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Precise U–Pb baddeleyite dating of the Derim Derim Dolerite, McArthur Basin, Northern Territory: old and new SHRIMP and ID-TIMS constraints

S. Bodorkos[a], J. L. Crowley[b], J. C. Claoué-Long[a], J. R. Anderson[a] and C. W. Magee Jr[a]

[a]Minerals, Energy and Groundwater Division, Geoscience Australia, Canberra, Australia; [b]Isotope Geology Laboratory, Department of Geosciences, Boise State University, Boise, ID, USA

ABSTRACT

The Mesoproterozoic Roper Group of the McArthur Basin has excellent petroleum potential, but exploration has been hampered by poor constraints on its post-depositional history that has compromised understanding of the tectonostratigraphic evolution of the basin. The Derim Derim Dolerite occupies an important position in the event chronology of the McArthur Basin, having intruded the Roper Group prior to post-Roper basin inversion, and it is also a major component of Mesoproterozoic intraplate mafic magmatism in northern Australia. Since 1997, the Derim Derim Dolerite has been assigned a magmatic crystallisation age of 1324 ± 4 Ma (all uncertainties are 95% confidence), based on unpublished sensitive high-resolution ion micro probe (SHRIMP) U–Pb analyses on baddeleyite attributed to a dolerite sample from Bureau of Mineral Resources drill-hole Urapunga 5. Herein, we establish that the SHRIMP sample originated from the type locality of the Derim Derim Dolerite in outcrop 90 km northwest of Urapunga 5 and document the $^{207}Pb/^{206}Pb$ date interpreted from the 1997 dataset. New U–Pb SHRIMP reanalysis of the same grain-mounts yielded a mean $^{207}Pb/^{206}Pb$ date of 1320.1 ± 5.3 Ma, confirming the 1997 result, and isotope dilution-thermal ionisation mass spectrometry (ID-TIMS) analysis of baddeleyites plucked from the mounts yielded a precise mean $^{207}Pb/^{206}Pb$ date of 1327.5 ± 0.6 Ma. This date is significantly older than a baddeleyite U–Pb ID-TIMS date of *ca* 1313 Ma recently reported elsewhere from dolerite in the Beetaloo Sub-basin 200 km to the south, indicating that magmatism attributed to the Derim Derim Dolerite spanned at least 10–15 Ma. Previously documented geochemical variation in Mesoproterozoic intraplate mafic rocks across the Northern Territory (such as the 1325 ± 36 Ma Galiwinku Dolerite in the McArthur Basin, 1316 ± 40 Ma phonolites in the Nimbuwah Domain of the eastern Pine Creek Orogen, and 1295 ± 14 Ma gabbro in the Tomkinson Province) may reflect episodic pulses of magmatism hitherto obscured by the low precision of the available isotopic dates. The timing and geochemistry of Derim Derim-Galiwinku mafic igneous activity is strikingly similar to that of the Yanliao Large Igneous Province (LIP) in the northern North China Craton, and the global paucity of 1330–1300 Ma LIPs suggests that the North Australian Craton and the North China Craton were in relatively close proximity at that time.

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Derim Derim Dolerite; McArthur Basin; Roper Group; baddeleyite; SHRIMP; ID-TIMS; U–Pb dating

KEY POINTS

- We document a previously unpublished U–Pb baddeleyite date of 1324 ± 4 Ma for the Derim Derim Dolerite in the McArthur Basin, obtained via sensitive high-resolution ion micro probe (SHRIMP), and substantiate it with an isotope dilution-thermal ionisation mass spectrometry (ID-TIMS) date of 1327.5 ± 0.6 Ma from the same sample.
- Our dates are significantly older than a U–Pb baddeleyite ID-TIMS date of *ca* 1313 Ma from dolerite in the Beetaloo Sub-basin 200 km to the south, indicating that magmatism attributed to the Derim Derim Dolerite spanned at least 10–15 Ma.
- Contemporaneous intraplate mafic magmatism extended hundreds of kilometres across the Northern Territory, spanning the Tomkinson Province, the McArthur Basin, and the Nimbuwah Domain of the eastern Pine Creek Orogen.
- The timing and geochemistry of Derim Derim Dolerite magmatism strongly resembles the Yanliao Large Igneous Province (LIP) in the northern North China Craton, which suggests that the North Australian Craton and the North China Craton were in close proximity during the Mesoproterozoic.

CONTACT S. Bodorkos simon.bodorkos@ga.gov.au Minerals, Energy and Groundwater Division, Geoscience Australia, GPO Box 378, Canberra, ACT, 2601, Australia
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Introduction

The Mesoproterozoic hydrocarbon-bearing Roper Group within the McArthur Basin of northern Australia (Figure 1) has excellent potential for both unconventional and conventional petroleum (*e.g.* Abbott *et al.*, 2001; Ahmad, *et al.*, 2013; Cox *et al.*, 2016; Munson, 2014, 2016; Munson & Revie, 2018; Sweet *et al.*, 1999; Yang *et al.*, 2018). Effective exploration for hydrocarbon resources requires a sound understanding of the tectonostratigraphic evolution of the basin; however, the post-depositional history of the Roper Group is relatively poorly constrained. In this context, the timing of Derim Derim Dolerite emplacement into the McArthur Basin is significant. First, this geographically widespread network of dolerite sills and dykes establishes an important minimum age for deposition of the host Roper Group. Second, bedding-parallel sills of Derim Derim Dolerite are deformed within the host sedimentary successions (Abbott *et al.*, 2001; Ahmad *et al.*, 2013; Munson, 2016), so its magmatic crystallisation age also constitutes a maximum for deformation associated with the 'Post-Roper Inversion' event (Rawlings *et al.*, 1997).

In the mid-1990s, the Australian Geological Survey Organisation (AGSO, now Geoscience Australia [GA]) extracted baddeleyite from a sample of the Derim Derim Dolerite, and U–Pb analyses undertaken via sensitive

