially related to zones of mechanical weakness in the lower-middle crust and continental lithospheric mantle. Where preserved, these zones of lithospheric heterogeneity or lithospheric discontinuities reflect the finite cumulative lithospheric damage associated with paleotectonic events in a given region, including rifting and collision. This fundamental architecture is regarded as applying a first order control on the locus of tier one ore deposits. Accordingly, the identification and mapping of this fundamental architecture of the deep crust and continental lithospheric mantle is critical for explorers in order to improve their predictive capacity. However, the confident identification of such fundamental architecture through traditional geological, geochemical and geophysical datasets is a difficult exercise, especially in polydeformed and poly-metamorphosed Precambrian terranes.

Using the well-endowed and well-explored Archean Yilgarn Craton as a natural laboratory, this project aims at imaging such fundamental architecture through multidisciplinary data integration (potential fields, seismic, isotopic geochemistry, topographic and geological data). Strike-extensive lineaments are identified in the lower-middle crust of the Yilgarn Craton, some of which are consistently imaged in geological, geophysical, isotopic and topographic datasets. The results of this lineament analysis indicates that some strike-extensive lineaments mimic the orientation of the craton margins and largely reflect the post-cratonization history of the Yilgarn Craton. In contrast, a discrete set of strike-extensive lineaments appears oblique to the main northnorthwest–south-southeast oriented structural grain established during tectonostratigraphic terrane assembly of the Yilgarn protocraton. By comparing our results against current knowledge on the geological evolution of the Yilgarn Craton, it is proposed that such oblique lineaments represent discontinuities in the proto-Yilgarn crust that existed prior to, or at the onset of intracratonic rifting at c. 2730 Ma and deposition of the supracrustal cover in the Kalgoorlie-Kurnalpi Rift between c. 2720 and 2690 Ma. Importantly, these lineaments are shown to broadly overlap with the location of tier one gold deposits and, thus, represent key features to incorporate in a targeting workflow at the craton to terrane scale.

# Unravelling post-volcanic deformation of komatiite associated nickel sulphides: Cassini deposit, Yilgarn Craton

**HB McFarlane*, M Le Vaillant, SJ Barnes, S-Y Hu**

* corresponding author: helen.mcfarlane@csiro.au

CSIRO Mineral Resources, Kensington, WA 6151, Australia

Komatiitic ultramafic rocks are common in Archean greenstone–granite terranes. The Eastern Goldfields Superterrane (EGST) of the Yilgarn Craton, Western Australia, is of particular interest as it hosts many nickel sulphide deposits in abundant thick cumulate-rich komatiite packages within the greenstone belts. Komatiites magmas are characterized by high MgO contents (>18 wt%) and show well-documented flow profiles of olivine cumulates overlain by spinifex-textures and flow top facies (e.g., Barnes 2006). Komatiite associated massive nickel sulphides accumulate in narrow channelized deposits at the base of the cumulate package. Distinct mineralization profiles and ore body morphologies, including open contact and pinch out geometries with the underlying basalt, develop along the deposits through thermo-mechanical erosion (Lesher et al., 2002). Whilst it is critical to understand the spatial distribution and morphology of volcanological features to delineate ore bodies within the komatiite package, challenges frequently arise from post-volcanic deformation, metamorphism and alteration of the host komatiitic sequences. This is especially important when trying to distinguish multiple komatiite flows from structural repetitions, as hypothesized for areas of the Yilgarn Craton (e.g. Swager and Griffin, 1990). Here we examined the structural history of the recently discovered Cassini Ni deposit (Mincor Resources), located in the southern apex of the Widgiemooltha Dome of the Kalgoorlie Terrane, to unravel the deformation overprint of komatiitic volcanic facies and associated nickel sulphide deposits. New lithological classifications were derived from the company whole rock geochemical database, coupled with structural logging and 3D analysis of the datasets to resolve subsequent overprinting regional Neoarchean deformation. Nickel tenor analysis revealed two possible magmatic flow channels along the basal contact of the Mount Morgan Komatiite. The earliest deformation generated a foliation at low angles to lithological contacts as well as overthrusts noted above massive and net textured sulphides. These structures and the Cassini ore body were passively refolded during regional $D_2$ east-northeast – west-southwest deformation. Subsequent oblique slip deformation is localized along the eastern limb of the Widgiemooltha anticline. The best preservation of the classic mineralization profile is documented in parasitic $F_2$ synclines on the western limb of the Widgiemooltha anticline. The $F_2$ axial trend is subparallel to the highest tenor trend, providing critical guidance for understanding modification of the primary channel morphology. The results of this study have important implications for improving prediction of magmatic nickel sulphide deposits in poly-deformed terranes.

## References

Barnes SJ 2006, Komatiites: Petrology, Volcanology, Metamorphism, and Geochemistry in Nickel Deposits of the Yilgarn Craton: Geology, Geochemistry, and Geophysics Applied to Exploration. Society of Economic Geologists Special Publication No. 13, p. 13–49.

Lesher C, Keays RR, Cabri L 2002, Komatiite-associated Ni–Cu–PGE deposits: Geology, mineralogy, geochemistry and genesis. Canadian Institute of Mining, Metallurgy and Petroleum, v. 54, p. 579-618.

Swager, C, and Griffin, TJ 1990, An early thrust duplex in the Kalgoorlie-Kambalda greenstone belt, eastern Goldfields Province, Western Australia: Precambrian Research, v. 48, p. 63-73

# Oldest magmatic Ni-Cu deposit a consequence of secular change in global tectonic regime

H Olierook[1,2], J Combs[3], B Mcinnes[2], N Evans[1,2], B McDonald[2] , S Tessalina[2], B Ware[2], A Crawford[4], AS Kumara[2], K Baublys[5], C Kirkland[1], T Rovira[3]

*corresponding author: hugo.olierook@curtin.edu.au

1. School of Earth and Planetary Sciences and The Institute for Geoscience Research (TIGeR), Curtin University, GPO Box U1987, Perth, WA 6845, Australia
2. John de Laeter Centre, Curtin University, GPO Box U1987, Perth, WA 6845, Australia
3. Azure Minerals Limited, Level 1, 34 Colin St, West Perth, WA6005
4. Centre for Ore Deposit and Earth Sciences (CODES), University of Tasmania, Hobart, Tasmania, Australia,
5. School of Earth and Environmental Sciences, The University of Queensland, Queensland 4072, Australia.

The styles of ore deposit have changed over time due to secular change in an ever-cooling Earth. Prior to this study, no intrusive magmatic Ni-Cu-(Co) deposits were confidently known to exist before 2930 Ma, begging the question: is this is a function of preservation bias or geological consequence? Here, we use zircon U–Pb and sulfide Re–Os geochronology of the mineralizing gabbro at the Andover Deposit in the Pilbara Craton, WA, to show that it formed at 3015.6 ± 1.5 Ma, approximately 85 Ma older than the next oldest deposit, through mantle-melting induced by slab breakoff. Complementary zircon Hf, stable S and initial Os isotopes reveal assimilation of continental crust, an interaction that is crucial to cause S immiscibility and yield economic Ni-Cu deposits. At c. 3.2–3.0 Ga, a global extraction of mantle material occurred to produce major, buoyant continental crust as part of the transition of dominantly stagnant-lid to plate tectonics on Earth. Prior to this time, the lack of preservation potential of buoyant felsic continental crust meant that Ni-Cu deposits are unlikely to have formed in economic quantities, nor be preserved. Ultimately, we posit that the secular change of Earth's tectonic regime led to the rise of magmatic Ni-Cu deposits in the Mesoarchean.

