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A. J. Mory
Geological Survey of Western Australia

J. Crowley
Boise State University

J. Backhouse
University of Western Australia

R. S. Nicoll

J. D. Gorter

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Early Permian zircon ages from the *P. confluens* and *P. pseudoreticulata* spore-pollen zones in the southern Bonaparte and Canning basins, northwestern Australia

A. J. Mory[a], J. Crowley[b], J. Backhouse[c], R. S. Nicoll[d] and J. D. Gorter[e]

[a]Geological Survey of Western Australia, East Perth, Australia; [b]Department of Geoscience, Boise State University, Boise, ID, USA; [c]School of Earth Sciences, The University of Western Australia, Crawley, Australia; [d]Bungendore, NSW, Australia; [e]John D Gorter PL, Claremont, WA, Australia

ABSTRACT
The *Pseudoreticulatispora confluens*–*P. pseudoreticulata* spore-pollen zonal datum typically coincides with the end of widespread Permian glacial deposits in Western Australia. Although previously attributed to the mid-Sakmarian, chemical abrasion isotope dilution thermal ionisation mass spectrometry (TIMS) dating of zircons from volcanic tuffs in the Ditji Formation of the Bonaparte Basin and the Grant Group in the Canning Basin point to an Asselian age of about 295.25 Ma for this datum. All dated zircons from the Ditji Formation came from petroleum well cuttings but the accompanying palynology was mostly from sidewall cores; however, all Grant Group samples were from conventional core. TIMS dates from the Ditji Formation range in age from 295.2 to 292.7 Ma whereas the only productive tuff from the Grant Group yielded a 296.26 Ma date. By comparison, there are no zircon dates to constrain the onset of glacial deposition in Australia. The Bonaparte Basin ages overlap with those for the Edie Tuff (296.1–294.5 Ma) in Queensland's Galilee Basin, approximately 2000 km to the southeast, which also lies close to the base of the *P. pseudoreticulata* Zone. To date the only fossil group within the *P. confluens* Zone in Western Australia to provide independent age control, albeit loosely, are goniatites from the northern Perth Basin (*Uraloceras irwinense* and *Juresanites jacksoni)* that have consistently been attributed to the Sakmarian; these require a reassessment of their affinity with Russian faunas and therefore to global stratotypes. The position of the Carboniferous–Permian boundary is elusive in Australia and will remain so until additional volcanic tuffs containing young datable zircons are found; however, spore-pollen and zircon dates from Namibia place this boundary within the *P. confluens* Zone.

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Introduction

The Australian Carboniferous–Permian spore-pollen zonation is based mostly on endemic species but is widely used to constrain stratigraphic correlations within and between the many basins of this age across the continent (Figure 1; *e.g.* Backhouse, 1998; Jones & Truswell, 1992; Kemp *et al*., 1977; Laurie *et al*., 2016; Mory & Backhouse, 1997). However, use of this zonation is confined largely to the subsurface as outcrops typically are too oxidised to preserve palynomorphs. Even where macrofossils are recorded, links between them and the spore-pollen zonation can be tenuous, as are relationships to the international chronostratigraphic scheme (Gradstein *et al*., 2020), particularly for the mid-Pennsylvanian–lowermost Cisuralian. Within this interval, Australian marine faunas, where present, yield unclear ages owing to endemism, low diversity and sporadic distributions influenced by adverse climates—most notably the Late Paleozoic Ice Age (LPIA). Similarly, the associated spore-pollen zonation relies on relatively few species that yield only broad age control. The age of Asselian faunas has been especially difficult to confirm as conodonts, fusulinids and critical ammonoid species are unknown across most of Gondwana and its periphery (Archbold, 2001). Consequently, existing biostratigraphic schemes, even those based on marine organisms, have provided only tenuous or ambiguous age control. There has been a concerted effort to remedy this for the Guadalupian and Lopingian in Australia, mostly from the eastern part of the continent, using chemical abrasion isotope dilution thermal ionisation mass spectrometry

CONTACT A. J. Mory arthur.mory@dmirs.wa.gov.au Geological Survey of Western Australia, East Perth, WA, Australia
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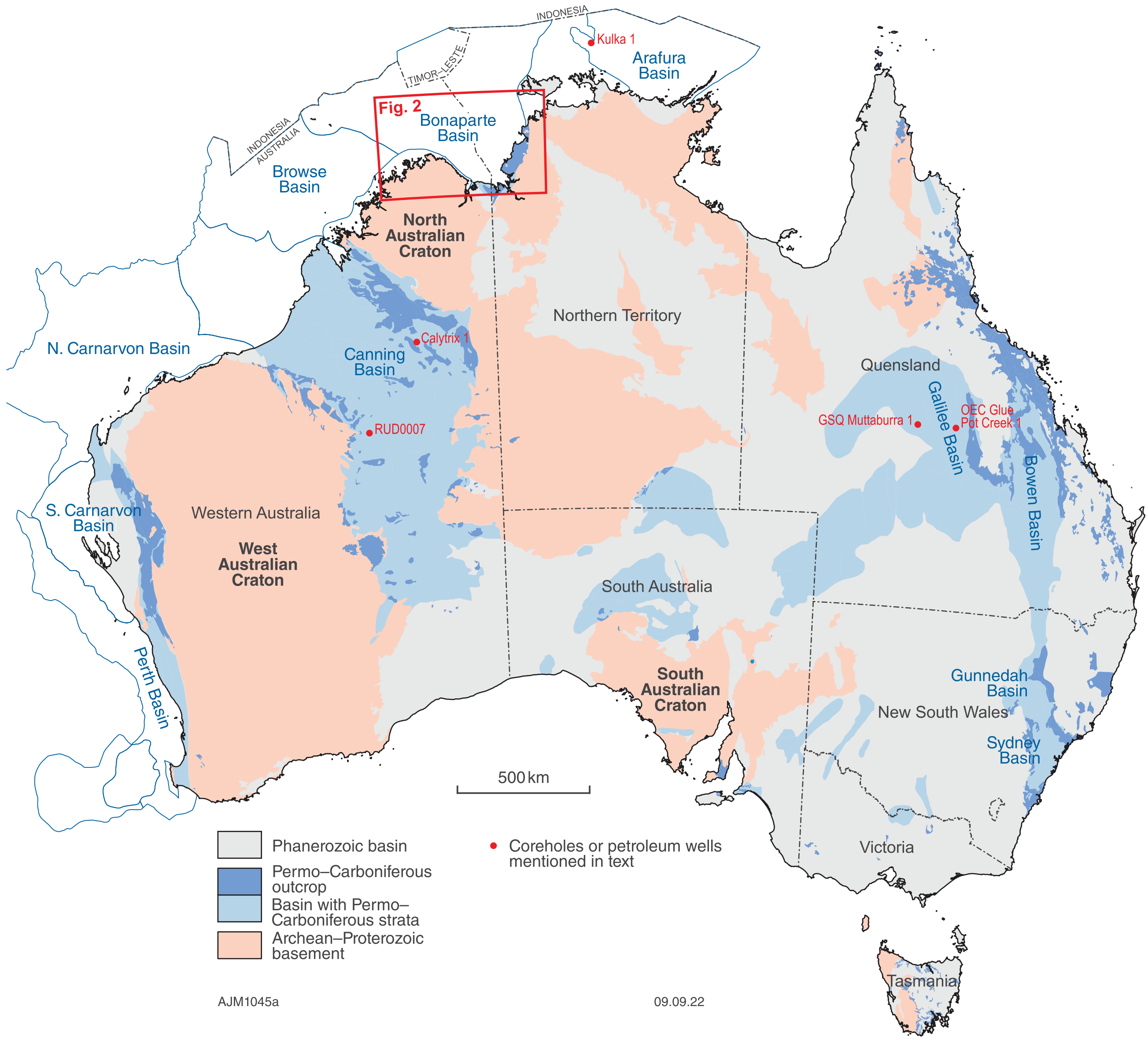

