RECORD
2023/9

6IAS: REDEFINING ARCHEAN TERRANE BOUNDARIES, A RADICAL UPDATE WITHIN THE YILGARN CRATON – A FIELD GUIDE

R Quentin de Gromard and TJ Ivanic

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

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PERTH 2024

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REFERENCE
The recommended reference for this publication is:
Quentin de Gromard, R and Ivanic, TJ (compilers) 2024, 6IAS: Redefining Archean terrane boundaries, a radical update within the Yilgarn Craton – a field guide: Geological Survey of Western Australia, Record 2023/9, 41p.

ISBN 978-1-74168-032-4
ISSN 2204-4345

Grid references in this publication refer to the Geocentric Datum of Australia 1994 (GDA94). Locations mentioned in the text are referenced using Map Grid Australia (MGA) coordinates, Zone 50. All locations are quoted to at least the nearest 100 m.

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 2024 by the Geological Survey of Western Australia
This Record is published in digital format (PDF) and is available online at <www.demirs.wa.gov.au/GSWApublications>.

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Cover image
6IAS participants examining metasedimentary rocks of the Poison Creek section west of Toodyay. Photo by Tim Ivanic

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6IAS: Redefining Archean terrane boundaries: a radical update within the Yilgarn Craton – a field guide

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Introduction

This Record is an edited version of the field guide that was produced for the FT2 pre-conference field excursion, held on 20–23 July, of the 6th International Archean Symposium 2023, Perth, WA, 25–27 July 2023. The four-day excursion visited key exposures of deformed and metamorphosed supracrustal sequences and high-grade gneisses in the well-exposed Toodyay–Northam area (about 100 km northeast of Perth). Excursion localities are located on either side of the recently redefined terrane boundary between the South West Terrane and the Youanmi Terrane (Quentin de Gromard et al., 2021). This field guide is presented in two parts: Part 1 is a synthesis of our current understanding of the geology of the southwest Yilgarn Craton, and Part 2 provides descriptions of each of the excursion localities, and additional detail on the relevant lithological units, structures, geochemical, geochronological and pressure–temperature–time (*P–T–t*) constraints that form the rationale for the terrane boundary update.

The definition that we are using in this Record for the term 'terrane' (or 'cratonic terrane') is: 'a tectonically bounded body of rock of regional extent within a craton, characterized by a geological history different from that of contiguous tectonic fragments.' This definition does not imply any geodynamic mode of how Earth operated at the time – a topic which is currently still debated – nor does it imply any tectonic setting in which these particular terranes formed. The differing geological history between the South West and Youanmi 'terranes' presented in this Record shows that their separation using the above 'terrane' definition is justified. The main datasets justifying this redefinition are the geochronological record, the differing structural history and the differing supracrustal lithological associations between the South West Terrane and the Youanmi Terrane.

The southwest Yilgarn is a large and geologically diverse portion of variably reworked Archean cratonic lithosphere. The area requires much more work in order to fully understand the geodynamic and metallogenic processes that led to its present constituents and their configuration. Recently, the Geological Survey of Western Australia (GSWA) produced an interpreted bedrock geological (IBG) map of the southwest Yilgarn Craton, which integrates geophysical data, field and exploration data, geochemistry, geochronology, metamorphic data, Nd, Hf and O isotope maps, and legacy GSWA and company mapping (Quentin de Gromard et al., 2021; Geological Survey of Western Australia, 2022). This update has changed our understanding of the geology of the South West and Youanmi Terranes and proposes a new location for the boundary between them.

In this interpretation, the Youanmi Terrane is shown to host distinctly older crustal and supracrustal rocks than the South West Terrane. In the Youanmi Terrane, the emplacement of granitic rocks was broadly coeval with the deposition of mafic-dominated greenstones from 3018 to 2930 Ma (Thundelarra Supersuite and Southern Cross Supergroup) and from 2825 to 2686 Ma (Annean and Austin Downs Supersuites and Murchison Supergroup), all of which appear to be missing from the South West Terrane. Younger 2697–2600 Ma granitic magmatism in the Youanmi Terrane transitions temporally from highCa to lowCa geochemical affinity, and has chronological and geochemical similarities within the South West Terrane, although post-2640 Ma granitic rocks are more abundant within the South West Terrane. The South West Terrane contains <2705 Ma greenstones at Boddington and Balingup, which are absent from the Youanmi Terrane.

The generally north-striking anastomosing shear zones forming the characteristic lozenge-shaped structural pattern of the Youanmi Terrane, formed during the 2730–2660 Ma Yilgarn orogeny, are not observed within the redefined South West Terrane. These structures were reactivated and progressively reoriented counter-clockwise from a northerly trend in the central Youanmi Terrane to a north-northwest trend in the southern portion of the Youanmi Terrane and were completely obliterated, sheared, and reoriented to parallelism with the NWtrending terrane boundary in a region of high strain defined as the Corrigin Tectonic Zone (CTZ). The CTZ is a 50 to 150 kmwide zone of intense, pervasive deformation formed in the hangingwall of the proposed terrane boundary, with moderately to steeply northeast-dipping fabric, and recording peak *P–T* conditions of 4–5 kbar and 700–900 °C dated at 2665–2635 Ma. Interpreted fold vergence and shear sense indicators suggest a sinistral transpressive regime for the formation of the CTZ.

Most known gold deposits in the southwest Yilgarn (e.g. Boddington, Katanning and Tampia) are proximal to major shear zones and sanukitoid and sanukitoid-like rocks. Corridors of sanukitoid-affiliated shear zones form newly prospective search spaces for mineral exploration. Orthomagmatic Ni–Cu–PGE and V–Ti mineralization occurs in mafic–ultramafic intrusive rocks dated at c. 2665 Ma within the South West Terrane. A tholeiitic (highFe) mafic intrusive suite at Red Hill is possibly coeval with the 'Coates Siding Gabbro'. A highMg suite in the far west of the South West Terrane, between Yarrawindah and Julimar (and possibly as far south as Yornup), includes the highly Ni–Cu–PGE-endowed 'Gonneville Peridotite'.

KEYWORDS: Archean, geochemistry, geochronology, granite–greenstone terrain, South West Terrane, structural geology, tectonics, Yilgarn Craton, Youanmi Terrane

Part 1: Geological synthesis

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This part contains an overview of the basement geology of the southwest Yilgarn Craton (Fig. 1) and the rationale for redefining the terrane boundary between the South West Terrane and the Youanmi Terrane. We describe here the geological units, the crustal architecture and varying geological history on either side of the redefined boundary based on field observations, structural interpretation, interpretation of the potential field datasets, metamorphic *P–T–t* data, granite geochemical classification and resulting granite map, greenstone lithological associations, and geochronological and isotopic constraints.

Previous work

Earlier work by the Geological Survey of Western Australia (GSWA) in the southwest Yilgarn interpreted the region as a high-grade, polymetamorphic portion of the Yilgarn Craton and was correlated with the high-grade Narryer Terrane of the northwestern Yilgarn Craton, together forming a tectonic unit called the 'Western Gneiss Terrain' (Gee et al., 1981). However, the 'Western Gneiss Terrain' term is misleading as it does not differentiate between the Archean to Paleozoic polymetamorphic history of the western margin of the Yilgarn Craton. Several Archean and Proterozoic

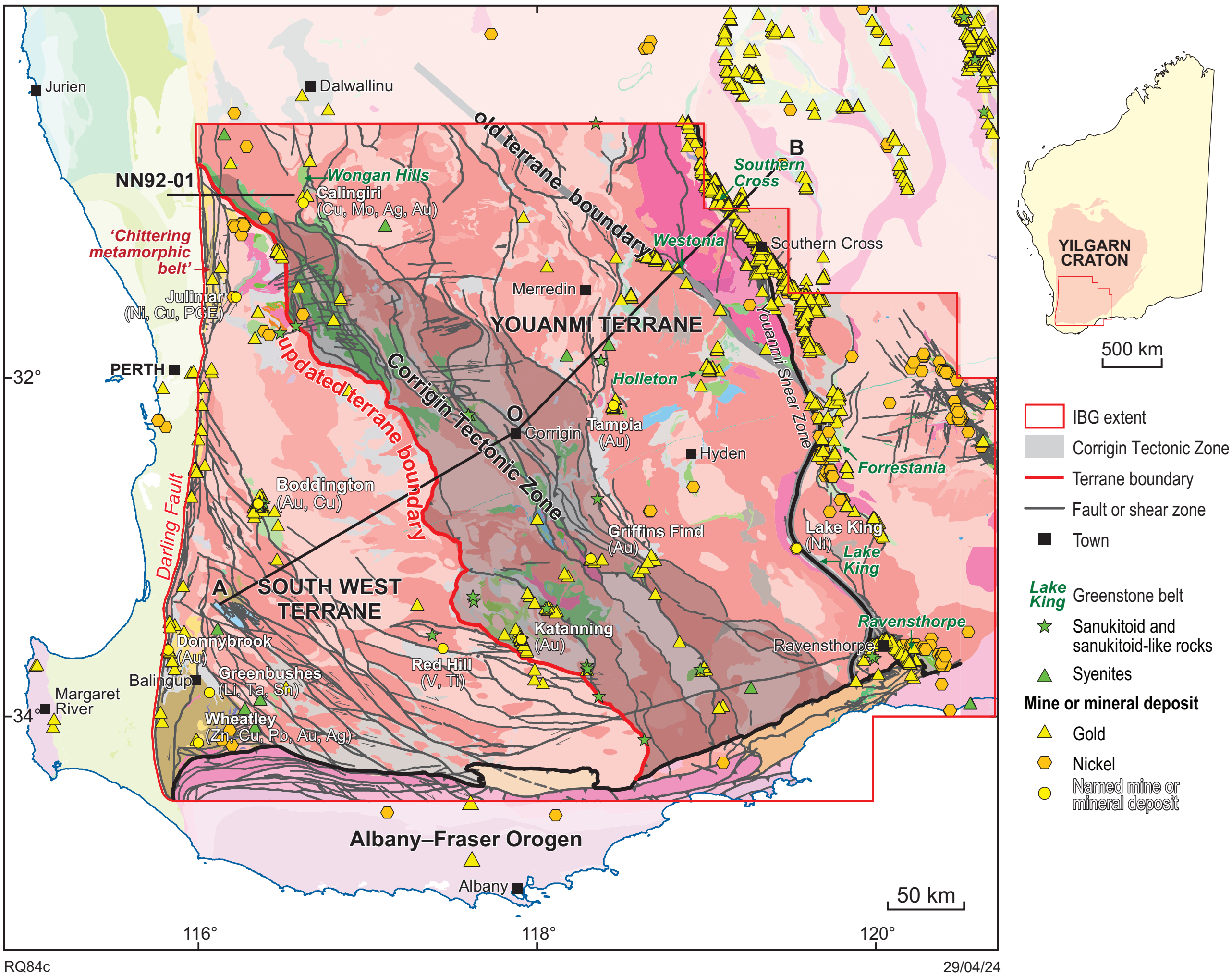

Figure 1. Simplified geological map of the southwest Yilgarn Craton showing the location of the redefined terrane boundary between the South West and Youanmi Terranes, the location of the old terrane boundary, and the traces of deep seismic profile NN9201 and seismic refraction profile AOB. IBG extent from this publication

high-grade metamorphic events affected portions of the ‘Western Gneiss Terrain’ differently and not all parts of the ‘Western Gneiss Terrain’ contain Archean high-grade metamorphic rocks (Gee et al., 1981; Gee et al., 1986). Myers (1993) divided the southwest Yilgarn from the Youanmi Terrane along a northwest-striking metamorphic boundary: metamorphic grade is amphibolite to granulite facies on the southwest side and prehnite–pumpelleyite to greenschist facies on the northeastern side. Myers (1995) later proposed that the two sides were distinctly separate terranes recording different tectonic histories. Wilde et al. (1996) further subdivided the southwest Yilgarn, from west to east, into the informal ‘Balingup’, ‘Boddington’ and ‘Lake Grace’ terranes, separated by north to northwest-trending boundaries. The South West Terrane was formalized in Cassidy et al. (2006) broadly using the original metamorphic boundary of Myers (1993) to define the terrane margin, although the authors state that ‘the boundary between the South West Terrane and the Youanmi Terrane is poorly defined.’ and that ‘additional work is required on the boundaries and geological components of each terrane [i.e. the Narryer and South West Terranes] to establish their relationship with the adjacent Youanmi Terrane’.

Recent work by the GSWA and others, combined with reassessment of fieldwork and analyses, has led to reinterpretation of the geology of the southwest Yilgarn Craton. The work is summarised by Quentin de Gromard et al. (2021) and includes repositioning the South West – Youanmi Terrane boundary approximately 200 km southwestwards.

Deep crustal structure

The southwest corner of the Archean Yilgarn Craton contains a long-wavelength, high-amplitude gravity anomaly forming, in map-view, an approximate right-angled triangular shape bounded to the south by the east-trending Paleo to Mesoproterozoic Albany–Fraser Orogen and to the west by the north-striking Darling Fault (Fig. 2a). This large gravity anomaly suggests that either the crust beneath the anomaly is relatively thin or dense or both, or that the source of the gravity anomaly resides in an anomalously dense upper mantle. The 2023 Australia-wide Moho depth compilation shows a relatively thick crust underlying both the South West Terrane and the southern Youanmi Terrane with Moho depths of ~37–42 km and ~34.5–42.5 km respectively, both significantly thicker than the central Youanmi Terrane, which has Moho depths of ~31–38 km (Kennett, 2019). The lack of major variation in crustal thickness mimicking the southwest Yilgarn gravity anomaly suggests that the source for the

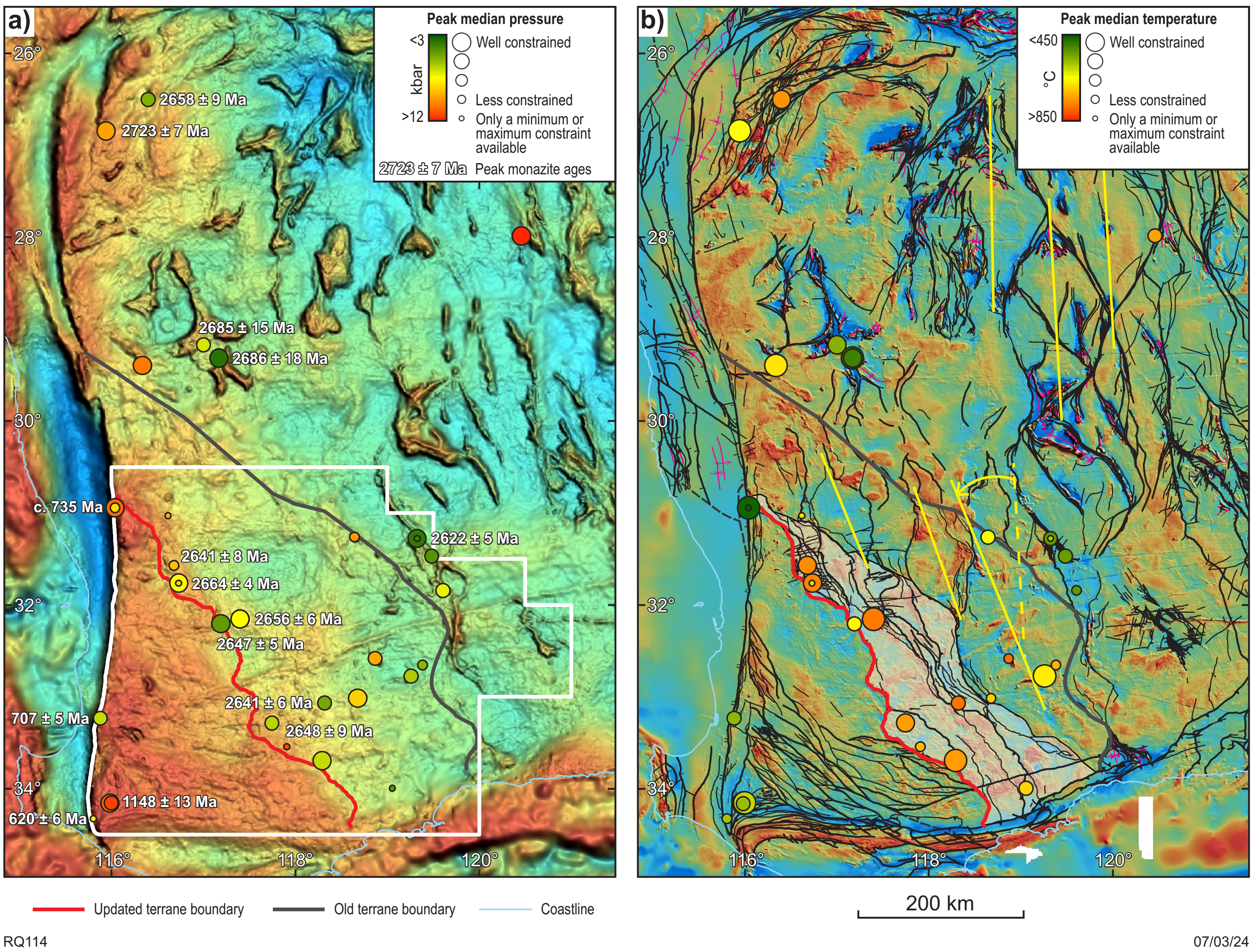

Figure 2. Potential field data of the west Yilgarn Craton showing the position of the redefined South West – Youanmi Terrane boundary in regional context: a) the location of peak median pressure data and interpreted peak metamorphic monazite ages are shown on the gravity data; b) the ductile structural architecture, the Corrigin Tectonic Zone (CTZ; indicated on map by grey overlay), the location of the old terrane boundary and the peak median temperature estimates are shown on the aeromagnetic data. The yellow lines represent the long axes of the lozenge-shaped areas referred to in the text and their interpreted counter-clockwise rotation is shown by the yellow arrow. Metamorphic data from Korhonen et al. (2021). IBG extent from GSWA (2022)

gravity anomaly resides in the upper mantle. The redefined terrane boundary between the South West Terrane and the Youanmi Terrane lies near the margin of the gravity anomaly, suggesting that the lateral extent of the material causing the gravity anomaly may have been controlled by the location of the terrane boundary (Fig. 2a).

The New Norcia deep seismic reflection line (NN92–01) across the Darling Fault, the 'Chittering metamorphic belt' and the 'Jimperding metamorphic belt' images a series of gently east-dipping structures within the craton (Fig. 3; Middleton et al., 1993; Middleton et al., 1995), interpreted by Wilde et al. (1996) as evidence for terrane-accretion tectonics between the 'Balingup', 'Boddington' and 'Lake Grace' terranes.

Seismic refraction data along a northeast-trending profile across the southwest Yilgarn suggest a northeast-dipping high-velocity zone (Fig. 4; Dentith et al., 2000) located directly underneath the recently defined Corrigin Tectonic Zone (CTZ; Quentin de Gromard et al., 2021). Dentith et al. (2000) interpreted this high-velocity zone as a possible remnant of oceanic crust trapped between two accreted exotic terranes, in broad agreement with the terrane boundary between the 'Boddington' and 'Lake Grace' terranes proposed by Wilde et al. (1996). The high-velocity zone of Dentith et al. (2000) may instead lie directly against and within the footwall of the northeast-dipping terrane boundary between the South West Terrane and the Youanmi Terrane of Quentin de Gromard et al. (2021), in a structural location that may also have been used for the emplacement of the c. 1390 Ma Biberkine Dolerite dykes (see 'Mafic dykes' section).

Geological units

Granitic rocks

The reinterpretation of the terrane boundary is largely based on U–Pb zircon geochronology of granitic rocks of the southwest Yilgarn. Together with the extensive granite geochemical dataset (Lowrey et al., 2022), Quentin de Gromard et al. (2021) assigned granitic rocks of the southwest Yilgarn to previously defined formal suites of the northern Youanmi Terrane. Granitic rocks of the Youanmi Terrane form several supersuites between 3018 and 2606 Ma (Fig. 5). The 3018–2928 Ma Thundelarra Supersuite, 2825–2733 Ma Annean Supersuite and 2735–2686 Ma Austin Downs Supersuite are restricted to the Youanmi Terrane, and we interpret that exposed rocks of the South West Terrane are younger than c. 2705 Ma (Fig. 5).

Southern Youanmi Terrane

The oldest exposed rocks of the southern Youanmi Terrane are 3018–3010 Ma monzogranitic and syenogranitic gneisses from the Dasher prospect near Calingiri, which are assigned to the 3018–2928 Ma Thundelarra Supersuite (Figs 1 and 5; GSWA 224760, Wingate et al., 2021c; GSWA 205930, Wingate et al., 2018b; GSWA 205931, Wingate et al., 2018c). Using the automated geochemical classification process of Lowrey et al. (2023), which is based on the classification schemes of Champion and Sheraton (1997) and Champion and Cassidy (2002), these older granitic rocks classify as either highCa (Na+, low Sr/Y) granite,

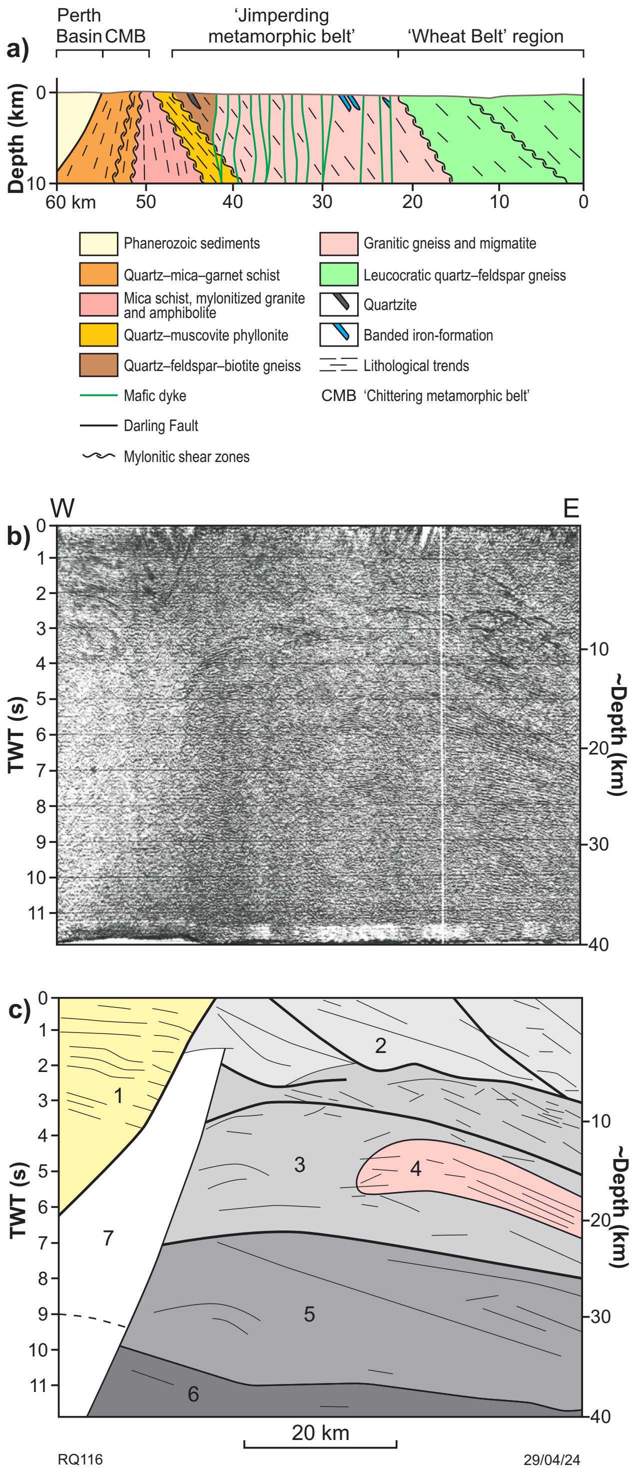

Figure 3. Collage of figures from Middleton et al. (1993, 1995) related to the deep seismic reflection profile NN9201 shown on Figure 1: a) schematic geological cross-section to a depth of 10 km along the seismic line; b) stacked section of the deep seismic reflection data; c) interpreted seismic section with 1. Perth Basin; 2. 'Western Gneiss Terrane'; 3. an intermediate crustal zone within the Yilgarn Craton; 4. zone of strong reflection within zone 3; 5. deep crustal zone truncating zone 3; 6. Moho zone; 7. Proto-Darling Fault: a zone of non-reflection.