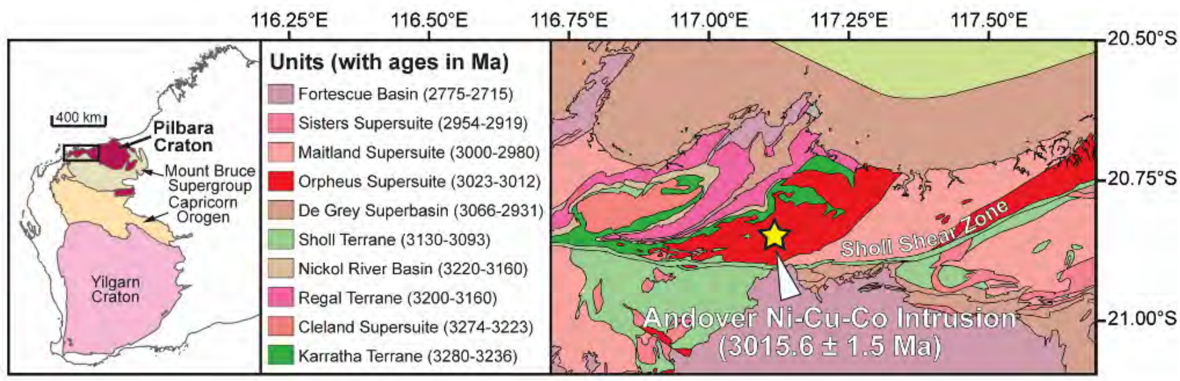



Figure 1: Location of the oldest magmatic Ni-Cu-Co intrusion

# Large-scale controls of the Congo Craton on the PanAfrican aged mineral system on the example of worldclass uranium deposits in Namibia

**A Otto**

alex.otto@deepyellow.com.au

Deep Yellow Limited, Subiaco WA 6008, Australia

The Congo craton is an assemblage of Archean crustal blocks surrounded by Proterozoic belts. The evolution of the southern Proterozoic margin had direct influence on the development of a large mineral system in the Damara orogen resulting in uranium, tin and lithium deposits. The southern Central Zone of the c. 540–500 Ma Damara orogen hosts the world-class leucogranite-hosted Roessing and Husab deposits. Uranium mineralization is associated with sheeted leucogranite intrusions, which Nex et al. (2001) classified into 6 types (A-F) based on field relationships, with types D and E being the most uraniferous type.New interpretation of existing work and new data demonstrate the importance of magma derived hydrothermal fluids in forming uranium mineralization. The stratigraphy is dominated by metamorphosed Neoproterozoic clastic sediments with inherited magmatic zircon ages of 2 Ga and 1 Ga. Nd isotopy on zircons shows that clastic rocks of the southern Central Zone have undergone a prolonged crustal recycling. Due to the high concentration of radiogenic elements (U, Th, K) in these sedimentary packages, the metamorphic grade reached temperatures of about 800 °C and pressures of 4–5 kbar resulting in widespread partial melting. Field evidence shows that the leucogranite melts preferentially intrude the core of domes (e.g. Ida Dome) and minor anticlinal structures as evident at the Ongolo and MS7 deposits. The majority of leucogranite intrusions are similar in textural style and composition albeit show significant differences in relative ages across the Omahola area. The observed cross cutting nature between different sets of leucogranites and their relationship to its deformed host rocks is a feature of a highly ductile and inhomogeneous host rock that exhibits high competency contrast. Thus, the classification into different types of leucogranites regarding uranium mineralization is thought to be irrelevant for the study area. Another significant observation is the spatially extensive occurrence (1–10 km) of skarns within the Rössing formation marbles. The distal and earlier assemblage is dominated by wollastonite, scapolite and clinopyroxene. The proximal garnet rich skarn is hosted in gneisses of the Khan formation and are spatially associated with uranium mineralization (i.e MS7, Ongolo, Inca, Garnet Valley). The observations of pegmatite pods within fine-grained granite and quartz veins indicate the significant role of hydrothermal fluids during uranium mineralization. The reaction of carbonates to various skarn minerals produced porosity within the Rössing formation, thus creating an outlet that focuses the regional fluid flow. The magmatic fluids within the leucogranite melt reacted to that pressure differential by percolating throughout the melt and concentrating uranium towards the Rössing-Khan boundary. At Inca, uranium mineralization is part of an evolving hydrothermal system that is associated with skarn alteration including hedenbergite, Fe–actinolite and magnetite. At an even larger scale, the outermost expression of this mineral system is the Shiyela magnetite/hematite deposit about 25 km south of the alaskite hosted Ongolo deposit.

## Reference

Nex, PAM, Kinnaird, J and Oliver, GJH 2001, African Earth Sciences, 33, 481-502

# Carbon contribution to forming high-grade gold mineralization

**L Petrella[1*], N Thébaud[1], D Fougerouse[2], L Martin[3], L Virnes[1]**

* corresponding author: laura.petrella@uwa.edu.au

1. Centre for Exploration Targeting, University of Western Australia, Crawley 6009, WA, Australia
2. School of Earth and Planetary Sciences, Curtin University, Bentley 6102, WA, Australia
3. Centre for Microscopy Characterisation and Analysis, The University of Western Australia, Perth, WA, Australia

World-class Archean orogenic gold mineralization is often associated with hydrothermal fluids rich in $CO_2$ and $CH_4$. This association has been demonstrated from fluid inclusions studies in quartz associated to gold in veins (Chi et al., 2006). The presence of carbon in ore forming hydrothermal fluids has been recognized as a potential important indicator of the source of the fluids, it has also been considered as playing a role in buffering fluid pH, allowing for transport of a larger quantity of dissolved gold aqueous complexes in solution (Phillips and Evans, 2004). Recent work has shown that carbon may play a more important role in the formation of high-grade ore bodies. In our recently published study, we observed gold nanoparticles within an amorphous carbon phase preserved in micro-inclusions in gold from high-grade orogenic deposits (Petrella et al., 2022). Such intimate association between amorphous carbon and gold raises questions on the role of carbon in ore forming processes and on gold transport mechanism. To address these questions a better understanding of the nature of the carbon in the hydrothermal orogenic fluids is needed. Investigating the nature of the carbon in the aforementioned microinclusion might inform in which form it was transported in the hydrothermal system. This information could help resolve the dilemma of the potential presence of hydrocarbon in the hydrothermal system and its contribution to gold transport (Gaboury, 2021). The temperatures under which these systems are formed (350–400 °C) might not be favourable for gold transport by hydrocarbon (Crede et al., 2019; Migdisov et al., 2017). Alternatively, results could show that such complex organic molecules where not involved in the transport and deposition of gold but that much less dense volatile compounds (Parkhomenko et al., 2012) might have played a role in metallogenic processes. Both hypotheses are novel and challenge the accepted model for gold transport in hydrothermal fluids and this study raises the innovative idea of considering carbon as a potential ligand for gold in Archean orogenic systems.

## References

Chi, G, Dubé, B, Williamson, K and Williams-Jones, AE 2006, Formation of the Campbell-Red Lake gold deposit by $H_2O$-poor, $CO_2$-dominated fluids. Mineralium Deposita 40, 726.

Crede, L-S, Liu, W, Evans, KA, Rempel, KU, Testemale, D and Brugger, J 2019, Crude oils as ore fluids: An experimental in-situ XAS study of gold partitioning between brine and organic fluid from 25 to 250° C. Geochimica et Cosmochimica Acta 244, 352-365.

Gaboury, D 2021, The neglected involvement of organic matter in forming large and rich hydrothermal orogenic gold deposits. Geosciences 11, 344.

Migdisov, AA, Guo, X, Williams-Jones, A, Sun, C, Vasyukova, O, Sugiyama, I, Fuchs, S, Pearce, K and Roback, R 2017, Hydrocarbons as ore fluids. Geochemical Perspectives Letters 5, 47-52.

Parkhomenko, RG, Morozova, NB, Zharkova, GI, Shubin, YV, Trubin, SV, Kriventsov, VV, Kuchumov, BM, Koretskaya, TP and Igumenov, IK 2012, Deposition of Au Thin Films and Nanoparticles by MOCVD. Chemical Vapor Deposition 18, 336-342.

Petrella, L, Thébaud, N, Fougerouse, D, Tattitch, B, Martin, L, Turner, S, Suvorova, A and Gain, S 2022, Nanoparticle suspensions from carbon-rich fluid make high-grade gold deposits. Nature Communications 13, 3795.

Phillips, GN and Evans, KA 2004, Role of $CO_2$ in the formation of gold deposits. Nature 429, 860.

