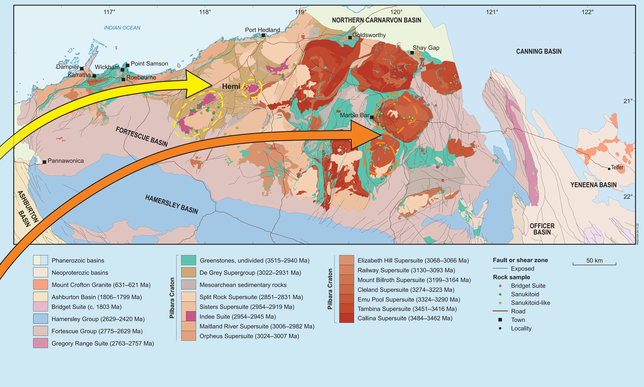
Department of Mines, Industry Regulation and Safety
GOVERNMENT OF WESTERN AUSTRALIA

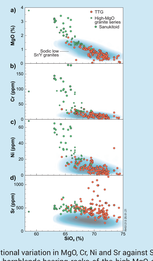
SCIENTIFIC ADVANCES IN UNDERSTANDING THE PILBARA CRATON

Geological Survey of Western Australia

Recent work sheds new light on the role of lithospheric mantle source regions that became hydrated and enriched in trace and precious elements by crustal dripping, sagduction or subduction. Remobilization of such sources can ultimately produce oxidized and hornblende-rich high Sr/Y dioritic magmas. Examples include c. 2.95 Ga sanukitoids within the Sisters Supersuite that intrude the Mallina Basin and have been implicated in the formation of the giant Hemi gold discoveries in the Central Pilbara Tectonic Zone.



Although previously thought to be restricted to Mesoarchean and younger terrains, this style of magmatism is likely to have played an integral role in the evolution of older crust and the associated mineral systems. Primitive hornblende-bearing granites with compositions distinct from those of the tonalite–trondhjemite–granodiorite (TTG) series, but transitional with sanukitoids, are located throughout the Pilbara Craton and date as far back as c. 3.43 Ga. They represent an ancient period before the translithospheric fractures that channelled younger sanukitoids to the surface formed. Instead, these intrusion stalled in the lower crust, where they became hydrous additions to later, TTG-hybrid magmas.



Compositional variation in MgO, Cr, Ni and Sr against SiO_2 for TTG and hornblende-bearing rocks of the high-MgO granite series. The blue field in each panel is a kernel density field enclosing 90% of the data for sodic low Sr/Y granites. Mesoarchean (approximately 2.95 Gyr old) hornblende diorite and granodiorite identified as sanukitoid (larger green dots) form the more primitive, mafic part of the high-MgO granite series, but also overlap extensively with Palaeoarchaean hornblende granodiorites (smaller green dots). One Palaeoarchaean hornblende granodiorite with >3.75 wt% MgO is a partial hornblende cumulate. Trends for many major and trace elements (e.g. Sr) between TTG and the high-MgO granite series are continuous, but for others (MgO, Cr, Ni) the two distinct trends merge. (Smithies et al., 2021, Nature, 592, 70–75).

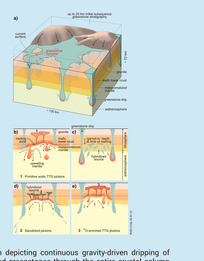
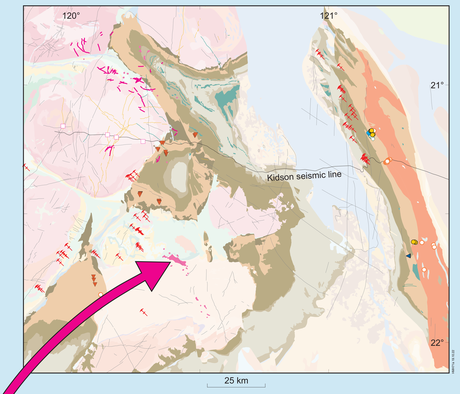


Illustration depicting continuous gravity-driven dripping of ^{18}O-enriched greenstones through the entire crustal column and into the mantle. b) Primitive Pilbara TTG indicates that the earlier Archaean mafic lower crust was already at least locally hydrated enough in low ^{18}O mantle-derived water to undergo partial melting during periods of lithospheric extension and dripping. Lower crustal drips may have caused limited metasomatic enrichment of lithosphere, augmenting the trace element inventory of TTG sources. c) Greenstone that dripped into the mantle released ^{18}O-enriched fluids and hydrated partial melts that metasomatized the lithospheric mantle. d) Under extension, the metasomatized lithospheric mantle melted to produce large ion lithophile element-enriched, Th-enriched and light rare earth element-enriched sanukitoid, containing >7 wt% dissolved H_2O. e) In turn, the enriched sanukitoid infiltrated and mingled with ductile mafic lower crust to form the hybridized source for ^{18}O-enriched TTG. Although addition of only ~17% sanukitoid to the lower mafic crust satisfies the enriched trace element source requirements of ^{18}O-enriched TTG, mass balance calculations require that at least 40% of the oxygen in that source came from greenstone drips, indicating that upon crystallization, sanukitoid magmas also exsolved large volumes of ^{18}O-enriched fluids that pervasively hydrated the evolving TTG sources. (Smithies et al., 202,1 Nature, 592, 70–75).