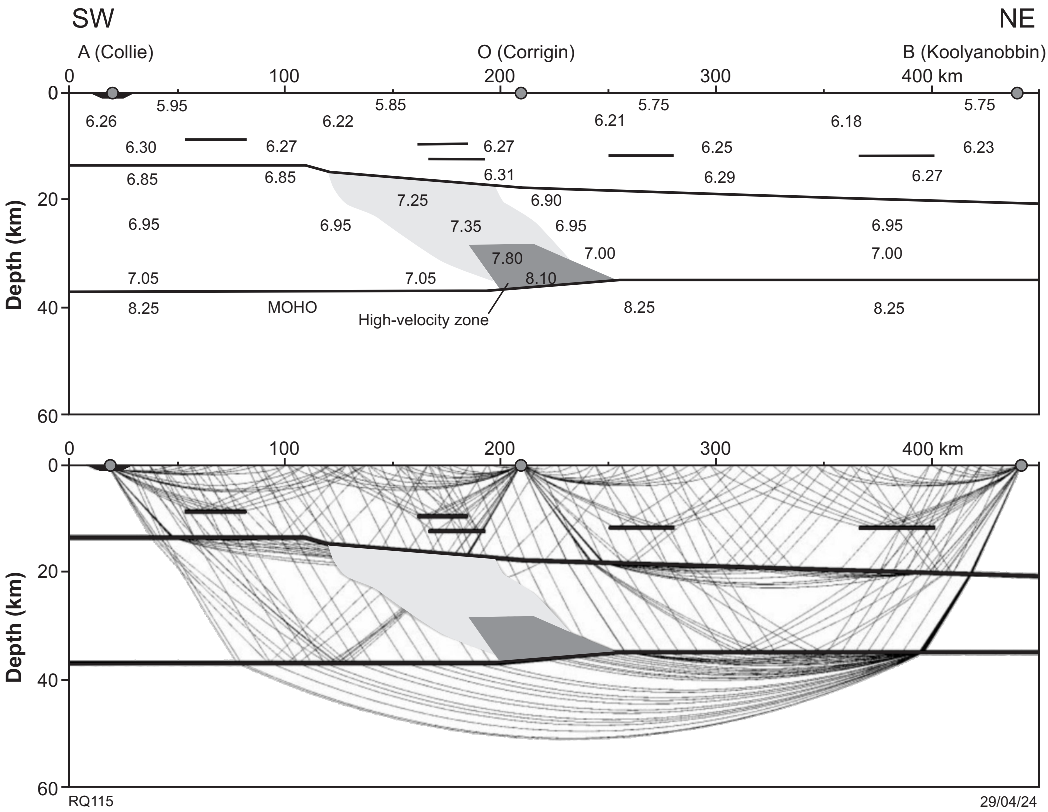

Figure 4. Crustal velocity model (top) and complete ray coverage (bottom) for the AOB seismic refraction profile of Dentith et al. (2000). Velocities are indicated in km/s. See location of profile on Figure 1

diorite (K) or lowCa granite. Rocks of this age are only known to occur in the Calingiri region and are interpreted as a basement raft caught in a shear-zone bounded domal feature composed of c. 2670 Ma highCa granitic gneiss and flanked by greenstones in the north (Wongan Hills) and south (Fig. 1). Other Thundelarra Supersuite granites occur around Ravensthorpe; a metatonalite classified as a sodic diorite and a metagranodiorite classified as a highly sodic highCa (high Sr/Y) granite yielded crystallization ages of 2985 ± 4 Ma and 2978 ± 5 Ma, respectively (GSWA 207510, Wingate et al., 2018a; GSWA 224357, Lu et al., 2018). A metamonzogranite collected from the southeastern end of the CTZ and classified as a sodic highCa (high Sr/Y) granite yielded a crystallization age of 2940 ± 6 Ma (GSWA 224351, Lu et al., 2019a). A biotite augen gneiss xenolith, collected from the northwestern end of the CTZ and classified as a highly sodic highCa (low Sr/Y) granite, yielded a similar zircon date of 2940 ± 5 Ma (Fletcher and McNaughton, 2002).

Three foliated to gneissic granitic samples collected from various parts of the southern Youanmi Terrane range from monzogranitic to granodioritic in composition and classify as lowCa granite. They yielded dates of 2808 ± 4, 2800 ± 4 and 2787 ± 4 Ma (GSWA 224450, Wingate et al., 2021b; GSWA 224396, Lu et al., 2019b, ; Fletcher and McNaughton, 2002, , respectively), corresponding to the 2825–2733 Ma Annean Supersuite.

At present, we have not identified any granitic rocks in the southern Youanmi Terrane corresponding to the 2735–2686 Ma Austin Downs Supersuite.

The bulk of the interpreted granite crystallization ages in the southern Youanmi Terrane (***n*** = 34) fall between 2678 and 2622 Ma, which correlates to the 2697–2657 Ma Tuckanarra Suite, 2665–2640 Ma Jungar Suite and 2650–2600 Ma Walganna Suite. These granites occur throughout the southern Youanmi Terrane and classify chemically as lowCa granite (***n*** = 15), lowCa (highTi) granite (***n*** = 4), highCa granite (***n*** = 11; including variably sodic and both high and lowSr/Y subtypes), sanukitoid (***n*** = 1), sanukitoid-like (***n*** = 1) and diorite (***n*** = 2). The lowCa granitic rocks are mostly younger than 2665 Ma and are distributed widely across the southern Youanmi Terrane and typically occur as undeformed monzogranite plutons intruding highCa granitic bodies. However, within the CTZ, lowCa and highTi lowCa granite bodies have typically elongate forms with charnockitic compositions and were emplaced along structures of the CTZ synchronously with high-grade metamorphism.

South West Terrane

The oldest exposed rock in the South West Terrane is a porphyritic meta-andesite collected from the Boddington gold mine with a crystallization age of 2704 ± 3 Ma (GSWA 236419, Lu et al., 2020) that classifies chemically as a sanukitoid (Na). Several granites exposed in the southern portion of the South West Terrane or in the Boddington area have crystallization ages ranging from 2702 to 2680 Ma and highCa (sodic or highly sodic, mostly high Sr/Y) granite compositions. These dates correlate with the 2735–2686 Ma Austin Downs Supersuite, which otherwise only occurs in the northern Youanmi Terrane. Despite the apparently younger crystallization ages of felsic igneous rocks in the South West Terrane (compared to the Youanmi Terrane), they yield Sm–Nd two-stage depleted mantle model (T_{DM}^2) ages ranging from 3431 to 2882 Ma, suggesting that their magmatic sources included Meso to Paleoarchean components.

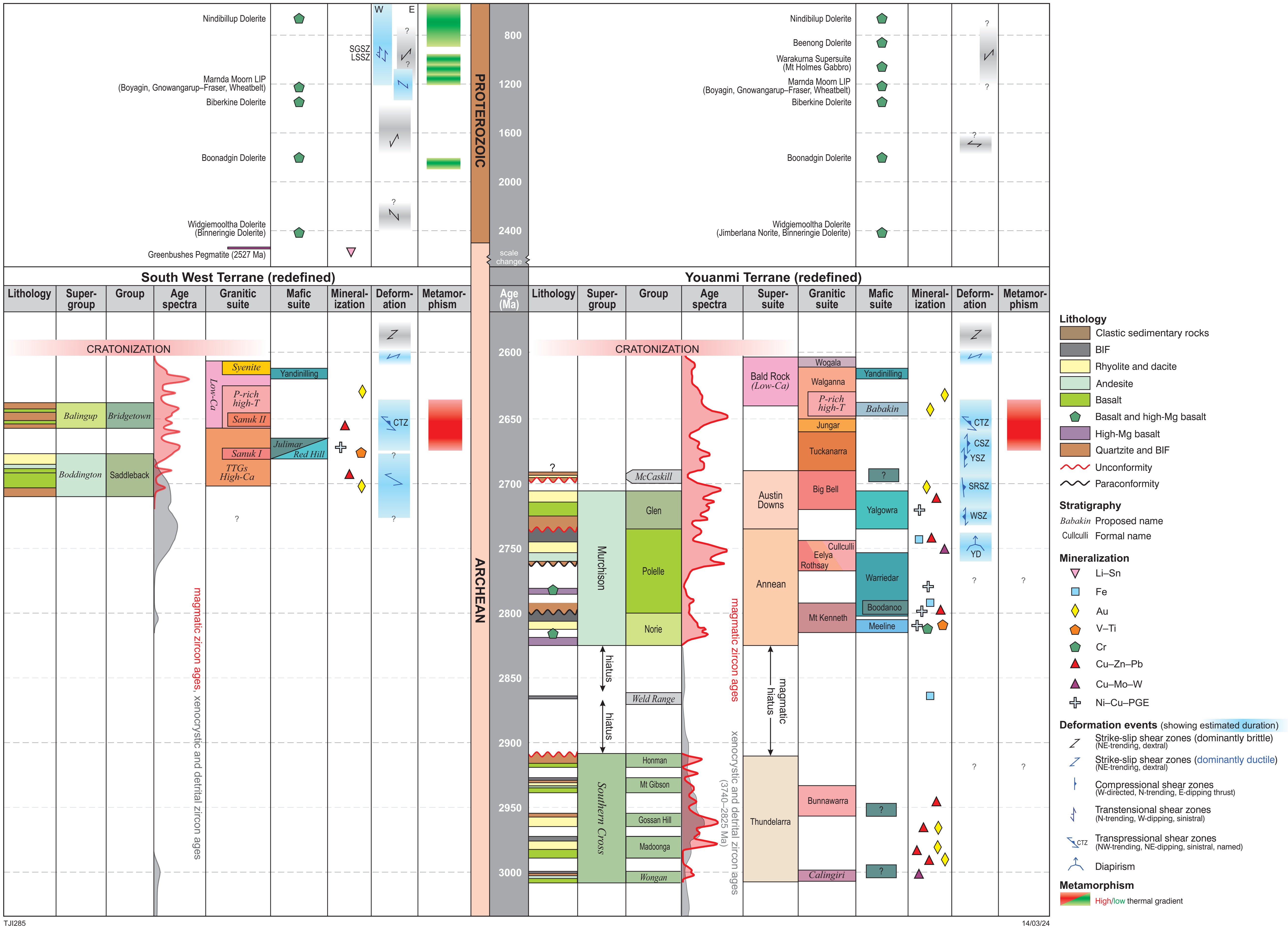

Figure 5. Time–space plot of the redefined South West and Youanmi Terranes from Quentin de Gromard et al. (2021)

The South West Terrane is dominated by 2677–2607 Ma biotite-monzogranite that is typically undeformed and has compositions that classify as lowCa granite, and broadly correlates with the Tuckanarra, Jungar, Walganna and Wogala Suites of the Younami Terrane (Fig. 5).

Granite classification map

Aeromagnetic and gravity datasets within the map area were interrogated in ArcGIS, with distinct bodies of similar aeromagnetic and gravity characteristics interpreted to be coherent bodies (such as plutons, sheets, lenses) of granitic lithologies. Those interpretations were also informed by lithological descriptions recorded in WAROX (GSWA's field observation database) that were captured during GSWA field mapping.

Granite chemical classes (modified after Champion and Sheraton, 1997; Champion and Cassidy, 2002) were then assigned to those granitic bodies based on the automated geochemical classification process of Lowrey et al. (2023), where coincident geochemical data was available in sufficient density to confidently do so. The resulting interpretation (Fig. 6) was then extrapolated to granitic bodies with sparse (or nil) geochemical data based upon their geophysical similarities to domains already classified. Small granite plutons of specific granite classes, such as sanukitoids, were not captured in the granite map, because it was not possible to individually map polygons from the resolution of the geophysical datasets. As a result, these have been included as minor components within larger mappable units dominated by other granite types.

Five granite geochemical groups are shown on the granite map:

1. **HighCa (Na to high Na, high Sr/Y) granite**: largely consisting of metamorphosed, foliated to gneissic, locally migmatitic tonalite–trondhjemite–granodiorite (TTG). These typically have a low to medium gravity response, low to moderate magnetic intensity and are textureless in magnetic maps. In Domain 2 (see discussion under 'Crustal domains of the southwest Yilgarn: a synthesis'), they form an extensive area bounded by a distinctive lozenge-shaped shear zone pattern similar those observed in the northern part of the Youanmi Terrane. The TTGs intrude into greenstones of the Youanmi Terrane, where the greenstones form dismembered rafts 'floating' in a 'sea' of highCa granite.

2. **HighCa (Na, low Sr/Y) granite**: typically hornblende granodiorite, mostly occurring within the South West Terrane as relatively undeformed intrusions, except for areas of Proterozoic deformation along the Darling Fault.

3. **HighCa (undifferentiated) granite**: undifferentiated either because of insufficient data points or because it was not possible to differentiate mixed high and lowSr/Y types as unique map polygons.

4. **LowCa granite**: typically weakly foliated porphyritic biotite monzogranite, commonly forming low-density features within the highCa granites with moderate magnetic intensity and a well-developed mottled texture. The 2677–2610 Ma lowCa granites were emplaced synchronously with 2665–2635 Ma deformation and metamorphism of the CTZ. In the CTZ, they occur as sheets emplaced along the footwalls of ductile shear zones; however, their occurrence is not restricted to the CTZ. In the northern part of the map area, outside of the CTZ, they form plutons often emplaced at a triple junction between earlier ductile structures and seem to inflate, overprint and crosscut these structures. These are interpreted as post-tectonic granites, post-dating the north-trending shear zone system resulting from 2730–2660 Ma deformation. They also occur as domes within large areas of highCa granite, for example, the lowCa granite pluton exposed at Wave Rock. The emplacement of the lowCa granite is therefore not the result of orogenesis in the CTZ, but simply coincides with c. 2665–2635 Ma deformation and metamorphism in the CTZ.

5. **LowCa (highTi) granite**: commonly monzogranite and syenogranite, rarely granodiorite, typically biotite-bearing and forming high magnetic intensity areas, with a well-developed mottled texture, of low to moderate density. These appear to be cogenetic with the lowCa granites but are possibly later highTi phases within a lowCa intrusion cycle. Where they occur in the CTZ, they appear as sheets intruded directly along the footwalls of the shear zones and are interpreted as syntectonic granite. Outside the CTZ, post-tectonic granitic bodies show concentric zonation between the lowCa and lowCa (highTi) chemical affinities.

Greenstones

Archean greenstones form approximately 20% of the bedrock geology of the southwest Yilgarn. The Youanmi Terrane contains well-documented stratigraphic units with most belonging to two supergroups: the 3010–2920 Ma Southern Cross Supergroup (Ivanic et al., 2022) and the 2820–2710 Ma Murchison Supergroup (Fig. 5). In the southern Youanmi Terrane, stratigraphic and age constraints are less well known since the metamorphic grade is elevated and most rocks are recrystallized at upper amphibolite and granulite facies. Thus, in the southwest Yilgarn area, there are only two regions (belts) where stratigraphy has been assigned (Ivanic et al., 2022): (1) Wongan Hills with the c. 3010 Ma Wongan Hills Formation (Southern Cross Supergroup) and (2) Ravensthorpe with the c. 2950 Ma Annabelle Volcanics Member (Southern Cross Supergroup) and the c. 2780 Ma Hatfield Formation (Polelle Group, Murchison Supergroup). Figure 5 shows the plutonic time-equivalents to these formations and groups on a stratigraphicmagmatic chart. The South West Terrane has distinctly younger greenstone depositional ages than the Youanmi Terrane at <2705 Ma (Quentin de Gromard et al., 2021), although some maximum depositional ages of c. 3000 Ma allow for older stratigraphy as well. Due to the incomplete documentation of greenstones in the South West Terrane, the stratigraphic groupings remain informal with the 2705–2670 Ma 'Boddington supergroup' and the c. 2640 Ma 'Bridgetown supergroup'.

In general, southwest Yilgarn greenstones are typically too deformed and recrystallized to preserve continuous and significant stratigraphic sections with known way-up. One exception to this is at the Poison Creek locality (see Locality 5), which preserves way-up indicators and an

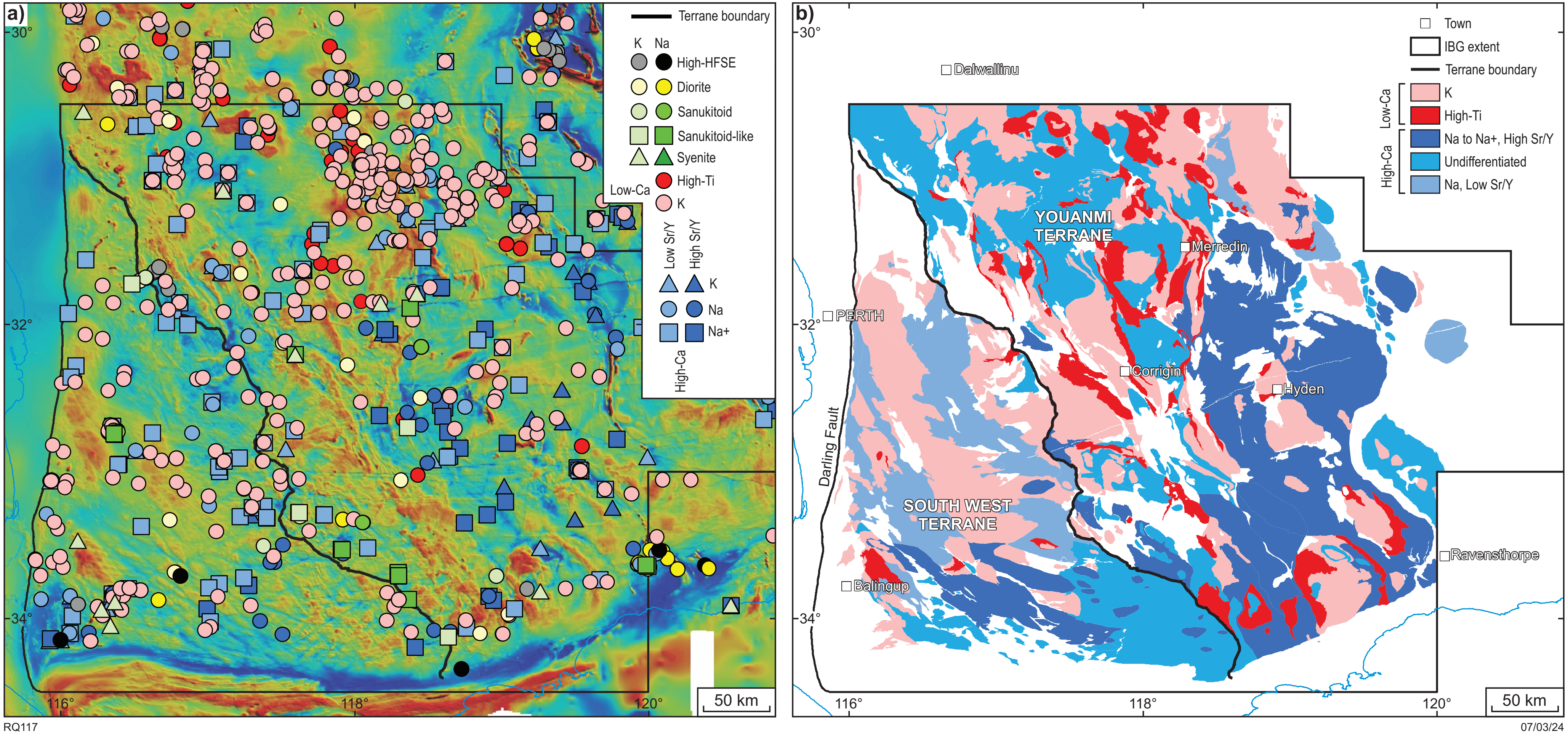

Figure 6. Granitic suites: a) classified granite data points from Lowrey et al. (2023) displayed over 500 metre upward-continued, reduced-to-the-pole, total magnetic intensity data; b) interpreted granite map. IBG extent from GSWA (2022)

intraformational unconformity. Therefore, stratigraphic assignment in the southwest Yilgarn dominantly uses radiogenic isotope-based geochronological constraints.

The greenstones map (Fig. 7) shows the distribution of seven lithological assemblages that typically form northwest-trending domains in the southwest Yilgarn. The first four assemblages are found across the southern Youanmi Terrane while the latter three are found across the South West Terrane. Initial geochemical classification of the magmatic lithotypes was given in Ivanic et al. (2021) and for the Boddington greenstone belt in Smithies et al. (2021), which are summarized in the relevant sections below.

Southern Youanmi Terrane

Assemblage 1 includes greenstone belts at Forrestania, Lake King and Ravensthorpe (Figs 1, 7), which have lithological assemblages typical of the Murchison Supergroup. These comprise higher proportions of ultramafic volcanic rocks, mafic volcanic and intrusive rocks, metasedimentary siliciclastic rocks and banded iron-formation (BIF), with lower proportions of felsic–intermediate volcanic rocks and ultramafic intrusive rocks. Geochronology from the Ravensthorpe and Forrestania areas also indicates a lesser component of >2920 Ma Southern Cross Supergroup and Thundelarra Supersuite units in this domain. This assemblage is the only one to include volcanic rocks with >18 wt% MgO (komatiites and komatiitic rocks) that show spinifex textures. Initial geochemical investigations in these greenstones indicate that the mafic–ultramafic volcanic rocks share broad major and trace element similarities to the Polelle Group in the northern Youanmi Terrane (Ivanic et al., 2021, Lowrey, 2021).

Assemblage 2 includes greenstone belts at Wongan Hills, Westonia and Holleton, which have lithological assemblages more typical of the Southern Cross Supergroup. These comprise high proportions of mafic volcanic, mafic intrusive rocks, metasedimentary siliciclastic rocks and BIF, with lower proportions of felsic–intermediate volcanic and ultramafic volcanic rocks. These greenstones are proximal to several dated TTGs of the c. 2950 Ma Thundelarra Supersuite. Ivanic et al. (2021) presented limited geochemical data on mafic volcanic rocks from these greenstones, which indicate a high proportion with lowTh tholeiitic compositions.

Assemblage 3 consists of greenstones within the CTZ (Figs 1, 7), which are granulite-facies mafic intrusive, mafic volcanic and sedimentary rocks (siliciclastic and banded iron-formation) with lesser ultramafic rocks. The lithologies are consistent with protoliths derived from the Southern Cross Supergroup that have been recrystallized at high metamorphic grades within the CTZ (i.e. 4–5 kbar and 700–900 °C at 2665–2635 Ma), which result in widely scattered geochemical compositions, negating their classification into geochemical groups (Ivanic et al., 2021).