# Genesis of Archean goldfields

**GN Phillips[1,2*], R Powell[1], JR Vearncombe[3]**

*corresponding author: neil@phillipsgold.com.au

1. School of Earth Sciences, The University of Melbourne, 3010, Vic., Australia
2. Department of Earth Sciences, Stellenbosch University, South Africa
3. Effective Investments Pty Ltd (Australia), PO Box 99699, Newmarket 1149, New Zealand

There is a direct link between scientific breakthroughs in gold geology, advances in exploration methods, discovery and the rise of Yilgarn gold production since 1980 (Phillips et al. 2019). The 20 000 or more Archean goldfields worldwide share characteristics that constrain their genesis. A fundamental subdivision is into gold-only deposits with gold as the economic product, and gold-plus with economic base metals. This subdivision is easy to apply, relatively unambiguous and reflects different ore-forming processes. Gold-only deposits are dominant in Archean cratons and their distribution in provinces reflects the scale of genetic processes. Most Archean greenstone belts contain gold deposits and some are inordinately rich with linear concentrations of goldfields for hundreds of kilometres (e.g. Kirkland Lake – Larder Lake fault system, Canada) and districts with multiple large deposits (e.g. Kambalda – St Ives goldfield, Western Australia). The intervening granite batholiths, however, are devoid of gold workings over most of their area except within 0–2 km of greenstone margins.

Gold-only deposits represent enrichment of gold by four orders of magnitude and extreme segregation of base metals from gold. A distinctive feature is the $H_2O$–$CO_2$–$H_2S$ fluid recorded from Archean gold-only deposits from most cratons and from gold-only deposits of younger age. Structurally, the gold-only deposits are all later than sedimentation and volcanism (thus synchronous with periods of orogeny) and larger goldfields coincide with areas of structural complexity.

The metamorphic devolatilization model can account for these shared characteristics of Archean gold-only deposits. The model can be conveniently divided into: 1) extraction of an auriferous fluid from crustal source rocks; 2) transport of gold in that fluid via structural channel ways; and 3) gold deposition. The source involves greenschist to amphibolite facies metamorphism of mafic or greywacke sequences to generate a metamorphic fluid. The $H_2O$–$CO_2$–$H_2S$ fluid reflects the source rock mineralogy and grain-by-grain breakdown of cubic kilometres of rock mass undergoing metamorphism. This fluid has the capacity to dissolve gold while the fluid forms and provides an effective way to remove gold from large volumes of rock. The transport stage begins on grain boundaries, migrates to shear zones and may end in faults, breccias, veins or the wall rock alteration halo. Deposition is facilitated by fluid reduction near carbonaceous rocks, or fluid interaction with Fe-bearing wall rocks to precipitate pyrite and gold. The overall appearance of deposits today reflects subsequent modifying events including partial melting and high-grade metamorphism, retrogression, weathering and erosion. These need to be considered before gold genesis can be unravelled.

## References

Phillips GN 2022, Formation of Gold Deposits. Springer Nature Singapore. doi.org/10.1007/978-981-16-3081-1. 320 pages

Phillips, GN, Vearncombe JR, Anand RR, Butt CRM, Eshuys E, Groves DI and Smith RE 2019, The role of scientific breakthroughs in gold exploration success: Yilgarn Craton, Western Australia. Ore Geology Reviews, v. 112. doi.org/10.1016/j.oregeorev.2019.103009

# Proterozoic sediment-hosted copper mineral systems in the Birrindudu Basin, Northern Territory

**S Schmid*, V Crombez**

*corresponding author: susanne.schmid@csiro.au

Mineral Resources – Discovery Program, CSIRO, Kensington WA 6151, Australia

The Birrindudu Basin is located in north-western Northern Territory and comprises sedimentary successions of Palaeo-to Mesoproterozoic age. The basin overlies volcanic-sedimentary and magmatic rocks of the Tanami Region, Pine Creek Orogen, and parts of the Halls Creek Orogen. Multiple sedimentary packages occur in the basin: i) the Birrindudu Group located to the South of the basin with a maximum depositional age of 1837–1812 Ma; ii) the overlying Limbunya, Wattie, and Bullita groups in the central part of the basin with a maximum depositional age of 1653–1600 Ma.

Our research aims at evaluating the potential of the basin for hosting sedimentary copper mineralization by applying a mineral systems approach. Particular focus is on the palaeo-environmental evolution of the basin, the basin-basement interface, the identification of potential host/source rocks for copper, favourable metal carriers and fluid pathways.

Our preliminary results show that Palaeoproterozoic basalts and volcaniclastic units of the basement have been strongly leached by migrating fluids. Moreover, there is evidence for localized remobilization of copper in a succession immediately below the basin-basement contact (Fig 1a). The overlying Mesoproterozoic sandstones (Fig 1b) is highly porous/permeable and thus could have been a pathway for mineralizing fluids. Evaporitic (anhydrite) dolostones (Fig 1c) and siliciclastic successions above the sandstone intervals could provide sulphur necessary for mineralization. Further research is necessary to identify potential host rocks and the timing of fluid flow associated with metal transport.

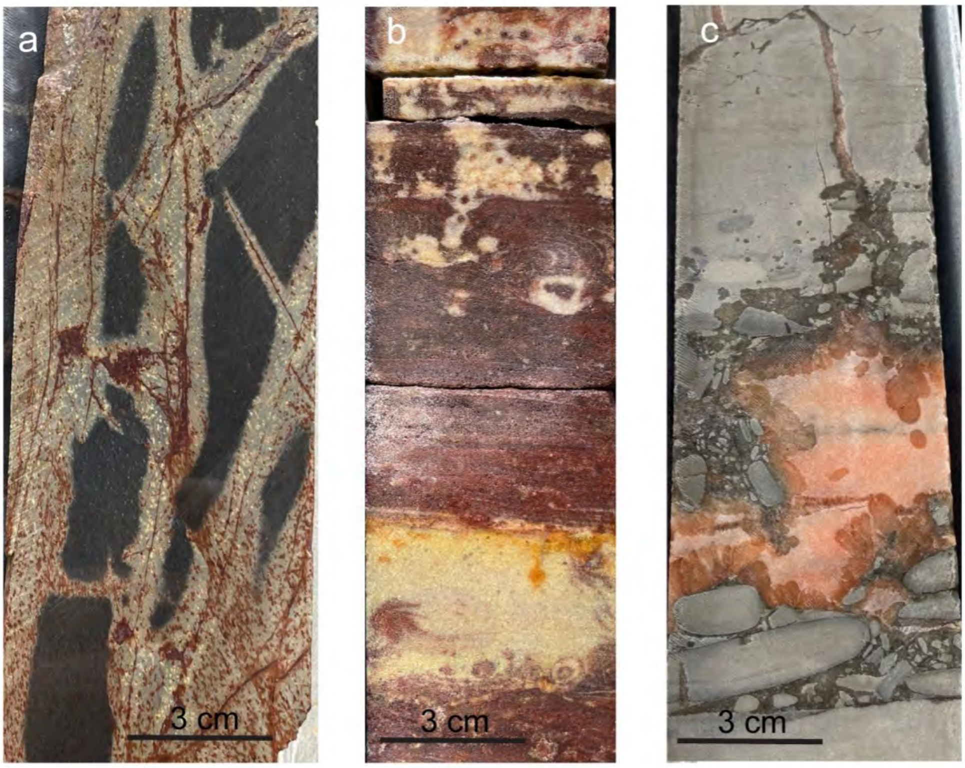



Figure 1. Drill core images: a) altered basalt; b) altered sandstone; c) dolostone with anhydrite

# Biogenically mediated metallogeny: a comprehensive study from Precambrian carbonaceous phyllites, Dharwar Craton, India

**CS Sindhuja*, C Manikyamba**

* corresponding author: sindhujachalla29@gmail.com

CSIR-National Geophysical Research Institute, Habsiguda, Hyderabad, Telangana, India- 500007