Figure 1. Australian basins and localities external to the Bonaparte Basin mentioned in the text. Onshore geology after Craddock *et al.* (2019, Figure 6a).

(TIMS) dating of zircons from volcanic tuffs intercalated within palynomorph-bearing strata (Laurie *et al.*, 2016; Phillips *et al.*, 2018a). However, Pennsylvanian–lower Cisuralian strata have received relatively little attention. Volcanic tuffs are rare in this interval, apart from within the Pennsylvanian of New South Wales where the SHRIMP dating of Roberts *et al.* (1995a, 1995b, 1996) and Birgenheier *et al.* (2009) provided limited links to the spore-pollen zonation; however, their dates have yet to be revisited using more precise methods such as TIMS.

In Western Australia (WA), the only published Permian tuffs dates are Guadalupian from the Kennedy Group (Lever & Fanning, 2004) and Liveringa Group (Laurie *et al.*, 2016; Mory *et al.*, 2017) of the Southern Carnarvon and Canning basins, respectively. Possible Permian tuffs from the Artinskian Irwin River Coal Measures in the Perth Basin yielded only reworked pre-Permian zircons (Vladimir I. Davydov, pers comm.). The present study focusses on tuffs from the Ditji Formation in the southern Bonaparte Basin (Figures 2 and 3), first reported by Gorter *et al.* (2008), and a recently located tuff in the Grant Group of the southern Canning Basin from mineral exploration core hole Fortescue RUD0007.

Here we present laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) and TIMS zircon dates from volcanic tuffs within the Grant Group of the southern Canning Basin and the Ditji Formation in the southern Bonaparte Basin (Figures 3 and 4; Gorter *et al.*, 2008). The former unit in the sampled core hole lies entirely within the *P. confluens* spore-pollen Zone, whereas the latter lies immediately above in the lower *P. pseudoreticulata* Zone. That level typically coincides with the end of

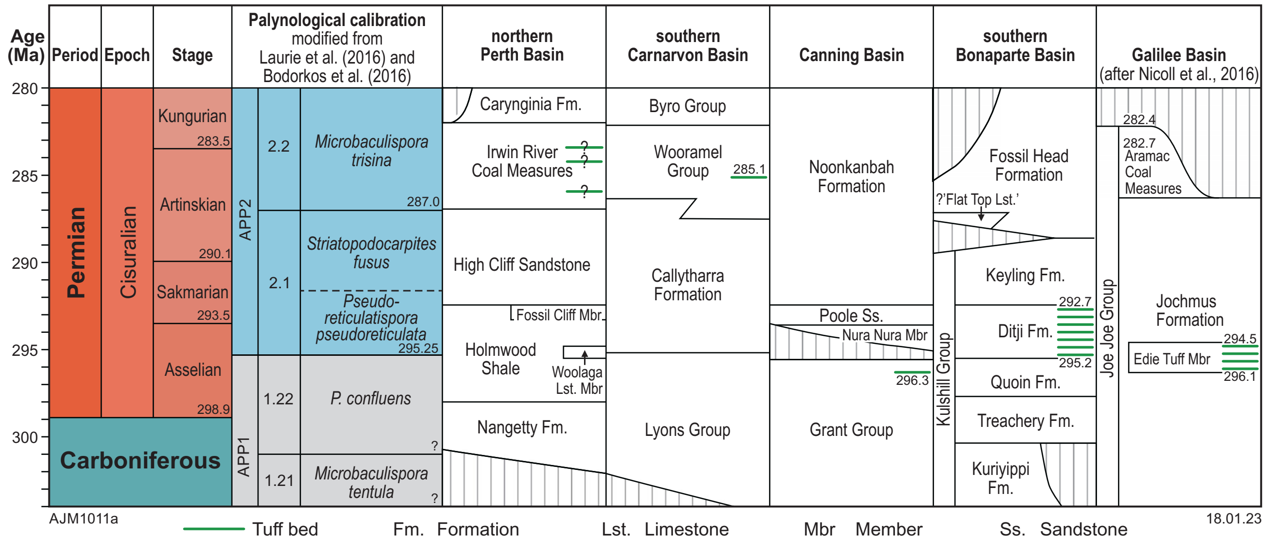

Figure 2. Upper Pennsylvanian–mid-Cisuralian stratigraphic correlation of the Bonaparte Basin with other basins in Western Australia and the Galilee Basin in Queensland to the international chronostratigraphic scheme.