Assemblage 4 consists of greenstones in the Northam area which have lithological assemblages comprising BIF interlayered with metamorphosed siliciclastic, mafic volcanic

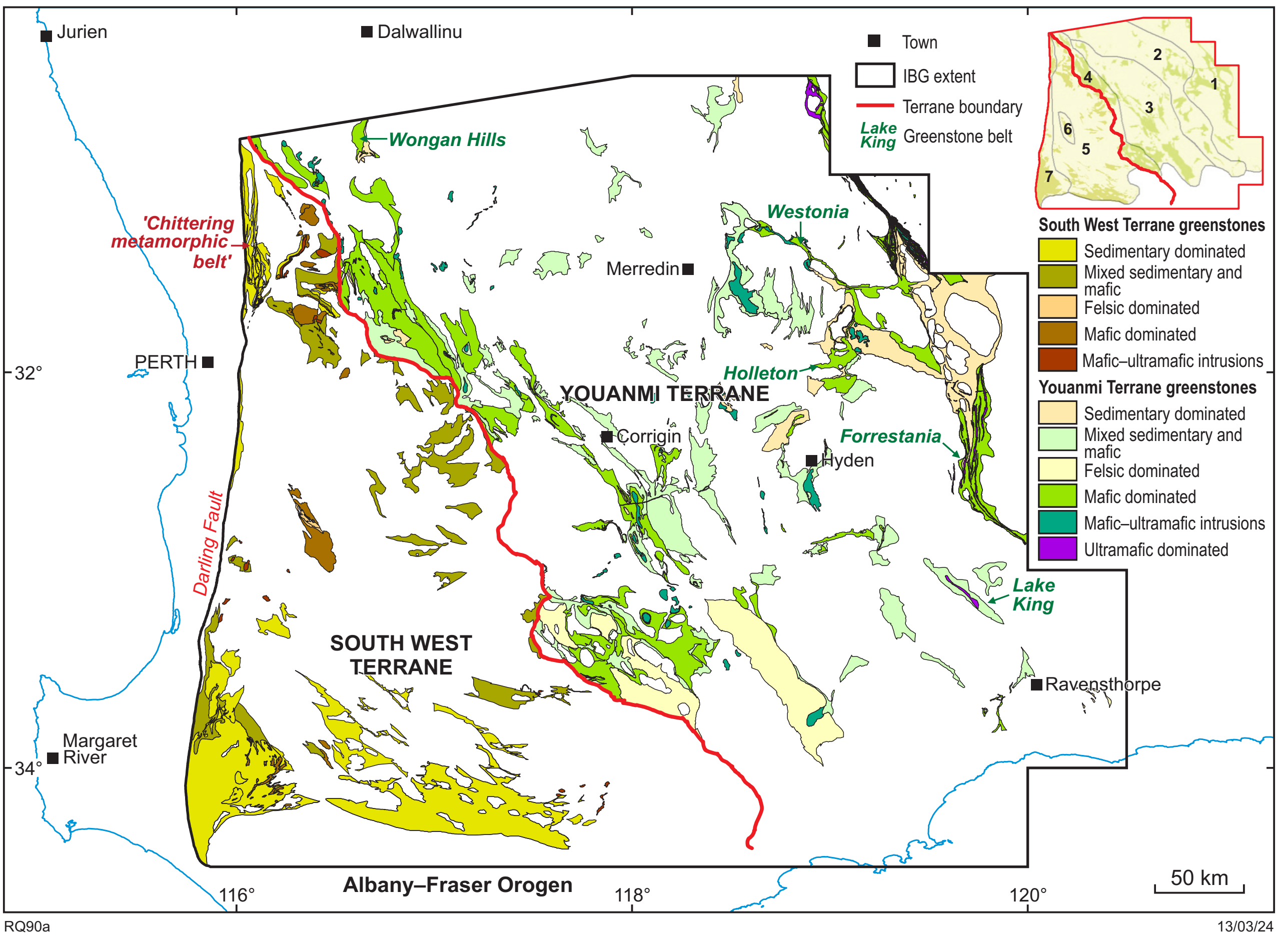

Figure 7. Interpreted greenstone map groups of the South West Terrane and the southwestern Youanmi Terrane. Inset shows numbered domains of distinct lithological assemblages (see text for explanation). IBG extent from Quentin de Gromard et al. (2021)

and mafic intrusive rocks. Though undated, this stratigraphy is consistent with parts of the Southern Cross Supergroup, but with a higher abundance of metasedimentary rocks. Geochemical data on greenstones is currently lacking in this area and geochronological sampling has mainly targeted metasedimentary rocks (see Locality 3), thus chronostratigraphic constraints are limited.

South West Terrane

Assemblage 5 occurs in the north and east of the South West Terrane, where the majority of greenstones comprise metamorphosed siliciclastic rocks intruded by mafic–ultramafic sills and plugs. Mafic–ultramafic intrusions have been dated and are informally assigned to the c. 2670 Ma, Ni–PGErich ‘Julimar suite’ and Ti–Vbearing ‘Red Hill suite’ (Fig. 7). The psammitic host rock to the ‘Julimar suite’ has detrital zircons between 3680 and 2652 Ma and a maximum depositional age of 2669 ± 2 Ma (GSWA 248205, Wingate et al., 2022) indicating a new and currently unassigned stratigraphic unit in this area. Ivanic et al. (2021) presented initial geochemical results from mafic–ultramafic intrusions in this assemblage. Ultramafic (and lesser mafic) plutonic rocks from the Yarrawindah Ni–PGE prospect contain 8–37 wt% MgO and 37–55 wt% SiO_2 and are tentatively assigned to the ‘Julimar suite’. The ‘Gonneville Peridotite’ at Julimar yielded a crystallization age of 2668 ± 4 Ma (GSWA 203747, Wingate et al., 2021a) and is inferred as the age of the suite as a whole. Mafic and ultramafic plutonic samples from the Katanning area (Red Hill deposit) are characteristically magnetite rich, reflected in their Ferich (7–72 wt% Fe_2O_{3Total}) compositions, with 1–11 wt% MgO and 34–51 wt% SiO_2. These mafic intrusions near Katanning are similar in composition to the c. 2664 Ma ‘Coates Siding Gabbro’ (Wilde and Pidgeon, 2006) and are tentatively grouped into the ‘Red Hill suite’.

Assemblage 6 comprises the Boddington greenstone belt which has a distinct lithological assemblage of mafic–intermediate volcanic rocks and lesser metasedimentary rocks and ultramafic sills. Volcanic rocks have been well dated and the greenstones have been informally assigned to the 2705–2670 Ma ‘Boddington supergroup’. Wilde and Pidgeon (1986) divided the stratigraphy into three formations: (1) the basal, metasedimentary ‘Hotham formation’, (2) the felsic volcanic-dominated ‘Wells formation’ and (3) the metabasaltic ‘Marradong formation’, all of which are informal at this stage. Felsic volcanic rocks and diorites at the Boddington mine have a hydrous and calc-alkaline composition (Smithies et al., 2021). For magmatism at c. 2705 Ma, and possibly at c. 2690 and c. 2670 Ma, fractionation from primary magmas derived from hydrated mantle is required. Although the origin of source hydration can be debated, this magmatism is most likely related to a fundamental translithospheric structure, and a long-lived thermal anomaly. The magmatic evolution of the Boddington area shows striking similarities with similarly aged units in the Kalgoorlie–Kambalda region. In both, mafic volcanism was succeeded by hydrous, hornblende-bearing, enriched magmas of variable compositions, and subsequent anhydrous, relatively high-temperature crustal melts.

Assemblage 7 occurs in the far west and southwest of the South West Terrane (Fig. 7). This assemblage mostly comprises quartz-rich siliciclastic rocks, locally with numerous small ultramafic sills. Supracrustal rocks have been informally attributed to the c. 2640 Ma ‘Bridgetown supergroup’ (Quentin de Gromard et al., 2021), although age constraints are sparse and further work is required here. Mafic volcanic rocks are minor and have not yet been sampled for lithogeochemistry. Mafic–ultramafic intrusive rocks are highMg in composition, and the Yornup nickel deposit has ultramafic intrusive rocks with lowNb trace element compositions similar to the Yarrawindah deposit (see Assemblage 5; Ivanic et al., 2021).

Mafic dykes

At least nine mafic dyke suites intruded the southwest Yilgarn between the Neoarchean and the Neoproterozoic. Individual dykes are grouped within suites based on available geochronology, orientation, and consistency of crosscutting relationships with other units and structures (Fig. 8a). The magnetic polarity of individual dykes can be interpreted from aeromagnetic data. Mafic dykes showing positive or negative anomaly in the aeromagnetic data indicate upward or downward magnetic inclination respectively, and thus may suggest periods of Earth’s magnetic pole inversion (Fig. 8b). In chronological order, the mafic dyke suites are:

1. **‘Babakin metadolerite’**: a north to northeast-trending, Archean mafic dyke suite, interpreted to be c. 2640 Ma in age. This informally named and undated suite was identified from aeromagnetic data primarily within the CTZ and is interpreted as a suite of deformed mafic dykes emplaced synchronously with the syntectonic to post-tectonic intrusions of the 2651–2630 Ma lowCa (highTi) granites. The dykes all have a positive magnetic polarity.

2. **Yandinilling Dolerite**: c. 2615 Ma northeasterly to north-northeasterly trending dykes, dated by Stark et al. (2018b). These dykes are largely restricted to the northwest portion of the map area. They crosscut and are not affected by the CTZ and thus form an absolute minimum age for this deformation event. Most of the dykes are positive, but a few negative dykes occur.

3. **Widgiemooltha Dolerite**: c. 2410 Ma westerly to west-southwesterly trending dykes. Individual dyke segments are commonly 100–200 km long, and occur over most of the map area. This dyke swarm hosts some of the widest mafic dykes in the map area, which are locally up to ~600 m wide. Both positive and negative magnetic polarities occur and the age of this magnetic pole reversal was previously bracketed between 2408 ± 3 and 2401 ± 2 Ma for a positive and a negative dyke, respectively (Wingate, 2007; Pisarevsky et al., 2015).

4. **Boonadgin Dolerite**: c. 1888 Ma west-northwesterly trending dykes, dated by Stark et al. (2019). These dykes mostly occur in the southwest portion of the map area and are almost entirely restricted to the redefined extent of the South West Terrane. The dykes all preserve a positive magnetic polarity.

5. **Biberkine Dolerite**: c. 1390 Ma north-northwesterly trending dykes, dated by Stark et al. (2018a). The dykes occur in the western part of the map area, and were mostly intruded into the redefined extent of the South West Terrane, but also within the southwestern margin of the Youanmi Terrane. The dykes are emplaced along and parallel to the boundary between the South West

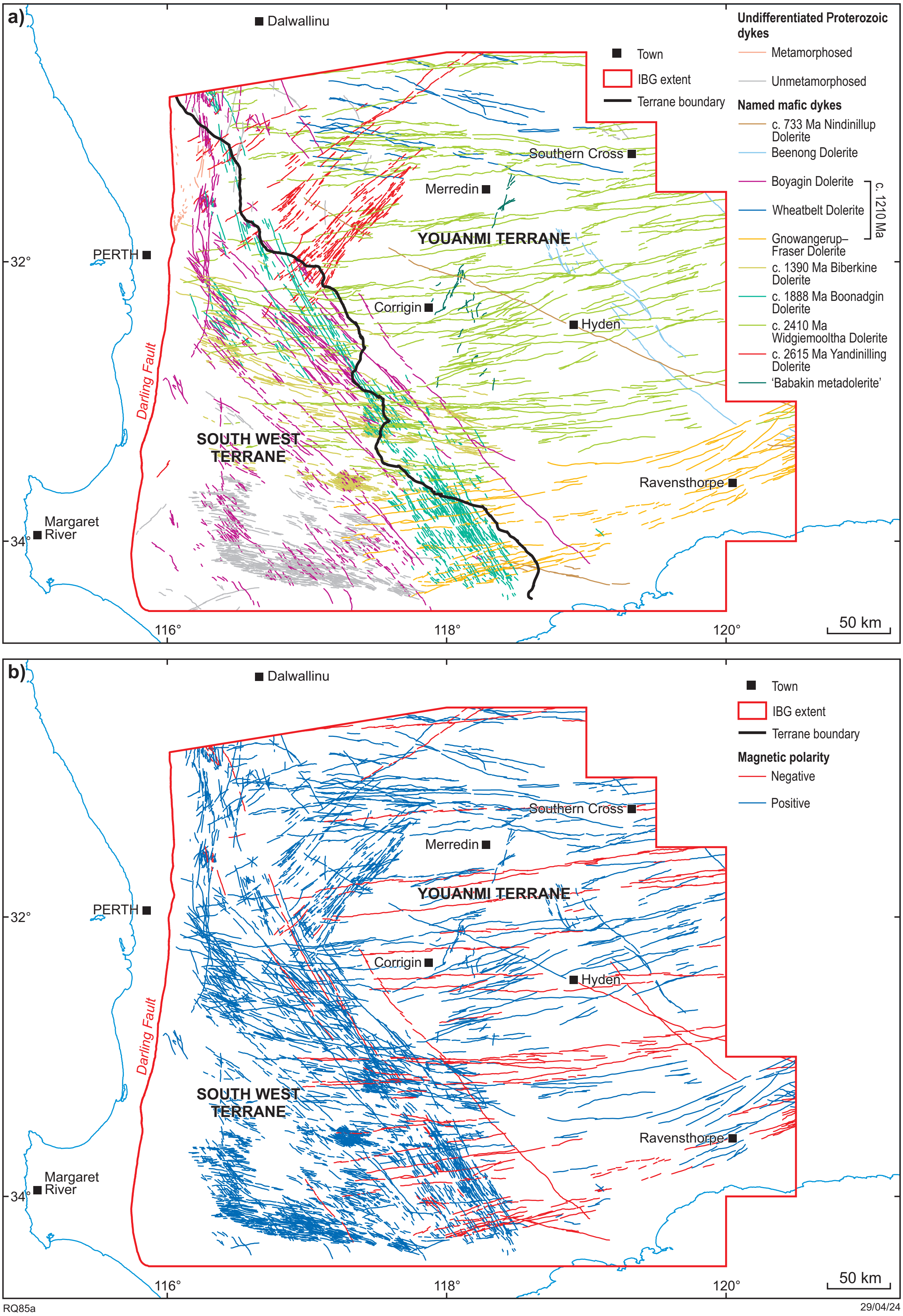

Figure 8. Mafic dykes differentiated by suite (a) and magnetic polarity (b). IBG extent from Quentin de Gromard et al. (2021)

Terrane and the Youanmi Terrane, and lie parallel to the regional to terrane-scale, north-northwesterly trending, long-wavelength gravity anomaly that underlies the South West Terrane. Both positive and negative polarity dykes are present.

6. Dykes of the c. 1210 Ma Marnda Moon Large Igneous Province (Wingate, 2017):

    6.1. **Boyagin Dolerite**: northwesterly trending dykes, largely occurring in the redefined extent of the South West Terrane; only minor occurrences were interpreted east of the terrane boundary. The dykes all preserve a positive magnetic polarity.

    6.2. **Gnowangerup–Fraser Dolerite**: west-southwesterly trending dykes, occurring in the southern portion of the map area, across the Youanmi and South West Terranes, and emplaced parallel to the western Albany–Fraser Orogen margin. Both positive and negative dykes occur.

    6.3. **Wheatbelt Dolerite**: these west-northwesterly trending dykes occur in the northern portion of the map area and were mostly intruded into the Youanmi Terrane. The dykes all preserve a positive magnetic polarity.

7. **Beenong Dolerite**: undated northwesterly trending dykes, bracketed between c. 1218 and 541 Ma, occurring in the eastern part of the map area and exclusively within the Youanmi Terrane. The dykes mostly preserve a positive magnetic polarity; only minor negative dykes were identified.

8. **Undifferentiated Proterozoic mafic dykes**: these dykes, mostly occurring in the far southwestern corner of the map area, are abundant and tightly spaced, and all preserve a positive magnetic polarity.

9. **Nindibillup Dolerite**: these c. 733 Ma west-northwesterly trending dykes are rare and limited to the redefined extent of the Youanmi Terrane. The dykes can be hundreds of kilometres long and preserve both positive and negative magnetic polarity.

Structures

Southern Youanmi Terrane

From field observations, the interpretation of gravity and magnetic worms, and the structural interpretation of magnetic data, we interpret the South West – Youanmi Terrane boundary as a moderately northeast-dipping structure. In the aeromagnetic data, the hangingwall of the terrane boundary, i.e. on the Youanmi Terrane side, is characterized by a 50–150 km-wide zone of elongated moderately to highly magnetic bodies and elongated well-aligned, locally folded, highly magnetic linear horizons collectively defining the Corrigin Tectonic Zone (CTZ, Area 3 in Fig. 9a; Quentin de Gromard et al., 2021). Consistently with field observations, we interpret this zone as a region of high strain comprising a dense network of northwest-striking, commonly moderately northeast-dipping shear zones. Within two specific areas closer to the terrane boundary, the shear zones of the CTZ appear to flatten out to become gently northeast-dipping structures with clear top-to-the southwest shear sense, i.e. Youanmi Terrane over South West Terrane, particularly evident in the region around Northam (Fig. 1; see Locality 10). Between the CTZ and the old terrane boundary, anastomosed sets of shear zones form lozenge-shaped patterns with north-northwesterly trending long axes (Fig. 2b). These lozenges have similar aspect ratios to those observed in the eastern and northern portion of the Youanmi Terrane, obvious in both the gravity and magnetic datasets, albeit with a different orientation. However, these lozenges are not visible in the South West Terrane, suggesting a different deformation history on either side of the terrane boundary. In the northern Youanmi Terrane, some of these shear zones are interpreted to have been active from c. 2730 Ma and the bulk of them between 2680 and 2660 Ma (Zibra et al., 2017). We interpret that the shear zones forming lozenges in the southern Youanmi Terrane were subsequently reactivated, resulting in the counter-clockwise rotation of the long axes of the lozenges and were eventually completely reoriented into parallelism within the CTZ together with newly formed shear zones against the northwest-trending terrane boundary (Fig. 2b).

Kinematics of the 2665–2635 Ma CTZ

In the aeromagnetic data, magnetic horizons that show systematic curvature, or a progressive increased density of magnetic layering (locally with progressive thinning of individual layers that in places may also be segmented and truncated), may be interpreted as evidence for tectonic structures such as folding, transposition, attenuation and boudinage. In addition to field measurements, the magnetic gradients on either side of an individual magnetic horizon observed in aeromagnetic images processed without sun shading or with overhead sun can be interpreted to infer the dip orientation and estimated dip angle of the horizon of interest based on the principles of structural geophysics (Jessell, 2001). Used systemically over the whole CTZ, this approach allowed us to interpret two main structure types, i.e. compressional structures and strike-slip structures, as well as the intermediate oblique-slip structures. This suggests that, over the whole CTZ, the strain is partitioned in compressive structures and strike-slip structures, indicating that the CTZ was formed in a transpressional environment. Asymmetric folds with moderately northeast-dipping axial planes and truncated southwestern limbs can be interpreted as southwest-verging folds developed on the hangingwalls of southwest-directed thrusts (Fig. 10a). A series of ovoid magnetic bodies showing sinistral lateral offsets are interpreted as asymmetric boudins with sinistral shear bands developed in boudin necks (Fig. 10b). Together with the regional-scale counter-clockwise rotation of the long axes of lozenge-shaped sets of anastomosed shear zones, this strongly suggests that the structures of the CTZ and the reactivation of the lozenges were formed in response to sinistral transpression with main compressive stress orientated approximately E–W.

South West Terrane

The central part of the South West Terrane, forming about half of the terrane, appears devoid of major structures (Fig. 9a). It is difficult to assess whether any major structures ever affected this portion of the South West Terrane or whether it is because it has been intruded by

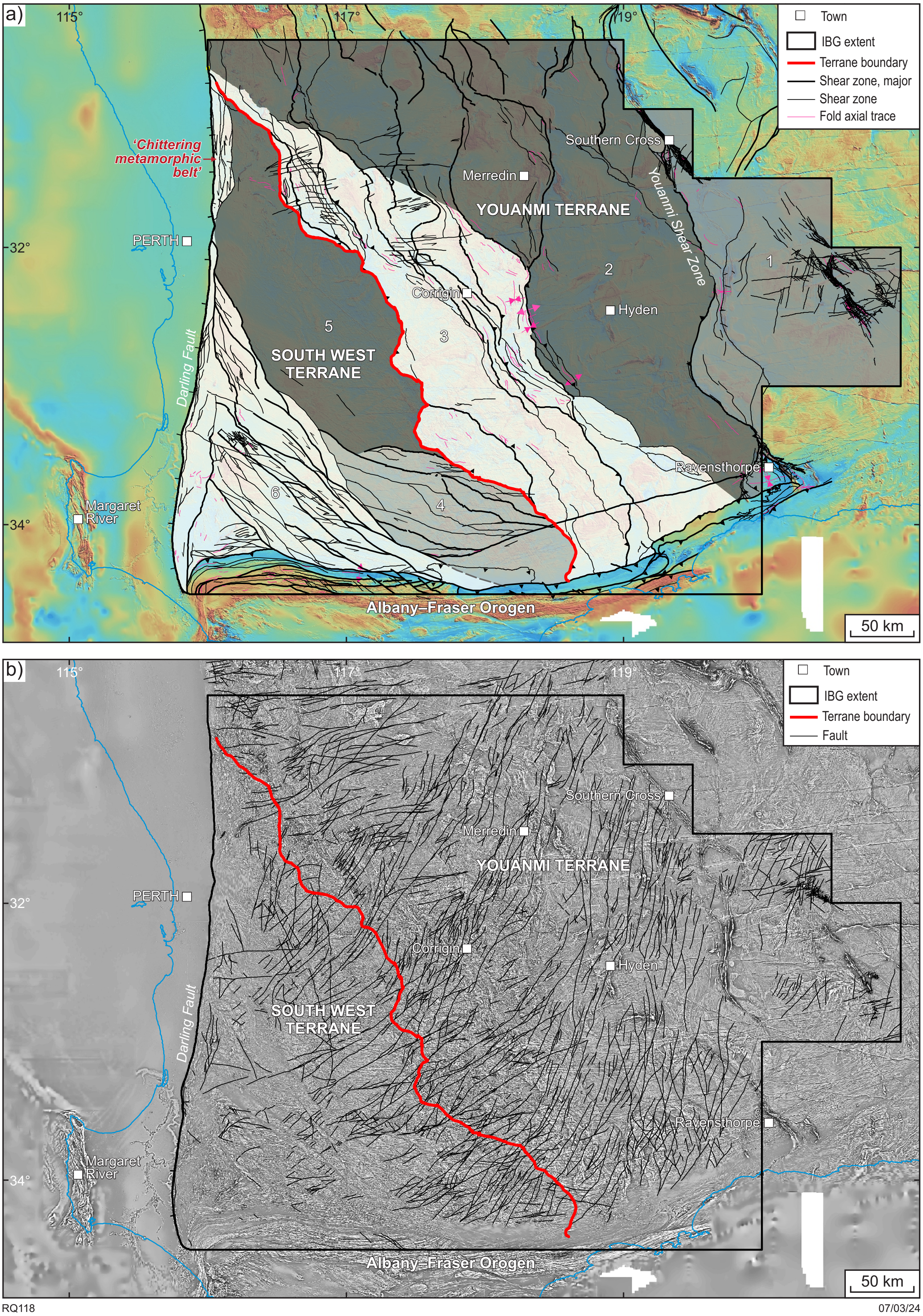

Figure 9. Structural architecture maps showing the location of the South West – Youanmi Terrane boundary: a) shear zones and crustal domains (see text for numbering) displayed over reduced-to-the-pole, total magnetic intensity data; b) faults displayed over grey-scale, first vertical derivative of the reduced-to-the-pole, total magnetic intensity data. IBG extent from GSWA (2022)

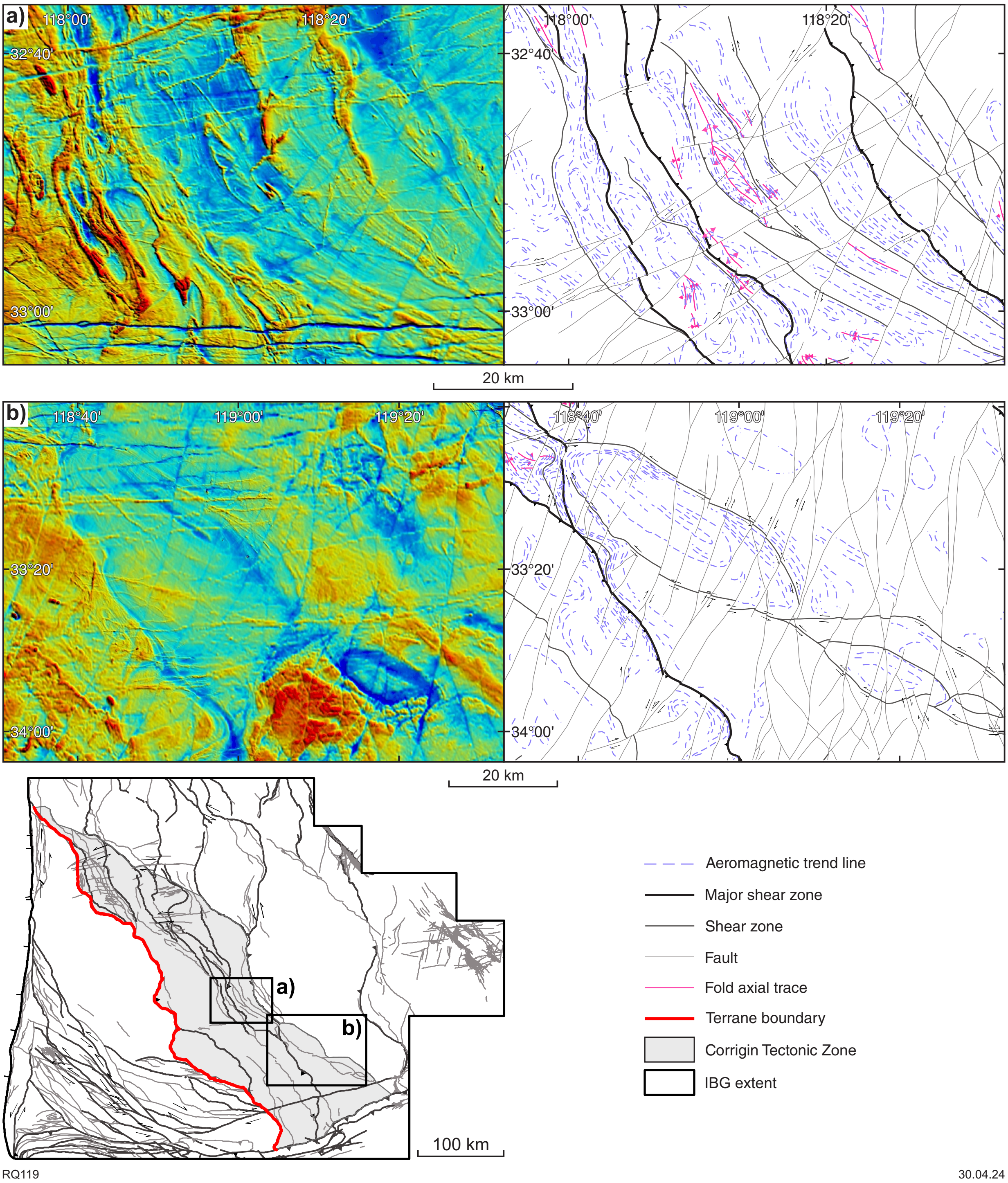

Figure 10. Two key locations within the CTZ showing (left) the reduced-to-the-pole, total magnetic intensity data and (right) the corresponding interpreted structures and kinematics. IBG extent from GSWA (2022)

voluminous bodies of late granites — the vast majority of exposures in the region consist of largely undeformed biotite monzogranite — that obliterated any pre-existing crustal architecture. In the southeastern part of the South West Terrane, we interpret a series of west-northwesterly striking major and minor shear zones (Fig. 9a). These structures are probably steeply dipping to subvertical and no consistent kinematic could be interpreted. The older age of these structures is unknown but their eastern ends are truncated by the northwest-striking structures of the CTZ and their western ends by a series of northwest-striking shear zones, only present within the southwest corner of the South West Terrane and that seem genetically linked to structures of the west Albany–Fraser Orogen (Fig. 9a). These structures are steeply dipping and a consistent sinistral strike-slip shear sense is interpreted based on lateral offsets of earlier structures and mafic dykes and on the resulting regional-scale steeply dipping sinistral duplex geometry they produce. The northwest-striking shear zones are in turn truncated by the north-striking faults and shear zones of the Proto-Darling Fault (Fig. 9a).