Organic carbon rich meta-sedimentary rocks are potential hosts for gold, platinum-group element (PGE) mineralization and vestiges of the biogeochemical cycles that prevailed during the Precambrian time frame. The Neoarchean carbonaceous phyllites/shales of Chitradurga, Gadag, Sandur and Shimoga greenstone belts of Western Dharwar Craton are associated with stromatolitic carbonates, banded iron formations and other detrital sediments whereas the Proterozoic counterparts of Cuddapah basin are associated with the barites. The mineralized Archean carbonaceous phyllites from Chitradurga and Gadag greenstone belts display three generations of pyrites and their mineral chemistry suggests hydrothermal imprints while Proterozoic carbonaceous shales from Mangampeta have two generations of diagenetic pyrites. Chitradurga phyllites (avg. Au=180ppb) show elevated concentrations of refractory gold compared to Gadag (avg. Au=38 ppb) and Mangampeta shales (avg. Au=23 ppb). The Archean carbonaceous shales contain high PGE concentration (ΣPGE=55–37 ppb) compared to Proterozoic counterparts (ΣPGE=27 ppb). The PGE geochemistry is characterized by enrichment of PPGE over IPGE with Au>Pt>Pd and the Au/Pd, Pd/Pt, Ru/Ir, Ir/Pd ratios coupled with negative Pt (Pt/Pt*) anomalies indicate hydrothermal source. The Chitradurga and Gadag Carbon phyllites yielded low sulphur isotopic signatures ($\delta^{34}S$ = 1.8-2 and 1.3–2‰ respectively) whereas the Proterozoic carbonaceous shales have comparatively higher values (8.4–34.3‰) suggest that the sulphate present in Archean and Proterozoic sea water was converted to sulphur by bacterial sulphate reduction which led to the formation of pyrites. The rare earth elements (REE) concentrations are characterized by positive Europium anomalies indicating hydrothermal source and their ratios such as Eu/Sm and Sm/Yb reflect onsea water characteristics. Cr/Th, La/Sc, Th/Sc and Co/Th ratios in all the carbon shales/phyllites imply mafic provenance and the Cr-Zr relationship suggests deep sea depositional setting. Low Sr/Cu and high V/(V+Ni) ratios indicate humid palaeoclimatic environment and anoxic to euxinic redox conditions respectively. The predominantly negative $\delta^{13}C_{org}$ values of Archean greenstone belts range from -38.5‰ to -8.06‰ VPDB while the Proterozoic counter parts from Cuddapah basin consists of -30.19 to -13.98‰ VPDB, suggesting the role of primitive life forms through biological processes during the deposition of organic matter. Higher Vanadium (V=19.4–248 ppm) and Chromium (Cr =31–240 ppm) contents in Archean Carbonaceous phyllites suggest reducing environment that supported mineralization. Thus, biogenically mediated redox depositional environments that prevailed during the Archean and Proterozoic times have enhanced the metal sequestration processes and subsequently facilitated mineralization hosted by these carbonaceous shales.

# Insights into the formation of high-grade gold mineralization at the 10 Moz. Jundee gold camp in Western Australia

**Sumail*, N Thébaud, Q Masurel, C Fisher**

* corresponding author: sumail.sumail@research.uwa.edu.au]

Centre for Exploration Targeting, School of Earth Science, The University of Western Australia, Perth, WA, Australia

Most, if not all, gold systems irrespective of their type (e.g. epithermal Au, orogenic Au, porphyry Cu-Au, Au skarn) have long been associated with a prominent structural control on their ore-forming process. In the case of orogenic gold deposits, structural complexity is regarded as the principal control on mineralization and a significant amount of research in the last century has thus focused on better understanding such controls in order to improve our predictive capability. Although orogenic gold deposits form one unified class, individual deposits vary significantly in terms of their mineral paragenesis, deformation styles and associated gold grades. Understanding the processes that control the variation in gold grade has significant implications for predicting how and more importantly where high-grade mineralization is formed.

In this study, we focus on the 10 Moz. Jundee gold camp, located in the Yandal greenstone belt of the Kalgoorlie Terrane in the Yilgarn Craton of Western Australia. The mining camp comprises the high-grade Jundee gold mine (9 Moz. at 5 g/t Au) and the refractory-style Bogada deposit (1 Moz.) hosted in Archean mafic-ultramafic sequences. The high-grade gold mineralization style observed at Jundee along with the refractory Bogada style mineralization provides an excellent case study to learn insights into the formation of high-grade gold mineralization. Furthermore, determining whether the two distinct mineralization styles reflect a single mineralization event or a polyphased evolution is critical in understanding the development of orogenic gold systems. By combining structural geology and mineralogy, this study examines in detail the structural and alteration paragenesis at the two deposits and places relative timing constraints on events leading to the formation of gold mineralization.

Detailed structural evolution of the gold camp reveals that gold mineralization at Jundee developed over at least three distinctive events. Early low-grade mineralization hosted in shallow-crustal veins is overprinted by dominantly brittle structures comprising high-grade free gold mineralization. Late thrusting in the gold camp is further associated with the remobilization of gold and the addition of a low-grade mineralization. Contrarily, at the Bogada deposit, limited evidence exists for punctuated gold mineralization and gold mineralization is refractory-style hosted in ductile shear zones. Based on the detailed structural and paragenetic framework established in this study, we can conclude that the high-grade gold mineralization at Jundee and the low-grade refractory style mineralization at the Bogada deposit occurred as two protracted events. However, the fundamental question remains as to what processes result in the formation of the exceptionally high-grade ore shoots at the Jundee deposit and how they differ from that at Bogada.

# Proterozoic Pb isotope history recorded in Archean Pilbara conglomerate gold – pilot study

**ST Tessalina*, NJ McNaughton**

* corresponding author: Svetlana.Tessalina@curtin.edu.au

John de Laeter Centre, Curtin University, Bentley 6102 WA, Australia

Western Australia is well known for its Archean gold endowment, spanning across the Yilgarn and, in lesser extent, Pilbara Cratons. The renewed interest into the origin and age of gold mineralization was recently fuelled by the finding of 'conglomerate gold' in Pilbara sedimentary sequences, with some arguing the similarity with the major Witwatersrand gold event in South Africa. Previous studies of gold mineralization in Western Australia were based on gold-associated minerals. In this study, we focused on the native gold itself, performing state-of-the-art analysis of Pb isotopes coupled with gold nugget morphology and inclusions. We report that the Pb isotope composition of native gold and its galena inclusions can provide valuable information about the timing of gold formation and subsequent history (e.g. Tessalina et al., 2023).

In our study, we analysed one 2.9 g gold nugget collected from the informally named Egina Gravels unit, composed of unconsolidated conglomerate fragments bearing gravels, thought to be derived from the conglomerate unit in the 2780–2629 Ma Fortescue Group and overlying gold mineralized Mallina Formation (3015–2931 Ma) in the Central Pilbara.

The nugget has been divided into several sub-samples and analysed for Pb isotopes by TIMS in JdLC using a Pb double spike. The $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios span a range between 16.00–27.33 and 15.55–17.42, respectively. The least radiogenic group of sub-samples with $^{206}Pb/^{204}Pb$ ratios averaging 16.14+/-0.09 (n=5), is similar to the least radiogenic Pb isotope analyses from other well dated deposits located within the Capricorn Orogen: Magellan sediment-hosted Pb deposit (c. 1.8 Ga), Labouchere and Nathans orogenic gold deposits (c. 1.8 Ga), and less radiogenic DeGrussa VHMS deposit (c. 2 Ga). All the least-radiogenic Pb isotope analyses from these deposits and the studied gold plot above all $^{206}Pb$–$^{207}Pb$ lithospheric growth curves, indicating a high U/Pb signature of an older Pb source, probably coming from the Archean basement. Our data also plot well below the $^{208}Pb$–$^{206}Pb$ lithospheric growth curve, indicating low Th/U in the Pb source of the studied conglomerate gold nugget.

The studied nugget could be formed by two different mechanisms: (1) an older (c. >2.9 Ga) detrital nugget with strong overprint and Pb addition during the c. 1.8 Ga event related to the regional Capricorn orogenic event; or (2) nugget formation at c. 1.8 Ga in-situ. First model is supported by previous evidence of post-deposition isotopic disturbance, based on Rb–Sr and Pb isotopes (e.g. Oversby, 1976). Further advances in understanding the source and timing of conglomerate gold in Pilbara await more comprehensive studies.