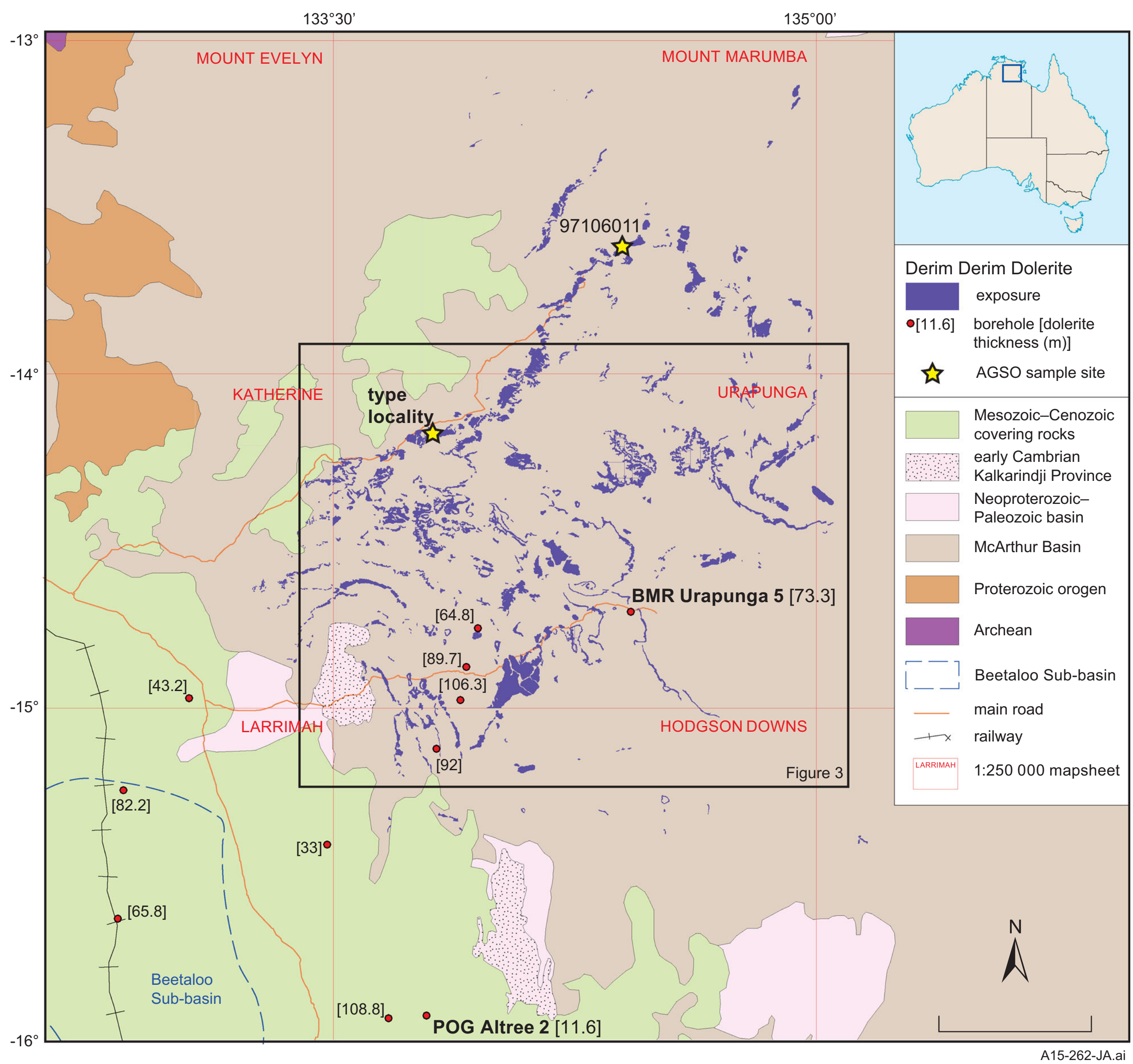

Figure 1. Geological elements of the northeastern Northern Territory (modified after Munson, 2016), showing the distribution of Derim Derim Dolerite exposure, and locations of boreholes (red circles) with intersected dolerite thickness in metres (in square brackets). BMR, Bureau of Mineral Resources; POG, Pacific Oil and Gas Ltd, operators of drill-holes Urapunga 5 and Altree 2, respectively. Bold labels denote sites that have (or have traditionally been attributed) U–Pb datasets from dolerite-hosted baddeleyite. Yellow stars denote Derim Derim Dolerite samples collected in the 1990s by NTGS and AGSO for U–Pb geochronology, including the type locality (Abbott *et al.*, 2001). One site is labelled with its GA SampleID; the other four sites (and their SampleIDs) are shown in Figure 3.

high-resolution ion micro probe (SHRIMP) in 1997 yielded a weighted mean $^{207}Pb/^{206}Pb$ date of 1324 ± 4 Ma. Abbott *et al.* (2001, p. 78–79) attributed the result to 'J. Claoué-Long, Geoscience Australia, personal communication, 1997', as part of the stratigraphic definition of the Derim Derim Dolerite. However, this result is clouded in two respects.

First, from the outset, there has been confusion regarding the sampling location of the baddeleyite-bearing dolerite, with the contradictory data inadvertently captured by Abbott *et al.* (2001). The Derim Derim Dolerite unit description (Abbott *et al.*, 2001, p. 47) attributed the SHRIMP date to an outcrop sample from the type locality; however, both the summary of isotopic data (Abbott *et al.*, 2001, table 1; p. 6) and the stratigraphic definition of the Derim Derim Dolerite (Abbott *et al.*, 2001, p. 78–79) attributed the date to a sill intersected by Bureau of Mineral Resources drill-hole BMR Urapunga 5, 90 km to the southeast of the type locality. Second and more recently, the historic $^{207}Pb/^{206}Pb$ date of 1324 ± 4 Ma has been challenged by a new isotope dilution-thermal ionisation mass spectrometry (ID-TIMS) baddeleyite U–Pb date of 1312.9 ± 0.7 Ma (Collins *et al.*, 2018; Yang *et al.*, in press) from dolerite intersected by Pacific Oil and Gas Ltd drill-hole POG Altree 2, within the Beetaloo Sub-basin of the southern McArthur Basin (Figure 1). The difference between the two dates is statistically significant, but careful appraisal of the isotopic data and interpretations is required before geological meaning can be attached to the spread of reported ages.

In this contribution, first we describe the range of dolerite samples targeted by AGSO and the Northern Territory Geological Survey (NTGS) for U–Pb geochronology in the 1990s and identify the specific sample that yielded baddeleyite for SHRIMP analysis. Second, we document the U–Pb SHRIMP data collected in 1997 and trace the provenance of the interpreted mean $^{207}Pb/^{206}Pb$ date of 1324 ± 4 Ma. Third, we present new U–Pb SHRIMP data collected from the same grain-mounts (and, in many cases, the same baddeleyite crystals) aimed at confirming the 1997 result, as well as new U–Pb ID-TIMS data on baddeleyite crystals plucked directly from the grain-mounts, collected in order to corroborate the SHRIMP dates and improve the precision of the result. Fourth, we briefly discuss the geological implications of the new results with respect to (1) the Derim Derim Dolerite date from the Beetaloo Sub-basin of the southern McArthur Basin (Collins *et al.*, 2018; Yang *et al.*, in press), and (2) other mafic rocks of Mesoproterozoic age and intraplate geochemical affinity across the Northern Territory (*e.g.* Carson *et al.*, 1999; Goldberg, 2010; Hollis & Glass, 2012; Whelan *et al.*, 2016). Fifth, we compare the Derim Derim Dolerite and associated rocks to Mesoproterozoic intraplate mafic magmatism in the Yanliao rift zone of the northern North China Craton (*e.g.* Zhang *et al.*, 2009, 2017) as part of the so-called

Table 1. Identifiers, locations and metadata for Derim Derim Dolerite samples targeted by NTGS and AGSO for U–Pb geochronology in the 1990s.

GA SampleNo	GA SampleID	Drill hole/field site	MGA94 easting[a]	MGA94 northing[a]	Location description	Geological notes	Zircon/Baddeleyite
2804838	95640001	BMR Urapunga 5 (239.05–240.74 m)	437263	8373361	Within 73.3 m-thick sill spanning the depth interval 198.1–271.4 m	Near centre of differentiated sill that intrudes Jalboi Formation	Nil
2804832	97106009	Outcrop	383828	8429272	Maori Creek region	Partly disintegrated sill at this locality intrudes Crawford Formation	Nil
2804835	97106010	Outcrop	371817	8433362	Bed of Derim Derim Creek at Policemans Yard. Basal contact of type locality (Abbott *et al.*, 2001)	Disintegrated dolerite sill at this locality intrudes Crawford Formation	Baddeleyite
2804836	97106011	Outcrop	435342	8493482	Track just south of Central Arnhem Road, about 9 km ENE of Bulman Weemol	Boulder on rock platform, partly disintegrated sill	Nil
2804837	97106012	Outcrop	398220	8428259	Boulder in creek bed, Jalboi River region	Mostly disintegrated sill	Nil

[a]Eastings and northing are Map Grid of Australia 1994 (MGA94) Zone 53. Positional accuracy is about 100 m.

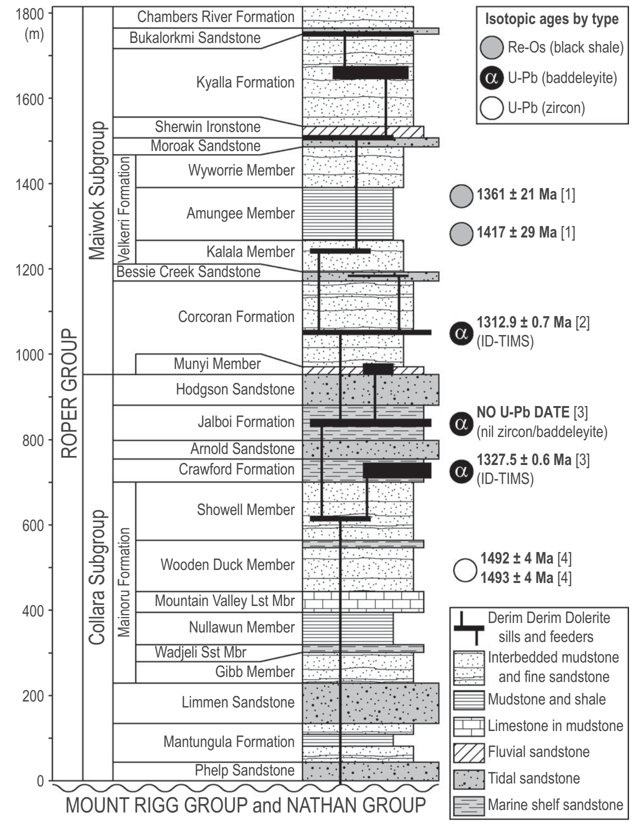

Figure 2. Simplified stratigraphic column for the Roper Group, modified after Cox *et al.* (2016) and Yang *et al.* (2018) following Munson (2016) and Munson and Revie (2018). Age data sources: 1, Kendall *et al.* (2009); 2, Collins *et al.* (2018) and Yang *et al.* (in press); 3, this study; and 4, Jackson *et al.* (1999). Derim Derim Dolerite representation is largely schematic but draws on observations by Abbott *et al.* (2001) and Munson (2016). Labelled sills within Corcoran Formation, Jalboi Formation and Crawford Formation represent those sampled for U–Pb baddeleyite dating by Collins *et al.* (2018) and Yang *et al.* (in press), GA SampleID 95640001 (this study), and GA SampleID 97106010 (this study), respectively.

McArthur-Yanliao Gulf (Collins *et al.*, 2019), and contrast both with broadly contemporaneous mafic magmatism in the Fraser Complex of the Albany-Fraser Orogen in south-western Australia (*e.g.* Glasson *et al.*, 2019; Morrissey *et al.*, 2017; Smithies *et al.*, 2013).