Faults

Most of the southwest Yilgarn is affected by a dense network of northeast to north-northeast striking faults, characterized in aeromagnetic data by thin, linear, commonly demagnetized features across which other magnetic horizons show sharp offsets with consistent displacement (Fig. 9b). These structures, here referred to as faults to distinguish them from the shear zones described above, are interpreted as steep to subvertical strike-slip faults commonly showing dextral lateral displacement. They affect the shear zones of the CTZ and extend across the old terrane boundary. They also affect most of the South West Terrane but are offset by the series of west-northwesterly striking shear zones of the southwest corner of the terrane, suggesting that these faults predate the Albany–Fraser Orogeny. It seems that these faults did not extend as far west as the Proto-Darling Fault structures. Based on aeromagnetic data interpretation, the faults are crosscut by and locally used as a propagation medium by mafic dykes of the Widgiemooltha Dolerite. Some of the northeast-striking faults appear to have been reactivated after the emplacement of the c. 1390 Ma Biberkine Dolerite and others after the c. 1210 Ma Boyagin Dolerite suite.

Structural evolution

Based on crosscutting relationships between dated units — mostly granitic rocks and mafic dykes — and faults and shear zones, we were able to attribute some age constraints to thirteen sets of faults and shear zones (Fig. 11). These are listed below:

1. **?2840–2665 Ma**: a series of major west-northwesterly striking shear zones restricted to the southern South West Terrane around Katanning. These structures are truncated to the east by northwest-striking major shear zones of the CTZ and to the west by a dense network of curved, dominantly northwest-striking, Proterozoic shear zones (see number 10 below; Fig. 11). The maximum age is unknown but is here attributed to the oldest known granitic gneiss in the area dated at c. 2840 Ma, which may have been emplaced syntectonically. The minimum age constraint is the maximum age of the 2665–2635 Ma CTZ, which truncates the west-northwesterly trending shear zones and does not appear to have significantly reactivated these structures.

2. **2730–2660 Ma initiation with 2665–2635 Ma reactivation**: the anastomosing shear zone systems forming northwest-trending lozenges within the high-grade portion of the Youanmi Terrane. We interpret these shear zones as having originated together with the 2680–2660 Ma shear zones forming the north-trending lozenges in the central Youanmi Terrane; some may have originated as early as c. 2730 Ma during the Yilgarn orogeny (Zibra et al., 2017). These shear zones are interpreted to have been reactivated and reoriented during the 2665–2635 Ma formation of the CTZ. Their minimum age is therefore the minimum age of the CTZ.

3. **2665–2635 Ma**: major northwest-striking shear zones, generally northeast-dipping, defining the CTZ and interpreted to have formed in sinistral transpression (Figs 2, 10). The maximum and minimum age constraints are defined by the oldest and youngest metamorphic zircons in the CTZ, which also encompass the age range obtained from monazite and the crystallization ages of syntectonic lowCa ± Tirich metagranites.

4. **2630–2410 Ma**: prominent set of northeast-striking faults; some individual faults exceed 200 km. They mostly show dextral shear sense, and cut across the South West and Youanmi Terranes. These faults displace structures of the 2665–2635 Ma CTZ and affect lowCa granite plutons dated at c. 2630 Ma but predate the c. 2410 Ma Widgiemooltha Dolerite. These faults are interpreted as having formed in the upper crust in a more brittle regime, which is consistent with the emplacement of the c. 2615 Ma Yandinilling Dolerite dykes in brittle fractures.

5. **2615–2410 Ma**: east-northeasterly striking minor shear zones in the northern part of the map affecting the CTZ structures and the c. 2615 Ma Yandinilling Dolerite dykes. The minimum age is constrained by the age of the undeformed 2410 Ma Widgiemooltha Dolerite dykes.

6. **<2410 Ma**: minor set of northwest-striking faults, mostly dextral, restricted to the South West Terrane and affecting the 2410 Ma Widgiemooltha Dolerite.

7. **1888–1390 Ma**: minor set of dominantly sinistral faults affecting the c. 1888 Ma Boonadgin Dolerite dykes but not affecting the c. 1390 Ma Biberkine Dolerite dykes.

8. **1800–1140 Ma**: major east-striking shear zones of the Albany–Fraser Orogen. The maximum age for these shear zones is interpreted to be related to extensional faulting that formed the 1800–1590 Ma Barren Basin and the minimum age is likely related to deformation during the 1225–1140 Ma Stage II of the Albany–Fraser Orogeny.

9. **<1390 Ma**: minor set of mostly sinistral northeasterly to north-northeasterly striking faults, restricted to the southern part of the map area and truncating the redefined terrane boundary between the South West and Youanmi Terranes, affecting the c. 1390 Ma Biberkine Dolerite dykes.

10. **1390–1140 Ma**: major northwesterly trending, sinistral, ductile shear zones, restricted to the southern part of the South West Terrane, in the southwestern corner of the map area. These shear zones are interpreted to be Proterozoic in age, as they affect the c. 2610 Ma granites, and are possibly synchronous with compressional or transpressional deformation related to the c. 1390–1140 Ma Albany–Fraser Orogeny. Alternatively, they may be related to the early stages of sinistral transtensional deformation producing the north-trending fabric within basement rocks close to the Darling Fault and the regional-scale sinistral drag of tectonic fabrics of the western end of the western Albany–Fraser Orogen; however, they are truncated by the latest stages of north-trending fabrics parallel to the Darling Fault.

11. **<1210 Ma**: minor set of mostly sinistral northeast-trending faults restricted to the South West Terrane

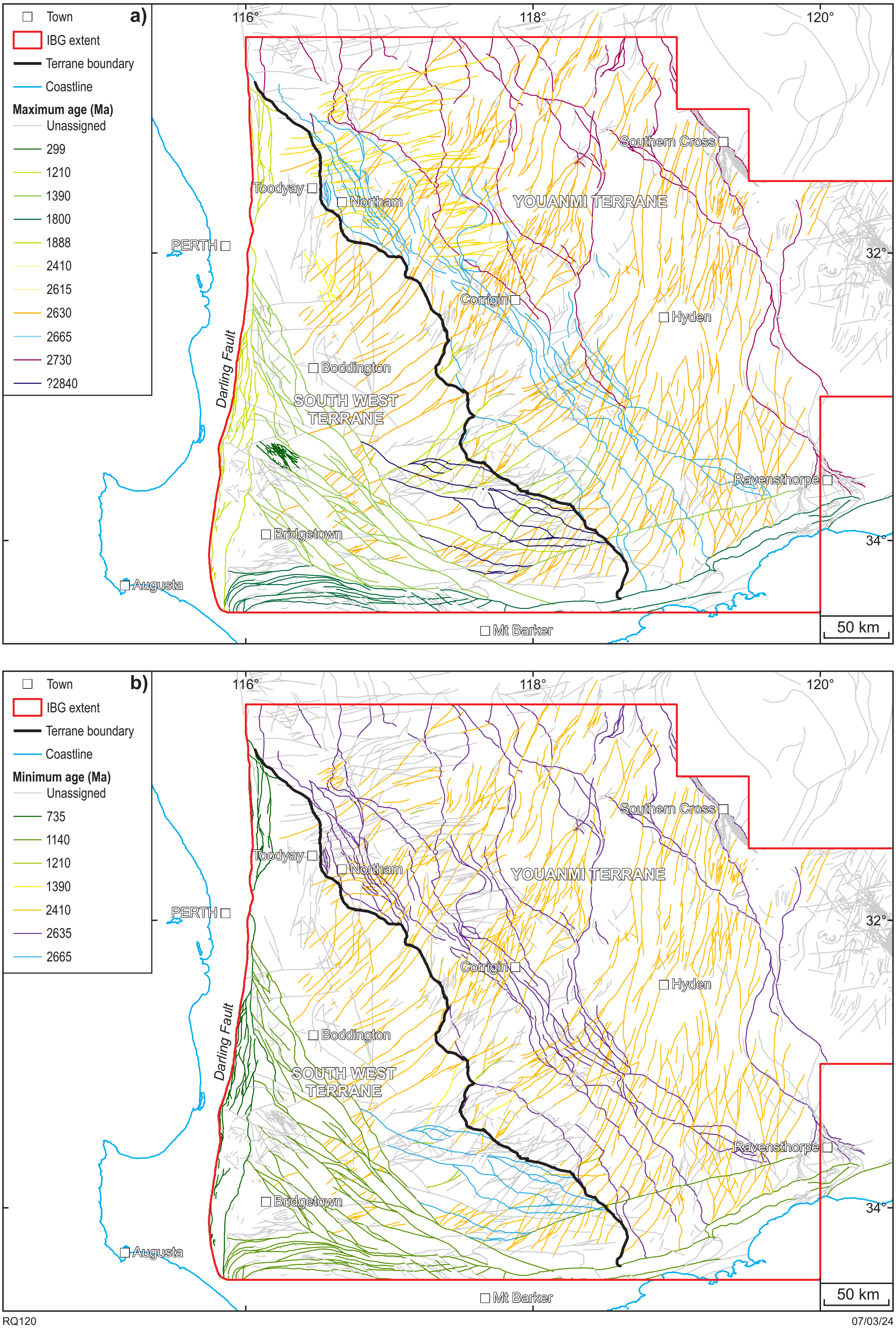

Figure 11. Faults and shear zones coloured by (a) maximum age and (b) minimum age. IBG extent from GSWA (2022)

affecting the c. 1210 Ma Boyagin Dolerite dykes that probably reactivated the 2630–2410 Ma faults of the same orientation.

12. **<1210–735 Ma**: major set of north-trending structures parallel to the Darling Fault scarp, produced during sinistral transtension as identified in the 'Chittering metamorphic belt' (Zibra, 2021) and likely producing the regional-scale apparent sinistral drag of tectonic fabrics of the western end of the western Albany–Fraser Orogen. These structures deform north-trending dolerite dykes attributed to the c. 1210 Ma Boyagin Dolerite suite providing a maximum age of deformation for the sinistral transtensional event. However, this maximum age likely represents an age of reactivation of these structures as Proto-Darling Fault structures were likely active since the Archean (Blight et al., 1981). At the northern end of the 'Chittering metamorphic belt', these north-trending structures are truncated by the northwest-striking structures extending from the CTZ structures, possibly due to late reactivation of some structures of the CTZ. A metamorphic date of c. 735 Ma has been identified in the truncation region, tentatively providing a minimum age for these structures.
13. **<299 Ma**: mostly northwest-trending faults affecting the Carboniferous–Permian Collie Subbasin in the southwest part of the map area that likely reactivated the pre-existing 1330–1140 Ma major northwesterly trending shear zones in the area.

Metamorphic data

The *P–T–t* conditions of the southern Youanmi Terrane are very well characterized, with twenty metamorphic data points showing pervasive granulite and amphibolite-facies conditions exhibiting peak median metamorphic conditions within the range of 4.8 – 8.6 kbar and 700–890 °C at 2665–2635 Ma (Fig. 2). However, an estimate for peak median conditions at 2665–2635 Ma are likely best represented by 5.5 – 6.5 kbar and 750–850 °C based on most robust and most reproduced data. The thermal gradient was moderate to high, ranging between 95 and 225 °C/kbar, and a combination of high radiogenic heat production and mantle input at c. 2670 Ma is thought to be responsible for this elevated gradient. Much of the current dataset is from granulite-grade mid-crustal meta-igneous and metasedimentary rocks of the northwest-trending CTZ. East of the CTZ, the data suggests that *P–T* conditions are broadly similar to the conditions recorded in the CTZ, although no metamorphic age data could be obtained in this region as these were recorded from mafic lithologies. Distinctly lower *P–T* conditions of 3.0 – 5.8 kbar and 615–670 °C are recorded from samples east of the old terrane boundary (Fig. 2). West of the CTZ, within the South West Terrane, there is a scarcity of robust *P–T–t* data, but field observations are suggestive of a generally lower metamorphic grade, as suggested by the greenschist-facies assemblages from rocks of the 2704–2670 Ma Saddleback greenstone belt containing the Boddington gold mine. However, Archean migmatites are known from several locations in the South West Terrane, including in the Toodyay area (see Localities 6A and 6B), but their metamorphic conditions are not known. The only robust *P–T–t* data from the South West Terrane were obtained in the proximity of the Darling Fault and reflect amphibolite-facies Proterozoic conditions, 5.5 – 9.0 kbar and 420–680 °C at 1150–620 Ma (Fig. 2).

Crustal domains of the southwest Yilgarn: a synthesis

We identify six main shear zone-bounded crustal domains of different geological history across the interpreted bedrock geology area (Fig. 9a); these are:

Domain 1: a greenschist to amphibolite-facies domain within the Youanmi Terrane, bounded to the west by the Youanmi Shear Zone. This domain includes characteristic linear and fault-bounded greenstone belts such as Southern Cross, Forrestania, Lake King and Ravensthorpe (Figs 1, 9). These are intruded by large granitic domes that dominantly show regional-scale sinistral asymmetry.

Domain 2: an amphibolite to granulite-facies domain within the Youanmi Terrane, bounded to the east by the Youanmi Shear Zone and to the west by the Corrigin Tectonic Zone. This domain contains a shear zone system that anastomoses and forms lozenges of similar shapes and probably of similar geological history to the 2730–2665 Ma north-trending lozenges observed farther north in the Youanmi Terrane; however, here the long axes of the lozenges trend north-northwest. This change in orientation from northerly to north-northwesterly trending is interpreted as a far-field expression of the 2665–2635 Ma sinistral transpression event that affected the southeastern margin of the Youanmi Terrane along the South West – Youanmi Terrane boundary (see Domain 3: the Corrigin Tectonic Zone). This resulted in reactivation of the shear zones, forming lozenges during combined flattening and simple shearing, thus producing the rotation of the long axes of the lozenges. Domain 2 is largely dominated by highly sodic highCa (high Sr/Y) gneissic TTGs intruded into Youanmi Terrane greenstones, including the Holleton greenstone belt (Figs 1, 6, 9). The greenstone associations in this domain, occur as dismembered rafts within the gneissic TTGs. Porphyritic lowCa, potassic, biotite monzogranite, such as that observed at Wave Rock near Hyden, may form large domes within the centres of the gneissic TTG-dominated lozenges (Figs 1, 6, 9).

Domain 3 (the Corrigin Tectonic Zone): a strongly deformed, largely migmatitic, granulite-facies domain forming the southwestern margin of the Youanmi Terrane (Figs 1, 9). The area is moderately to steeply northeast-dipping, shows abundant asymmetric southwest-verging tight to isoclinal folds, and contains small to regional-scale asymmetric boudins showing apparent sinistral displacement. The deformation structures are partitioned into moderately northeast-dipping thrusts and steeply dipping, northwest-striking, sinistral strike-slip shear zones, which, together with the counter-clockwise rotation of the long axes of the lozenges of Domain 2 along the CTZ, suggest a sinistral transpressive tectonic regime. Migmatitic rocks of the CTZ record metamorphic conditions of 5.5 – 6.5 kbar and 750–850 °C. U–Pb zircon and monazite metamorphic ages for this zone are between c. 2665 and 2635 Ma, interpreted as the age of high-grade metamorphism and likely as the age of melt-present deformation in the CTZ. The area hosts a high proportion of migmatitic, gneissic TTGs intruded by syntectonic lowCa, potassic and lowCa, Tirich metamonzogranite and metasyenogranite, intruded as tabular sheets along and in the footwalls of northwest-striking shear zones of the CTZ, and with magmatic crystallization ages that all fall within the metamorphic age-range. Zircon $\delta^{18}O$ values from c. 2800 to 2641 Ma granitic rocks from the CTZ yielded values ranging between 6.5 and 6.9‰ (Lu et al., 2021) suggesting significant tectonic burial of supracrustal material into the source region of the c. 2800 to 2641 Ma granite, which is consistent with the underthrusting inferred from the transpressional interpretation for the CTZ.

Domain 4: potentially a relatively old and deep crustal domain within the otherwise apparently younger South West Terrane (Fig. 9). The basement aeromagnetic features within this domain are largely obscured by the very high density of northwesterly to north-northwesterly striking mafic dykes. Mapping the aeromagnetic form lines in the background of these dykes revealed a systematic west-northwesterly striking domain. West-northwesterly trending ovoid features in this domain with concentric aeromagnetic trend lines and associated with highCa, highNa and highSr/Y granite analyses are interpreted as ovoid TTG plutons (Fig. 6). Major west-northwesterly striking shear zones bound and occur within this domain, and are interpreted to predate and control the emplacement of the TTG plutons dated at c. 2702 and 2669 Ma, and are also truncated by the northwest-striking major shear zones of the 2665–2635 Ma CTZ. The shear zones bounding this domain control the distribution of exposed highCa granites with high Sr/Y values in the South West Terrane. Domain 4 is largely dominated by TTGs with highCa (± Na) and high Sr/Y, while the highCa (± Na) granites of Domains 5 and 6 have almost exclusively low Sr/Y values. Additionally, Domain 4 contains very few lowCa granites while Domains 5 and 6 are largely dominated by them. Domain 4 also coincides with a high gravity anomaly and we interpret the basement into which the TTG plutons were intruded as a mixed intermediate and mafic gneissic crust, which is possibly a lower crustal-level exposure. One major west-northwesterly trending shear zone in this domain is spatially associated with sanukitoid and lowCa, Tirich intrusions and has been found to host gold occurrences. The west-northwesterly striking structures of Domain 4 have likely been reused during the intrusion of the west-northwesterly trending c. 1888 Ma Boonadgin Dolerite dykes.

Domain 5: a domain largely dominated by undeformed lowCa, potassic biotite monzogranite, a large area of hornblende-bearing granodiorite and minor highCa (± Na) granite exclusively with low Sr/Y values. This domain is bounded to the east by the CTZ and to the west by Proterozoic shear zones of the Proto-Darling Fault and also includes the Julimar (Ni) and Boddington (Au) deposits (Figs 1, 9). Although unconstrained, the overall metamorphic grade of Domain 5 appears lower than that of the CTZ (i.e. Domain 3); indeed the rock succession at Boddington is at greenschist facies (Wilde and Pidgeon, 1986). We interpret this domain as an upper crustal-level exposure.

Domain 6: this domain is bounded to the west by the Darling Fault and to the south by the Albany–Fraser Orogen. It includes the 'Chittering metamorphic belt', as well as the sedimentary succession around Balingup and hosts REE-bearing pegmatite at Greenbushes (Figs 1, 9). It is mainly characterized by the widespread Proterozoic overprint that produced the numerous major shear zones that dissect this domain, either as north-striking shear zones subparallel to the Darling Fault or as closely spaced, northwest-trending shear zones in the southwest corner of the map area. The Archean metamorphic conditions are unknown and difficult to assess due to the pervasive high-grade Proterozoic overprint along the Darling Fault. This domain contains a larger proportion of sedimentary rocks than any other domain, and also contains a younger 2615–2610 Ma suite of granite.

Rationale for the South West – Youanmi Terrane boundary update

Three significant issues were identified with the previous terrane boundary between the South West and Youanmi Terranes of Cassidy et al. (2006), which:

- cuts geophysical trend lines at a high angle
- does not differentiate between crustal domains with contrasting geological histories
- does not represent a change in lithological assemblages within greenstone belts.

In our new interpretation, the Youanmi Terrane has been extended southwest to include Domain 2 and the CTZ (i.e. Domain 3; Figs 1, 9). The terrane boundary with the South West Terrane is now interpreted to lie along the southwestern deformation front of the northwest-trending Corrigin Tectonic Zone, which, together with Domain 2, are now interpreted to be an upper amphibolite to granulite-facies equivalent to the rest of the Youanmi Terrane. Key variations within many new or updated datasets were used to guide interpretation of the new terrane boundary: Nd and O isotopes, the distribution of igneous crystallization ages, the nature of the greenstone belts, mineralization data, granite geochemistry, structural patterns, deformation style and metamorphic history data. Regarding the metamorphic data, nearly all new pressure and temperature data are from samples within the amphibolite to granulite-facies Youanmi Terrane, but it is clear that there has to be a significant change towards the western portion of the South West Terrane because supracrustal rocks at Boddington have been identified to be at greenschist facies (Wilde and Pidgeon, 1986). Among these datasets, the geochronology of granite and greenstone samples was the one that most clearly differentiated the two terranes. We have identified that Domain 2 is characterized by an anastomosed system of north-northwesterly striking shear zones that collectively form lozenge-shaped patterns that closely resemble those of the central and northern parts of the Youanmi Terrane (Fig. 2). The similar lithological associations and geochronology data between Domain 2 and the rest of the Youanmi Terrane strongly suggests that the lozenge patterns affected similarly aged rocks to those in the rest of the Youanmi Terrane, indicating that they also formed during tectonic events occurring between 2730 and 2665 Ma (Zibra et al., 2017). The lack of lozenge-shaped shear-zone patterns in the South West Terrane marks a strong difference in structural style and suggests that it experienced a different tectonic history. Similarly, the zircon O isotopes also indicate that the South West Terrane and the Youanmi Terrane did not experience the same tectonic history (Lu et al., 2021). The South West Terrane contains zircon dominated by mantle-like $\delta^{18}O$ values (4.7 – 5.9‰), indicating that no significant supracrustal reworking has occurred prior to or during granite generation. By contrast, values from the Youanmi Terrane commonly have $\delta^{18}O$ values greater than 5.9‰, suggesting at least a minor amount of crustal reworking and burial of supracrustal material into the source regions of granites in the amphibolite to granulite-facies portion of the Youanmi Terrane. The highest zircon O isotope values ($\delta^{18}O$ up to 6.9‰) in the whole Yilgarn Craton have been obtained from granitic rocks along the redefined terrane boundary between the South West and the Youanmi Terranes, possibly indicating that maximum burial of supracrustal material has occurred along this boundary. The Sm–Nd two-stage depleted mantle model ($T_{DM}{}^2$) ages across the map area indicate an overall change to younger model ages (3 Ga Nd model ages), which is similar to the Youanmi Terrane (Fig. 12). However, the overall texture of the isotopic map changes to the southwest, where domains of similar age are much smaller. This pattern within the South West Terrane may indicate local Youanmi Terrane-like basement, such as in the area around Boddington, but also a different geological history involving multiple younger juvenile input events, which are not known from the Youanmi Terrane. Magmatic crystallization ages within granitic rocks indicate that >2.8 Ga granitic rocks are restricted to the Youanmi Terrane. Xenocrystic zircons within granitic rocks show that the oldest grains within the South West Terrane are c. 2.8 Ga, whereas 2.9 – 3.1 Ga xenocrystic zircons are widely present in granitic rocks of the Youanmi Terrane. Magmatic crystallization ages constraining the age of deposition and mafic magmatism within greenstones differ across the new terrane boundary. Figure 5 shows that the Youanmi Terrane experienced a distinct, older history of greenstone deposition from 2.7 to 3.1 Ga, compared to 2.7 – 2.4 Ga in the South West Terrane. The c. 2.69 Ga 'McCaskill group' in the Youanmi Terrane is very localized and occurs as very low-volume slivers, whereas the 2704–2670 Ma Saddleback Group in the South West Terrane is more voluminous and protracted, with a higher proportion of volcanic rocks.