We acknowledge the Novo Resources Corporation for donating the nugget and background information.

## References

Oversby, VM 1976, Isotopic ages and geochemistry of Archean acid igneous rocks from the Pilbara, Western Australia: Geochimica et Cosmochimica Acta 40, 817-829.

Tessalina, SG et al. 2023, Isotopic fingerprinting of native gold from Western Australia: Geological Survey of Western Australia, Report 229, 32p.

# Contrasting dome-and-keel and linear accretionary architectures in the eastern Wabigoon subprovince, Archean Superior Province, Canada: implications for gold mineralization

**Z Tóth, B Lafrance*, K Strongman, B Mark, HL Gibson, A Haataja, DK Tinkham**

* corresponding author: blafrance@laurentian.ca

Mineral Exploration Research Centre, Harquail School of Earth Sciences, Laurentian University, Sudbury, Ontario, Canada P3E 2C6

The Wabigoon subprovince in northwestern Ontario, Canada, is a Mesoarchean and Neoarchean greenstone-granite terrane, bounded to the north and south by the younger Neoarchean metasedimentary English River and Quetico subprovinces. The eastern Wabigoon subprovince includes the Onaman-Tashota Belt (OTB) and the Beardmore-Geraldton Belt (BGB). The OTB occupies the centre of the eastern Wabigoon subprovince where it consists of Mesoarchean (2975–2922 Ma) and Neoarchean (2780–2740 Ma) metavolcanic and metasedimentary assemblages, older tonalitic gneisses, and syn-volcanic and syn-tectonic Neoarchean plutons. Younger 2710–2695 Ma metasedimentary sequence of interlayered sandstone, argillite and conglomerate are infolded with the metavolcanic rocks. The OTB has a dome-and-keel structural architecture characterized by tightly folded metavolcanic and metasedimentary rocks in between the Neoarchean Ombabika batholith and Onaman pluton, a steeply-dipping and northerly-striking foliation and down-dip stretching lineation wrapping around these intrusions, high strain zones along intrusion-volcanic rock contacts, and an overall younging of the metavolcanic rocks away from the intrusions.

The BGB is located along the southern margin of the eastern Wabigoon subprovince and represents a transitional belt between the metasedimentary Quetico subprovince to the south and the Wabigoon subprovince to the north. It consists of E-trending and steeply-dipping, interleaved panels of 2700–2694 Ma metasedimentary and 2725 Ma metavolcanic rocks, which are bounded by thrust faults that were reactivated as transcurrent faults. It has a linear accretionary architecture that contrasts with the dome-and-keel architecture of the adjacent OTB to the north, although both are coeval and formed between 2700 Ma to 2690 Ma during closure of the Quetico basin and collision with a greenstone-granite terrane to the south.

The OTB and BGB further differ in gold endowment. The OTB hosts few small gold deposits, past-producing mines, and early 20$^{th}$ century artisanal mines, which collectively produced less than 120,000 ounces of gold, whereas gold deposits in the BGB collectively produced 4.1 million ounces of gold. Gold is typically associated with early quartz-carbonate veins hosted by high strain zones and shear zones that formed during the downward flow of the supracrustal rocks between uprising granitic domes in the OTB and during accretion and imbrication of supracrustal rock panels in the BGB. Gold was further emplaced during the transcurrent reactivation of the panel-bounding shear zones in the BGB, which coincide with steeply-dipping zones of low reflectivity and resistivity that extend down to crustal depths of 15 km on the Metal Earth seismic and magneto-telluric transect across the eastern Wabigoon subprovince. The shear zones acted as conduits for the upward migration of hydrothermal fluids and possibly magmas, which in turn altered the rocks and produced the geophysical responses observed on the Metal Earth transect. Thus, the presence of deeply penetrating reactivated structures in the BGB explains its preferential gold endowment and suggest that accretionary horizontal tectonics is more favourable for the formation of gold deposits than vertical dome-and-keel tectonics, although both may be coeval.

# Alteration and mineralization model for the giant Kerr-Addison orogenic gold deposit, Canada

**G Tuba*, RL Sherlock**

* corresponding author: gtuba@laurentian.ca

Mineral Exploration Research Centre, Harquail School of Earth Sciences, Laurentian University, Sudbury ON P3E 2C6, Canada

The Kerr-Addison gold mine (Ontario, Canada) sits in the structural footwall of the crustal-scale Larder Lake – Cadillac deformation zone (LLCDZ) in the southern Abitibi greenstone belt and ranks as one of the largest past-producing gold deposits in Canada with over 11 Moz produced gold. Despite its size and significance, however, the number of geological studies available on the deposit is limited and date back to the early 1990s. With recently renewed exploration, the volume of new geological and geochemical data offered the possibility for a much needed updated model for the deposit.

Ultramafic and mafic volcanic units in the area underwent multi-stage alteration in the presence of a NaCl-KCl-$CO_2$ hydrothermal fluid that also carried $H_2S$, As, Sb and Au. The mineral paragenesis shows spatial and temporal progression during the chemical evolution of the system, primarily driven by pH and relative element concentration changes due to fluid-rock interaction. The diversity of alteration assemblages are explained by differences in host rock compositions interacting with the same fluid.

The initial hydrothermal stage is characterized by pervasive carbonate ± sodic alteration traceable for over 700 m lateral distance in the LLCDZ footwall. In areas distant to mineralization, the advanced hydrothermal stage is present as an overprinting, pervasive to fabric-controlled chlorite alteration defining the footprint chlorite-carbonate facies. As a contrast, the initial carbonatization is followed by sulfidation of the host rock in the alteration envelope associated with mineralization, producing contrasting alteration and mineralization types as a function of $Fe^{2+}$ availability. At this stage, pyrite-arsenopyrite mineralization associated with advanced albite alteration and economic gold grades (historically termed ‘flow ore’) occurred in the mafic volcanic units, while disseminated pyrite in the komatiite is generally sparse, and elevated gold grades, if present, are associated with As- and Sb-bearing Ni-sulfide species (gersdorffite, skinnerite). Ultramafic flow type mineralization occurs in locally derived, graphitic interflow sediments, where sulfidation of the relatively Fe-poor host is suggested to have occurred through redox reactions caused by graphite.

Subsequent potassic alteration is uniformly defined by K-mica (sericite or fuchsite) in both rock types as the system became fluid buffered. Several generations of gold-hosting quartz-carbonate±albite veins developed in the potassic altered komatiite, representing the primary mineralization style in the ultramafic host (‘green carbonate ore’). Although visible gold is present in the veins, it is frequently found in subgrain zones of the deformed vein material intergrown with calcite, post-dating vein formation. Excess Ca is a product of a late fluid event that can be traced along major faults in the deposit area, and may be responsible for the partial remobilization of gold.

The hydrothermal system is broadly coeval with regional $D_2$ deformation with development of $S_2$ fabric following the onset of the sulfidation and advanced sodic alteration stage. Potassic alteration is primarily controlled by $S_2$ foliation and gold-bearing veins are progressively deformed during the same deformation event. A magmatic source for the mineralizing fluid, as concluded by former deposit models based on the presence of albitized (‘albitite) dikes, is not evidenced in the current study.

# Towards a generalized model of hydrothermal fluid evolution in orogenic gold systems: a systematic study from the Abitibi greenstone belt, Canada

**G Tuba*, DJ Kontak**

* corresponding author: gtuba@laurentian.ca

Mineral Exploration Research Centre, Harquail School of Earth Sciences, Laurentian University, Sudbury ON P3E 2C6, Canada

Studies of orogenic gold deposits have provided abundant information and insight in regards to their age distribution, nature of mineralization and alteration styles as well as structural controls, yet uncertainty remains about certain aspects of the ore-forming hydrothermal processes. Whereas a low-salinity aqueous-carbonic fluid is the preferred mineralizing agent, a unified physicochemical model that explains gold formation remains elusive, despite numerous fluid inclusion studies carried out on orogenic deposits globally.