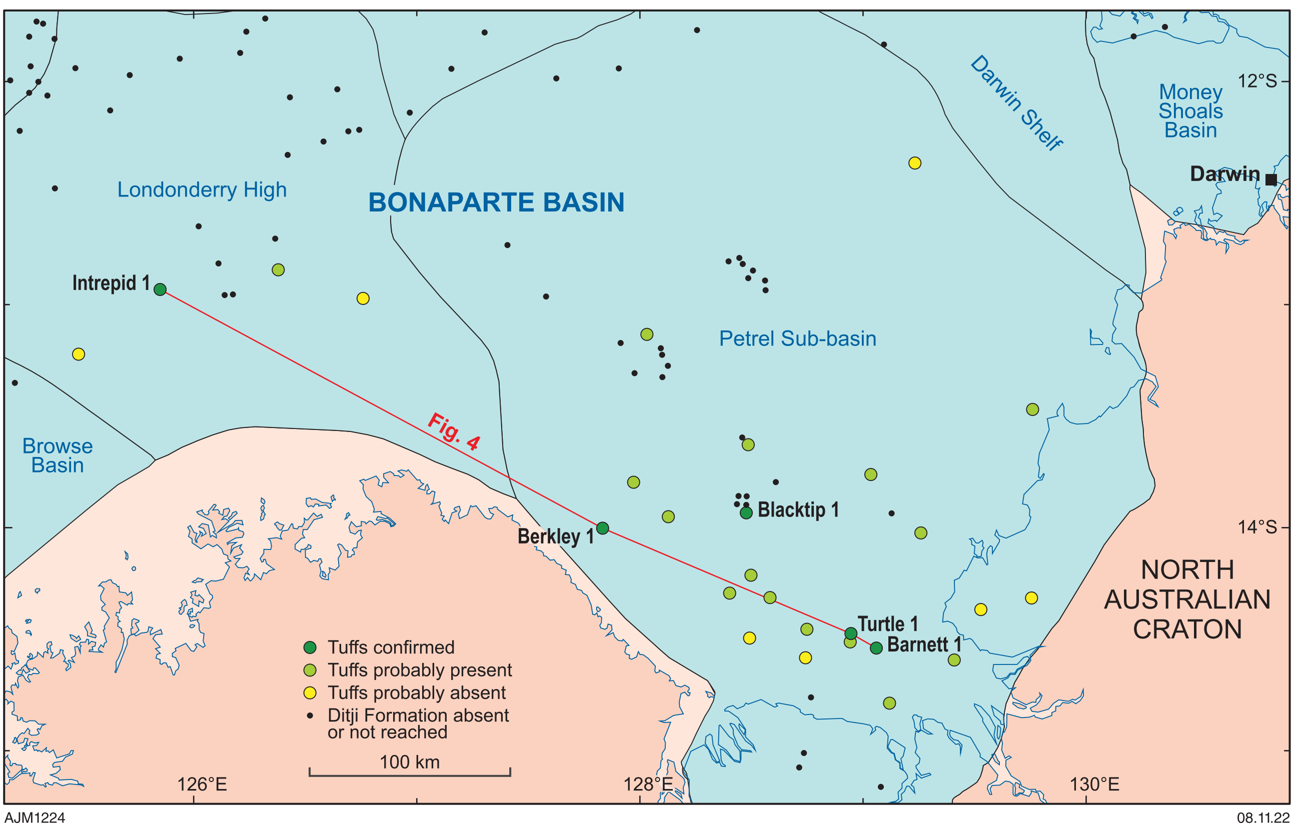

Figure 3. Southern Bonaparte Basin showing the distribution of the Ditji Formation in petroleum exploration wells and those with volcanic tuffs (mostly based on wireline log interpretations, formation picks summarised in Supplemental data, Table S2).

widespread LPIA glacial facies in WA, especially in the Perth, Southern Carnarvon and Canning basins (Figure 2; Backhouse, 1993b; Backhouse & Mory, 2020; Mory & Backhouse, 1997; Mory *et al.*, 2008). In earlier literature (summarised in Backhouse & Mory, 2020, p. 5–9) this datum equates with the top of palynological Unit II in WA or the top of Stage 2 in eastern Australia.

Regional geology

In eastern Australia three distinct Carboniferous and four Permian LPIA glacial pulses have been identified (Birgenheier *et al.*, 2009; Fielding *et al.*, 2008a, 2008b, 2022) but their veracity in WA is uncertain (Haig *et al.*, 2014) where a hiatus, attributed to major ice sheets inhibiting deposition, spans much of the Pennsylvanian (Backhouse & Mory, 2020). This break was followed by deposition of widespread glacial facies during the latest Pennsylvanian to early Cisuralian, with subsequent minor and less continuous Artinskian–Kungurian (late Cisuralian) glacial deposits attributed to sea ice in WA (Haig *et al*., 2014) possibly coeval with the end of the P2 glacial pulse in eastern Australia. The end of the main glacial phase in WA is typically regarded to be within the Sakmarian based on regional correlations (*e.g.* Haig *et al*., 2014) and goniatite faunas from the Perth Basin considered close to Russian assemblages, even though there are no species in common (Leonova, 1998, 2011, 2018). Differences in the durations and timing of Permian glacial pulses between the east and west of the Australian continent are attributed to a temperate Tethyan oceanic influence in the west compared with a combination of alpine glaciation and direct seaway connection from the South Pole in the east (Brakel & Totterdell, 1990).

In WA, Carboniferous–Permian glacial facies extend across all Paleozoic basins and arguably represent the first time when there was little, if any, difference in facies between basins. These facies are assigned to the lower–middle Kulshill Group in the Bonaparte Basin, the Grant Group in the Canning Basin, the Lyons Group in the Northern and Southern Carnarvon basins, and the Nangetty Formation in the Perth Basin (Mory *et al*., 2008). Directly overlying these strata in all WA basins are marine facies typically including carbonate, indicative of a warmer climatic phase than the glacially influenced interval (Figure 4; Haig *et al*., 2014).

Bonaparte Basin stratigraphy

The sampled wells from the southern Bonaparte Basin (Figures 3 and 4; Table 1) illustrate a 385-km traverse along the southwestern margin of the basin encompassing glacial–post-glacial, dominantly siliciclastic facies of the Pennsylvanian–Cisuralian Kulshill Group. As revised by Gorter *et al*. (2008), this succession transitions from dominantly glacio-fluvial fining-up cycles, each up to 90 m thick, within the Kuriyippi Formation, to glacio-marine facies of the Treachery Formation showing basal sub-glacial valleys eroded into the underlying strata and evidence of freshwater influx during deglaciation. The overlying Quoin Formation demonstrates waning glacial conditions in a tidal environment in response to deglaciation of the hinterland. The succeeding Ditji Formation contains dominantly marine facies with thin volcanic tuffs up to 85 cm thick, overlain by largely fluvial facies of the Keyling Formation, which is the uppermost unit of the Kulshill Group. Initial correlations tied to seismic profiles by Gorter *et al*. (2008) show distinct incisions or erosional surfaces at most formation boundaries. The base of the Ditji Formation shows a flooding event coincident with the *Pseudoreticulatispora confluens*–*P. pseudoreticulata* palynological datum.