Geology and sampling history of the Derim Derim Dolerite

Geological framework

The Derim Derim Dolerite comprises medium- to coarse-grained dolerite sills and dykes that intruded the Mesoproterozoic Roper Group (Figure 2) at most stratigraphic levels between the Mainoru Formation of the Collara Subgroup and the Bukalorkmi Sandstone of the Maiwok Subgroup (Abbott *et al.*, 2001; Munson, 2016; see also Figure 2), before being deformed with the enclosing stratigraphy during the 'Post-Roper Inversion' event (Abbott *et al.*, 2001; Ahmad *et al.*, 2013; Rawlings *et al.*, 1997). The unit therefore occupies an important position in the relative chronology of Mesoproterozoic sedimentation, magmatism and deformation in the McArthur Basin.

The age of the host Roper Group sedimentary rocks is imperfectly constrained. Most of the Roper Group post-dates felsic volcanic rocks of the *ca* 1492 Ma Mainoru Formation (Jackson *et al.*, 1999; see also Figure 2), but depositional ages for the sedimentary rocks of the upper Maiwok Subgroup are constrained chiefly by an Rb–Sr date of 1429 ± 31 Ma for carbonate-hosted illite of interpreted diagenetic origin (Kralik, 1982), and Re–Os dates of 1361 ± 21 Ma and 1417 ± 29 Ma (Figure 2) for black shales of the Velkerri Formation (Kendall *et al.*, 2009). More recently, Yang *et al.* (2018) dated detrital zircons as young as 1308 ± 41 Ma ($n = 1$) from the Velkerri Formation, and two samples from the Kyalla Formation yielded dates of 1313 ± 47 Ma ($n = 1$) and 1317 ± 36 Ma ($n = 2$), respectively; however, it is unclear whether these dates represent maximum ages for deposition of the host sedimentary rocks, owing to the sparsity of post-1400 Ma dates in the measured spectra. It is possible that some or all of these isolated grains were affected by post-crystallisation isotopic disturbance associated with emplacement of the Derim Derim Dolerite.

Samples targeted for geochronology

McDougall *et al.* (1965) made the first attempt to date the Derim Derim Dolerite. Pyroxene and plagioclase from 'somewhat altered' dolerites intruding the Roper Group yielded a series of K–Ar dates spanning the range 1280–1150 Ma; McDougall *et al.* (1965) attributed this dispersion to varying degrees of post-crystallisation loss of radiogenic argon, and interpreted a minimum age of *ca* 1280 Ma for the unit. During the 1990s, NTGS and AGSO undertook second-edition 1:250 000 mapping in the Mount Marumba, Urapunga and Roper River map sheet areas as part of the National Geoscience Mapping Accord (*e.g.* Abbott *et al.*, 2001; Sweet *et al.*, 1999). This included new sampling of the Derim Derim Dolerite aimed at improving the accuracy and precision of its magmatic crystallisation age, via U–Pb dating of zircon or baddeleyite.

The first sample of Derim Derim Dolerite targeted by AGSO for U–Pb dating was diamond drillcore from BMR Urapunga 5 (GA SampleID 95640001; Table 1, Figure 3), which intersected 73.3 m of coarse-grained dolerite spanning the interval 198.1–271.4 m (Sweet & Jackson, 1986). In this drill hole, Derim Derim Dolerite intrudes the Jalboi Formation of the Collara Subgroup, which comprises the lower part of the Roper Group (Figure 2). Sample 95640001, which has hitherto been widely regarded as the source of the SHRIMP $^{207}Pb/^{206}Pb$ date of 1324 ± 4 Ma obtained in 1997 (*e.g.* Table 1; Abbott *et al.*, 2001, appendix 1), was crushed in the conventional manner for mineral separation targeting zircon but yielded no zircon or baddeleyite. In fact, NTGS and AGSO geologists collected a

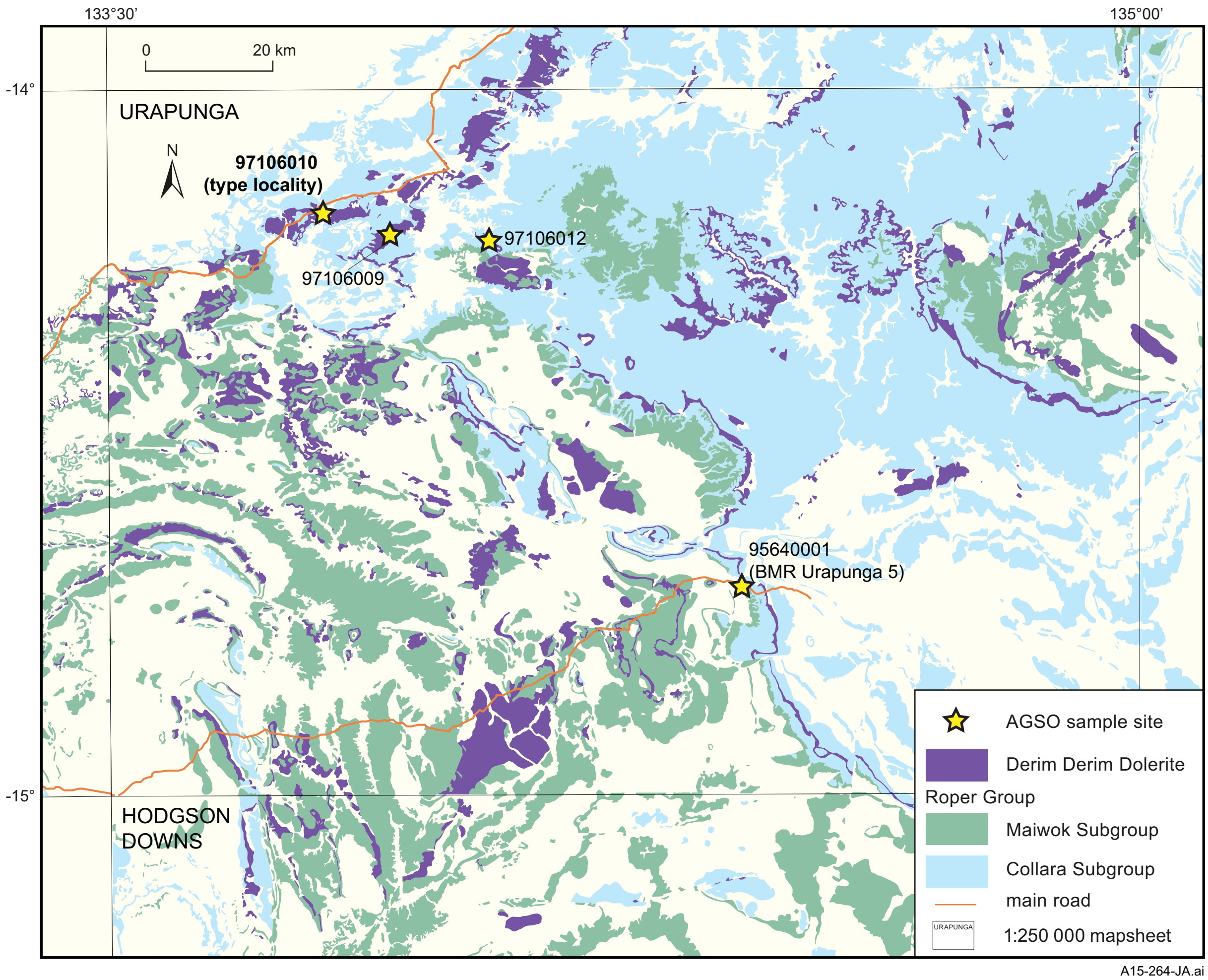

Figure 3. Geological map of the Urapunga region (modified after Munson, 2016) showing the distribution of Roper Group exposure at Subgroup-level, and its relationship to the Derim Derim Dolerite. The varying width (across-strike) of each unit primarily reflects dip angle and demonstrate that most Derim Derim Dolerite exposures are sills concordant with (and co-deformed within) the host sedimentary succession (Munson, 2016). Yellow stars denote Derim Derim Dolerite samples (labelled with GA SampleID) collected in the 1990s by NTGS and AGSO for U–Pb geochronology.

further four outcrop samples of Derim Derim Dolerite for U–Pb geochronology (SampleIDs 97106009–97106012 inclusive; Table 1; Figure 3), one of which yielded the dated baddeleyite population. Sample 97106010 was collected from the type locality (Abbott *et al.*, 2001, p. 78–79), 90 km northwest of BMR Urapunga 5 (Table 1), where the lower contact of the Derim Derim Dolerite intrudes the Crawford Formation of the Collara Subgroup.

More recently, Collins *et al.* (2018) and Yang *et al.* (in press) presented an unpublished ID-TIMS U–Pb baddeleyite age of 1312.9 ± 0.7 Ma (2σ) obtained from dolerite intruding the Corcoran Formation of the lowermost Maiwok Subgroup (which in turn comprises the upper part of the Roper Group), in the Beetaloo Sub-basin, some 200 km south of the Derim Derim Dolerite type locality (Figure 1). In detail, the age quoted by Collins *et al.* (2018) is a weighted mean $^{206}Pb/^{238}U$ date defined by five out of six baddeleyite analyses, and it is supported by a statistically coherent weighted mean $^{207}Pb/^{206}Pb$ date of 1313.8 ± 1.0 Ma (2σ) defined by all six analyses (Yang *et al.*, in press). The concordance of the $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ results permits confidence in interpreting the analyses as a cogenetic, isotopically undisturbed baddeleyite population formed during igneous crystallisation of the dolerite.