To address the problem, we carried out a multiscale fluid inclusion study of over 30 Archean orogenic deposits from the gold-endowed Abitibi greenstone belt of the Canadian Shield. The research systematically employed a new approach to fluid inclusion investigations which provided the means to obtain physicochemical information beyond what is normally attained by conventional fluid inclusion petrography and microthermometry. Special emphasis was given to: 1) recording and assessing fluid inclusion modification textures and evaluating the related implications (e.g. plastic versus brittle deformation, pressure cycling); 2) constraining the timing of entrapment of fluid inclusion assemblages (FIA) relative to presence of gold; 3) the quantification of fluid chemistry at different stages of the orogenic fluid system (e.g. evaporate mound analysis, in situ LA ICP-MS); and 4) the $\delta^{13}C$ isotope signatures of fluid inclusion extracts.

The studied deposits cover a wide range of settings in terms of affinity to felsic intrusions, host rock, gold endowment and depth of formation, yet the hydrothermal fluid evolution reconstructed from fluid inclusions is remarkably uniform. Results show that, in general, orogenic hydrothermal systems are long-lived and cover a range of P and T with a significant volume of continuous fluid flow. Early mineralizing fluids have a geochemical signature of Na, As, B, S, K, Cu, W and Sb but are in constant physicochemical evolution due to gradual and/or rapid pressure changes as well as continuous fluid-rock interaction. As a result, the maturing fluid becomes enriched in elements and components sourced from the host rocks, such as Ca, Fe, Mg, K and $CO_2 \pm CH_4$. That some of the $CO_2$ and most of the $CH_4$ originates from metasedimentary rocks is inferred from $\delta^{13}C$ on fluid extracts which range down to -30‰. At late stages, unmixing often produces a carbonic-rich fluid that is preferentially trapped as the latest FIA associated with the orogenic system.

Pyrite-hosted gold mineralization in vein selvages is associated with the early fluid stage, but the timing of precipitation of free gold in quartz veins differ in epizonal versus mesozonal systems. It is broadly coeval with vein formation in the former, but in the latter, including many bonanza-grade ore bodies, it occurs in the late fluid stages and has an affinity to both low pressure regimes and carbonic-rich fluids.

The model established in this study is in good agreement with observations from other orogenic gold deposits across geological time and space globally. The study also highlights that some of the fundamental conclusions regarding orogenic gold models acquired using conventional fluid inclusion methods should be reconsidered.

# The Meso-Archean Murchison Belt, Kaapvaal Craton: an island arc with early gold mineralization

**J Vearncombe**

julian@vearncombe.com

University of Stellenbosch, RSA & Effective Investments Pty Ltd, PO Box 675, South Perth 6951 WA, Australia

The Murchison-Thabazimbi-Lineament in northern South Africa is up to 20 km wide, with polyphase deformation traced for more than 500 km, in a punctuated history of more than 2500 Ma. The east-northeast-trending lineament is one of the world's most important structures for its Archean structure, control on Proterozoic sedimentary basins, igneous intrusions and world-class mineral deposits. The lineament penetrates the Archean granitoid-greenstone terrain where it is the 2980 to 2960 Ma Murchison Belt, an exhumed Archean island arc sequence with a basal layered meta-igneous complex with Ti-V-bearing magnetites, overlying calc-alkaline volcanic rocks with volcanic massive sulphides, and a mafic-ultramafic volcanic sequence and clastic sediments with orogenic gold-antimony. It lies along a cratonic sub-terrain boundary but is not a suture with ophiolites. Formation, deformation, granitoid intrusion and mineralization all occurred prior to Limpopo Orogeny to the north at 2672 to 2620 Ma. Murchison Sb-Au mineralization formed at about 2832 Ma. This makes the Murchison Belt rare as one of the world's few goldfields with gold known to be introduced prior to the global event at about 2650 Ma. Murchison antimony-gold mineralization is hydrothermal, structurally controlled and post-dates belt formation by >100 Ma.

## Reference

Vearncombe, JR, McNaughton, NJ, Porter, J, Zi, J-W and Talavera, C 2021, Age of the Archaean Murchison belt and mineralisation, South Africa. (Special memorial volume for Maarten de Wit.) South African Journal of Geology, 124: 315-342. https://doi.org/10.25131/sajg.124.0001

# Early structural architecture controlling komatiite-hosted nickel sulphide and orogenic gold mineralization at Beta-Hunt Au-Ni mine, Kambalda, Western Australia

**LT Virnes[1*], N Thébaud[1], L Petrella[1], HB McFarlane[2], L Martin[3], D Fourgerouse[4]**

* corresponding author: lauri.virnes@research.uwa.edu.au

1. Centre for Exploration Targeting (CET)/School of Earth Sciences/University of Western Australia/Crawley Australia
2. Commonwealth Scientific and Industrial Research Organisation (CSIRO)/Bentley Australia
3. Centre for microscopy, Characterisation & Analysis (CMCA)/University of Western Australia/Crawley, Australia
4. The Institute for Geoscience Research (TIGeR)/Curtin University/Bentley, Australia

At the Beta-Hunt mine, orogenic gold and komatiite-hosted massive nickel sulphide mineralization are locally coincident. This indicates that crustal architecture plays a role in the localization of the two mineral systems. A structural framework was derived based on field observations to evaluate how both mineral systems may have been influenced by the crustal architecture. We show that the deposition of komatiite-hosted massive nickel sulphide mineralization was controlled by SW-dipping $D_0$ growth faults. These structures were reactivated during a southwest–northeast directed basin inversion ($D_1$). During this inversion, strain within the deposit was partitioned into southwest-dipping reverse shear planes along lithological contacts and steeply southwest-dipping foliation corridors associated with early growth faults. Ductile deformation was assisted by fluid migration causing strong hydrothermal alteration and deposition of gold. During subsequent $D_2$ extension, the steep foliation corridors became dilated. $D_2$ phase coincided with a major fluid flux, which led to the formation of moderately and steeply northeast-dipping hydraulic extension veins and thick sub-vertical breccia veins following $D_1$ steep structural corridors. This event represents the main phase of gold deposition. We suggest that at Beta Hunt, early growth faults related to the formation of nickel sulphide mineralization were also critical for the formation of high-grade gold mineralization.

# Crustal S sources for komatiite hosted Ni deposits and implications for sulfide transport and deposition

**AB Virnes[1*], ML Fiorentini[1], S Caruso[1,2], K Baublys[3], Q Masurel[1], N Thebaud[1]**

* corresponding author: anne.virnes@research.uwa.edu.au

1. Centre for Exploration Targeting, School of Earth Sciences, The University of Western Australia, Crawley, WA, Australia
2. Commonwealth Scientific and Industrial Research Organisation, Mineral Resources, Kensington, WA, Australia
3. School of Earth and Environmental Sciences, The University of Queensland, Brisbane, Qld, Australia

Previous S isotope works suggested that the Mount Keith and Cliffs komatiite hosted Ni deposits in the Yilgarn Craton of Western Australia formed in different volcanic environments. The Mount Keith deposit was interpreted to have formed near the komatiite vent and a volcanogenic massive sulfide (VMS) style S source in the felsic volcanic substrate, whereas the Cliffs deposit formed at a distal position on a basaltic substrate. It was inferred that the felsic stratigraphic substrate at Mount Keith was more prospective than the mafic substrate at Cliffs. However, recent modelling of metal upgrading during transport of assimilated crustal sulfides in komatiites indicates a positive relationship between the travel distance and the resulting metal tenors of the deposited sulfides (Yao and Mungall, 2021). This relationship has not been observed between the Mount Keith and Cliffs deposits. New S isotope data from the Cliffs Ni deposit confirm the presence of a VMS style S source in the immediate footwall to the deposit. We suggest that the Cliffs Ni deposit also formed in a rift environment, proximal to its crustal S source. This implies that rift environments where bimodal magmatism occurs, mafic-hosted systems may be as prospective as felsic-hosted ones, significantly increasing the search space for high-tenor mineralisation associated with komatiites. The proximity of the Ni deposits to their crustal S sources for both mount Keith and Cliffs emphasises the importance of complex flow dynamics and multistage entrapment and re-entrainment of assimilated and transported sulfide droplets over extensive lateral flow and distal deposition of sulfide mineralisation.