Gorter *et al*. (2008, p. 95) interpreted a distinctive volcanic ash bed in the Ditji Formation, based on wireline logs showing consistent high radioactivity, low resistivity, low sonic velocity and high density, and traced 36 km south of the Barnett oilfield and Blacktip gasfield to Weasel 1. The temporal relationship they suggested with an intrusive dolerite dated at 293 ± 3 Ma by K–Ar in Kulka 1, 620 km northeast in the Goulburn Graben in the Arafura Basin (Diamond Shamrock, 1985, Appendix 4) remains speculative, even though the updated K-decay constant from Renne *et al*. (2011) indicates an age of 295.5 ± 3.0 Ma. Demonstration of a genetic relationship between the Arafura Basin intrusion and the Bonaparte Basin tuffs requires zircon Lu–Hf isotope analyses from both areas but first requires the recovery and dating of zircons from the Arafura Basin. Such analyses could also confirm that the tuffs within the Ditji Formation in Intrepid 1, 375 km west-northwest of the Turtle oilfield, are from the same source, but is beyond the scope of the present study. Other wells apart from those sampled for this study probably also contain tuffs in at least the Ditji Formation based on interpreted wireline log responses (Figure 3) but cannot be easily substantiated given the lack of core.

Canning Basin stratigraphy

Recent revisions of the Permian stratigraphy of this basin (Backhouse & Mory, 2020; Mory, 2010) emphasise the variation in lower Permian glacial and deltaic facies within the Grant Group, and suggest all formations identified within the group are of too limited extent to be useful for regional correlations. Directly overlying the group are warmer water facies of the Nura Nura Member at the base of the Poole Sandstone, which is a lateral equivalent to the Ditji Formation based on the contained palynoflora (Figure 2). The only known Cisuralian tuff in the basin known to date is from the Grant Group about 180 m below the Poole Sandstone in Fortescue RUD0007 where the group directly overlie Precambrian gabbro.

Spore-pollen zonation

The *Granulatisporites confluens* Oppel-zone, established by Foster and Waterhouse (1988) from Calytrix 1 in the Canning Basin (Figure 1), is widely recognised across Australia and other Gondwanan basins including within Namibia (Stephenson, 2009). As *Granulatisporites* is a non-cheilocardioid spore from the European Pennsylvanian with a sculpture of discrete grana only, Backhouse (1991) and Playford and Dino (2002) re-assigned the eponymous species to *Pseudoreticulatispora*, a Gondwanan genus within the cheilocardioid lineage, characteristic of Permian strata, and emended the zone's name accordingly, but the definition of the zone remains largely unchanged. This reassignment is in accord with Price and Foster (in Price, 1983, p. 169), who previously included forms with a reticulate distal

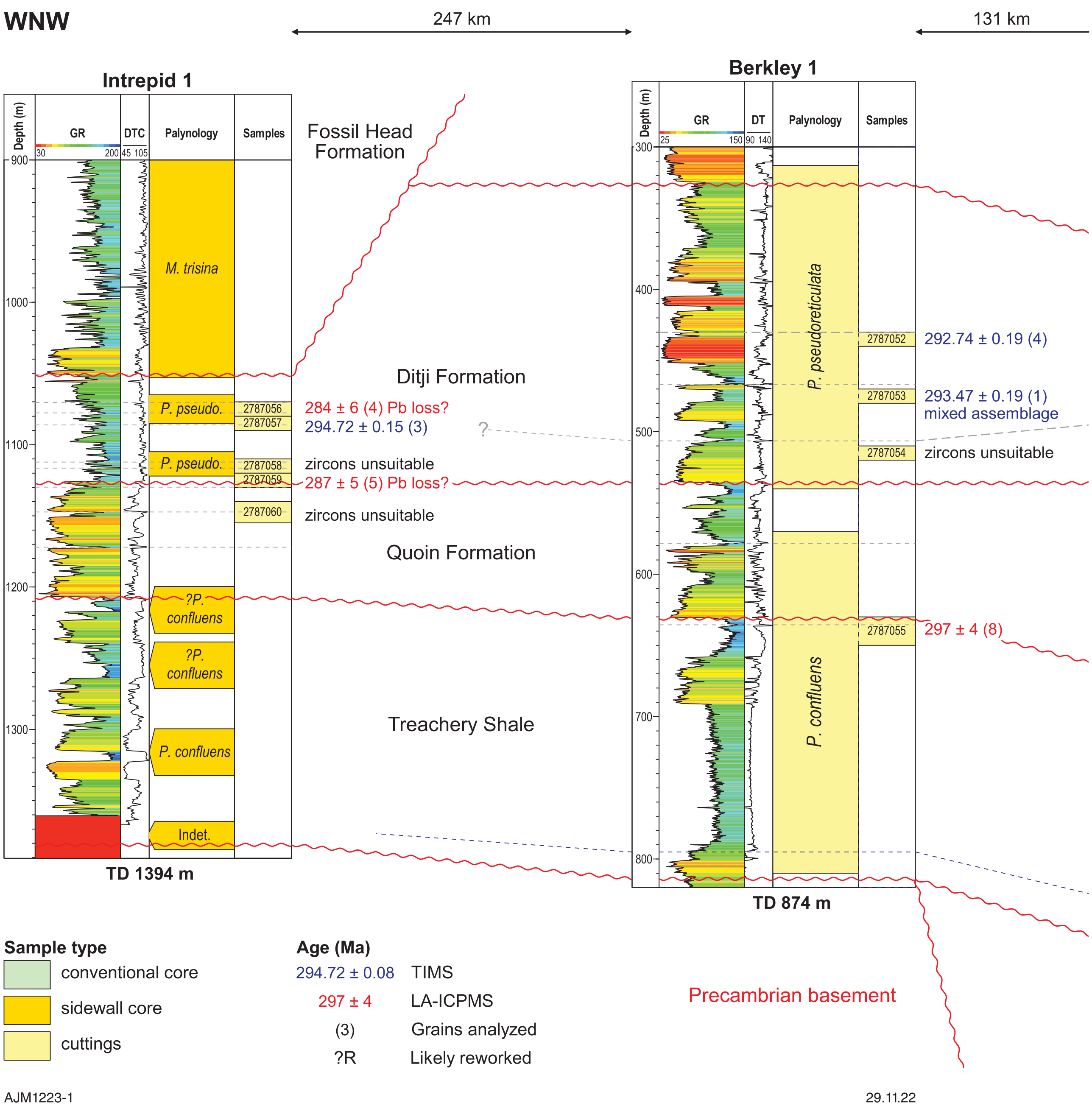

Figure 4. Correlation from Intrepid 1 to Barnett 1 summarising zircon dates and spore-pollen zones (location shown in Figure 3).

sculpture and a proximal sculpture that may be similar to the distal sculpture, or with 'free clavae, verrucae or grana' in *Pseudoreticulatispora*—this is an accurate description of the sculptural arrangement on this species. By comparison, for the corresponding spore-pollen assemblage in Namibia, Stephenson (2009) followed the initial designation of the species by Archangelsky and Gamerro (1979) as *Converrucosisporites confluens*. Although present throughout the Asselian–Artinskian *Vittatina costabilis* Zone in South America (*e.g.* Souza *et al*., 2021), few other of the species identified there are present in Australian assemblages in spite of seemingly significant commonality at a generic level.