The 'Balingup supergroup' has limited geochronological constraints, as follows:

- Metasandstone at Wheatley has an interpreted maximum depositional age of c. 2646 Ma (Sircombe et al., 2007).
- In the far southwest corner of the South West Terrane, a pelitic gneiss has a maximum depositional age of 2597 ± 4 Ma and a single zircon date of 2636 ± 4 Ma (1σ), interpreted as the age of an older detrital zircon (GSWA 198551, Lu et al., 2015b).
- c. 3200 Ma detrital zircons are present in some parts of the stratigraphy (Lu et al., 2016).
- The metasedimentary units to the north are locally cut by a suite of c. 2615 Ma granitic rocks, providing a minimum age constraint.

Thus, while we can say that the 'Balingup supergroup' is different in age (and composition, being very quartzite rich) to anything found in the Youanmi Terrane, further work is required to establish the geological history of the 'Balingup supergroup'. In terms of mafic–ultramafic intrusive rocks, the geological history of the South West Terrane is independent to the Youanmi Terrane until 2615 Ma (Fig. 5). The 'Julimar suite' and 'Red Hill suite' at c. 2665 Ma only intrude units of the South West Terrane. Further work is required to test whether these suites extend across the terrane boundary in the north. If so, they would provide a minimum age for amalgamation of the two terranes. Across the map area, the lithological assemblages within greenstones form distinct, northwest-trending domains

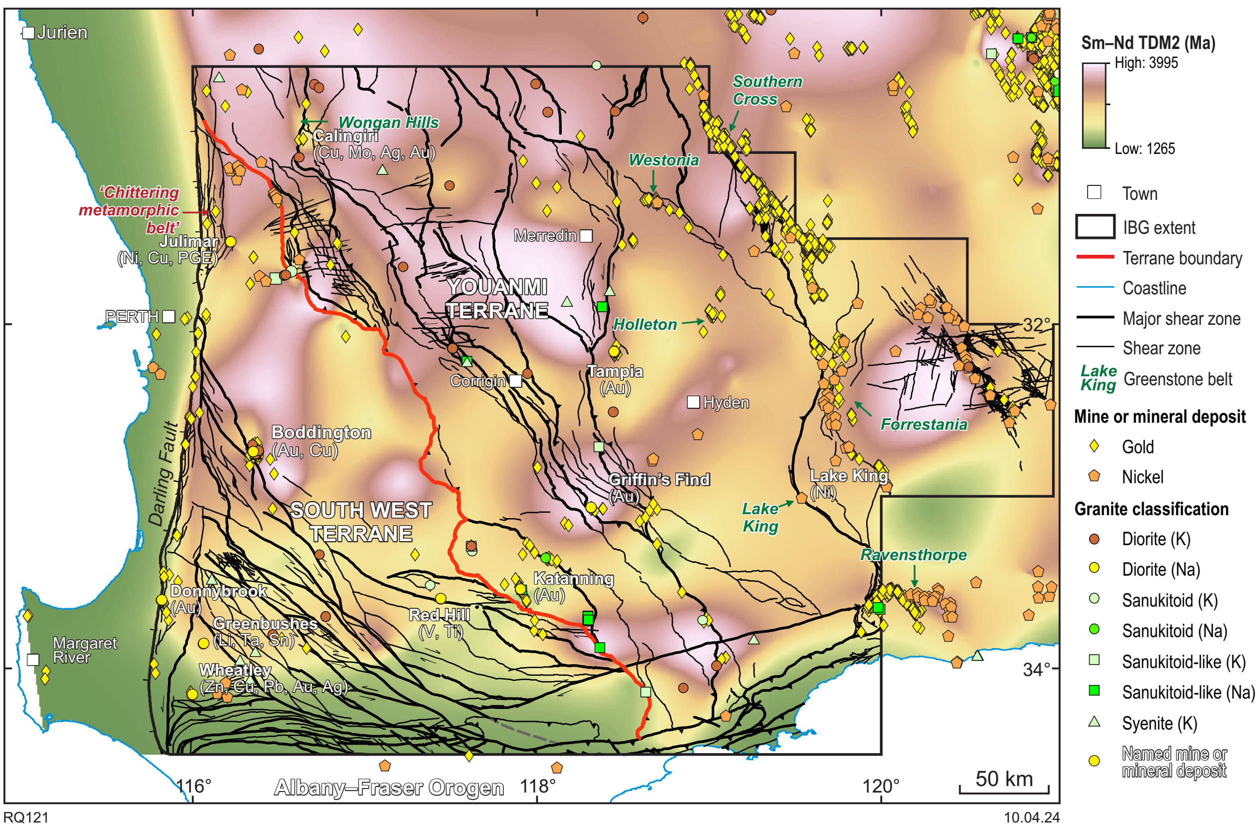

Figure 12. Shear zones, sanukitoid, sanukitoid-like rocks and other mantle-derived felsic rocks, Sm–Nd-isotope map, and gold and nickel occurrences. IBG extent from GSWA (2022)

(see Fig. 7 inset), where the most significant change is located at the new terrane boundary between the South West Terrane and the Youanmi Terrane. Overall, this change towards the southwest includes:

- an increase in quartz-rich metasedimentary rocks, including much more abundant quartzite
- an increase in younger (c. 2665 Ma), mineralized mafic–ultramafic intrusions
- a decrease in mafic volcanic rocks
- a decrease in BIF
- a decrease in granulite-facies rocks, particularly those with a very high thermal gradient (Korhonen et al., 2021).

The revised terrane boundary between the South West Terrane and the Youanmi Terrane is one of the major divisions within the Yilgarn Craton, second only to the Eastern Goldfields and Youanmi Terrane boundary (Ida Fault). Further work is required to understand the tectonic significance of this boundary and to refine its precise location. Nevertheless, such an important feature provides a crustal-scale (and potentially mantle-tapping) feature to explore for mineral deposits, opening up a corridor of exploration search space.

Relationships to mineralization

Unique features of the geological history of the southwest Yilgarn have had profound control on the distribution of mineral systems over time. Below are considerations relating to the focus of this study, which are the main geological features that lie to the west of the Youanmi Shear Zone (i.e. not including the Southern Cross, Forrestania and Ravensthorpe greenstone belts):

1. The terrane boundary between the South West and Youanmi Terranes separates significantly contrasting stratigraphic and magmatic histories of the two terranes along a major crustal boundary. We consider the terrane boundary as a major control on fluid pathways in the period 2670 to 2640 Ma during development of the CTZ, and these pathways were locally very conducive to gold mineralization such as at Katanning.
2. Sanukitoid, sanukitoid-like and syenitic felsic magmatic suites are interpreted to result from incorporation of a hydrous, metasomatized mantle component into the parental magmas and thus represent high connectivity between mantle and crust (Smithies et al., 2018). Thus the distribution of these suites (Fig. 12) is a proxy in time and space of mantle-tapping structures which may otherwise be cryptic in the complexly overprinted structural configuration of the southwest Yilgarn. This distribution correlates with some clusters of gold and a few nickel deposits (Fig. 12).
3. The distribution of the Southern Cross Supergroup with its interpreted geodynamic setting of a long-lived juvenile continental submarine rift (Ivanic et al., 2022) is indicative of an environment conducive to volcanogenic massive sulfide (VMS) deposits. Felsic magmatism at Calingiri (adjacent to the Wongan Hills Formation) hosts significant polymetallic Au–Ag–Cu–Mo mineralization and is dated at c. 2990 Ma (Outhwaite, 2018). BIF is a common component of Southern Cross Supergroup stratigraphy and iron deposits are widespread within the southern Youanmi Terrane. The supergroup forms the likely protoliths to the granulite-facies paragneisses within the CTZ and the recrystallization and fluid migration associated with this high-grade metamorphism may have remobilized existing metalliferous deposits (e.g. Tampia Au).
4. Extensive, thick and homogenous siliciclastic basins are present in the west of the South West Terrane, possibly as a late phase of the ‘Boddington supergroup’ at c. 2670 Ma. These basins are host to locally abundant layered mafic–ultramafic intrusions and are likely a result of a significant extensional event, which allowed juvenile magmas to intrude near surface. Sulfides within some of these sedimentary host rocks of this stratigraphic package were likely conducive to the formation of Ni-sulfide mineralization in the c. 2670 Ma ‘Julimar suite’.
5. Similarly, the ‘Red Hill suite’ (V–Ti rich) has intruded siliciclastic-rich stratigraphic units within the South West Terrane, although these have scarce age constraints and are not assigned to a stratigraphic group.
6. Further work is required to uncover the total extent of the ‘Julimar suite’, as we expect that several intrusive mafic–ultramafic intrusions in a wide area of the South West Terrane may be related. Likewise, further work is required to establish the full extent of the ‘Red Hill suite’, which may occur as sills in a wide area between Katanning and Northam, including the ‘Coates Siding Gabbro’ (Ivanic et al., 2021).
7. The magmatism at Boddington, although showing striking similarities to the Kalgoorlie–Kambalda region (Smithies et al., 2021), is unique in the southwest Yilgarn Craton and we consider it to be a distinct stratigraphic package (in age as well as composition) comprising a higher proportion of intermediate volcanic rocks than anywhere else in the South West Terrane.
8. Significant gold deposits in the southern Youanmi Terrane (west of the Youanmi Shear Zone; e.g. Tampia and Griffins Find) are associated with mafic granulites in the eastern CTZ. These locations correlate with high Sm–Nd isotopic gradients (Fig. 12), which may be heterogenous crustal blocks later affected by large c. 2660 Ma north-trending shear zones as seen further north in the Youanmi Terrane. The interaction of crustal blocks with shear zones may have been conducive to auriferous fluid migration during this earlier phase of deformation, prior to development of the CTZ. Subsequent granulite-facies metamorphism may have acted to concentrate or remobilize gold at c. 2650 Ma.
9. The Darling Fault system has acted as an enhanced hydrothermal pathway for mineralizing fluids at multiple stages. Thus deposits such as Donnybrook (Au) are likely strongly linked to their proximity to the Darling Fault.
10. The differing history of post-2640 Ma granitic rocks in the South West Terrane has resulted in large Krich

plutons in the west of the terrane, which have weathered to produce widespread bauxite deposits. This granitic magmatism also gave rise to the unique Greenbushes Li–Sn–REE deposit which has no clear analogue in other terranes of the Yilgarn Craton.

11. The unknown stratigraphy of the far southwest corner of the South West Terrane hosts the polymetallic Wheatley deposit (Zn, Cu, Pb, Au, Ag). Here, the metasedimentary units hosting mineralization are not exposed, and lack of exposure in this part of the South West Terrane means that lithologies and mineralization are essentially stratigraphically unconstrained.

Work on the evolution of these mineral systems and their relationship to the stratigraphy that controls them is in its early stages and there are numerous possible lines of inquiry open. For example, what is the character of the mantle source regions for Ni, PGE, Au, and Cu systems? What are the ages of felsic magmatic suites associated with Li–Sn–REE pegmatites? What is the age of the stratigraphy hosting VMS or nickel mineralization in the far southwest corner of the South West Terrane? What is the distribution of the 'Julimar suite' and the 'Red Hill suite', and which host-rock stratigraphy do they intrude? Which structural networks control each mineral system, and during which time periods?

Conclusion

The full integration of field observations, geochemistry, geochronology, metamorphic data, Nd, Hf and Oisotopic data, legacy GSWA and company mapping and drillhole information, all captured in a regional-scale interpreted bedrock geology map unified by full coverage, high-resolution, potential field data, permitted a strong and sound reinterpretation of the geological evolution of the southwest Yilgarn Craton. The South West Terrane and the southern Youanmi Terrane, components of the Archean Yilgarn Craton, have been redefined and the major crustal boundary between these terranes is now interpreted to lie about 200 km southwest of its previously interpreted location. The redefined South West – Youanmi Terrane boundary is located along a series of northwest-striking, northeast-dipping structures that separate the high-metamorphic grade southern Youanmi Terrane from the lower-metamorphic grade South West Terrane.

The South West Terrane is now interpreted to expose 2704–2607 Ma rocks evolved from basement components older than c. 2800 Ma and possibly as old as c. 3400 Ma. The terrane is dominated by mostly undeformed biotite-monzogranite and minor migmatite, orthogneiss and mafic intrusions and greenschist to amphibolite-facies, siliciclastic-dominated, supracrustal sequences. The redefined extent of the South West Terrane broadly corresponds with the extent of the large amplitude, long-wavelength gravity anomaly of the southwest corner of the Yilgarn Craton. It is bounded to the south by the western portion of the Paleo to Mesoproterozoic Albany–Fraser Orogen which produced or reactivated a northwest-striking network of major shear zones along which are preserved the 2704–2640 Ma Saddleback greenstone sequence containing the Boddington gold mine, and the Carboniferous to Permian coal-rich sequence of the Collie Subbasin. The South West Terrane is bounded to the west by the north-striking Darling Fault, which separates the Archean Yilgarn Craton from the Paleozoic to Cenozoic Perth Basin. The western margin of the South West Terrane preserves a long, protracted overprinting history of deformation and metamorphic events related to the 1205–1150 Ma Darling Orogeny, the 1095–995 Ma Pinjarra Orogeny and the 780–515 Ma Leeuwin Orogeny during the amalgamation of Gondwana followed by rifting-related deformation during the Mesozoic.

The southern Youanmi Terrane exposes 3018–2630 Ma orthogneiss, migmatite, metamorphosed volcanic-dominated supracrustal rocks and minor relatively undeformed granitic rocks evolved from basement components older than c. 2885 Ma and possibly as old as c. 3513 Ma. Most rocks have been deformed and metamorphosed during a widespread 2665–2635 Ma synmagmatic, granulite-facies event, which reactivated and overprinted 2730–2680 Ma structures and fabrics. The hangingwall of the terrane boundary exposes a 50 to 150 km-wide zone of intense, pervasive, melt-present deformation called the Corrigin Tectonic Zone (CTZ) which corresponds to the highest strained portion of the southern Youanmi Terrane. This zone is thought to have formed in sinistral transpression during broad E–W shortening either during amalgamation of the South West and Youanmi Terranes or during reactivation of a major crustal boundary between them.

This new interpretation of the evolution of this portion of Archean lithosphere and redefinition of the location of a terrane boundary within it present a significantly updated and united geological framework for the southwest Yilgarn. Although further work is required to test and expand this dataset and interpretation of the geological history of the southwest Yilgarn, this work provides a significant leap in geological understanding and can broaden the scope for the exploration of diverse types of mineral deposits.

Part 2: Excursion localities

TJ Ivanic, CE Gill, R Quentin de Gromard and SA Wilde[1]

Introduction

This four-day excursion starts less than an hour's drive from Perth within the South West Terrane of the Yilgarn Craton (Fig. 13). The excursion later moves farther east and traverses the boundary with the Youanmi Terrane and examines rocks within the Corrigin Tectonic Zone (CTZ). Figure 3 shows interpreted seismic features from the east–west geophysical traverse (location shown in Fig. 1) which lies to the northwest of the excursion area outlined in Fig. 13. Part 2 of this guide provides descriptions of each of the excursion localities, and highlights sites of active research as part of collaborations between GSWA, The University of Western Australia and Curtin University.

***Note**: please refrain from hammering at any of the localities, as there are many documented and undocumented Aboriginal heritage sites in the region.*

Localities

Locality 1: Noble Falls migmatite

Coming out of Perth, drive on Guildford Road and the Great Eastern Highway. Turn left onto Morrison Road and keep left onto the Great Northern Highway. After 1.3 km*, turn right onto Toodyay Road. Continue for 27* km *and park at the Noble Falls parking area. Walk down to the riverbed exposures.*

This locality (WAROX site TJISWT220017, MGA 428124E 6484847N) is within the northwestern part of the South West Terrane and lies to the west of subsequent localities except for locality 13 (Fig. 13). Here is a good 3D exposure and a polished riverbed surface (Fig. 14) of migmatitic gneiss and a variety of diverse crosscutting relationships. Migmatitic banded gneiss contains leucosomes indicating an early stage of melting with locally derived melt pathways preserved. Pegmatitic dykes could be migmatitic melt, since they tend to be intruded parallel to the gneissic foliation. There are domains with more diffuse leucosomes and also domains with veins with sharp contacts. The northwest-striking gneissic layering is tightly to isoclinally folded and wraps around boudins of mesocratic mafic layers. At least four generations of crosscutting relationships of veins and shear zones with the gneissic layering can be mapped. Structural measurements are approximately 75/048 for the gneissic layering that is affected by northeast-striking local high-strain zones (75/130) showing apparent sinistral shear sense indicated by the deflection of the gneissic layering and by the weak sigma shape of feldspar phenocrysts. The orientation of the aplitic dykes is 85/292. At this outcrop can be seen multiple orientations of steep, late-stage brittle fractures and a >5 m-wide undeformed Proterozoic mafic dyke trending approximately 060.

This locality is situated in the east of a large, undated and unassigned granitic unit on the 2021 1:100 000 interpreted bedrock geology (IBG) map (Quentin de Gromard et al., 2021), which is mapped as a composite pluton of monzogranite and granitic gneiss. It lies about 10 km southwest of the metasedimentary units of the Toodyay area, which are the focus of the next three localities. The dominant monzogranitic composition of this unit has resulted in a few bauxite and numerous kaolinite and gravel deposits, and also indicates that this exposure at Noble Falls may be a large raft of an older gneissic unit within a later lowCa monzogranitic pluton, likely emplaced at c. 2630 Ma (cf. GSWA 205935 from the adjacent monzogranitic unit, Lu and Wingate, 2018). The abundant supracrustal rocks of the South West Terrane have no definable basement and the lithological units at this locality are a likely candidate for such basement.

Over the last five years, GSWA has amassed >5000 high-quality geochemical analyses of granitic rocks in the Yilgarn Craton (WACHEM database, <www.dmp.wa.gov.au/geochem>), which is a world-class dataset for the study of granitic crustal evolution in the Archean. From the South West Terrane geochemistry data, about 30% of granitic rocks classify as tonalite–trondhjemite–granodiorite (TTG) and most of these are grouped as highCa (Na) lowSr/Y which are not considered true TTGs, with only a few classifying as higher pressure highCa (Na+) highSr/Y TTG (e.g. Smithies et al., 2018). Most monzogranite plutons in the South West Terrane classify as lowCa with a notable absence of lowCa (highTi) (i.e. high-temperature monzogranite) which are abundant in the western Youanmi Terrane.

The Sm–Nd-isotopic model age map of the South West Terrane (Fig. 12) indicates incorporation of an evolved (Paleoarchean) component in some of the adjacent granitic plutons. This is consistent with incorporation of some ancient xenolithic material within Neoarchean magmas of this terrane.

Locality 2: Lovers Lane andalusite

From Locality 1, continue northeast along Toodyay Road for 24.7 km and turn left onto Lovers Lane. Locate the driveway of the first house on the left. As this is private property, make sure you seek permission from the owner before proceeding. Walk to the back of the house onto a small rise with low rocky outcrops (WAROX site RQGSWY000178, MGA 440489E 6504328N).

1 Curtin University

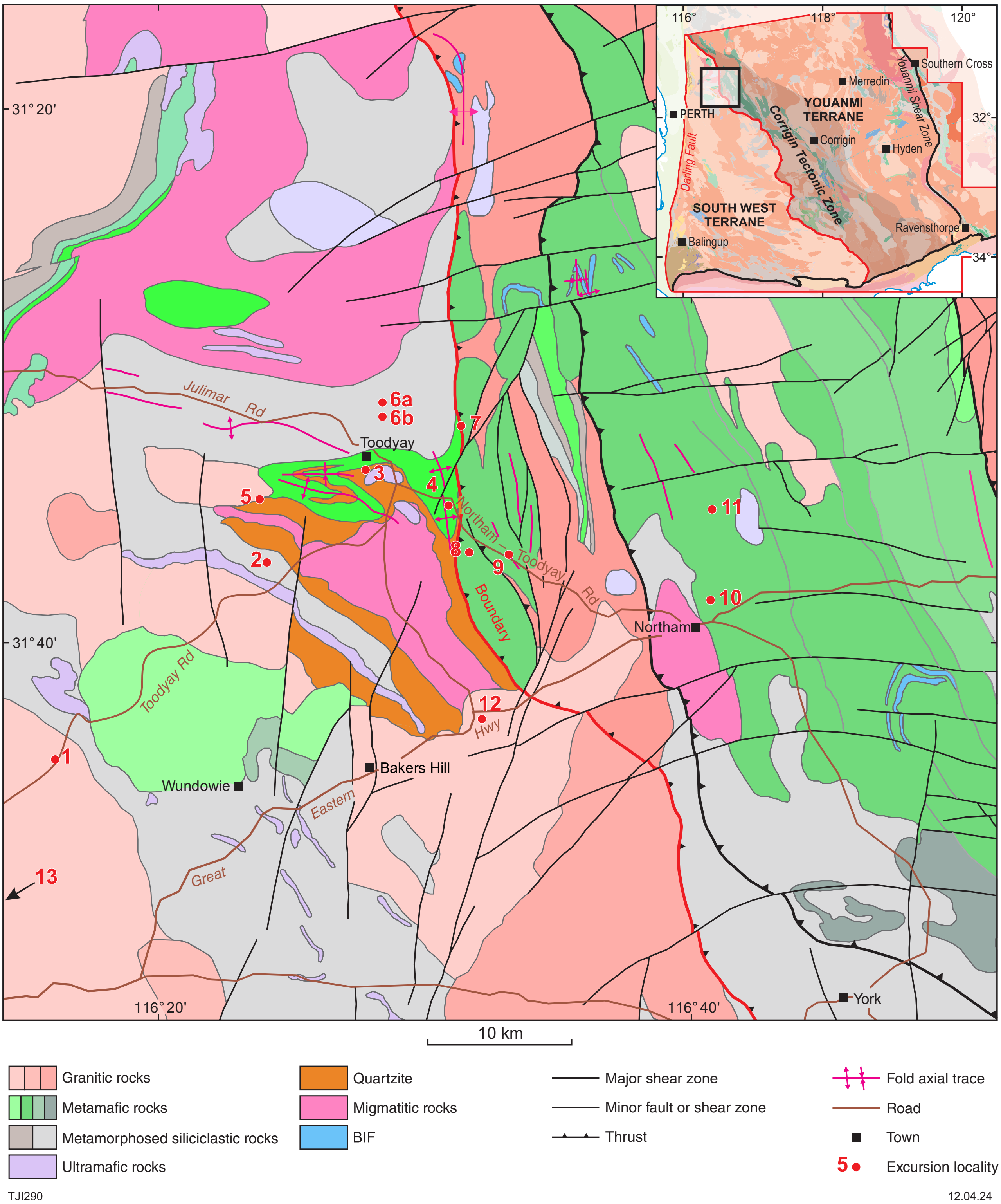

Figure 13. Map of excursion Localities 1–13 in the Toodyay–Northam area of the southwest Yilgarn showing the terrane boundary between the South West and Youanmi Terranes. Basemap is 1:100 000 pre-Mesozoic interpreted bedrock geology (Quentin de Gromard et al., 2021). IBG extent from Quentin de Gromard et al. (2021)