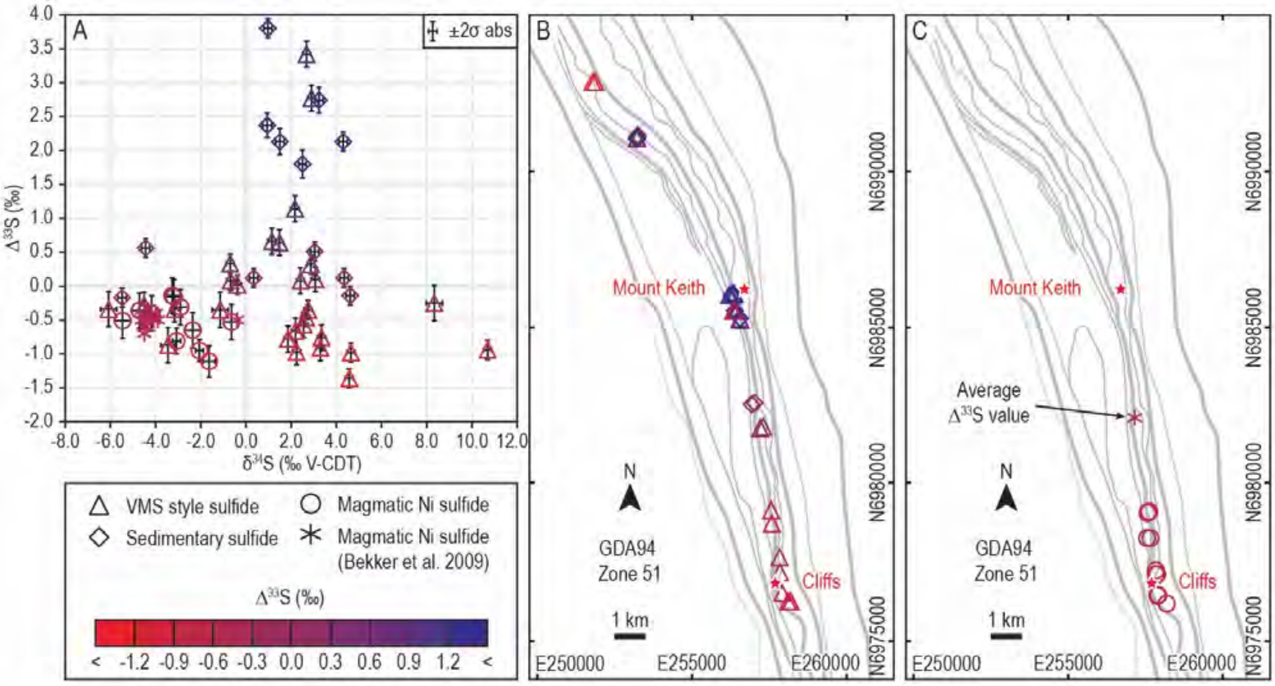



Figure 1. A) Plot of $\delta^{34}S$-$\Delta^{33}S$; B) Spatial distribution and $\Delta^{33}S$ variability of stratigraphic footwall sulfides; and C) magmatic sulfides

## Reference

Yao, Z-s and Mungall, JE 2021, Kinetic controls on the sulfide mineralization of komatiite-associated Ni-Cu-(PGE) deposits: Geochimica et Cosmochimica Acta v. 305, p.185-211.

# Evolution of Earth's global mineralizing systems and related exploration targeting: revised view using EagleEye Data

**RB Watchorn**

bobwatchorn123@yahoo.com

Bob Watchorn Research Mandurah Western Australia 6210, Australia

Over the last 30 years successful experimentation with structural recognition and enhancement programs to look into Earth's geological structure have been developed into the EagleEye system. We can now obtain MRI-type Earth structural geology from the surface to the inner core. Everywhere Earth has been examined there is evidence of a brittle geological lithospheric environment to the outer core. There is also abundant evidence of continental scale block movement. This block movement is generated from the core to the surface as the plate margins extend subvertically to the core. Thus, there are release paths from the core to the surface.

It is suggested that the mass of the giant subductions around the original Theia Impact in the Pacific Ocean are 'scraped off' by the hotter outer core, which is then pressurized releasing heat and mass back up to the surface. The over-pressuring and subsequent release of the outer core probably precipitates the cycles of mineralization on Earth.

It is suggested the first major tectonism occurred at 3–2.6 Ga forming the first worldwide mineralization events. In Figure 1, A, B and C show surface mineralization structures can be followed down right to the outer core. This indicates that some mineralization, heavy metals in particular, may have derived straight from the core. D (Fig. 1) suggests structures from deep geology can be used to target surface mineralization in the Yilgarn. The facility of EagleEye to define geological structure, at all scales, from geophysical and geographical data aids immensely in exploration targeting.

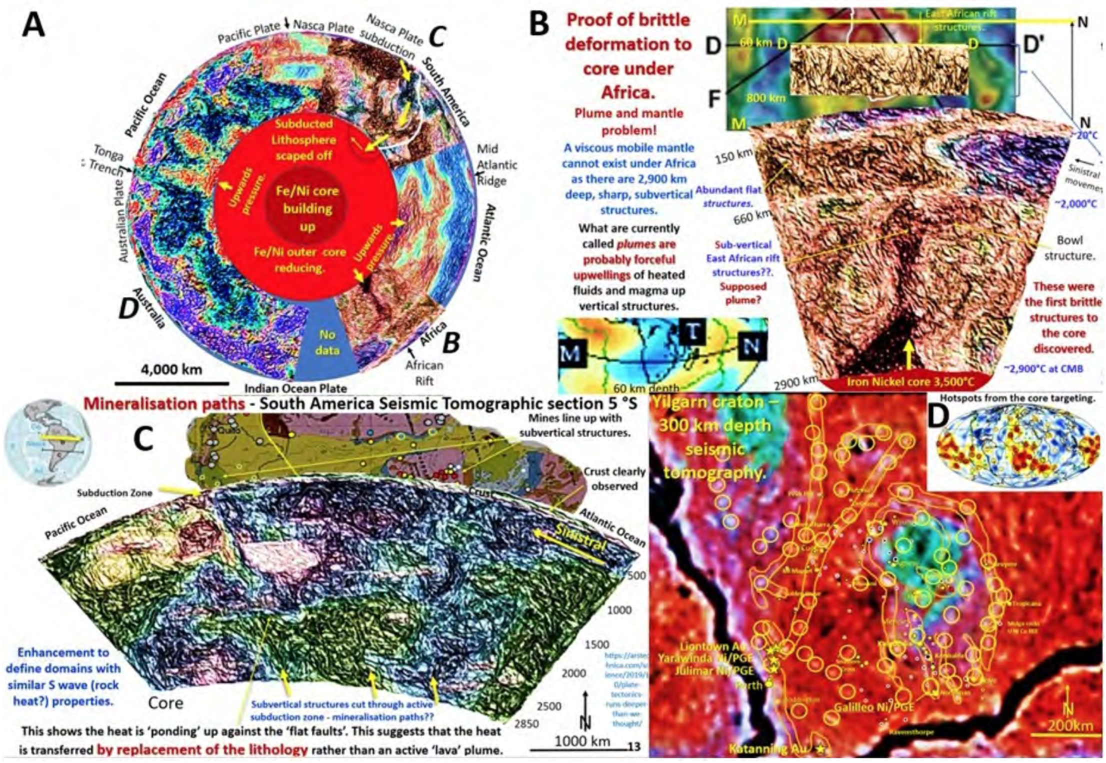



Figure 1. A. Section through Earth; B. Africa section; C. South America section; D. Yilgarn exploration targeting

# Discovery of zoned fluorapatite in the Yinachang Fe-Cu-Au-U-rare earth deposit of southwest China: implications for the mineralization of rare earth elements

**L Zhu[1*], L Bagas[2*], Z Wang[1], M Roberts[3], M Saunders[3]**

* corresponding authors: zhuligangsdnu@163.com; leon.bagas@uwa.edu.au

1. General Prospecting Institute of China National Administration of Coal Geology, Beijing 100039, China
2. Centre for Exploration Targeting (CET), The University of Western Australia, Crawley WA 6009
3. Centre for Microscopy, Characterisation and analysis (CMCA), The University of Western Australia, Crawley WA 6009, Australia