Associated with the zonal species (*P. confluens*) in wells used in this study from the Bonaparte Basin are *Brevitriletes cornutus*, *B. levis*, *Cycadopites cymbatus*, *Densosporites rotundidentatus*, *Microbaculispora tentula*, *Protohaploxypinus limpidus*, *Punctatisporites gretensis* and *Striatoabieites multistriatus* (listed in Foster, 1984, 1985, 1986; Purcell, 2001; Purcell & Hooker, 2000; reviewed by Backhouse, 2021). This assemblage closely matches the majority of wells from the Canning Basin analysed by Backhouse and Mory (2020) including Fortescue RUD0007 from the south-western part of the basin (Backhouse, 2020).

The upper limit of the *Pseudoreticulatispora confluens* Zone marks a significant palynofloral boundary defined by

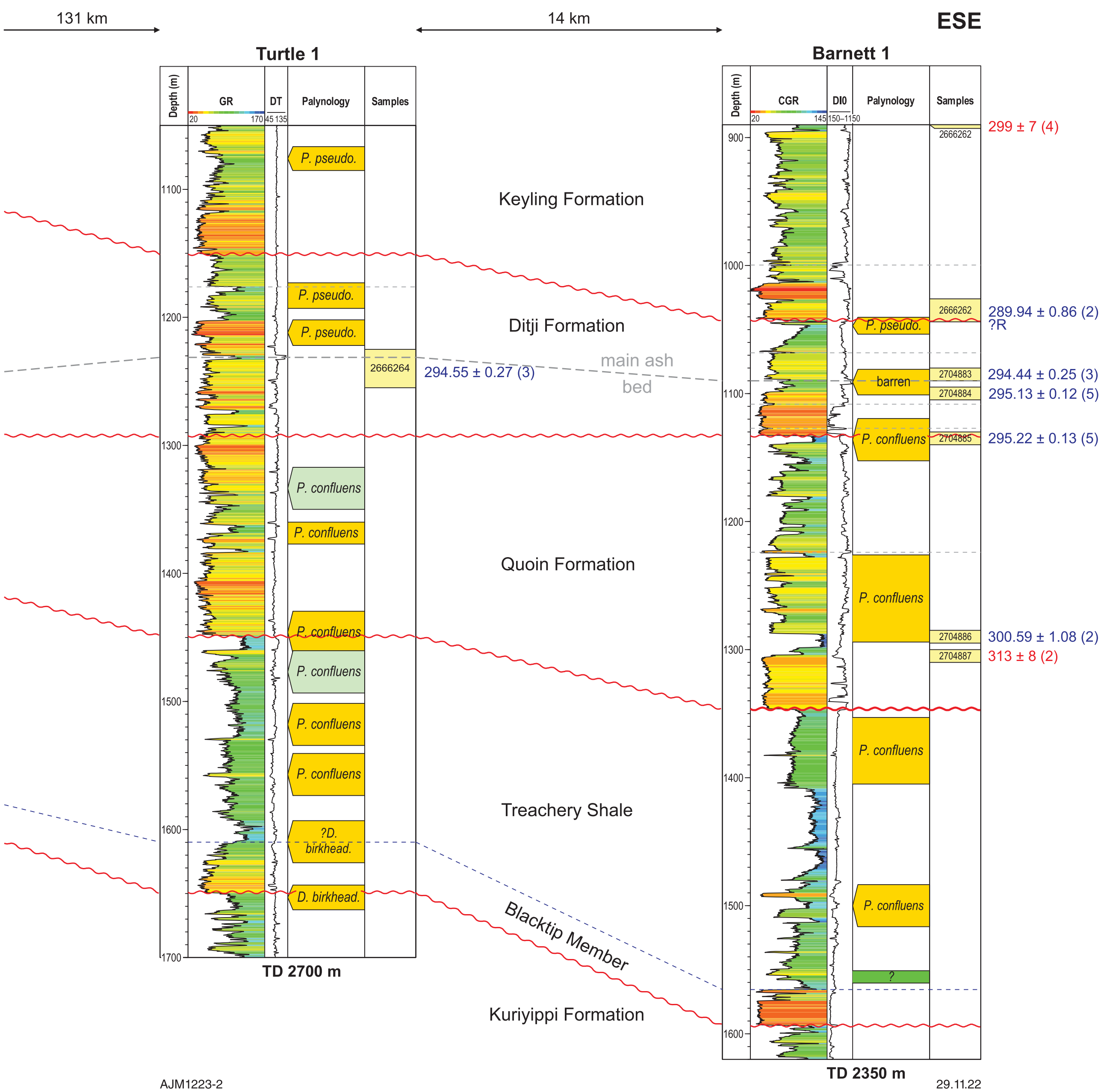

Figure 4. Continued.

the first appearance of *Pseudoreticulatispora pseudoreticulata*, the eponymous species for the succeeding zone. Other species also appearing at or near the base of this zone include *Diatomozonotriletes townrowii*, *Laevigatosporites vulgaris* (*L. colliensis* of Backhouse, 1991), *Procoronaspora spinosa* and *Tiwariasporites simplex*. In the Bonaparte Basin, reliable samples (such as sidewall or conventional cores) from the two zones are typically separated by 100 m, whereas this gap is as little as 11 m in the Canning Basin (Backhouse & Mory, 2020). Nevertheless, this zonal boundary appears to lie close to the contact between the Quoin and Ditji formations (Figure 4; Supplemental data, Tables S2 and S3).

Previous age allocations

The ages of Cisuralian faunal elements (especially brachiopods, bivalves, and bryozoans) and palynological assemblages in WA rely greatly on their stratigraphic position alongside goniatites. Unfortunately, the stratigraphic record of the earliest western Australian Permian goniatite faunas is patchy with none known from the main glacial facies (~lower 'P1' of Fielding *et al.*, 2008a, 2008b, 2022), and Middle–Late Pennsylvanian faunas are completely unknown (*e.g.* Jones *et al.*, 2000), even in other parts of the continent. Previous age determinations of lowermost Permian glacial strata in WA have largely depended on marine macrofossils and stratigraphic evidence, but these have

Table 1. Summary of zircon dates from this study.