The apparent difference between the historic *ca* 1324 Ma SHRIMP date from sample 97106010 and the new *ca* 1313 Ma ID-TIMS result raises the possibility that dolerites currently attributed to the Derim Derim Dolerite were emplaced over several million years (*i.e.* 5–15 Ma, based on the 95% confidence intervals of the U–Pb dates), despite the absence of identifiable cross-cutting relationships within the sills and dykes, and their relatively uniform chemistry (Abbott *et al.*, 2001; Whelan *et al.*, 2016). However, it is necessary to substantiate the original SHRIMP date (via reassessment of the original interpretation, and acquisition of new SHRIMP data on the same grains), and to test the correspondence of SHRIMP and ID-TIMS analytical data, before attaching geological significance to the apparent spread of U–Pb dates.

Table 2. Summary of SHRIMP session-specific metadata, and parameters measured on reference materials.

Parameter	Session 1	Session 2	Session 3	Session 4
MountID	Z2779	Z2895	Z2895	Z2779
Analyst	J. C. Claoué-Long	J. C. Claoué-Long	S. Bodorkos	S. Bodorkos
Instrument	ANU SHRIMP II	ANU SHRIMP II	GA SHRIMP IIe	GA SHRIMP IIe
Session dates	13–14 July 1997	17–19 August 1997	25–27 March 2019	26–27 March 2019
Session duration (h)	28	46	33	31
Data processing software	PRAWN/Lead	PRAWN/Lead	SQUID 2.50.11.02.03	SQUID 2.50.11.02.03
Reference baddeleyite[a]	**Phalaborwa (2059.6 Ma)**	**Phalaborwa (2059.6 Ma)**	**Phalaborwa (2059.6 Ma)**	**Phalaborwa (2059.6 Ma)**
Analyses used	9 of 9	12 of 12	16 of 16	17 of 17
^{238}U/^{206}Pb session-to-session error (2σ)	Not recorded	Not recorded	1.53%	1.04%
^{238}U/^{206}Pb spot-to-spot error (1σ)	6.36%	7.47%	6.06%	4.17%
Weighted mean uncorrected ^{207}Pb/^{206}Pb date (95% confidence)	2066.8 ± 6.2 Ma (MSWD = 4.8, P = 0.000)	2056.3 ± 3.5 Ma (MSWD = 3.8, P = 0.000)	2066.6 ± 5.0 Ma (MSWD = 1.51, P = 0.09)	2065.6 ± 5.0 Ma (MSWD = 0.66, P = 0.83)
Weighted mean ^{204}Pb-corrected ^{207}Pb/^{206}Pb date (95% confidence)	2059.1 ± 4.6 Ma (MSWD = 1.93, P = 0.05)	2055.4 ± 3.6 Ma (MSWD = 3.7, P = 0.000)	2061.9 ± 5.2 Ma (MSWD = 1.55, P = 0.08)	2058.3 ± 5.2 Ma (MSWD = 0.90, P = 0.57)
Reference zircon (to monitor ^{204}Pb overcounts)[b]	**None**	**None**	**SL13 (575.7 Ma)**	**SL13 (575.7 Ma)**
Analyses used	—	—	15 of 15	19 of 20
Robust mean ^{204}Pb-corrected ^{207}Pb/^{206}Pb date (95% confidence)	—	—	542 ± 44 Ma	586 ± 34 Ma
Robust mean ^{204}Pb overcounts/second from ^{207}Pb (95% confidence)	—	—	+0.010 ± 0.028 (no correction applied)	−0.004 ± 0.020 (no correction applied)
Concurrent analyses of sample 97106010	**31 analyses of 29 grains**	**56 analyses of 55 grains**	**36 analyses of 36 grains**	**39 analyses of 34 grains**

[a]Individual spot analyses of Phalaborwa baddeleyite are presented in Appendix Table A1.
[b]Arithmetical definition of ^{204}Pb overcounts, and individual spot analyses of SL13 zircon, are presented in Appendix Table A2.

SHRIMP U–Pb geochronology

Sample preparation and history of analyses

About 400 baddeleyite crystals were separated from sample 97106010, by crushing the sample coarsely and digesting the rock chips in hydrofluoric acid, as described in the Appendix (available, along with Appendix Figures and Appendix Tables, at http://pid.geoscience.gov.au/dataset/ga/127403). About half of the separated grains were set in epoxy mount Z2779, together with several large chips of the reference baddeleyite Phalaborwa (ID-TIMS ^{207}Pb/^{206}Pb date = 2059.60 ± 0.35 Ma; Heaman, 2009) and the reference zircon SL13 (ID-TIMS ^{206}Pb/^{238}U date = 572.2 ± 0.4 Ma; Claoué-Long *et al.*, 1995). U–Pb isotopic data were acquired using the SHRIMP II instrument in the Research School of Earth Sciences at the Australian National University [ANU], Canberra on 13 July 1997 (Table 2, 'Session 1'), and comprised nine analyses of Phalaborwa and 31 analyses on 29 baddeleyites from 97106010.

The mount was repolished in order to remove the July 1997 probe-pits and facilitate a second analytical session; unfortunately, most of the baddeleyite crystals on Z2779 were mounted with a strong cleavage parallel to the polished surface, and the repolishing process resulted in many grains being plucked from the mount, or otherwise damaged (Appendix Figure A1). As a result, a new grain-mount (Z2895) was prepared using the remaining baddeleyite concentrate from sample 97106010, and the same reference materials as Z2779. Mount Z2895 was also analysed on the ANU SHRIMP II, in a session that commenced on 17 August 1997, and comprised 12 analyses of Phalaborwa and 56 analyses on 55 baddeleyites from 97106010 (Table 2, 'Session 2'). Neither of the 1997 sessions acquired data from the SL13 zircon.

In order to evaluate the repeatability of the 1997 SHRIMP data, both mounts were recovered from the GA archive in March 2019 and prepared for reanalysis. We used potassium iodide solution to remove the legacy layer of gold on the polished surfaces and rephotographed each mount in transmitted and reflected light. Note that the August 1997 probe pits are preserved on the surface of Z2895 (Appendix Figure A2), in contrast to Z2779. The risk of further grain-plucking precluded further repolishing of either mount prior to reanalysis, however desirable it would have been in removing surface Pb accumulated during 20 years in storage, and (on Z2895) legacy probe-pits.

The two mounts were reanalysed during consecutive days (25–27 March 2019) using the SHRIMP II housed at GA, and both sessions incorporated suites of SL13 reference zircon to evaluate the accuracy of mount-specific count-rates at the ^{204}Pb and 204.1 (background) mass-stations. Session 3 (Table 2) on mount Z2895 comprised 15 analyses of Phalaborwa, 20 analyses of SL13, and 36 analyses of 36 baddeleyites from 97106010. Session 4 (Table 2) on mount Z2779 comprised 17 analyses of Phalaborwa, 15 analyses of SL13, and 39 analyses of 34 baddeleyites from 97106010.

Data reduction and interpretation

Individual analyses of 97106010 baddeleyites are labelled 'mount.grain.spot', with grain-numbering coordinated for consistency across the 1997 and 2019 sessions. Further details of the analytical sessions, calibration protocols, and data-processing procedures and parameters are provided in the Appendix, along with the underlying arrays of analytical data for the reference baddeleyite Phalaborwa (1997 and 2019; Appendix Table A1), the reference zircon SL13 (2019 only; Appendix Table A2), and Derim Derim Dolerite sample 97106010 (1997 and 2019; Appendix Table A3). All statistical data are calculated directly on isotopic ratios, with the end-results converted to dates afterwards, to aid visualisation. The 95% confidence intervals on quoted means are defined as t – sigma (where t is Student's t) for populations whose mean square of weighted deviates (MSWD; McIntyre *et al.*, 1966) is less than or equal to unity, and t – sigma $\times$ sqrt (MSWD) when MSWD $>$ 1. In general, populations of isotopic measurements are assumed to be equivalent within their analytical uncertainties when the probability of equivalence (P) is greater than 0.05.

Baddeleyite is a valuable U-bearing phase for dating silica-undersaturated magmatic rocks because: (1) unlike zircon, its physical fragility largely precludes its occurrence as an inherited phase, and (2) baddeleyite is relatively resistant to post-crystallisation loss of radiogenic Pb, and thus commonly preserves an unaltered record of the crystallisation age (Heaman & LeCheminant, 1993). However, ion-probe U–Pb dating of baddeleyite presents several difficulties. In addition to the challenges associated with mineral separation, mounting and polishing described above, very slender baddeleyite crystals require the use of a small-diameter primary ion beam, in turn leading to poor counting statistics, especially in crystals poor in U and radiogenic Pb. An additional artefact specific to ion-probe U–Pb dating of baddeleyite is the 'crystal orientation effect' (Wingate & Compston, 2000), whereby the calibrated ^{238}U/^{206}Pb varies widely from spot to spot, depending on the local orientation of the target crystal lattice, relative to the primary ion beam. This largely precludes meaningful measurement of ^{238}U/^{206}Pb, restricts ion-probe dating to baddeleyites containing enough radiogenic Pb to use orientation-independent ^{207}Pb/^{206}Pb (*i.e.* typically Mesoproterozoic or older), and compromises evaluation of isotopic concordance, which is a primary test of the reliability of ^{207}Pb/^{206}Pb dates.