Oxidized and hornblende-rich dioritic to monzonitic magmas also play a role in the Proterozoic crustal evolution of the Pilbara Craton, where they may be related to processes that shaped the eastern margin of the Pilbara Craton. Our ongoing work on the c. 1.8 Ga Bridget Suite highlights the capacity for fossil zones of enriched and hydrated (or rehydrated) Archean lithospheric mantle and lower crust to become remobilized. While the Bridget Suite rocks are not as primitive (lower $Mg^{\#}$ and Cr and Ni concentrations) and often more alkalic than typical sanukitoids and sanukitoid-like rocks (cf. $Mg^{\#}$ Ni, Cr plots, TAS, SiO_2vs K_2O and K_2O/Na_2O plots), they show similarly enriched trace element patterns and overlap th ecompositional field for sanukitoid-like rocks of the Eastern Yilgarn Craton. Mineral systems with a potential to be associated with these intrusions have not been fully appraised, but would include Au, Cu–Au and IOCG systems.

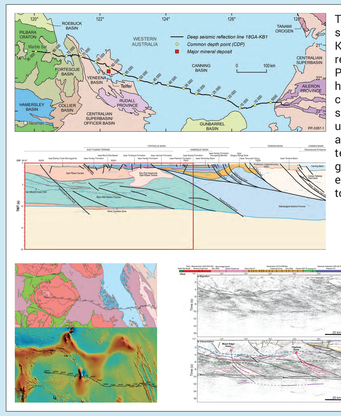
Hornblende bearing monzodiorite

The north-northwesterly trend of the Bridget Suite gives rise to speculation of a link to basement structures and processes related to Neoarchean rifting of the Pilbara Craton that is recorded in the formation of the c. 2.76 Ga Gregory Range suite of A-type magmas. Ongoing studies of the preserved outcropping eastern margin of the Pilbara Craton have clearly fingerprinted Neoarchean felsic intrusions and extrusive rocks associated with the early evolution of the Fortescue Group as being enriched, dry and high-temperature A-type magmatism. These rocks are likely to be related to rifting of the Pilbara Craton and provide some of the oldest known physical evidence on Earth for a combination between crustal-scale brittle fracturing and A-type magmatism. This Neoarchean structure is likely to have played a key role in the later formation of Proterozoic and Phanerozoic basins and associated mineral systems.

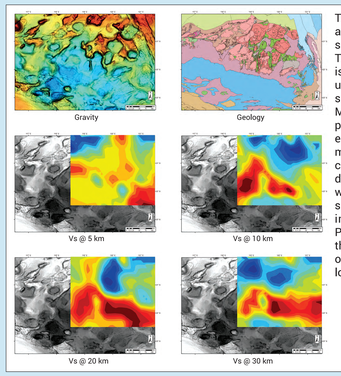


The c. 1.8 Ga age of the Bridget Suite gives rise to further speculation of a link to processes operating during convergence of the West and North Australian Cratons, as the 1.95–1.9 Ga Mirning Ocean was consumed. In situ zircon U–Pb–O–Hf analyses of igneous rocks from drillholes that intersected basement beneath the northwestern Canning Basin reveal the presence of a substantial domain of juvenile Proterozoic lithosphere, the Percival Lakes province, which is interpreted as part of a 1700 × 400 km Proterozoic lithospheric domain that lacks evidence of Archean provenance, but consists mainly of reworked remnants of Mesoproterozoic oceanic crust that survived WAC–NAC–SAC convergence.

The eastern end of the deep seismic reflective survey 18GA-KB1 is the first deep seismic reflection survey in the East Pilbara Terrane. It shows a horizontally layered continental crust where dense greenstone sequences are restricted to the upper crust with no evidence for a vertical-scale equivalent of the tens-of-kilometre wavelength granite–greenstone geometry exposed on Earth's surface today.



TShear wave velocity data from ambient noise tomography show that the East Pilbara Terrane dome and keel pattern is restricted to less than the upper 10 km of the current land surface, showing that Paleo- to Mesoarchean tectonic processes have not left any evidence for vertical tectonic movements in mid to lower crustal levels. Instead two distinct velocity domains with a west-northwesterly to east-south easterly trend can be interpreted across the East Pilbara Terrane, suggesting that the southern domain consists of a more felsic (slow velocity) lower crust.