	Sample no.				TIMS						LA-ICPMS						
Well/Corehole	GA	GSWA	Sample depth (m)	Sample type	Weighted mean date (Ma)[a]	± (Ma)[b]	*n* in weighted mean	Total *n*	MSWD[c]	POF	Weighted mean date (Ma)[a]	± (Ma)[d]	*n* in weighted mean	Total *n*	MSWD[c]	POF	Age interpretation[e]
Barnett 1	2704880	229616	807–816	Cuttings	No zircon												
	2704881	229617	816–824	Cuttings	No zircon												
	2704882	229618	882–892	Cuttings			Not attempted				299	7	4	23	0.6	0.64	MDA
	2666262	219196	1026–1044	Cuttings	289.94	0.99	2	7	0.4	0.51	291	7	7	16	1.8	0.10	Likely caved
					294.16	0.86	2	7	0.1	0.73							?Reworked from unit below
	2704883	229619	1080–1095	Cuttings	294.44	0.25	3	7	0.9	0.41	297	4	12	26	1.7	0.07	MDA – near depositional?
	2704884	229620	1095–1110	Cuttings	295.13	0.12	5	10	1.1	0.36	304	5	11	15	1.7	0.08	MDA – near depositional?
	2704885	229621	1130–1145	Cuttings	295.22	0.13	5	8	1.2	0.30	295	5	13	18	1.5	0.12	MDA – near depositional?
	2704886	229622	1285–1300	Cuttings	300.59	1.08	2	4	2	0.15	307	5	5	8	1.5	0.19	MDA
	2704887	229623	1300–1315	Cuttings			Not attempted				313	8	2	7	3.05	0.09	MDA
Berkley 1	2787052	229649	430–440	Cuttings	292.74	0.19	4	6	0.4	0.75	286	4	9	55	1.0	0.43	MDA – near depositional?
	2787053	229650	470–480	Cuttings	293.47	0.19	1	8	–	–	290	3	10	39	1.8	0.06	?MDA
	2787054	229651	510–520	Cuttings	All zircon is round												
	2787055	229652	630–650	Cuttings			Not attempted				297	4	8	14	0.7	0.71	MDA
Blacktip 1	2666263	219197	2608–2640	Cuttings	296.01	0.28	1	3	–	–	293	7	5	33	1.7	0.15	?MDA/reworked
Intrepid 1	2787056	229653	1070–1080	Cuttings			Not attempted				284	6	4	14	0.3	0.84	Pb loss?
	2787057	229654	1080–1090	Cuttings	294.74	0.15	4	9	2.9	0.06	293	3	14	31	1.5	0.10	MDA
	2787058	229655	1110–1120	Cuttings	All zircon is round												
	2787059	229656	1120–1130	Cuttings			Not attempted				287	5	5	15	0.3	0.85	Pb loss?
	2787060	229657	1140–1155	Cuttings	All zircon is round												
Turtle 1	2666264	219197	1225–1255	Cuttings	294.55	0.27	3	7	0.3	0.75	300	5	19	52	1.3	0.16	MDA
Fortescue	7942946	229668	389.60–389.67	Core	296.26	0.25	3	3	1.1	0.32	300	6	3	4	0.7	0.48	MDA
RUD0007	7942947	229669	390.08–390.20	Core	No zircon												
	7942948	229673	450.55–450.65	Core	All zircon is round												
	7942949	229676	487.83–487.93	Core	No zircon												

[a]Based on dates on the young end of age spectra with probability of fit >0.05; excludes distinctly younger dates interpreted as Pb loss or contamination owing to caving from higher in well.
[b]Internal error at 95% confidence interval, except 2s for samples with $n = 1$.
[c]MSWD: mean squared weighted deviation.
[d]2s. Includes standard calibration uncertainty.
[e]Based on weighted mean dates.
MDA, maximum depositional age; Pb loss?, too young probably owing to Pb loss from LA-ICPMS spot; POF, probability of fit.

proved ambiguous or speculative owing to low species diversity and endemism (Skwarko, 1993), and the presence of fluvial facies. By comparison, strata post-dating the main glacial succession contain diverse faunas allowing more robust age assignations and are typically regarded as late Sakmarian and younger (*e.g.* Archbold *et al.*, 1993, 1998; Haig *et al.*, 2014). Dating subsurface Permian strata has relied greatly on palynology, but this is rarely possible for outcrops, which typically are strongly oxidised, thereby compromising preservation of these fossils. Thus, the relationship between palynological zones and macrofossil assemblages mostly relies on imprecise stratigraphic correlations that are rarely more detailed than by formation unless fully cored sections are available. As there are no outcrops of lowermost Permian marine facies in the Bonaparte Basin, the following discussion draws on evidence from farther south in the Perth and Canning basins, albeit reliant on long-range correlations.

Of all fossil groups present in the lowermost Permian glacial successions, only goniatites appear to provide independent evidence of age; however, their record is poor, and no Australian phylogenetic series can be established (Haig *et al.*, 2014). The oldest Permian faunas in WA are from the Woolaga Limestone Member in the middle of the Holmwood Shale within the northern Perth Basin and contain just two goniatite species, *Uraloceras irwinense* and *Juresanites jacksoni*. The Sakmarian age attributed to these species is based on 'the primitive nature of its [*J. jacksoni*] suture', and '*Uraloceras irwinense* is closely comparable with several species of *Uraloceras* from the Sakmarian and Artinskian of the Ural mountains' (Teichert & Glenister, 1952, pp. 14–15). Whereas this age mostly has been favoured in the literature (*e.g.* Glenister *et al.*, 1973, 1990; Glenister & Furnish, 1961), Archbold (1995, p. 96) indicated that 'discussion of the age of [*U.*] *irwinense* are equivocal'. Furthermore, Glenister *et al.* (1993, pp. 55–56) noted that that the 'possibility of an Asselian age cannot be rejected completely' for the Holmwood Shale fauna and that 'Early Permian ammonoid faunas are strikingly provincial'. Notwithstanding changes in generic assignations (*J. jacksoni* was previously placed in *Metalegoceras*, and *U. irwinense* in *Svetlanoceras*), a Sakmarian age continues to be allocated to this stratigraphic level (*e.g.* Haig *et al.*, 2014, 2022; Playford, 2021). The generic assignations are seemingly unhelpful, as *Juresanites* and *Svetlanoceras* are present in Asselian strata, whereas *Uraloceras* and *Metalegoceras* first appear in the Sakmarian (Leonova, 2011, 2018). In WA, the two goniatite species are from the middle of the Holmwood Shale where they are loosely associated with the uppermost part of the *P. confluens* spore-pollen Zone (Backhouse, 1992, 1993a, 1993b). By comparison, Playford (2021, p. 58) suggested the associated palynoflora from this level (the Woolaga Limestone Member) could be assigned to either the *P. confluens* Zone or the *P. pseudoreticulata* Zone. There are no goniatites known from coeval strata in any other western Australian basin (see lists in Skwarko, 1993).