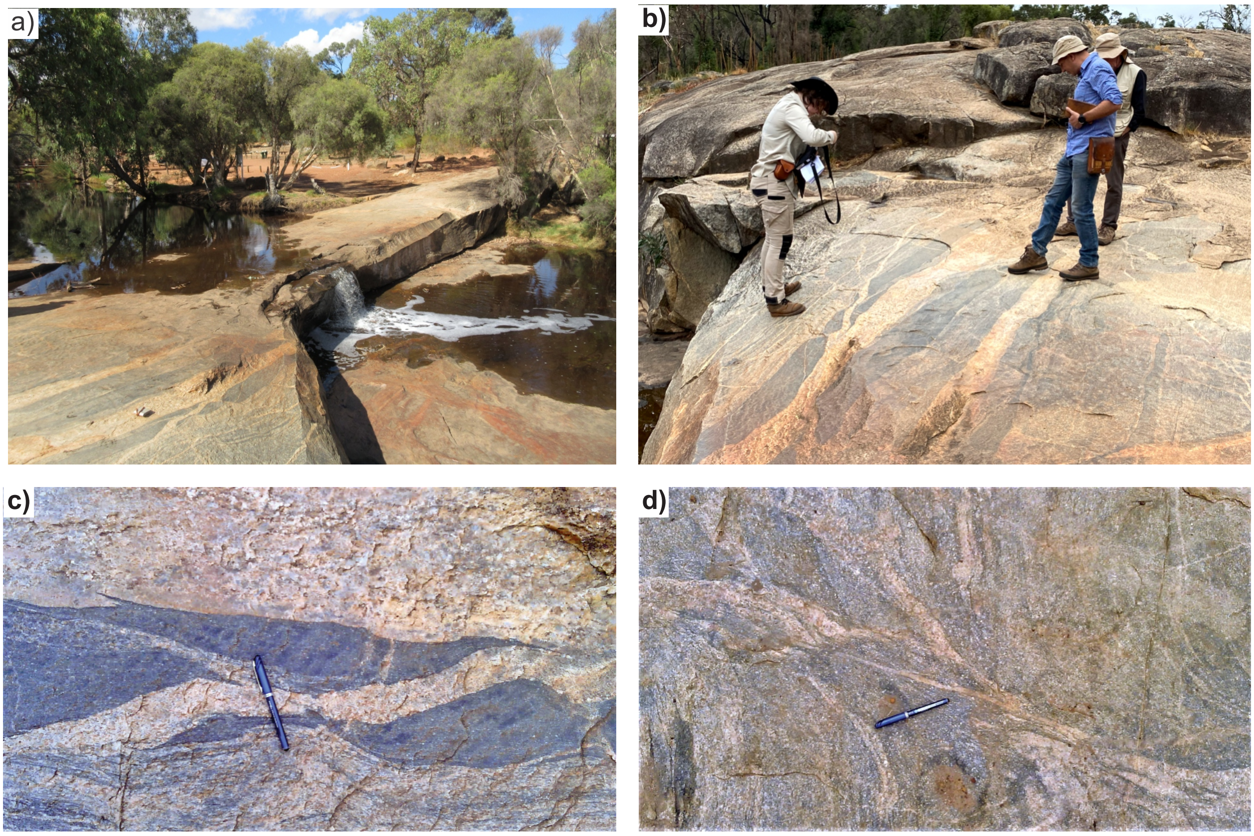

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Figure 14. Locality 1: Noble Falls: a) view over the Noble Falls; b) migmatitic gneiss at the riverbed; c) mesocratic tonalitic boudins within granodiorite to monzogranite gneiss; d) aplitic dyke crosscutting gneissic texture with sinistral shear sense indicators

This locality lies to the west of the main greenstone succession in the Toodyay area and is part of a northwesterly trending supracrustal belt crosscut to the west by granitic rocks. Adjacent rock units are dominantly quartzite and orthogneiss, with this pelitic unit lying between them.

The outcrop here is relatively homogenous and is composed of a strongly foliated, muscovite–andalusite schist (Fig. 15). The rock is composed of large, euhedral bluish andalusite porphyroblasts up to 2 cm in length, set in a reddish matrix rich in muscovite, with quartz and minor magnetite, chlorite and rutile as indicated in the TIMA scan (Fig. 15a). The gently south-dipping foliation (27/195) contains a moderately well-developed southeast-plunging mineral lineation (10/125) defined by the andalusite porphyroblasts. Asymmetrical strain shadows around the porphyroblasts and S–C-like fabric indicate a reverse shear sense.

There is no preserved monazite and the assemblage was deemed too low variance to establish metamorphic conditions other than to say that andalusite records high to moderate thermal gradients and the timing of peak metamorphism was likely similar to other samples in the region at c. 2650 Ma (Korhonen et al., 2021).

Locality 3: Greenstones at Pelham Reserve

From Locality 2, continue along Lovers Lane towards the north and turn right onto River Road, then continue towards Toodyay for about 11 km and arrive at the Pelham Reserve lookout. Park near the water tank on the hill immediately south of Toodyay.

The hills of Pelham Reserve mostly contain outcrops of quartzite, locally fuchsitic, interbedded with pelitic schist containing abundant sericite pseudomorphs probably after kyanite, amphibolite and quartzofeldspathic gneiss (Fig. 16). Of note are distinct and rare (in the South West Terrane), thin horizons of BIF and epidote–grossular-bearing calc-silicate rocks, which may be useful marker horizons in the stratigraphy of the Toodyay region. Way-up has not been determined in this area. The stratigraphy at this site is part of a broad belt of east-trending metasedimentary rocks on the limb of regional-scale tight to isoclinal folds.

Around the water tank is exposed an interbedded sequence of quartzite, schists, amphibolite, possible thin BIF and a prominent blocky outcrop of garnet-bearing calc-silicate rock (WAROX site TJISWT220020, MGA 448956E 6508155N). The large patches of sericite within the schist unit may be retrogressed kyanite porphyroblasts that define an early foliation (S1) affected by northwest-striking crenulation cleavages (S2) that are axial planes to the regional F2 refolding of the earlier east-striking F1 overturned folds.

At the top of the hill are two BIF units interlayered with ferruginous schist and local garnet-bearing psammitic

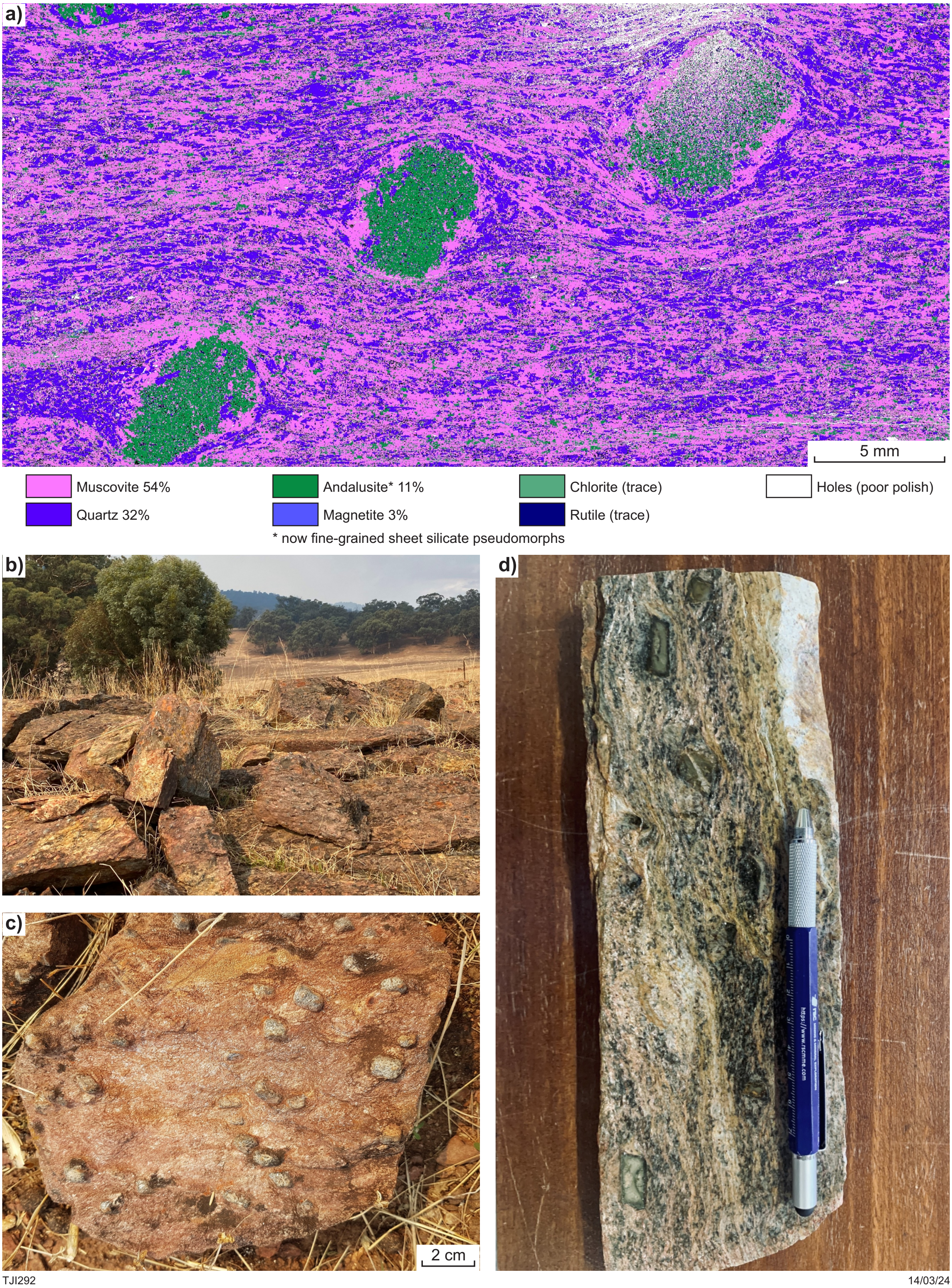

Figure 15. Locality 2: Lovers Lane: a) TESCAN Integrated Mineral Analyser (TIMA) image of an entire thin section from GSWA sample 242911A: andalusite schist, Lovers Lane. Volume percent proportion of major rock-forming minerals are calculated by the TIMA software; b) blocky exposures of andalusite schist; c) andalusite schist showing bluish-grey andalusite porphyroblasts up to 2 cm in size; d) sanded and polished slab of andalusite schist showing characteristic Xshape in the cross-section of the grains

rocks. Minor folds within the BIF indicate a moderately plunging hinge to the east (Fig. 16a). The BIF has been metamorphosed at upper amphibolite grade and is composed of quartz–magnetite–grunerite–orthopyroxene.

Follow the 4WD track behind the water tanks to the southwest and, after about 500 m, take the track on the right side where the track splits into three. This leads to a creek which winds its way down the hill below the lookout for another approximately 500 m.

In the creek bed, the same interbedded quartzite, psammitic and pelitic schists at the water tank can be observed outcropping. At the bottom of the waterfall, the monzogranite is intruded into a glomeroporphyritic metabasalt (Fig. 16b), the contact between which was subsequently sheared. Within gneissic monzogranite, rafts of migmatitic grey gneiss can be observed (Fig. 16c). In granitic veins intruding the metasedimentary rocks, fold interference patterns that define two generations of folding can be observed where bedding-parallel isoclinal folds are refolded by southeast-plunging tight folds (Fig. 16d), which locally contain garnet (Fig. 16e). Further down the track, the creek bed expands to become a waterfall and the metasedimentary rocks are intruded by a gneissic monzogranite.

Quartzite units along strike from here have been the target of several geochronological investigations (Fig. 16g). Results within 15 km of this site include five GSWA samples yielding maximum depositional ages of:

- 2669 ± 2 Ma (GSWA 248205, Wingate et al., 2022) at Julimar, eastern part of the ‘Chittering metamorphic belt’
- 3203 ± 29 Ma (GSWA 177901, Wingate et al., 2008a) 5 km southwest of Toodyay
- 3005 ± 26 Ma (GSWA 177904, Wingate et al., 2008b) at Windmill Hill cutting
- 3068 ± 6 Ma (GSWA 177907, Wingate et al., 2008c) at Noondeening Hill
- c. 2976 Ma (GSWA 198507, Lu et al., 2015a; reinterpreted by Blereau et al., 2022) at Mount Dick, Youanmi Terrane

Maximum depositional ages at c. 3000 Ma likely represent derivation from Southern Cross Supergroup and Thundelarra Supersuite magmatism in the Youanmi Terrane (Ivanic et al., 2022) since there is no known magmatism of this age within the newly defined South West Terrane. The older 3203 Ma age component is compatible with Youanmi Terrane-wide detrital and xenocrystic ages, although the 2669 Ma age (with a minimum age constraint provided by a crosscutting monzogranite of c. 2663 Ma; GSWA 248207, Wingate et al., 2021d) is distinctly younger and may indicate a significantly different stratigraphic package in terms of age and the eroding source units in these siliciclastic sedimentary precursors west of Toodyay.

Greenstones at Morangup (between Localities 1 and 2) are extremely poorly exposed and not visited on this excursion. However, it is worth mentioning that these greenstones are the only local examples of volcanic supracrustal rocks in the South West Terrane. Wilde (2001) notes that these rocks closely resemble those in the Saddleback Group at Boddington, with both sequences being metamorphosed to greenschist facies. Wilde (2001) describes them as follows: ‘Fine-grained, blue-grey metabasalt with a brown weathering rind. The rock consists of tremolite–actinolite, albite, and epidote, with accessory opaque oxides and titanite. The texture is variable, ranging from static (relict igneous) to more dynamic with strongly aligned blades of amphibole. Most amphibole laths are ragged and show acicular growth into neighboring epidote. The opaque oxides and titanite are present as small granules preferentially associated with tremolite–actinolite. Where relict igneous textures are preserved, granular epidote pseudomorphs the original plagioclase.’

Locality 4: Greenstones at the Windmill Hill rail cutting

Adapted from Wilde (2001).

From Toodyay Road, drive to the parking area past the village of Dumbarton, 4 km *east along the Northam–Toodyay Road.*

***Note**: this area is along railway tracks and dangerous. The locality is registered as both a State Geoheritage Site managed by GSWA, and a Municipal Heritage Site managed by the Shire of Toodyay. Due to its historical and scientific significance, care should be taken to not damage the outcrops, and no rocks should be removed from the locality.*

The locality is within the eastern limb of an interpreted isoclinal fold (Fig. 13) with a north-striking axial trace, and closes to the south. This fold is interpreted to have formed as a result of deformation along the terrane boundary during thrusting of the Youanmi Terrane over the South West Terrane.

Walk south of the tracks to a site (MGA 453971E 6506500N) where there is a view of lithologies within the cutting including quartzite, quartz-mica schist, and metadolerite, with granitic rocks out of sight to the west. This is a strongly weathered sequence of schist, gneiss and amphibolite, which passes westward into quartzite with a foliation oriented 170/335. The quartzite consists of alternating flaggy and more massive units, with foliation surfaces sparsely coated with fuchsite. There are some thicker layers up to 1 cm wide composed largely of fuchsite with minor sillimanite. Continuing westward, a 35 m-thick unit of well-foliated amphibolite (WAROX site north of the tracks is TJISWT220019, MGA 453971E 6506528N) is concordant within the quartzites. This rock is composed of a xenoblastic aggregate of calcic plagioclase and hornblende, with some quartz and biotite (showing chlorite alteration) and may be a Neoarchean sill of mafic–ultramafic layered cumulates.

Farther west, the quartzite is more flaggy and has a prominent lineation. There are some transgressive quartz and pegmatite veins, many of which are subhorizontal. Some excellent examples of cross-bedding are preserved in the quartzite (Fig. 17b) close to where the cutting is widest and these indicate that the sequence is right way up to the east. Thus the isoclinal fold is interpreted to be an anticline with a steeply plunging hinge.

An extensively weathered ultramafic intrusion, approximately 15 m wide, is present to the west. This rock is particularly

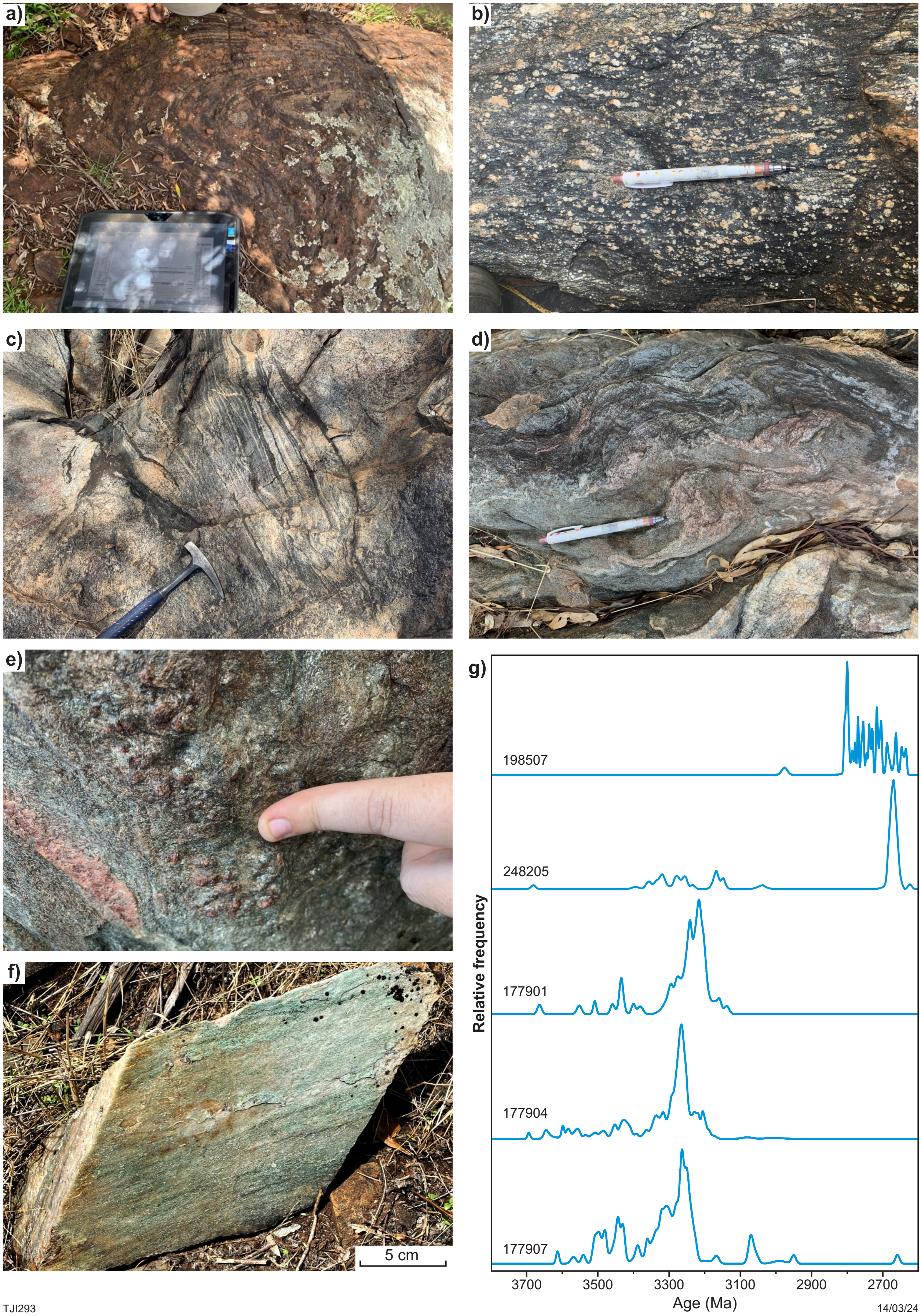

Figure 16. Locality 3: Pelham Reserve: a) close folding in the BIF behind the lookout (tablet is 30 cm across); b) mylonitic migmatite showing mafic restite and deformational fabric; c) migmatite xenolith in the monzonitic granite; d) refolded granitic veins in a biotite schist; e) garnets in the biotite schist in the creek bed below the lookout; f) fuchsitic quartzite block from 500 m west of the main section in this locality; g) probability density plots for detrital zircon age data from the five geochronology samples discussed in the text

Figure 17. Locality 4: Windmill Hill: a) overview looking northwest showing yellow-orange altered micaceous metasedimentary rocks in the cutting; b) cross-bedded quartzite right way up, looking east; c) U–Pb analytical data for zircons from GSWA sample 177904: quartzite, Windmill Hill. Blue square indicates Group 1 (youngest detrital zircon); yellow squares denote Group 2 (older detrital zircons); crossed squares denote ungrouped analyses (discordance >5% or ƒ204 >1%)

unstable and collapsed during construction of the cutting. A subvertical dolerite dyke cuts the quartzites to the west and is unmetamorphosed. At the extreme western end, granitic gneiss is faulted against the quartzite.

Fifty individual zircons were analysed using the SHRIMP (Sensitive High-Resolution Ion Microprobe) method from a sample of fuchsitic quartzite collected from the northern side of this railway cutting. Zircons from this unit had previously been studied by Nieuwland and Compston (1981) using multigrain techniques. From analyses of four grain-size fractions, they obtained a discordia line with an upper intercept age of 3341 Ma. They interpreted the good alignment of the analyses on the concordia diagram as indicating that the range in ages of rocks in the source area was rather small. However, it is clear from the ion microprobe analyses that the provenance ages span at least 550 Ma and a heterogeneous provenance for the quartzite is indicated. Two-thirds of the detrital zircon populations have $^{207}Pb/^{206}Pb$ ages in the range 3350 to 3200 Ma (median 3270 Ma), whereas the remaining one-third are older, having $^{207}Pb/^{206}Pb$ ages up to 3500 Ma. Additionally, one grain yielded an age of 3735 ± 10 Ma (2σ).

The youngest concordant analysis of lowU zircon thus provides an upper limit to the time of deposition of the quartzite at 3177 ± 15 Ma (2σ). Compare these results to Figure 17c, which shows a concordia plot for GSWA 177904 from a quartzite at this locality (Wingate et al., 2008b). If the above interpretation is correct, this sequence would be much older than the c. 2670 Ma stratigraphy at Boddington or Julimar to the south and west, respectively. However, younger maximum depositional ages have been interpreted in nearby quartzites (see discussion in Locality 3), bringing this potentially older depositional age into question.

Locality 5: Quartzite succession at Poison Creek

From Toodyay, drive out of town to the west-southwest along Folewood Road. After 9 km, at a Tjunction, turn left onto River Road. Drive west for 3.3 km and turn right onto the layby at the railway crossing and park. Walk across River Road to the south and proceed on paths at the edge of fields up Poison Creek to rocky outcrops (MGA 442214E 6505756N). The locality has several points of interest within a 400 × 300 m, north-facing hillside, including a steep waterfall area.

The area was first mapped and described by Prider (1934). The exposed rocks consist of a sequence of quartzites and granodioritic orthogneisses. Within the quartzites are thin schistose units, some of which contain abundant sillimanite. There are also thin layers of banded amphibolite. Several Proterozoic dolerite dykes transect the stratigraphy (e.g. at WAROX site TJISWT220036, MGA 442130E 6505730N). The main part of this locality is a gully which feeds the Avon River. Along this gully are near-continuous exposures of the quartzite intruded by the orthogneiss, with sporadic exposures of pelite.

Initial work in 2022 on a collaborative PhD project between The University of Western Australia and GSWA identified a previously undiscovered unconformity in this succession, which is well preserved at the waterfall, Locality 5.2.

Locality 5.1: Isoclinal folds within quartzite (bottom of valley)

Figure 18 (ad) is a set of photographs that shows examples of sedimentary and deformation structures within the quartzite at the base of the section. These features have been picked out by the development of fuchsite along the fabric, as well as by remnants of heavy mineral layers within the quartzite. However, as both intrafolial, syndepositional folds and tectonic folds are present in the quartzite beds at the Poison Creek locality (e.g. Fig. 18a), careful observations are needed to infer regional-scale deformation history.