The Yinachang deposit is interpreted as a Paleoproterozoic IOCG deposit containing iron-oxide Cu-Au mineralization in the Kangdian region of SW China. The deposit includes measured resources of about 17 Mt Fe at grades of 42–45%, approximately 700,000 t Cu at a grade about 1% and about 12 t of Au at about 0.5 g/t, and unmeasured occurrences of U, Nb, Co, Ag, Mo, and rare earth elements (REEs). Apatite is a ubiquitous accessory phosphate mineral in a wide range of rock types and is often used as a vector for mineral exploration. In this contribution, hydrothermal fluorapatite in banded Fe-Cu ore is studied at Yinachang. This is the first time zoned fluorapatite has been observed in Cathodoluminescence (CL) images of grains about 500 μm wide where the core is bright and the edge is dark. Electron probe micro-analyzer (EPMA) analyses of seven spots show that the core has an average content of 0.11% Cl, 0.28% $La_2O_3$, 0.65% $Ce_2O_3$, 0.33% $Nd_2O_3$, and 0.42% $SiO_2$. In contrast, the rims of 6 spots average 0.07% Cl, 0.11% $La_2O_3$, 0.13% $Ce_2O_3$, 0.09% $Nd_2O_3$, and 0.09% $SiO_2$. The EPMA scans of fluorapatite in Figure 1 show that the concentration of La, Ce, Nd, Cl, Si is significantly higher in the core, but the concentration of Ca, P, O, F is not significantly different for both zones. Scanning electron microscope (SEM) analysis also shows that the concentration of La, Ce, Nd, Cl is higher in the core. Transient electromagnetic (TEM) analysis shows that the bright part of the zoned fluorapatite is due to enrichment in Nd, Ce, Y and Si, although the atomic structure of the fluorapatite does not change. The above analyses show that there of the two stages of REE enrichment and the earliest one is richer.

# Isotopic mapping as a tool for understanding the evolution of the Australian continent

**Z Zhu[1,2,3*], M Lindsay[2], F Kohanpour[2]**

* corresponding author: ziyizhu000@gmail.com

1. Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
2. CSIRO Mineral Resources, Australian Resources Research Centre, Perth, WA 6151, Australia
3. School of Earth, Atmosphere and Environment, Monash University, Melbourne, Victoria 3800, Australia

This study highlights the crucial role of isotopic systems in uncovering the evolution of continents. The U–Pb system, for example, is used to determine the age of rock formation, while the Sm–Nd system reveals whether rocks formed from the new or pre-existing crust. The depleted mantle Nd model age can also be used to estimate the time that has passed since the source of the crust was separated from the depleted mantle source. The time difference between the extraction event from the mantle and the partial melting of source rock is referred to as the residence time.

Moreover, this study highlights that combining isotopic data with mapping can help track variations in the age and source of the crust over time and space. Such variations have been linked to different mineral systems such as gold, nickel and iron. Therefore, a comprehensive understanding of continental evolution based on isotopic mapping can help identify new mineral deposit locations.

The primary aim of this study is to investigate the evolution of the Australian continent using a combination of isotopic data. To achieve this, we collected data sets such as geochronology, Sm–Nd isotopes, crustal elements, surface geology, mineral occurrence and geophysics from Geoscience Australia. Animated maps spanning from Archean to the present-day were generated using geochronological and Sm–Nd isotopic data, but only the Archean part will be focused on in this presentation. These maps incorporate background maps that highlight crustal elements and surface geology. If there is a clear understanding of the connection between crustal evolution and mineralization, these maps could be a useful tool for mineral exploration.

# Eoarchean and Paleoarchean worlds as blueprints for the investigation of Hesperian geology on Mars

**Halla[1], J, Noffke, N[2*], and the Subcommission on Precambrian Stratigraphy**

* corresponding author: nnoffke@odu.edu

1. Finnish Museum of Natural History, University of Helsinki, Finland

2. Old Dominion University, Norfolk, VA 23529, USA

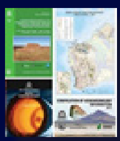
Exploration of Mars focuses on the detection of potential biosignatures as well as a thorough understanding of 3.7 –3.0 Ga Hesperian paleoenvironments and their possible habitability. On Earth, Eo-Archean and Paleoarchean sedimentary rock assemblages are commonly fluvial conglomerates, sandstones, mudstones, carbonates, cherts and banded iron formation all of which may be metamorphosed at low- to high-grade conditions. Similar lithologies are described from Martian successions as well. During the 4.0 to 3.6 Ga Eoarchean era, Earth had cooled down sufficiently to allow the development of increasing volumes of proto-continental crust, but not enough for large-scale plate tectonics. The igneous Archean lithology preserved from this time interval is characterized by typical tonalite-trondhjemite-granodiorite (TTG) suites and ultramafic to felsic volcanic igneous rocks. In the Paleoarchean (3.6-3.2 Ga), crustal growth by TTG formation continued and the protocrust thickened and stabilized by intracrustal granitoid magmatism. The early Earth's atmosphere was primarily anoxic ($CO_2$- and $CH_4$-rich) although very low levels of $O_2$ may have been present. Some of the oldest indicators of life are 12C- enriched isotope ratios and C–H–N–(P) elemental associations found in marine meta- sedimentary rocks of the ca. 3.7 Ga Isua Greenstone Belt, Greenland. While these rocks are of amphibolite metamorphic facies, the ca. 3.5 Ga and somewhat younger Paleoarchean rock units on the Pilbara craton of Western Australia and the Barberton Greenstone Belt, South Africa, include sedimentary rocks that did not experienced any significant petrological changes. In contrast, early silicification has led to the preservation of rare, carbonaceous microfossils of prokaryotes and microbial mats. Macroscopic expressions of such microbial mats are microbialites such as stromatolites in carbonate and chert as well as microbially induced sedimentary structures (MISS) in siliciclastic-evaporite deposits. The surprisingly high diversity of fossils show that Paleoarchean Earth may have teeming with life. Data suggest a close resemblance of these biota to modern ones. Geochemical analyses using a wide spectrum of methods reveal that the early Archean microbial communities included Bacteria and Archaea colonizing terrestrial and marine environments, as well as living in hydrothermal systems. The physical and biological changes of early Earth are discussed by the ICS Subcommission for Precryogenian Stratigraphy in order to formally establish the Eoarchean/Paleoarchean boundary. While on Earth Hadean rocks are absent, the Martian stratigraphy of same ages appears to be more complete and therefore may constitute a future archive of information on life's evolutionary pathway and planetary histories.

RECORD 2023/8

# 6IAS: 6th INTERNATIONAL ARCHEAN SYMPOSIUM – ABSTRACTS

K Gessner, TE Johnson, MIH Hartnady and D Wiemer (compilers)

## Access GSWA products



**All products**
All GSWA products are free to download as PDFs from the DMIRS eBookshop <www.dmirs.wa.gov.au/ebookshop>.
View other geoscience information on our website <www.dmirs.wa.gov.au/gswa>.

**Hard copies**
Limited products are available to purchase as hard copies from the First Floor Counter at Mineral House or via the DMIRS eBookshop <www.dmirs.wa.gov.au/ebookshop>.

**Fieldnotes**
Fieldnotes is a free digital-only quarterly newsletter which provides regular updates to the State's exploration industry and geoscientists about GSWA's latest programs, products and services.
Access by subscribing to the GSWA eNewsletter <www.dmirs.wa.gov.au/gswaenewsletter> or downloading the free PDF from the DMIRS eBookshop <www.dmirs.wa.gov.au/ebookshop>.


**GSWA eNewsletter**
The GSWA eNewsletter is an online newsletter that contains information on workshops, field trips, training and other events.
To keep informed, please subscribe <www.dmirs.wa.gov.au/gswaenewsletter>.

Further details of geoscience products are available from:

First Floor Counter
Department of Mines, Industry Regulation and Safety
100 Plain Street
EAST PERTH WESTERN AUSTRALIA 6004
Phone: +61 8 9222 3459 Email: publications@dmirs.wa.gov.au
www.dmirs.wa.gov.au/GSWApublications