Archbold (1982) appears to have made the first suggestion of an Asselian age for the uppermost part of the Permo-Carboniferous glacial succession for the Perth Basin, but not in other basins within WA. Foster and Waterhouse (1988) favoured a mid- to late Asselian age for faunas associated with the *P. confluens* Zone in the Grant Group in the Canning Basin based on loose macrofaunal associations. By comparison, Taboada *et al.* (2015) opted for a Sakmarian age for material from the same stratigraphic level and sub-basin. About 200 m stratigraphically higher than that level is a goniatite fauna from the type area of the Nura Nura Member (in the Fitzroy Trough of the Canning Basin near 18.0856°S, 124.4094°E) at the base of the Poole Sandstone, which directly overlies the Grant Group. Leonova (1998, 2011) and Boiko *et al.* (2008) assign a late Sakmarian age to this fauna, which includes *Metalegoceras clarkei* Miller, *Metalegoceras striatum* Teichert, *Thalassoceras wadei* Miller and *Propopanoceras ruzhencevi* Glenister & Furnish (Glenister *et al.*, 1993; Glenister & Furnish, 1961; Miller, 1936; Teichert, 1942). In contrast, subsurface sections assigned to the Poole Sandstone and Nura Member yield palynomorphs of the *P. pseudoreticulata* Zone, here considered to be late Asselian–mid-Sakmarian (Figure 2).

Methodology

Intervals judged to contain volcanic tuff beds in the Ditji Formation, based on wireline log correlations following the initial interpretation by Gorter *et al.* (2008), were sampled from available cuttings samples held at the Department of Mines, Industry Regulation and Safety (DMIRS) core library. These samples were collected from just below the interpreted depths owing to the likelihood of down-hole caving (Table 1; Figure 4). By comparison, the only tuffs known from the Grant Group are in Fortescue RUD00007, which was sampled from the core held by DMIRS.

Of the 23 samples processed, 16 yielded sufficient zircon for screening using cathodoluminescence (CL) images and LA-ICPMS (Table 1). This step helps discriminate young volcanic zircons from older ones, especially those of detrital origin, and thus the selection of grains likely to provide depositional ages using U–Pb isTIMS. Ten of the 16 samples with suitable zircons were analysed in this fashion. Appendix S1 of the supplemental data files outlines the LA-ICPMS and TIMS methods employed at Boise State University. Appendix S2 lists revised formation picks for wells initially considered to have intersected the upper Kulshill Group including the Ditji Formation. Appendix S3 summarises the re-evaluation of legacy palynological interpretations from company reports for the sampled wells.

U–Pb geochronology results

Bonaparte Basin

No core is available from the Ditji Formation in any of the 23 petroleum exploration wells that intersected this unit (Appendix S3). The core library permits the removal of no more than 20 g from each archived cuttings sample, so we amalgamated samples (mostly over 10 or 15 m intervals) to avoid excessive processing and to provide sufficient material for analysis, even though these intervals may not be ideal to differentiate individual volcanic tuffs. Even so, sample sizes were small, which may partly explain the low number of overlapping ages in some of the analyses (summarised in Figure 5, based on Appendix S1). The TIMS results for most samples indicate that zircons have caved from higher stratigraphic levels, *i.e.* contradictory ages that are too young based on regional correlations (Figure 4), and/or have been reworked based on markedly older ages. Thus, it is possible that some samples fortuitously include zircons from the same event reworked into different stratigraphic levels, but 'reunited' during drilling owing to down-hole caving. By comparison, the larger errors associated with LA-ICPMS results typically do not allow differentiation of caved *vs* unworn reworked zircons. All zircon dates considered reliable lie within or adjacent to the Ditji Formation, which has yielded spore-pollen of the *P. pseudoreticulata* Zone based on palynological reports (Foster, 1984, 1985, 1986; Purcell, 2001; Purcell & Hooker, 2000) and reviewed by Backhouse (2021; Supplemental data Appendix S3). By comparison, all other samples provide ambiguous zircon dates unlikely to be close to depositional ages deduced from MSWD analyses.

Barnett 1

Of the nine samples from this well, five yielded young zircons suitable for TIMS (Figure 5), two had insufficient zircons to proceed beyond LA-ICPMS or the age was out-of-place and therefore indicated likely reworking, and two had no zircons. The five successive samples over 1026 − 1300 m analysed by TIMS reveal ages that become progressively older down-hole: 294.16 ± 0.86 ($n=2$; 1026 − 1044 m), 294.44 ± 0.25 ($n=3$; 1080–1095 m), 295.13 ± 0.12 ($n=5$; 1095–1110 m), 295.22 ± 0.13 ($n=5$; 1130–1145 m) and 300.59 ± 1.08 ($n=2$; 1285–1300 m). The uppermost of these five samples is from the base of the Keyling Formation, the next three are from the Ditji Formation, and the deepest is from low within the Quoin Formation. However, regional correlations (Figure 2) point to the two youngest zircons in the uppermost sample (289.94 ± 0.99) being from a higher level within the well, whereas two slightly older zircons (294.16 ± 0.86 Ma) were probably reworked from the immediately underlying Ditji Formation. It is uncertain if the 300.59 ± 1.08 Ma date from the Quoin Formation is near the depositional age or is from reworked zircons.

Considering all the youngest TIMS zircon dates <297 Ma ($n=23$) in the three samples spanning 1080–1145 m from this well there may be as many as 6 or 7 individual tuffs within the section. Given the overlapping individual dates from this interval and the likelihood of mixing owing to caving and reworking in our amalgamated samples, the simplest interpretation is that only three tuffs can be discriminated, *i.e.* one from each sample. An older cluster (at *ca* 296.2 ± 0.13 Ma based on three grains from 1080 to 1110 m) is attributed to reworking. The age of this cluster overlaps with the tuff from Fortescue RUD00007 in the southern Canning Basin (296.26 ± 0.12 Ma) suggesting derivation from the same eruptive event, but such speculation requires confirmation from Lu–Hf isotopic analysis.

Berkley 1

Of the four samples processed from this well, only three yielded suitable zircons (Figure 5). The youngest zircons in the highest sample (430–440 m) from the Ditji Formation yielded a TIMS date of 292.74 ± 0.19 Ma ($n=4$). In the underlying sample from 470 to 480 m, the youngest zircon is 293.47 ± 0.19 Ma, but its significance is unclear, given it is from a single grain. Whereas both dates are somewhat younger than all the other TIMS dates not discounted, as from cavings, they are not young enough to be explicitly interpreted as such. The other productive sample from 630 to 650 m close to the Quoin Formation–Treachery Shale contact (631.2 m) provided a 297 ± 4 Ma LA-ICPMS age based on eight grains; however, TIMS was not attempted, given the likelihood of reworking/caving providing too broad a spectrum of dates.