Locality 5.2: Unconformity at the waterfall (midway up the hill and upstream from previous locality)

At the waterfall (WAROX site CEGSWT000012, MGA 442266E 6505721N) there is an overturned angular unconformity between quartzite and a finer grained metasedimentary rock. Here, bedding in the quartzite (S0) is truncated by fine-grained metasedimentary rocks (Fig. 18c), indicating that the sequence is overturned, and there are apparent graded bedding and scours at the contact which also indicate an overturned sequence. The metasedimentary rock contains lenses of coarser grained material which have been folded isoclinally. Both lithologies contain trace amounts of sillimanite.

Locality 5.3: Intrusion of gneissic granodiorite into quartzite (midway up the hill and top of the hill)

The orthogneiss intruding the quartzite is medium to coarse grained with particularly strong strain partitioning which affects the grain size (Fig. 18b). An anastomosing shear pattern is visible on both the centimetre scale, where shear bands wrap around individual feldspar grains, and the tens of metres scale, where bands of intensely deformed gneiss with strong S–C fabrics enclose less deformed, boudin-shaped lenses of the same lithology. This fabric is interpreted to represent S1 and is subparallel to S0. A mineral lineation is observed on both the orthogneiss and quartzite around the Poison Creek area and is particularly strong on the planar surfaces of the quartzite. It trends parallel to strike and is subhorizontal, making it difficult to tell which way is the true azimuth.

The contact between the orthogneiss and the quartzite is irregular and consistent with an intrusive relationship between the protoliths. Veins of granitic material extend down into the quartzite, crosscutting the bedding. The main body of the orthogneiss is subparallel to the quartzite and the original granite appears to have intruded as sills, all prior to the isoclinal folding event.

On the northern side of the hills forming the gully which face the Avon River, relict cross-bedding can still be observed within the quartzite and the relationships between units remains the same. However, the facing direction is different, with the stratigraphy being the correct way up while the dip and dip direction remain the same (Fig. 18d).

Locality 6A: Metatexitic migmatitic rocks at Coondle Reserve

From Locality 5, drive back towards Toodyay on River Road, then take the Bindi Bindi – Toodyay Road towards the north, crossing the Avon River. Continue for 9 km and turn right onto Coondle Reserve Road. Park 2.2 km along the road and walk to exposure in the creek.

A well-exposed pavement within a creek bed shows a metatexitic migmatite within the Coondle Reserve (WAROX site CEGSWT000118, MGA 448224E 6517466N). The protolith is a tonalitic to granodioritic gneiss with leucosomes along the layering and containing boudinaged amphibolite layers that have partially melted edges and local zones of preserved pyroxenitic restite (Fig. 19a). The isoclinally folded gneissic layering (Fig. 19b) is northeast-striking (60/120) and asymmetric boudins of amphibolite layers show both apparent dextral and sinistral shear sense; however, the asymmetry shown by the isoclinal folds suggests apparent dextral shear sense. At least three different generations of crosscutting shear zones are evident, with possibly more present. The gneissic fabric is affected by conjugate sets of leucosome-infilled east-northeasterly striking dextral shear zones, subsequently affected by a southeast-striking dextral fault at a high angle to the gneissic fabric. This was followed by the intrusion of a 10 cm-wide mafic dyke, and granitic melt was later intruded into the dextral fault. The leucosome-infilled east-northeasterly striking dextral shear was then reactivated to truncate the dextral fault and was accompanied by epidote veining (Fig. 19c, d).

Locality 6B: Diatexitic migmatitic rocks at Balgaling Reserve

Balgaling Reserve is a few kilometres' drive to the south of Coondle Reserve.

At Balgaling Reserve (WAROX site CEGSWT000121, MGA 447432E 6516239N) there is an extensive outcrop of

Figure 18. Locality 5: Poison Creek: a) isoclinally folded quartzite at the base of the valley, looking south (tablet is 30 cm across); b) granodiorite intrusion; c) angular overturned unconformity between older quartzite and greywacke at the waterfall locality; d) cross-bedding over the hill from the Poison Creek locality, showing right-way-up stratigraphy

diatexitic migmatitic pavements around a waterfall. These are part of a large granitic gneiss unit mapped to the north of Toodyay and away from the effects of the CTZ. Here there are strongly deformed and partially melted orthogneisses containing folded, dismembered, locally rotated, amphibolite and pyroxenite boudins, ranging from a few cm to 1 m in size, in a non-coherent migmatite (Fig. 19e). Local abundant epidote alteration seems to overprint a fuchsite or copper alteration (Fig. 19f). The isoclinally folded gneissic layering dips steeply towards the north, and the 3D nature of this exposure suggests that the apparent dextral shear zones exposed at the Coondle Reserve have a top-to-the-southwest shear sense component.

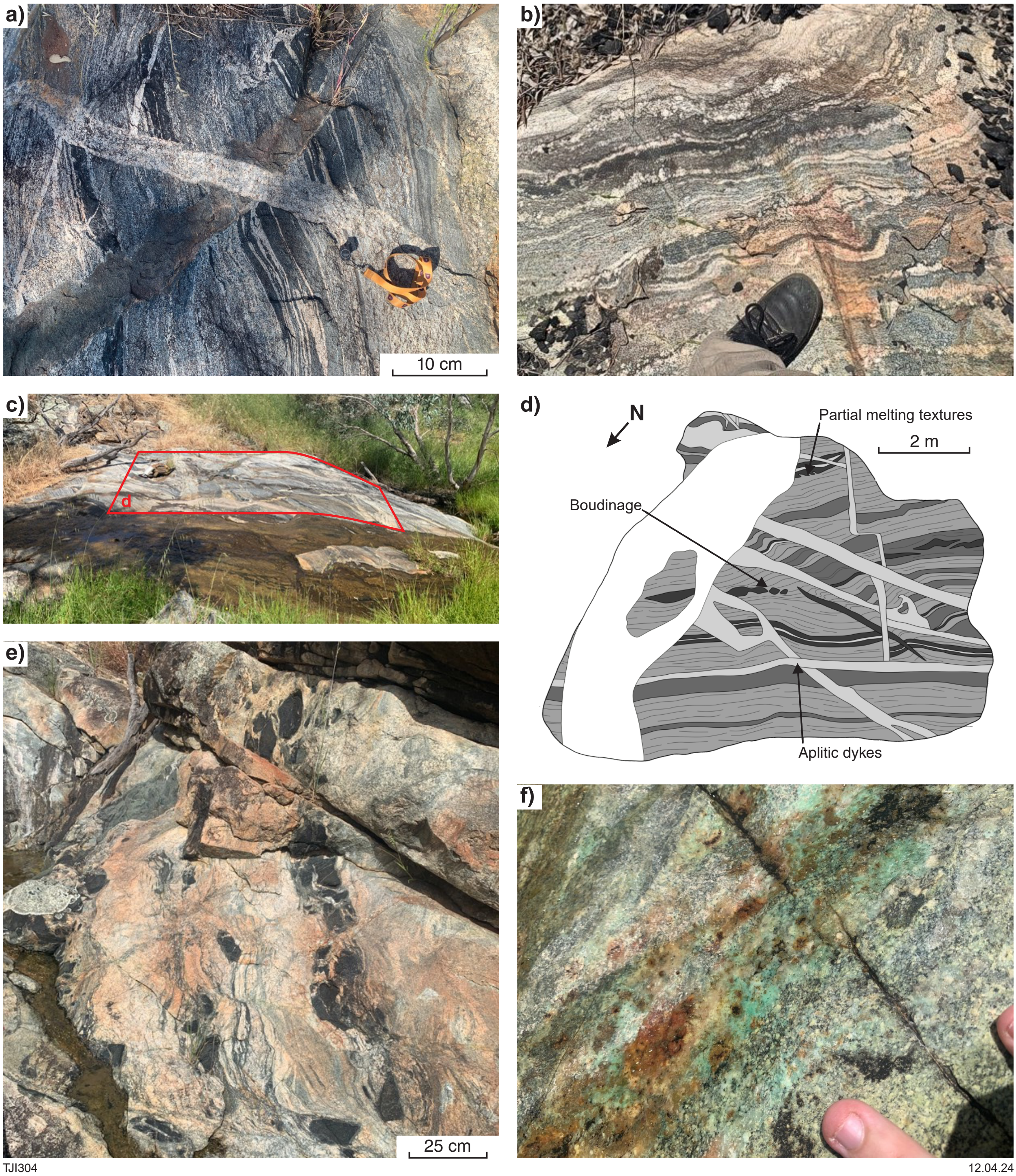

Figure 19. Localities 6A and 6B: Coondle and Balgaling Reserves: a) crosscutting relationships in the migmatitic gneiss, looking south; b) gneissic foliation in the migmatitic gneiss; c) migmatite outcrop in Coondle Reserve and (d) the outcrop map derived from it; e) amphibolitic xenoliths in migmatite, locally with pyroxene-rich cores; f) unidentified green mineral that appears similar to fuchsite

Locality 7: Mylonite along the terrane boundary at the Nunile Road turn-off

From Toodyay take the Goomalling–Toodyay Road across the Avon River to the north for 5.8 km*. Turn left onto Nunile Road and park immediately at the intersection. Walk west over the fence and about 50 m along the creek bed exposures to WAROX site TJISWT220034 (MGA 454474E 6512429N).*

This locality has good, extensive creek exposures of mylonitic, migmatitic granodiorite to tonalite gneiss with abundant amphibolite boudins along the new terrane boundary. It is located about 10 km north of other localities, which form a transect close to the Northam–Toodyay Road.

Proceed to WAROX site CEGSWT000031 (MGA 454511E 6512502N) where there is a mylonitic granitic gneiss with large feldspar porphyroblasts, as well as large migmatitic boudins (Fig. 20) similar to those at Locality 10 (near Northam on the Great Eastern Highway). Rafts of large, older, more mafic blocks occur in a granitic matrix, and all have undergone partial melting. The edges of these rafts are sheared into the dominant deformational fabric of the host metagranitic rock. In this area there is a pronounced stretching lineation along which reverse, top-to-the-west sense of movement is evident consistent with the alignment of pyroxenes, feldspars and quartz. Walk for about 200 m west along the outcrop where there is an olivine websterite and a 10 mwide Proterozoic dyke.

Locality 8: Mafic–ultramafic intrusions and migmatite at Masters sheep farm

From the junction near Toodyay, drive east on the Northam–Toodyay Road for 8.6 km *and call in at the Glenavon Homestead. Proceed with permission by crossing directly over the main road to the south, take a track to the south-southwest and take the first left through a gate along another track to the area around WAROX site TJISWT220025 (MGA 455591E 6501758N).*

Here are several hillslopes of outcrop and sporadic blocky rock exposures of mafic–ultramafic intrusive lithologies and, to the north, these are intruded by migmatitic metatonalite. The location is in a transitional zone, about 10 km away from the South West – Youanmi Terrane boundary where rocks are starting to be affected by reactivation along the northwesterly trend of the CTZ (Fig. 13).

At this site, within a >100 m radius, there is coarse, weakly foliated, amphibolitic metagabbro and local metapyroxenite. There are loose blocks of layered metagabbro, all likely part of a layered intrusion. Metagabbro commonly shows wispy, 5 cm long patches of tonalitic melt (Fig. 21b) and crosscutting granitic veins. About 100 m to the east is the start of large area of tonalitic gneiss with 5 mm-layering of biotite-rich and plagioclase-rich horizons. The tonalitic gneiss could be fractionated from metagabbro or it could be a TTG pluton which hosts the gabbroic rocks.

Along the fence line towards the crest of the hill is amphibolitic metagabbro with undeformed leucogranite–monzogranite to the northwest. A very fresh and locally well-exposed Proterozoic dolerite dyke is also present adjacent to the fence-line track which is about 10 m wide and trends about 300.

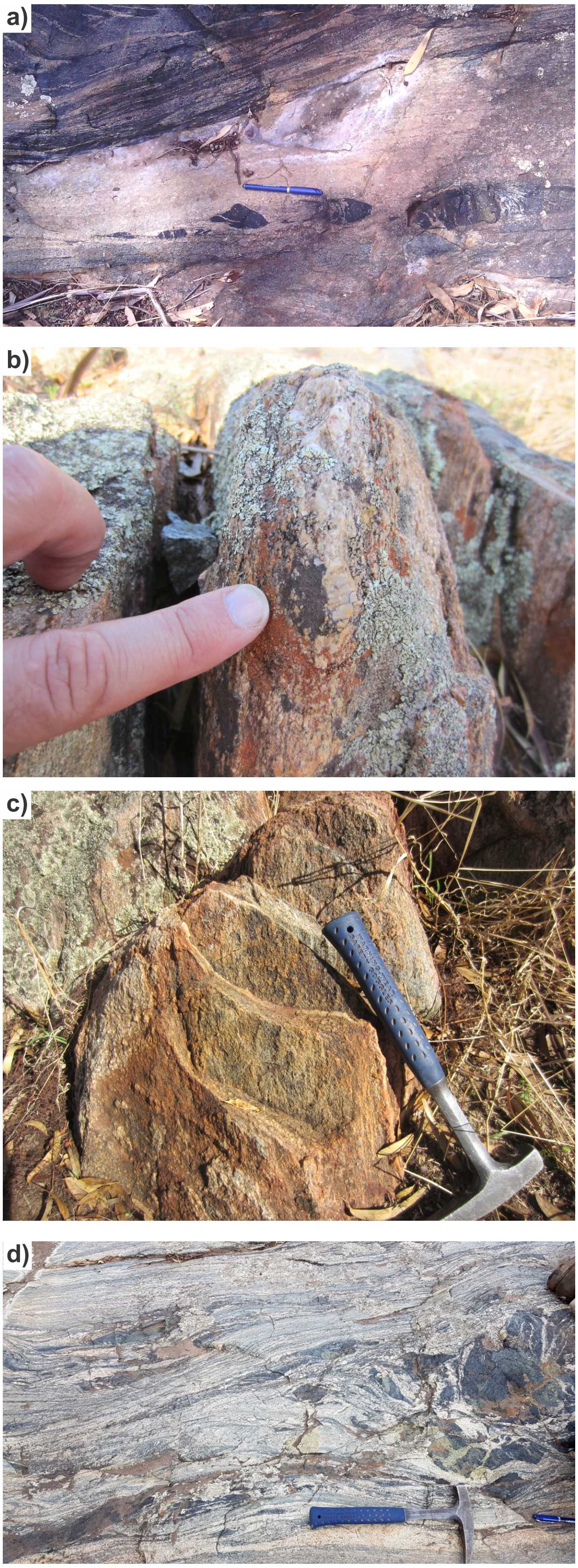

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Figure 20. Locality 7: Nunile Road intersection: a) amphibolitic boudins in migmatitic granodiorite gneiss at the riverbed; b) a sigma porphyroclast in granodiorite gneiss; c) steeply dipping linear fabric in granodiorite gneiss; d) amphibolitic boudins in migmatitic granodiorite

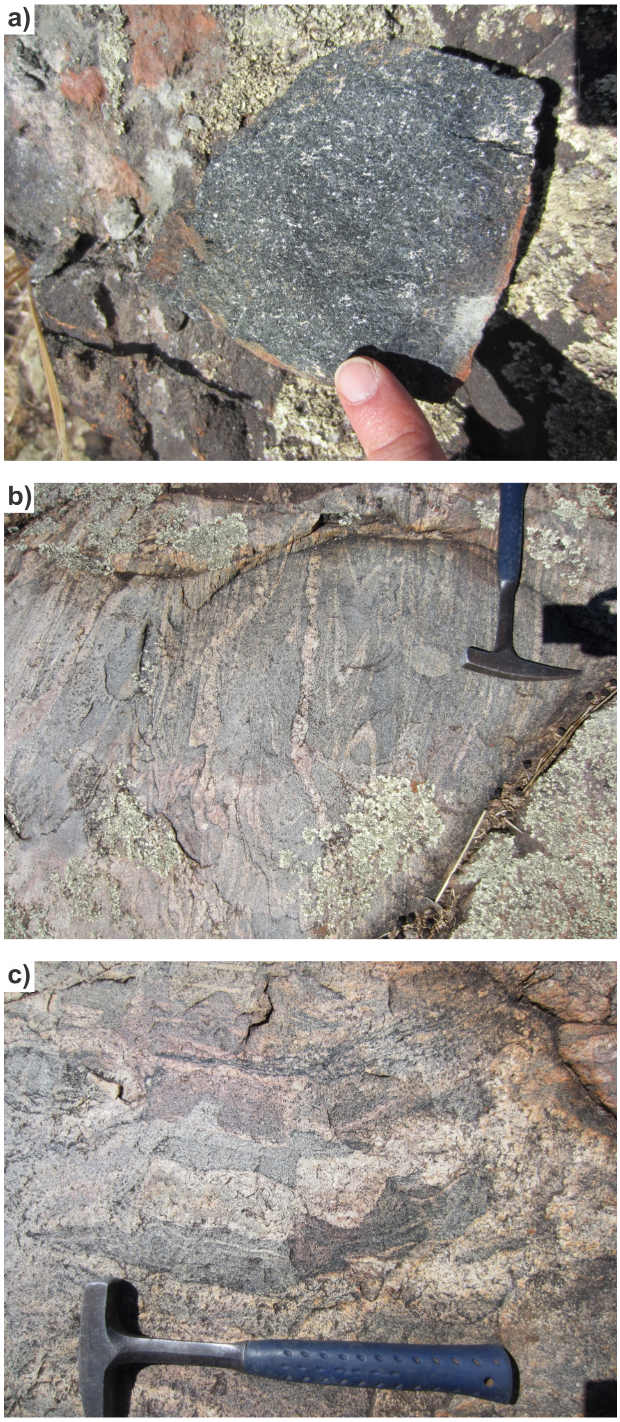

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Figure 21. Locality 8: Masters Farm: a) metagabbro; b) migmatitic metatonalite; c) melt-present sinistral offset of migmatitic layers in metatonalite

Further north, on top of a hill there is a pavement exposure of stromatic, steeply dipping migmatitic orthogneiss (Fig. 21c) with near vertical isoclinal fold axes (WAROX site TJISWT000022, MGA 456054E 6502369N).

Peridotites, pyroxenites and gabbroic rocks and mafic granulites in the region have 8–30 wt% MgO, 140–1540 ppm Ni, 300–2700 ppm Cr, whereas a dunite from Mount Dick (near Locality 11) has 37.7 wt% MgO, 2280 ppm Ni, 6220 ppm Cr (WACHEM database, <www.dmp.wa.gov.au/ geochem>).

Ivanic et al. (2021) classify mafic–ultramafic intrusive rocks of the southwest Yilgarn into several informal suites, including the 2668 Ma 'Julimar suite' which has a high proportion of ultramafic lithologies and is highly mineralized in Ni–Cu–PGE. Also dated within error at c. 2665 Ma is the Fe–Ti–V-rich 'Red Hill suite' which includes the nearby 'Coates Siding Gabbro' (Wilde et al., 1996). All dated mafic–ultramafic intrusive suites in the Youanmi Terrane are >2710 Ma.

We are working towards a better coverage of the geochemistry and geochronology of mafic–ultramafic intrusions in this part of the South West Terrane and may be able to assign suites to the rocks at this locality in the future. Current exploration drilling programs are targeting these lithologies with a view to expanding the known occurrences of Julimar-like deposits into the wider South West Terrane and terrane boundary regions.

It is difficult to obtain magmatic crystallization ages from mafic–ultramafic rocks in general due to the low Zr content and therefore there is a paucity of primary magmatic zircons in samples from these rocks. In some cases it has been possible to obtain maximum depositional ages from host metasedimentary rocks (or xenocrystic zircons in gabbroic rocks) and minimum ages from either metamorphic overgrowths on zircon rims, or crosscutting granitic plutons. It is only through long-lived geoscience programs in these terranes and collaborations with industry and academia that such work is possible.

Locality 9: Syenite at Katrine

Drive east from Toodyay and turn left onto the Northam–Toodyay Road. Proceed east 10.4 km *and turn left onto Katrine Road. After 200 m, turn left into St Saviour's Anglican Church parking area. Walk north about 100 m to WAROX site TJISWT220035 (MGA 458105E 6502196N).*

The 'Katrine syenite' (Wilde, 2001) consists of syenitic to monzogranitic rocks with variable modal quartz content (Fig. 22). The more syenitic rocks contain slightly bluish, likely sodic amphibole. These rocks are foliated in some areas with local primary magmatic layering and a local schistose solid-state overprint. There are very heterogeneous exposures in these low hills which show large variations in foliations, grain size and mineralogy.

The locality is about 3.5 km east of the terrane boundary and aeromagnetic images reveal a north-northwesterly trend of lineaments, indicating that most Archean geological units have been transposed by deformational events within the CTZ.

Lowrey et al. (2023) classified >5000 granitic rocks of the Yilgarn Craton into geochemical suites. These authors show that syenites are a particularly useful suite in that they indicate a significant mantle-derived component in their source magmas. Thus, the distribution of syenites, diorites, monzonites and sanukitoids (Fig. 12) delineate structurally controlled trends in particular regions of the Yilgarn Craton that are often associated with crustal-scale, mantle-tapping structures. It is possible that more syenitic intrusions lie along strike of this one in a northwesterly orientation in proximity to the mapped terrane boundary, continuing as far as Katanning where there are several known sanukitoid-suite intrusions.

Figure 22. Locality 9: 'Katrine syenite': a) coarse Kfeldspar cumulate layer (lower half of image) in 6–8 mm grain size syenite (upper half of image); b) metasyenite with planar deformational horizons showing higher degrees of recrystallization and locally reduced grain size

Locality 10: The Corrigin Tectonic Zone at Posselts Cutting

Drive east on Northam–Toodyay Road, past Northam, and on the Great Eastern Highway park at the junction on the south side of the road (MGA 468022E 6501071N), which is 100 m northeast of the Irishtown Road junction. Walk 500 m northeast along the southern side of the highway to the start of the roadcut (WAROX site TJISWT220029, MGA 474100E 6499868N).

Note*: take extra care on the side of the Great Eastern Highway and wear highvis clothing.*

This locality is an excellent section through rocks just 13.5 km to the east of the interpreted South West – Youanmi Terrane boundary and consists of tonalitic migmatite and meta-mafic–ultramafic intrusive rock rafts in dated metagranodiorite (Fig. 23a) that are cut by various dykes. Here is evidence for thrust tectonics developed on the hangingwall of the terrane boundary with rocks of the Youanmi Terrane thrust onto the South West Terrane in a southwesterly direction.

This spectacular roadcut outcrop exposes a large mylonitic shear zone developed in metatexitic tonalitic to granodioritic gneiss (Fig. 23b) forming the country rock containing sheared, boudinaged and folded lenses of older material, including diatexitic biotite-rich orthogneiss, interlayered mafic–ultramafic greenstones, and garnet–biotite pelite (Fig. 23c). Leucosomes and veins in the diatexitic orthogneiss lens do not extend into the host granodiorite, which indicate that this diatexitic migmatitic unit was incorporated as a coherent block into this melange. The overall shear sense is top to the west along gently east-dipping shear zones.

Proceed east to WAROX site TJISWT220029 (MGA 468375E 6501461N), where the tonalitic to granodioritic gneiss is intruded by a conspicuous 40 cmthick, horizontal mafic dyke (Fig. 23d). This dyke is recrystallized and has a rounded-raft texture composed of segregated tonalitic matrix (about 20%) with rounded blocks of pyroxene hornfels (possible restite material), possibly showing a transition from metatexitic to diatexitic texture, or alternatively, a magma-mingling texture. Also visible at this site is a steep dolerite dyke cutting the horizontal dyke, a pale green moderately dipping dyke and garnet-bearing migmatitic rocks. The whole area is further intruded by numerous generations of crosscutting felsic dykes and pegmatites.

Sample GSWA 224426 of metatonalite (Lu et al., 2019c) from the southwestern end of the roadcut yielded a magmatic crystallization age of 2670 ± 4 Ma (Fig. 23a) with a dominant inherited component at c. 2800 Ma and a minor component at c. 2740 Ma. A single zircon with a c. 3276 Ma date is also present.