Lithospheric structure, composition and thermal regime beneath western and central Australia: implications for lithosphere evolution

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Centre for EXPLORATION TARGETING

I- Introduction

Understanding the processes that drive sedimentary basin formation and subsidence is a key element in elucidating the evolution of the continental lithosphere. Particularly, the form and amount of subsidence, and the distribution and preservation of the sedimentary strata are direct consequences of the thermochemical and rheological state of the lithosphere.

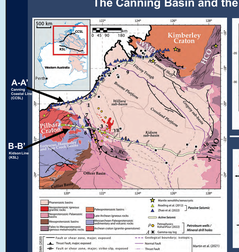
Here, we use LitMod2D to model the **thermal**, **compositional**, **density** , and **seismic** structure of the lithosphere and upper mantle beneath the Canning Basin with the aim of understanding **the role of the lithosphere in the long-term subsidence and preservation of the basin**. The evolution of this basin has been summarized mainly on the basis of structural and stratigraphic studies but never in terms of thermochemical properties and processes affecting the whole of the lithosphere.

Furthermore, different seismic studies in the area have provided self-consistent but rarely unique models ofl ithospheric structure and evolution. To overcome this problem, our models have been designed to **fit simultaneously multiple geophysical observables** with different sensitivities, reducing the uncertainties associated with the modelling of these observables alone or in pairs.

II – Proterozoic Australia: current understanding

1) Thick lithosphere, with significant radial anisotropy,
2) Negative velocity perturbations down to 120 km depth,
3) Surface relief has been continuously weathered over time scales of hundreds of Ma, based on apatite fission track analyses,
4) Proterozoic basement revealed by U-Pb zircon geochronology at drill cores intersecting the basement to the Canning Basin,
5) Isotopic Lu-Hf modelling favour Proterozoic lithosphere under cover.

The Canning Basin and the Proterozoic undercover



Fishwick and Reading (2008)

Anomalous lithosphere beneath the Proterozoic of western and central Australia: A record of continental collision and intraplate deformation?

Low S wave speed at 75 km depth and modest attenuation, with a high velocity gradient below 100 km attributed to the presence of pargasitic amphibole in the upper lithosphere.

Kennett and Iaffaldano (2013)

Role of lithosphere in intra-continental deformation: Central Australia

- Multiple episodes of deformation in Central Australia, achieving mechanical equilibrium.
- Does not consider the presence and migration of melts/fluids modifying the thermal, chemical and rheological structure of the lithosphere.

Yoshizawa and Kennett (2015)

The lithosphere-asthenosphere transition and radial anisotropy beneath the Australian continent

Frozen anisotropy interpreted to be associated with ancient convergent tectonics.

Full waveform tomography for radially anisotropic structure: New insights into present and past states of the Australasian upper mantle

Fichtner et al. (2010)

Low S wave speed believed to correlate with the redistribution of heat-producing elements in the crust, affecting the upper lithosphere.

Thermal LAB corrected for seismic attenuation calibrated using paleogeotherms derived from thermobarometry of mantle peridotite xenoliths and xenocrysts

Hoggard et al. (2020)

- The edges of thick lithosphere place first-order controls on the genesis of extensional basins and their mineral systems.
- However, do present-day lithospheric boundaries inferred from seismic tomography models represent the craton's margins at the timing of the mineralisation?

Thermal and Compositional Anomalies of the Australian Upper Mantle From Seismic and Gravity Data

Tesauro et al. (2020)

Unusual feature in central-western Australia interpreted to reflect Fe-enrichment of the lithospheric mantle, rather than hydration processes or a hotter mantle.

III – The dichotomy

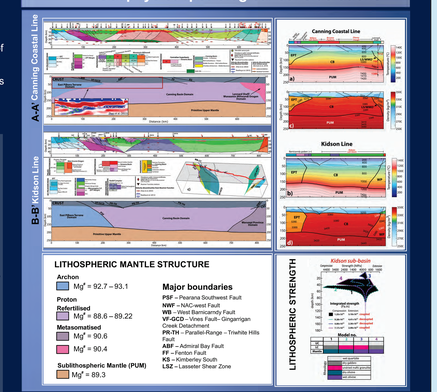
1) Can we distinguish between thermal and compositional variations in the density and elastic properties of the lithosphere?
2) If due to compositional changes, are the slow wave speeds related to metasomatic (slab dehydration in subduction zones) or re-fertilization (Fe-enrichment) processes?

IV - Methods

In our modelling scheme, properties vary with depth as a function of temperature, pressure, composition, and phase changes. This approach requires solving a number of equations describing various physical and chemical processes within the Earth such as heat transport, seismic wave propagation, and thermodynamic mineral phase equilibria (Afonso et al., 2008).