SHRIMP U–Pb isotopic data for sample 97106010

Z2779

In July 1997, 31 analyses were collected from 29 baddeleyites (Figure 4a, Appendix Table A3), with two grains (5 and 27) each analysed twice. The crystals yielded predominantly low U contents (19–204 ppm, median 69 ppm), low ^{232}Th/^{238}U (0.02–0.12, median 0.06), and mostly low common ^{206}Pb (median 0.39%). Two analyses are omitted from further consideration: one that featured shorter Pb-isotope counting times than the rest of the dataset, and one with common ^{206}Pb $>$ 4% and a post-1100 Ma ^{207}Pb/^{206}Pb date (Appendix Table A3). Elevated common ^{206}Pb (in a system typified by low values) is a reliable indicator of post-crystallisation disturbance of the U–Pb system in the analysed domain. High common ^{206}Pb commonly reflects ingress of non-radiogenic Pb into the crystal lattice along fractures or cracks, and such conduits can also facilitate leakage of previously ingrown radiogenic Pb. If the leakage event were not geologically recent, it would manifest as an erroneously young ^{207}Pb/^{206}Pb date for the measured domain. The remaining 29 analyses yielded ^{207}Pb/^{206}Pb values that are equivalent within their analytical uncertainties and define a weighted mean date of 1322 ± 9 Ma (MSWD = 1.15, P = 0.27; Figure 4a).

In March 2019, 39 analyses were collected from 34 baddeleyites (Figure 4b, Appendix Table A3), with three grains (3, 26 and 42) each analysed twice, and a fourth (29) analysed three times. Once again, the crystals yielded relatively low U (41–428 ppm, median 139 ppm), ^{232}Th/^{238}U (0.01–0.20, median 0.04), and common ^{206}Pb (median 0.29%). Omitting five analyses characterised by a combination of elevated common ^{206}Pb (>0.70%) and young ^{207}Pb/^{206}Pb dates (post-1210 Ma; Appendix Table A3) that is probably attributable to non-recent U–Pb isotopic disturbance, the remaining 34 analyses define a statistically coherent weighted mean ^{207}Pb/^{206}Pb date of 1313 ± 9 Ma (MSWD = 1.08, P = 0.34; Figure 4b).

Z2895

In August 1997, 56 analyses were collected from 55 baddeleyites (Figure 4c, Appendix Table A3), with one grain (1) analysed twice. The crystals yielded predominantly low U (22–238 ppm, median 82 ppm), low ^{232}Th/^{238}U (0.02–0.21, median 0.05), and mostly low common ^{206}Pb (median 0.05%). This analytical session was compromised by intermittent electronic instability affecting the SHRIMP II instrument, as recorded by the primary and secondary beam monitor traces. Nine analyses were excluded from further consideration on this basis, along with a tenth which has common ^{206}Pb $>$ 3% and a post-1100 Ma ^{207}Pb/^{206}Pb date (Appendix Table A3), reflecting non-recent U–Pb isotopic disturbance. The remaining 46 analyses define a weighted mean ^{207}Pb/^{206}Pb date of 1324 ± 5 Ma. Although the constituent analyses remain scattered beyond their analytical uncertainties (MSWD = 1.47, P = 0.022; Figure 4c), a similar degree of excess dispersion is evident in concurrent ^{207}Pb/^{206}Pb analyses of the Phalaborwa reference baddeleyite (MSWD = 3.7, P = 0.000; Table 2). On this basis, we attribute the observed dispersion in measured ^{207}Pb/^{206}Pb to the session-specific electronic instability affecting the instrument, rather than any real geological process.

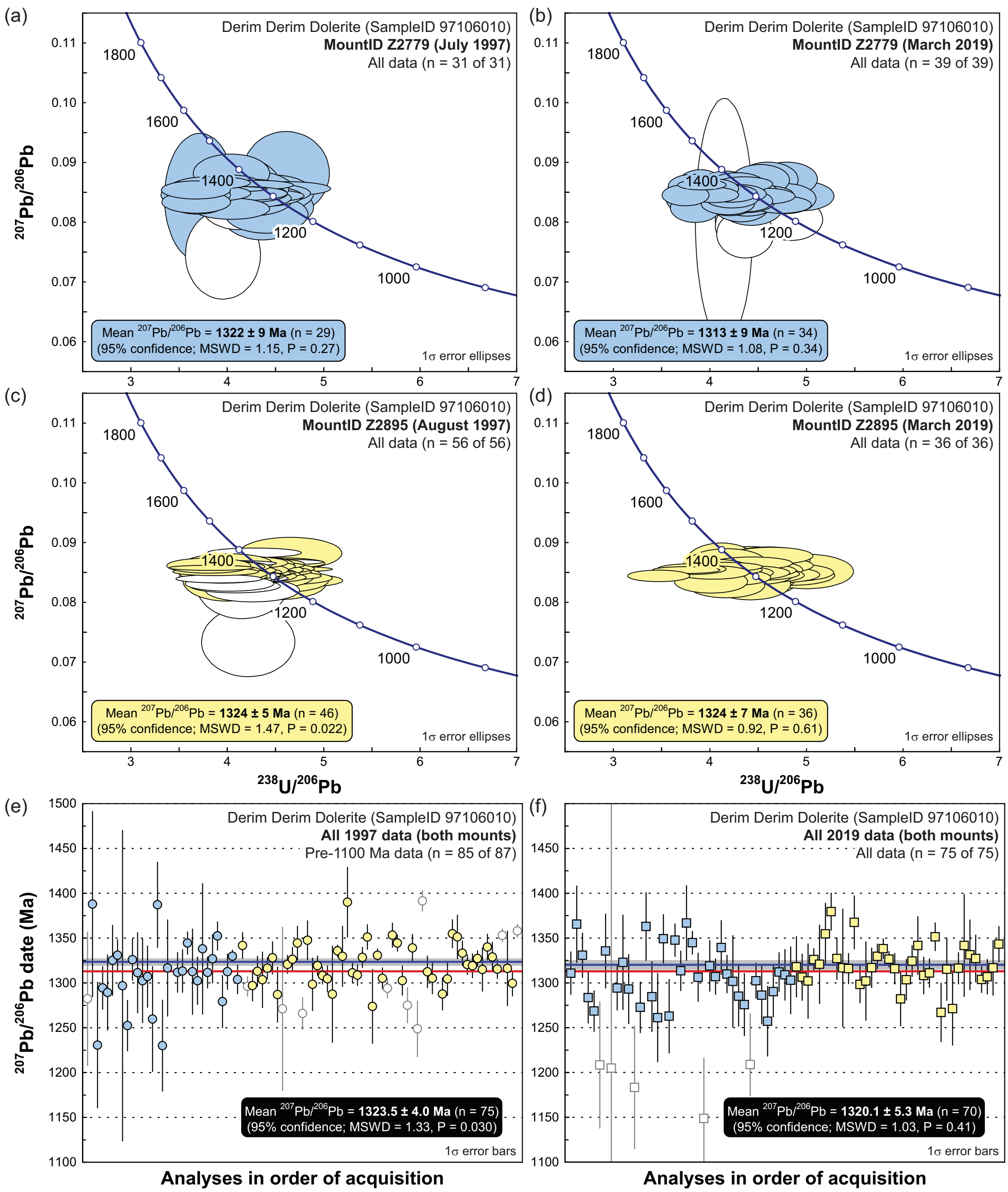

Figure 4. Tera-Wasserburg concordia diagrams for SHRIMP U–Pb baddeleyite data from sample 97106010, by mount and analytical session. Top row: all data collected from mount Z2779 in (a) 1997 and (b) 2019. Middle row: all data collected from mount Z2895 in (c) 1997 and (d) 2019. Bottom row: pre-1100 Ma $^{207}Pb/^{206}Pb$ dates for combined mounts from (e) 1997 and (f) 2019. Pale blue fill (Z2779) and pale-yellow fill (Z2895) denote magmatic crystallisation; white fill denotes excluded data. In (e) and (f), excluded data also has grey outlines; heavy blue lines with grey envelopes represent the weighted mean $^{207}Pb/^{206}Pb$ dates and their 95% confidence intervals for the combined 1997 and 2019 SHRIMP datasets respectively. Heavy red line denotes the ID-TIMS baddeleyite date of 1312.9 ± 0.7 Ma quoted by Collins *et al.* (2018) and Yang *et al.* (in press), for comparison.