Five high-resolution 3D Digital Outcrop models collectively capturing most of the exposure are freely viewable within GSWA's Sketchfab page <https://sketchfab.com/GSWA>:

From east to west:

Area 1: https://skfb.ly/o9vS7

Area 2: https://skfb.ly/o9vVJ

Area 3: https://skfb.ly/o9vXN (see Fig. 24)

Area 4: https://skfb.ly/o9vZy

Area 5: https://skfb.ly/o9wnw

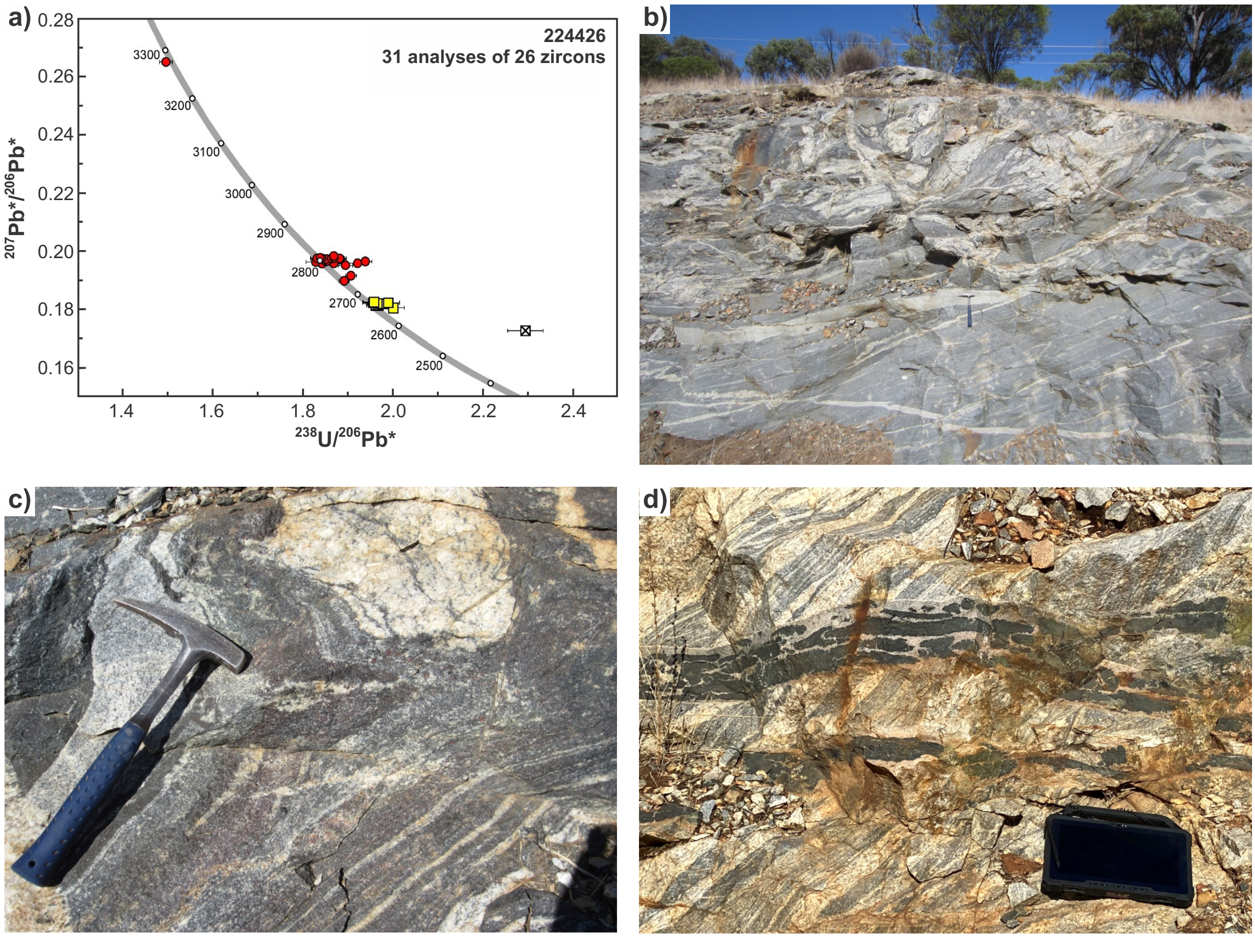

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Figure 23. Locality 10: Posselts Cutting: a) U–Pb analytical data for zircons from sample 224426: metatonalite, Northam. Yellow squares indicate Group I (magmatic zircons); red circles indicate Group X (xenocrystic zircons); crossed square indicates Group D (discordance >5%); b) photo looking south showing deformed migmatitic domain with top-to-the-west shear sense within grey, mylonitic gneiss, all intruded by several generations of aplitic and pegmatitic veins. Note that the generation of leucosomes within the boudin predates that within the gneiss host; c) folded and sheared garnet–biotite-rich layer within a metasedimentary boudin or xenolith preserved within the grey gneiss host; d) subhorizontal melt-segregated dyke (tablet is 30 cm across) intruded at a high angle to layering within migmatitic TTGs

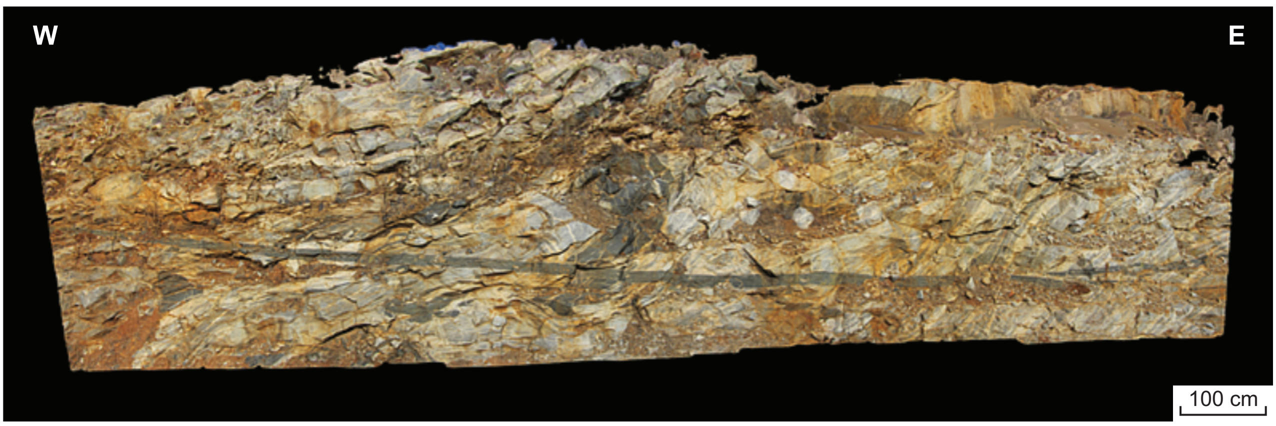

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Figure 24. Screen capture of one of the digital outcrops (Area 3) of Posselts Cutting stored in GSWA’s Sketchfab page

Locality 11: Metamorphosed banded iron-formation at Mount Dick

From Locality 10, head east on the Great Eastern Highway towards Northam. After 3 km, at Irishtown, exit to the right and go left under the underpass on the Northam–Pithara Road. After 4 km, turn right at the farm entrance and call in at the property. Proceed along tracks to the base of Mount Dick (MGA 471051E 6505479N).

This locality is within the CTZ, 16.5 km east of the South West – Youanmi Terrane boundary and about 7 km north of Northam.

At the start of the traverse are mafic–ultramafic intrusive rocks, likely a sill intruded into paragneiss exposed on the top of the hill. Here, on the west slope of Mount Dick (WAROX site TJISWT220028, MGA 471051E 6505479N), are low exposures of serpentinite and metagabbro. The serpentinite locally shows relict olivine cumulate texture, where the protolith was likely an olivine adcumulate dunite with abundant subrounded, 4 mm olivine cumulate crystals. This dunite has 37.7 wt% MgO, 2280 ppm Ni, 6220 ppm Cr (WACHEM database, <www.dmp.wa.gov.au/geochem>). The description for Locality 6 discusses the status of assigning ages and geochemical suites to such intrusive rocks.

At the top of the hill are highly oxidized garnet-bearing psammite and granulite-facies BIF (Fig. 25; Pidgeon, 1961). Although weathered, structural observations may be made on several outcrops. At this site, GSWA geochronology sample 198507 (Lu et al., 2015a), a garnet-bearing granulite, was interpreted to contain a 2976 Ma metamorphic zircon, whereas the Metamorphic History Record for this sample (Blereau et al., 2022) reinterprets this as the age of an inherited detrital component, likely representing a maximum depositional age. Based on the results from phase-equilibria modelling, peak metamorphic conditions are estimated at 810–865 °C and 4.2 – 9.1 kbar, with an apparent thermal gradient between 95 and 190 °C/kbar, and final-melt crystallization at 810–820 °C and 4.2 – 4.9 kbar.

A mafic granulite (GSWA 198510), 15 km to the southeast of this locality, comprises plagioclase, clinopyroxene, orthopyroxene, hornblende and ilmenite. The peak metamorphic assemblage of the mafic granulite yields a very high apparent geothermal gradient of 130–170 °C/kbar (Blereau et al., 2021). Nearby to the mafic granulite, monazite sample GSWA 219838 (Fielding et al., 2021) yielded a metamorphic age of 2664 ± 4 Ma.

Regionally, these results suggest that this part of the CTZ was affected by unusually high heat flow both in the source and at the level of emplacement. The thermal drivers for these extreme conditions were likely a combination of elevated crustal heat production, the effects of regional-scale granite magmatism, and a juvenile mantle contribution at depth (Korhonen et al., 2021).

Locality 12: Clackline Refractory

Located down Refractory Road off the Great Eastern Highway in the decommissioned kaolinite pits.

***Note**: access to the pits can be gained by either entering through the main drive to the refractory or by driving up further along Refractory Road and using the 4WD tracks to enter. If entering through the front of the refractory, park after the first building. **DO NOT** drive on the bridge over the creek bed, as it is in disrepair and there are several holes in the road where the track has washed away. Walking across the bridge should be safe, but proceed with caution.*

The old kaolinite quarry here consists of saprolitic mica schist, although relict metamorphic minerals and structural fabrics are well preserved, giving access to fine-scale features (Fig. 26).

Locality 12.1: Refolded folds

In the exposed wall next to the track (WAROX site CEGSWT000125, 452647E 6490586N), it is possible to observe the interaction between an early phase of N–S trending isoclinal folds and a later generation of upright N–S trending tight folds forming a Type 3 interference pattern. Facing eastwards, the hinge of an isoclinal fold makes the relict bedding / compositional layering appear horizontal in contrast to the vertical stratigraphy surrounding the locality. Facing northwards, the later upright folds are visible from this angle both here and around the corner behind the burnt-out car.

Locality 12.2: Metamorphic assemblages

In places around the quarry, more quartz-rich competent layers, quartz veins and intrusive granites are better preserved. Some remaining schist contains sillimanite (WAROX site CEGSWT000124, MGA 452562E 6490609N), while other layers contain relict garnet. This variation has been attributed to compositional differences in the metasedimentary protolith reflecting the original bedding. In this locality, the layering strikes N–S and varies between being completely vertical and dipping steeply to the west as part of a larger local F2 fold similar to the ones seen at Locality 12.1.

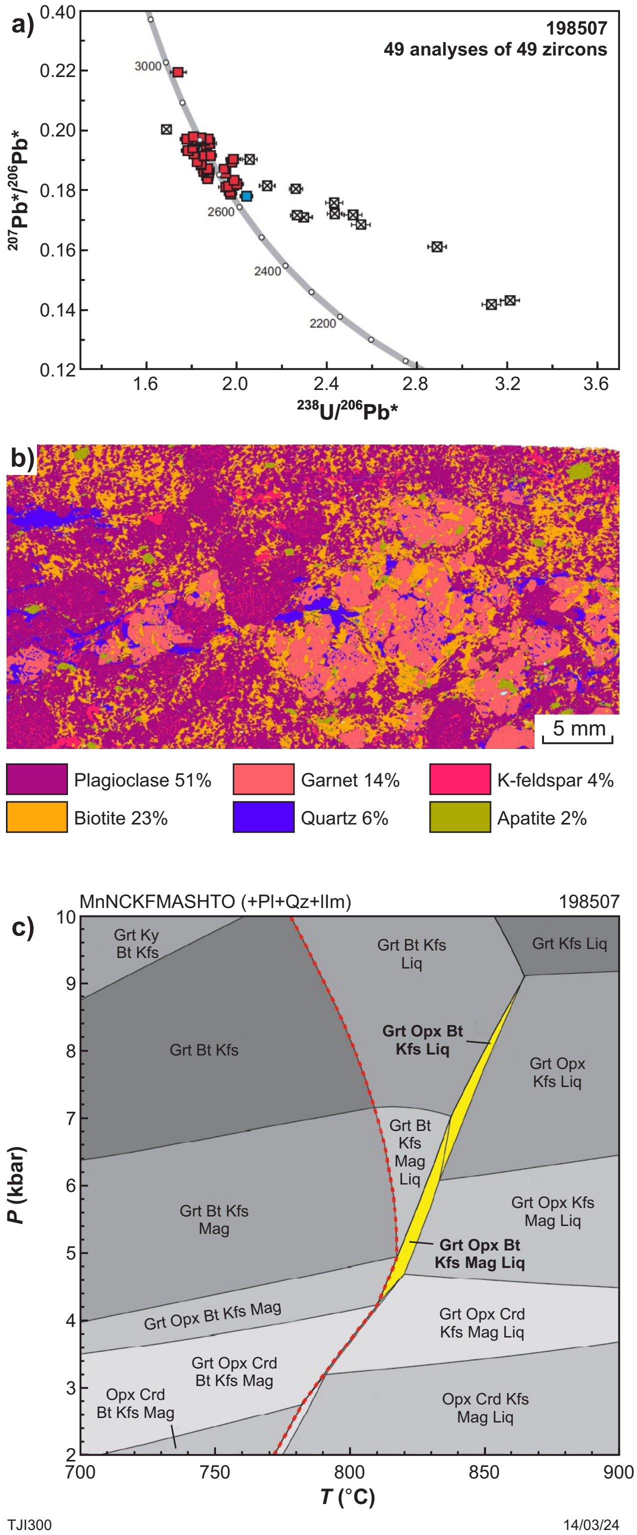

Figure 25. Locality 11: Mount Dick: a) U–Pb analytical data for zircons from GSWA sample 198507: garnet gneissose granulite, Mount Dick. Blue square indicates Group Y (youngest detrital zircon); red squares indicate Group S (older detrital zircons); crossed squares indicate Group D (discordance >5%); b) TIMA image of an entire thin section from sample 198507: garnet gneissose granulite, Mount Dick. Volume percent proportion of major rock-forming minerals are calculated by the TIMA software; c) P–T pseudosection calculated for sample 198507. Assemblage fields corresponding to peak metamorphic conditions are shown in bold text and yellow shading. Red dashed line represents the solidus. Abbreviations: Bt, biotite; Crd, cordierite; Grt, garnet; Ilm, ilmenite; Kfs, K feldspar; Ky, kyanite; Liq, silicate melt; Mag, magnetite; Opx, orthopyroxene; Pl, plagioclase; Qz, quartz

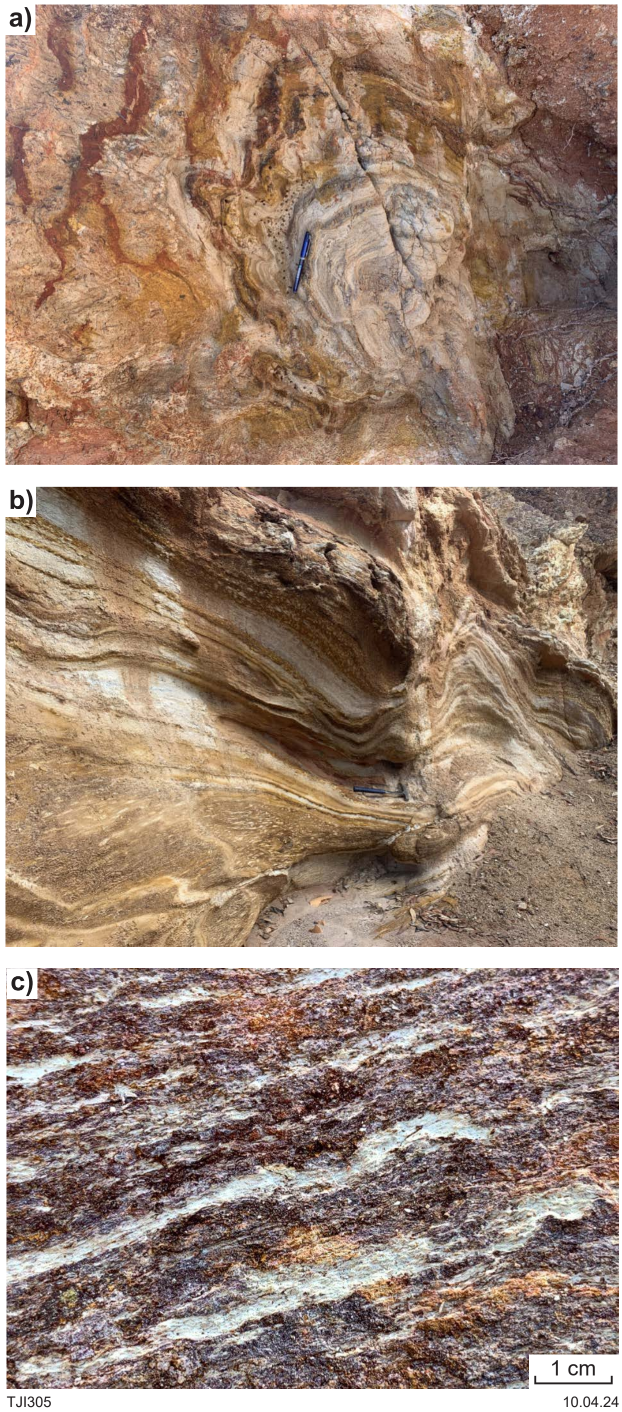

Figure 26. Locality 12: Clackline Refractory: a) upright local F2 fold with parasitic folds, looking north; b) fold interference between local F1 recumbent isoclinal and F2 upright tight folds; c) fibrous sillimanite in schist as thin white tendrils within the rock

Locality 13: Mylonites in the Darling Fault system at Bells Rapids

On the way back to Perth along Toodyay Road, turn right onto Neuman Road and right onto Campersic Road, then continue for 6.1 km. *Turn left onto Camargue Drive and, after 700 m, at the Tjunction turn right onto Cathedral Avenue. After 1.3* km, *find a parking place. Walk down to exposures on the banks of the Swan River at MGA 410597E 6483917N.*

The location is shown relative to the Chittering area map in Figure 27. Examine several exposures of mylonitic rock units between WAROX sites IXZWOO000004 and IXZWOO000010. These show mylonitic equigranular granite, locally with a sinistral shear sense on a gently southdipping linear fabric. There are knife-sharp boundaries with domains of ultramylonites, subparallel to the northstriking more pervasive fabric, which occur along quartz veins. Sinistral drag is visible on horizontal surfaces.

Proceed to MGA 410597E 6483917N and look for dextral shear indicators (e.g. Fig. 28a).

Proceed 160 m east, upstream (to MGA 410771E 6483917N), where ultramylonite is present along a quartz vein, showing sinistral drag (Fig. 28b).

Proceed 1 km east, upstream (to MGA 411936E 6483905N), and look for a dolerite schist, likely a Proterozoic dyke, sheared parallel to foliation in host metagranitic rocks (Fig. 28c).

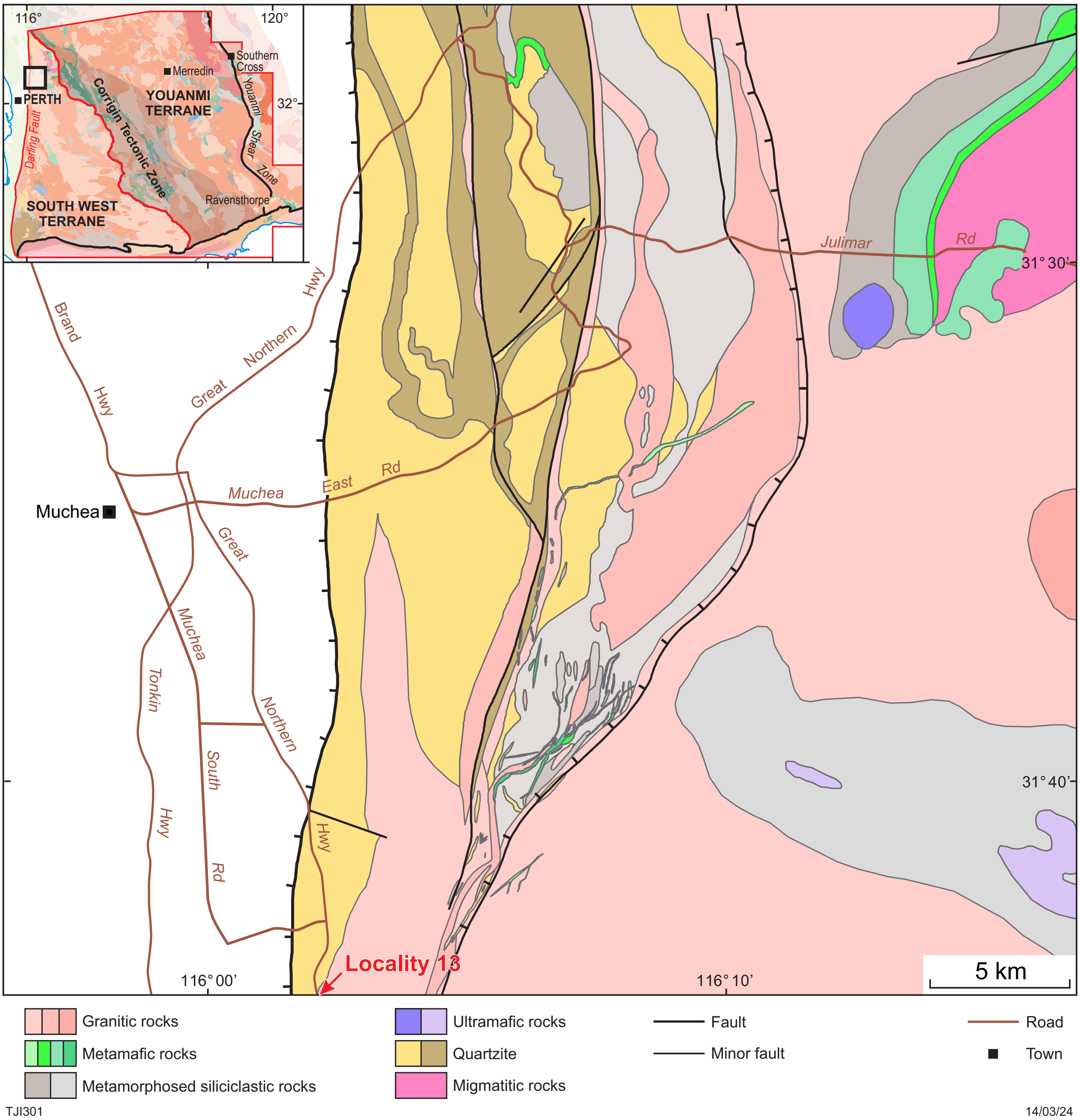

Figure 27. Locality 13: map of the area to the north of Bells Rapids to highlight mapped features of the 'Chittering metamorphic belt' (after Zibra, 2021). IBG extent from Quentin de Gromard et al. (2021)

Figure 28. Locality 13: Bells Rapids: a) mylonitic shear band in granitic gneiss; b) ultramylonite adjacent to quartz veins; c) metadolerite with preserved chilled margin cutting foliated metagranitic rocks

Discussion points:

- Ages and significance of post-Archean deformational reactivation events – cf. folded dyke on IBG map (Fig. 27, green horseshoe-shaped unit in the north of the map)
- Thermal or fluid-flow events related to the resetting of Sr, Nd and Hf isotopic systems (e.g. the Rb–Sr dataset of DeLaeter)
- Lithologies within the 'Chittering metamorphic belt' and their relationship to a potential 'Balingup terrane'
- Future work on the Darling Fault system
- Future work in the area of this field excursion.

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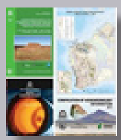

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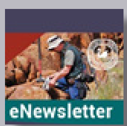

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