Once temperature, pressure, and density have been derived, surface heat flow, elevation, gravity, geoid, and seismic velocities can be computed. Theoretical/predicted values are then compared to measured data in order to validate models sequentially. We compute rheology profiles separately, following Byerlee's law of brittle failure and power-law creep offl ow failure.

V – Geophysical/petrological considerations



- A SCLM of Archean age is unlikely under the Canning Basin due to its buoyancy, fast wave speeds and low surface heat flow in contrast to the observations. The typical low densities of an Archean lithospheric mantle are irreconcilable with the geoid in the Canning Basin.
- The high #Mg number of the SCLM beneath the basin support intense lithospheric refertilisation in a rifting or plume setting.
- The high surface heat flow observed in the Canning Coastal line (> 80 mW/m^2) is compatible with high radiogenic heat generation in th ecrust, rather than a high mantle flux
- Topography modelling in the Canning Coastal and Kidson Lines considering regional isostatic adjustments support elastic thicknesses of the lithosphere of ca. 150 km. This favours a strong and thermally stable lithosphere under the basin.
- Yield strength envelopes of the crust and SCLM under the Canning Basin indicate a strong uppermost mantle that is compatible with estimates for the elastic thickness of the lithosphere (Te).
- In fact, a strong anhydrous refractory lower crust that is coupled with the mantle is highly likely and is in good agreement with the Te estimations and with other geophysical observations.

Acknowledgments

We thank Ian Tyler (UWA), Weronika Gorczyk (UWA), and Suzane Schmidt (CSIRO) for the constructive discussion around our work and Fariba Kohan Pour (UWA) for the petrophysical data and for valuable exchange of knowledge. We thank MRIWA for financial support.

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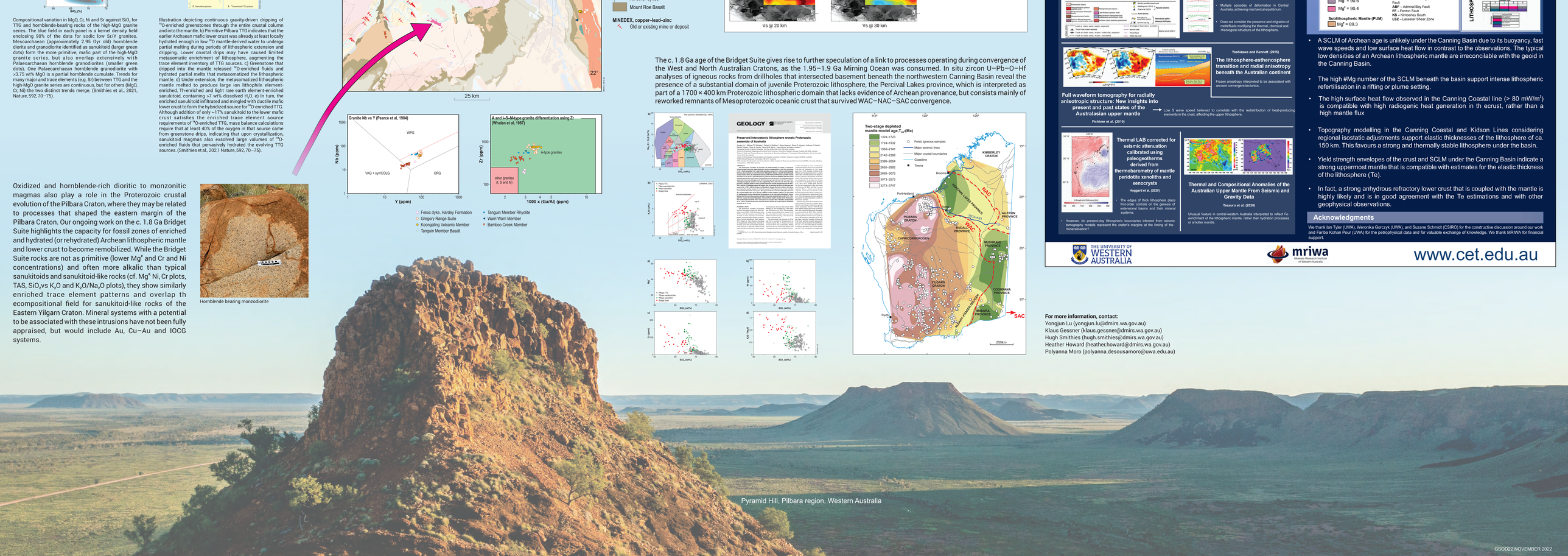
Pyramid Hill, Pilbara region, Western Australia

GSOD22 NOVEMBER 2022