In March 2019, 36 analyses were collected from 36 baddeleyites (Figure 4d, Appendix Table A3). Once again, the crystals yielded relatively low U (33–391 ppm, median 136 ppm), $^{232}Th/^{238}U$ (0.02–0.35, median 0.06), and common ^{206}Pb (median 0.09%). This statistically coherent population (Appendix Table A3) defines a weighted mean $^{207}Pb/^{206}Pb$ date of 1324 ± 7 Ma (MSWD = 0.92, $P = 0.61$; Figure 4d).

Combined mounts and sessions

In 1997, a total of 87 analyses were collected from 84 baddeleyites (Figure 4e), 12 of which are excluded from the magmatic population as described above. The two mount-specific weighted mean $^{207}Pb/^{206}Pb$ dates (1322 ± 9 Ma and 1324 ± 5 Ma) are indistinguishable, and combining the remaining 75 analyses into a single weighted mean yields a $^{207}Pb/^{206}Pb$ date of 1323.5 ± 4.0 Ma (MSWD = 1.33,

$P = 0.030$). This is the Derim Derim Dolerite age cited by Abbott *et al.* (2001, p. 78–79) as 1324 ± 4 Ma (J. Claoué-Long, personal communication, 1997)'.

Our March 2019 attempt to replicate the historic SHRIMP dataset employed a relatively small-diameter primary ion beam (18–20 µm, as opposed to the 35–40 µm beam used in 1997; Appendix Figure A2), because improved spatial resolution was needed first to probe scarce remnant crystal fragments in the repolished surface of Z2779, and second to avoid the historic probe-pits preserved in the surface of Z2895. The smaller probe-spot adversely affected ion-counting statistics, and therefore precision at the scale of individual analyses; nevertheless, the 2019 results corroborate those from 1997. The internal agreement of the weighted mean $^{207}Pb/^{206}Pb$ dates from 1997 (1322 ± 9 Ma on Z2779, 1324 ± 5 Ma on Z2895) is better than those measured in 2019 (1313 ± 9 Ma on Z2779, 1324 ± 7 Ma on Z2895); however the apparent difference between the latter pair is not statistically significant. In 2019, a total of 75 analyses were collected from 70 baddeleyites (Figure 4f), five of which were excluded from the Z2779 magmatic population as described above. Combining the remaining 70 analyses into a single weighted mean yields a statistically coherent $^{207}Pb/^{206}Pb$ date of 1320.1 ± 5.3 Ma (MSWD = 1.03, $P = 0.41$), which is indistinguishable from the analogous date of 1323.5 ± 4.0 Ma derived from the combined 1997 datasets. Furthermore all 145 of the analyses attributed to magmatic crystallisation (75 from 1997, 70 from 2019) are equivalent within their analytical uncertainties and yield a statistically coherent weighted mean $^{207}Pb/^{206}Pb$ date of 1322.3 ± 3.1 Ma (MSWD = 1.19, $P = 0.06$).

ID-TIMS U–Pb geochronology

Outcrop sample 97106010 at the Derim Derim Dolerite type locality has repeatedly yielded pre-1320 Ma SHRIMP $^{207}Pb/^{206}Pb$ dates that are distinguishably older than the ID-TIMS $^{207}Pb/^{206}Pb$ date of 1313.8 ± 1.0 Ma (Yang *et al.*, in press) obtained from dolerite intruding the upper Roper Group in the Beetaloo Sub-basin, 200 km to the south. However, we have not yet assessed the potential for a systematic offset between the measured ages, perhaps as a hitherto-unrecognised artefact of one or both measurement techniques. Furthermore, the existing comparison emphasises the value of high-precision data when seeking to assign geological significance to a discrepancy in measured ages. On that basis, we pursued ID-TIMS dating of baddeleyites from sample 97106010, using crystals plucked directly from our SHRIMP mounts.

Analytical methods

ID-TIMS analyses were conducted in May 2019 at the Isotope Geology Laboratory at Boise State University, USA. Six individual baddeleyite crystals previously analysed via SHRIMP (and labelled in red in Appendix Figures A1 and A2), were manually plucked from mounts Z2779 and Z2895, spiked with the EARTHTIME mixed ^{202}Pb–^{205}Pb–^{233}U–^{235}U tracer solution (ET2535), and each was analysed as a discrete ID-TIMS fraction. Fractions and grain-numbers are cross-referenced in Appendix Table A4, and analytical methods are described in detail in the Appendix.

ID-TIMS U–Pb isotopic data for sample 97106010

Six analyses were collected from six baddeleyites (Figure 5, Appendix Table A4). Common Pb was very low (0.106–0.144 pg, median 0.109 pg), and $^{206}Pb/^{204}Pb$ was quite high (5164–12792, median 6478) in view of the low U contents inferred from the SHRIMP analyses. Radiogenic ^{206}Pb as a percentage of total ^{206}Pb spanned the range 99.65–99.86 mol%, with a median of 99.72 mol%.

All six analyses are discernibly discordant (0.7–2.4%; Figure 5a, Appendix Table A4), but the population defines a statistically coherent discordia regression with upper and lower concordia intercepts of 1326.7 ± 1.1 Ma and −123 ± 180 Ma, respectively (95% confidence, excluding uncertainties on the ^{235}U and ^{238}U decay constants as measured by Jaffey *et al.*, 1971; MSWD = 0.62, $P = 0.65$). We interpret this array to reflect magmatic crystallisation of a cogenetic baddeleyite suite at *ca* 1326.7 Ma, with each crystal affected to varying degrees by geologically recent (zero-age) loss of radiogenic Pb. The fact that the lower intercept is indistinguishable from zero means that the magmatic crystallisation age is best estimated using the $^{207}Pb/^{206}Pb$ measurements (Figure 5b). These too form a statistically coherent population, with their weighted mean (0.085525 ± 0.000026 at 95% confidence, excluding decay constant uncertainties; MSWD = 0.87, $P = 0.50$) corresponding to a date of 1327.5 ± 0.6 Ma (Figure 5b).

The $^{207}Pb/^{206}Pb$ ratios and dates in Appendix Table A4 are predicated on present-day $^{238}U/^{235}U$ = 137.88 (Steiger & Jäger, 1977), for direct comparability with the multiple generations of U–Pb SHRIMP data processing. Using the more recently measured terrestrial average $^{238}U/^{235}U$ (137.818; Hiess *et al.*, 2012) would displace the weighted mean $^{207}Pb/^{206}Pb$ date *ca* 0.9 Ma younger.

Discussion

Comparing SHRIMP and ID-TIMS results for 97106010

The two technique-specific weighted mean $^{207}Pb/^{206}Pb$ dates constraining igneous crystallisation of sample 97106010 (1322.3 ± 3.1 Ma defined by 145 of 162 SHRIMP analyses, and 1327.5 ± 0.6 Ma defined by six of six ID-TIMS analyses) are completely distinct at the 95% confidence level. The high-precision ID-TIMS data indicate very minor (0.7–2.4%) loss of radiogenic Pb in geologically recent times, but no other isotopic dispersion is discernible, and

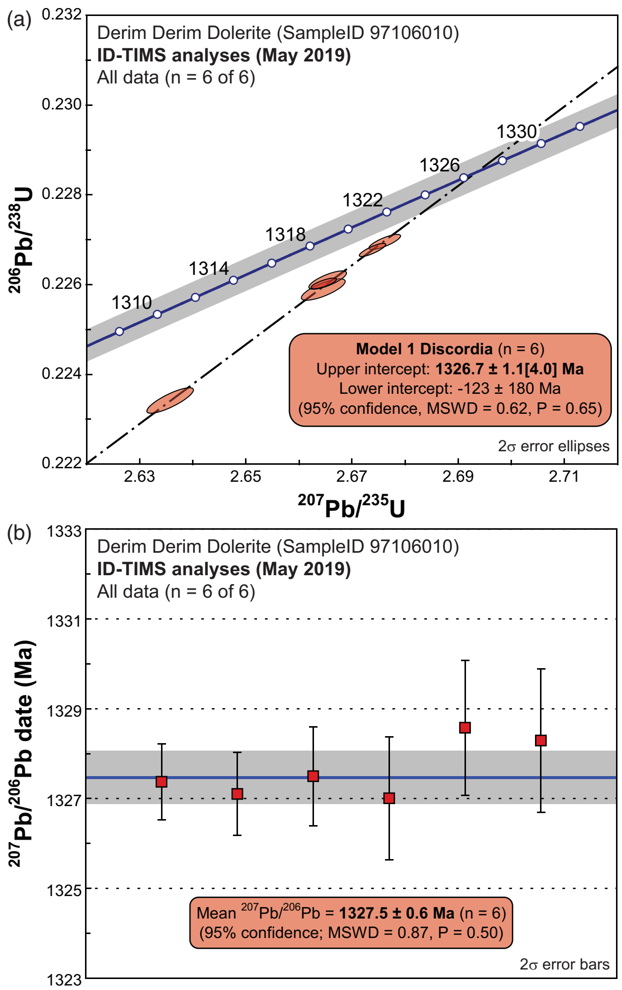

Figure 5. (a) Conventional (Wetherill) concordia diagram for ID-TIMS U–Pb baddeleyite data from sample 97106010. Heavy black dot-dashed line is the Model 1 discordia regression; grey envelope on concordia curve reflects ^{235}U and ^{238}U decay constant uncertainties of Jaffey *et al.* (1971), and the upper intercept 95% confidence intervals of 1.1 Ma and 4.0 Ma exclude and include (respectively) those uncertainties. (b) One dimensional $^{207}Pb/^{206}Pb$ dates in the sequence defined by Appendix Table A4. The 95% confidence interval excludes the decay-constant uncertainties, as the same decay constants are used for all ID-TIMS and SHRIMP datasets being compared.

the associated weighted mean $^{207}Pb/^{206}Pb$ date of 1327.5 ± 0.6 Ma is our best estimate of the true magmatic crystallisation age of the Derim Derim Dolerite at its type locality.

The overall tendency of the SHRIMP datasets towards slightly younger $^{207}Pb/^{206}Pb$ dates could represent analytical artefacts (such as instrumental mass fractionation of Pb isotopes, and/or isobaric interferences resulting in 'overcounting' of ^{204}Pb and consequent overcorrection of the measured $^{207}Pb/^{206}Pb$ for non-radiogenic Pb), or geological dispersion arising principally from varying degrees of ancient leakage of radiogenic Pb. The relative difference between the SHRIMP and ID-TIMS means is less than 0.5%, so analytical artefacts are difficult to rule out; however, instrumental mass fractionation of Pb isotopes is not resolvable at inter-session scale in the sets of concurrent measurements of the Phalaborwa reference baddeleyite (Table 2). Three of the four sessions yielded high-precision weighted mean $^{207}Pb/^{206}Pb$ values (with relative 95% confidence intervals of 0.25–0.30%); the fourth (Z2895 in 1997) yielded a marginally younger value (and a greater degree of internal dispersion), but the concurrently analysed 97106010 baddeleyites yielded the *oldest* of the four session-specific weighted mean $^{207}Pb/^{206}Pb$ values, so it is unlikely that the session was affected by instrumental mass fractionation. Isobaric interferences at the ^{204}Pb measurement position are best monitored using a Pb-poor reference material (Black, 2005), and the 2019 sessions employed the co-mounted SL13 reference zircon (Table 2). The universally low count-rates (of 'true' ^{204}Pb and of any putative isobaric interference) means that very low rates of ^{204}Pb-overcounting are difficult to detect, but both mounts yielded ^{204}Pb-corrected $^{207}Pb/^{206}Pb$ values well within error of the SL13 reference value (albeit with relative 95% confidence intervals of the order of 1.5–2.0%), and the two ^{204}Pb overcount-rates bracket zero (Table 2). No analogous measurements were made during the 1997 sessions, but the fact that ^{204}Pb-corrected $^{207}Pb/^{206}Pb$ values for 97106010 in 1997 tend to be *older* than those measured in the overcount-free 2019 sessions suggests that the 1997 sessions were similarly unaffected by ^{204}Pb overcounts.

We therefore turn our attention to ancient loss of radiogenic Pb as a potential mechanism for the tendency towards younger $^{207}Pb/^{206}Pb$ dates in the SHRIMP data relative to ID-TIMS. Although the 145 SHRIMP analyses defining magmatic crystallisation at 1322.3 ± 3.1 Ma are equivalent within their analytical uncertainties (MSWD = 1.19, $P = 0.06$) across the four analytical sessions, one striking feature of Figure 4 is the prevalence of younger $^{207}Pb/^{206}Pb$ dates obtained from Z2779 during its 2019 session (Figure 4c). This session was uniquely complicated by the need to analyse an over-polished mount-surface featuring a large number of suboptimal remnant shards of baddeleyite. Some domains within these shards are demonstrably affected by ancient loss of radiogenic Pb, as evidenced by the five analyses (with elevated common ^{206}Pb and post-1210 Ma dates) already culled from the younger end of the measured distribution (Figure 4c), so it is possible that other analyses are affected by minor 'cryptic' leakage of radiogenic Pb (*i.e.* insufficient to disperse the remaining population beyond its [large] experimental uncertainties, but sufficient to bias the weighted mean to a marginally younger value).

This idea can be tested by omitting all 34 of the magmatic analyses collected during the 2019 session on Z2779 and recalculating the combined SHRIMP date based solely on the 111 magmatic analyses collected in the remaining three sessions. The revised calculation yields a statistically coherent weighted mean $^{207}Pb/^{206}Pb$ date of 1323.5 ± 3.3 Ma (MSWD = 1.19, $P = 0.09$), which is slightly closer to the ID-TIMS weighted mean $^{207}Pb/^{206}Pb$ date of 1327.5 ± 0.6 Ma; however, the two 95% confidence intervals still do not overlap. This might indicate that one or more of the remaining three sessions is similarly affected by cryptic ancient loss of radiogenic Pb from some crystal domains.

The history of ancient leakage of radiogenic Pb inferred from the SHRIMP datasets is at odds with the ID-TIMS data (in which recent loss of radiogenic Pb is discernible, but ancient Pb loss is not), but this apparent difference mostly reflects limitations inherent in SIMS U–Pb analysis of baddeleyite, as well as the overall quality of target crystals as a function of the vastly different sizes of the technique-specific analytical populations.

Any assessment of recent loss of radiogenic Pb requires accurate and precise determination of $^{206}Pb/^{238}U$ for individual analyses so isotopic concordance can be evaluated. As noted above, this is not possible for baddeleyite SHRIMP data, owing to the crystal orientation effect (Wingate & Compston, 2000). In our SHRIMP datasets, 2σ uncertainties of individual calibrated $^{238}U/^{206}Pb$ analyses are of the order of 10–15%, so the 0.7–2.4% discordance indicated by the ID-TIMS data array might well be present in the SHRIMP data as well, but it will not be discernible.

We interpret the apparent prevalence of ancient loss of radiogenic Pb in the SHRIMP datasets as a combination of compromised mount-surfaces (for the 2019 sessions in particular), plus the increased likelihood of analysing non-pristine baddeleyite crystal domains in the course of collecting a total of 162 analyses from a target population numbering only about 400 baddeleyites. In contrast, ID-TIMS dating usually requires only a small number of analyses, so the selection of targets unlikely to be affected by post-crystallisation isotopic disturbance is correspondingly easier.

Mesoproterozoic intraplate magmatism in Northern Australia

All three baddeleyite $^{207}Pb/^{206}Pb$ datasets from outcrop sample 97106010 (1323.5 ± 4.0 Ma by SHRIMP in 1997, 1320.1 ± 5.3 Ma by SHRIMP in 2019, and 1327.5 ± 0.6 Ma via ID-TIMS) indicate a pre-1320 Ma magmatic crystallisation age for the Derim Derim Dolerite at its type locality in the northwestern McArthur Basin. Our result is distinctly older than the ID-TIMS baddeleyite $^{207}Pb/^{206}Pb$ date of 1313.8 ± 1.0 Ma (Yang *et al.*, in press) from drill-hole POG Altree 2 (and its corresponding $^{206}Pb/^{238}U$ date of 1312.9 ± 0.7 Ma; Collins *et al.*, 2018) in the Beetaloo Sub-basin 200 km to the south, and indicates a spread of ages for mafic magmatism attributed to the Derim Derim Dolerite.

The age range is regionally significant, as intraplate mafic plutonic rocks of similar geochemistry and broadly similar age extend well beyond the Roper Group, and the McArthur Basin. Whelan *et al.* (2016) reported a SIMS U–Pb baddeleyite age of 1325 ± 36 Ma (2σ) for the Galiwinku Dolerite (about 170 km northwest of sample 97106010), which is part of a radiating swarm of dykes within the northern margin of the McArthur Basin (Goldberg, 2010). These dykes are spatially associated with the peralkaline Maningkorrirr Phonolite and Mudginberri Phonolite in the Nimbuwah Domain of the eastern Pine Creek Orogen (Hollis & Glass, 2012; Stuart-Smith & Needham, 1984), for which Page *et al.* (1980) determined an Rb–Sr date of 1316 ± 40 Ma. Similarly, Melville (2010) reported a SHRIMP U–Pb baddeleyite age of 1295 ± 14 Ma from gabbro intruding the Renner Group in the Tomkinson Province southwest of the McArthur Basin, about 220 km south of Altree 2, and over 400 km south of sample 97106010. The samples dated by Melville (2010) and Whelan *et al.* (2016) are almost 600 km apart.

The relatively low precision of many of these age constraints precludes any detailed assessment of the timing or temporal span of individual pulses of mafic Mesoproterozoic magmatism. Based on the criteria of Bryan and Ernst (2008), the *ca* 15 Ma separation between the two high-precision ID-TIMS dates from the Derim Derim Dolerite does not preclude the two dated units belonging to the same mafic igneous province. However, the range of emplacement ages offers a partial explanation for some of the regional geochemical variations documented by Whelan *et al.* (2016), with particular respect to the transition from high- to low-Ti/Y rocks within the Galiwinku Dolerite, Maningkorrirr Phonolite and Mudginberri Phonolite (Whelan *et al.*, 2016). Hollis and Glass (2012) interpreted these geochemical variations in terms of different depths of partial melting in the source region, and the new high-precision ID-TIMS dating from the Derim Derim Dolerite raises the possibility that the observed variations in Ti/Y could reflect temporally distinct pulses of magmatism.

Correlation with the Yanliao Large Igneous Province in the North China Craton

Establishing a minimum duration of 10–15 Ma for emplacement of the Derim Derim-Galiwinku mafic igneous province strengthens already striking similarities between the nature and timing of intraplate mafic magmatism in the Northern Territory and that preserved within the predominantly Mesoproterozoic Yanliao rift zone in the northern North China Craton (*e.g.* Zhang *et al.*, 2017). A series of baddeleyite $^{207}Pb/^{206}Pb$ dates indicate that emplacement of the dolerite sills defining the Yanliao Large Igneous Province commenced at *ca* 1330 Ma and terminated at *ca* 1305 Ma, with an apparent peak in magmatic activity at *ca* 1323 Ma (Wang *et al.*, 2014; Zhang *et al.*, 2009, 2017). Zhang *et al.* (2017) also emphasised the strong geochemical similarities between the tholeiitic to subalkaline basaltic compositions common to the Yanliao and Derim Derim-Galiwinku igneous provinces, although the Yanliao rocks also encompass more andesitic compositions that are not yet known from Derim Derim-Galiwinku (Whelan *et al.*, 2016 and references therein).

Globally, intraplate mafic magmatism in the 1330–1300 Ma range appears to be restricted to the Yanliao and Derim Derim-Galiwinku LIPs (Ernst, 2014), which constitutes circumstantial evidence that the North Australian Craton and the North China Craton were at least near neighbours (if not connected) during the Mesoproterozoic (*e.g.* Collins *et al.*, 2019; Zhang *et al.*, 2017). Testing of this hypothesis awaits the establishment of mid-Mesoproterozoic paleomagnetic poles for the North Australian Craton, for comparison with existing data from the North China Craton (Xu *et al.*, 2014).

Contrast with contemporaneous mafic magmatism in southwestern Australia

The new ID-TIMS dates for the Derim Derim Dolerite establish at least partial contemporaneity between the Derim Derim-Galiwinku igneous province and voluminous mafic plutonism of the Fraser Complex within the Albany-Fraser Orogen of southwestern Australia. Fletcher *et al.* (1991) determined a whole-rock Sm–Nd age of 1291 ± 21 Ma on Fraser Complex gabbro, and Claoué-Long and Hoatson (2009) grouped the Fraser Complex and Derim Derim Dolerite into the *ca* 1310 Ma Fraser Event (Mafic Event ME 44 of Thorne *et al.*, 2014). Dating magmatic crystallisation of Fraser Complex mafic rocks is complicated by overprinting 1300–1290 Ma high-grade metamorphism (*e.g.* C. Clark *et al.*, 2014; D. J. Clark *et al.*, 1999; De Waele & Pisarevsky, 2008); however, Glasson *et al.* (2019) obtained a U–Pb date of 1315 ± 5 Ma from a texturally distinctive zircon–ilmenite association ascribed to igneous crystallisation.

The tectonic setting of Fraser Complex mafic magmatism remains debated (Glasson *et al.*, 2019), with interpretations of emplacement into an intracratonic rift (*e.g.* Smithies *et al.*, 2013; Spaggiari *et al.*, 2011) competing with hypotheses invoking a back-arc setting (*e.g.* Clark *et al.*, 2014; Kirkland *et al.*, 2011; Morrissey *et al.*, 2017). The latter emphasises the likelihood of an arc-related origin for temporally related (1330–1280 Ma) calc-alkaline felsic plutonism of the Wankanki Supersuite in the Musgrave Province (*e.g.* Howard *et al.*, 2011; Smithies *et al.*, 2010), and, to a lesser extent, the Recherche Supersuite in the southern Albany-Fraser Orogen (*e.g.* Kirkland *et al.*, 2015; Smithies *et al.*, 2015), including *ca* 1300 Ma granites within the Fraser Complex (*e.g.* Clark *et al.*, 1999).

Despite the absence of definitive geochemical and isotopic evidence (Glasson *et al.*, 2019; Smithies *et al.*, 2013), the tectonic setting of the Fraser Complex appears distinct from that of the Derim Derim Dolerite and its likely correlatives (Melville, 2010; Whelan *et al.*, 2016). Unlike the Fraser Complex, the Derim Derim-Galiwinku province is notable for its lack of (preserved) coeval felsic magmatic rocks; furthermore, it appears unaffected by post-magmatic regional metamorphism (as evidenced by the preservation of synmagmatic Rb–Sr dates within Jalboi Formation shales hosting the Derim Derim Dolerite in drill-hole BMR Urapunga 5; Collins *et al.*, 2019). Both of these features are consistent with an intraplate origin for the Derim Derim-Galiwinku province. It is therefore likely that Australia-wide mafic magmatism attributed to the *ca* 1310 Ma Fraser Event (Claoué-Long & Hoatson, 2009; Mafic Event ME 44 of Thorne *et al.*, 2014) spans a range of tectonic settings in the crust.

Conclusions

For two decades, the magmatic crystallisation age of the regionally significant Derim Derim Dolerite in the McArthur Basin has been constrained by a widely cited (but unpublished) U–Pb SHRIMP baddeleyite date of 1324 ± 4 Ma (J. Claoué-Long, personal communication, 1997 in Abbott *et al.*, 2001). Our review of the historic data established that the baddeleyite-bearing sample was collected in outcrop at the type locality of the Derim Derim Dolerite (rather than from drillcore from BMR Urapunga 5, located 90 km to the southeast), and confirmed the weighted mean $^{207}Pb/^{206}Pb$ date of 1324 ± 4 Ma derived from the U–Pb SHRIMP dataset collected in 1997. Our 2019 SHRIMP reanalysis of the same grain-mounts reproduced this result, yielding a weighted mean $^{207}Pb/^{206}Pb$ date of 1320.1 ± 5.3 Ma. ID-TIMS U–Pb analyses of baddeleyite crystals plucked from the SHRIMP mounts yielded a high-precision weighted mean $^{207}Pb/^{206}Pb$ date of 1327.5 ± 0.6 Ma, which is now the best estimate of the magmatic crystallisation age of the Derim Derim Dolerite at its type locality.

This date is significantly older than a baddeleyite U–Pb ID-TIMS date of *ca* 1313 Ma recently reported from dolerite in the Beetaloo Sub-basin (Collins *et al.*, 2018; Yang *et al.*, in press), some 200 km south of the Derim Derim Dolerite type locality, which indicates that magmatism attributed to the Derim Derim Dolerite spanned at least 10–15 Ma. The possibility of episodic emplacement of phonolites and intraplate mafic rocks as far afield as the Nimbuwah Domain of the eastern Pine Creek Orogen (Hollis & Glass, 2012; Whelan *et al.*, 2016), and the Tomkinson Province (Melville, 2010), has hitherto been obscured by the relatively low precision of the available isotopic dates. Hollis and Glass (2012) documented a range of Ti/Y values in mafic rocks of the Nimbuwah Domain, which they interpreted to reflect different depths of partial melting, and it is possible that such variations can be attributed to temporally distinct pulses of magmatism. Zhang *et al.* (2017) documented a strikingly similar range of baddeleyite $^{207}Pb/^{206}Pb$ dates (*ca* 1330 Ma to *ca* 1305 Ma, with peak activity at *ca* 1323 Ma) from the Yanliao rift zone of the North China Craton and demonstrated strong geochemical similarities between the Yanliao and Derim Derim-Galiwinku mafic rocks. Even in the absence of supporting paleomagnetic data, these relationships suggest that the North Australian Craton and North China Craton were near-contiguous in the Mesoproterozoic (Zhang *et al.*, 2017), and defined the epicontinental 'McArthur-Yanliao Gulf' within the supercontinent Nuna/Columbia (Collins *et al.*, 2019).

The Derim Derim-Galiwinku and Yanliao igneous provinces are also contemporaneous with voluminous *ca* 1315–1300 Ma gabbroic rocks of the Fraser Complex in the Albany-Fraser Orogen of southwestern Australia; however, the Fraser Complex is associated with calc-alkaline granitic rocks and was overprinted by regional granulite facies metamorphism. This indicates that coeval mafic magmatic events at continent-scale need not be tectonically linked.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

S. Bodorkos http://orcid.org/0000-0001-8605-0276
J. L. Crowley http://orcid.org/0000-0001-5069-0773
J. R. Anderson http://orcid.org/0000-0003-3360-2027

Data availability

The data (Appendix, Appendix Tables, and Appendix Figures) that support the findings of this study are openly available in the Geoscience Australia data repository at http://pid.geoscience.gov.au/dataset/ga/127403.

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