Blacktip 1

The single sample from the upper part of the Ditji Formation in this well (2608–2640 m) yielded five zircons with a mean LA-ICPMS age of 293 ± 7 Ma. However, the three youngest zircons analysed by TIMS were non-concordant or with a large error and possibly reworked, so the well was omitted from Figure 4.

Intrepid 1

Of the five samples from this well, just three (all from the Ditji Formation) yielded sharp zircon grains unlikely to be reworked. Two of these (1070–1080 m and 1120–1130 m) yielded Artinskian LA-ICPMS ages (284 ± 6 Ma, $n=4$ and 287 ± 5 Ma, $n=5$, respectively) presumably owing to Pb loss. The intermediate sample (1080–1090 m) yielded 14 young zircons when analysed by LA-ICPMS with a mean of 293 ± 3 Ma, but of the nine grains subjected to TIMS, five appeared reworked, and one may be from higher in the well. The remaining three grains yielded a mean of 294.72 ± 0.15 Ma (Figure 5), within the range of the dates considered reliable from Turtle 1 and Barnett 1, over 370 km to the southeast (Figure 4).

Turtle 1

A single sample from within the Ditji Formation (1225–1255 m) yielded three TIMS dates with a mean of 294.54 ± 0.27 Ma (Figure 5) consistent with dates from much the same level in Barnett 1, 14 km to the southeast.

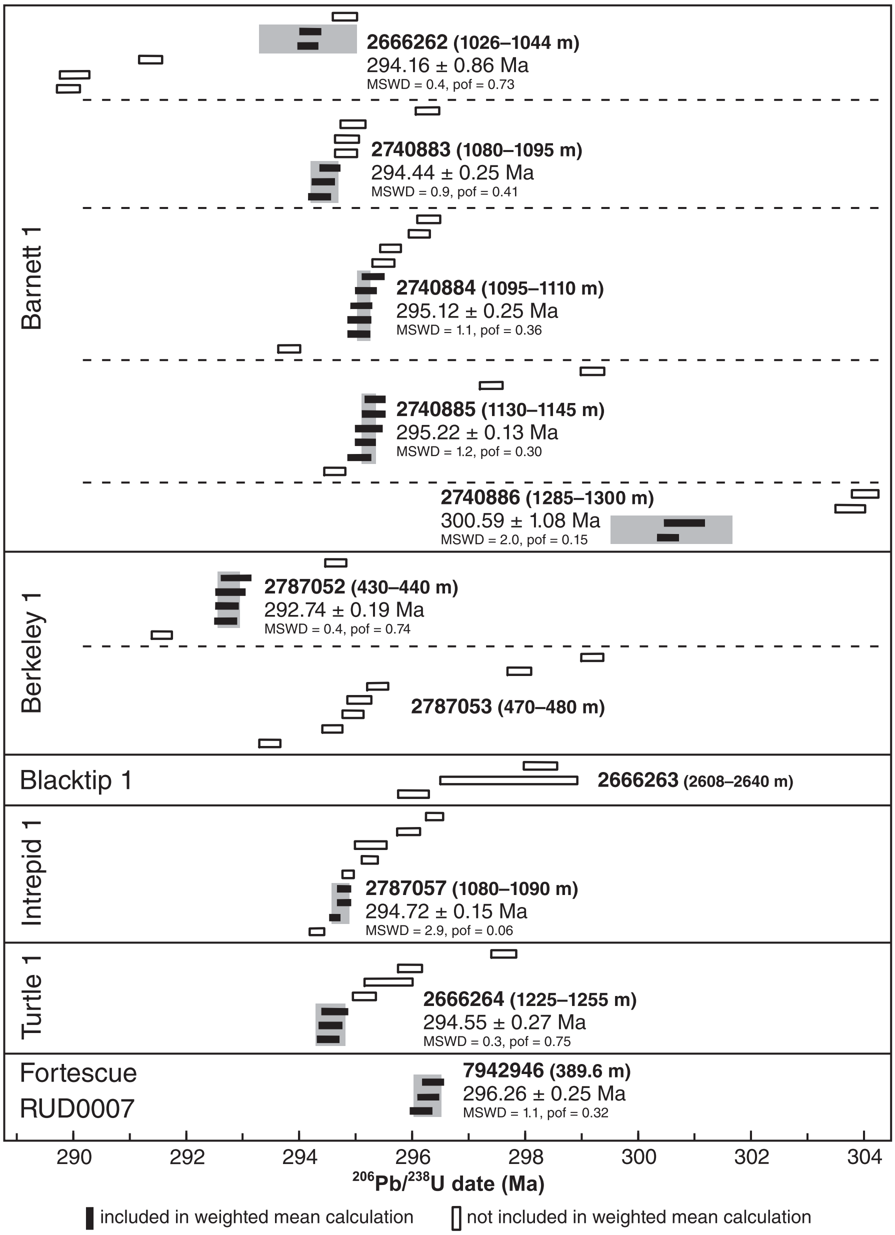

Figure 5. Plots of $^{206}Pb/^{238}U$ dates obtained by TIMS. Plotted with Isoplot 3.0 (Ludwig, 2003). Errors on individual dates are at 2σ. Weighted mean dates are shown and represented by the grey boxes, with errors on the weighted mean dates at the 95% confidence interval. A few older dates that plot off scale are not shown (see Supplemental data, Appendix 1c).

Canning Basin

Of the four potential tuffs sampled from Fortescue RUD0007 in the southern part of the Canning Basin (Figure 1), only one yielded zircon suitable for TIMS analysis. The 296.26 ± 0.25 Ma age is from three zircon grains (Figure 5). The tuff lies at 389.6–389.67 m below ground level within mudstone, sandstone and diamictite of the Grant Group. It is possible that the Poole Sandstone overlying the Grant Group is present in the uppermost part of the section or nearby but cannot be assessed, as core recovery commenced at 333.5 m, and no higher samples are available; in addition, no wireline logs were run in this borehole. All nine palynology samples (335–507.8 m) above and below the tuff yielded palynomorphs of the *P. confluens* Zone (Backhouse, 2020).

Discussion

All of the Bonaparte Basin samples are cuttings from petroleum exploration wells that inevitably incorporate grains and rock fragments caved from higher levels during drilling. No conventional cores are available from the volcanic tuffs targeted for analysis from this basin or, in the case of sidewall cores, too little remains as exploration companies preferentially use them for palynology to avoid down-hole contamination. As well as reworking from older levels during deposition, down-hole caving is potentially significant in assessing the veracity of our zircon dates. The probability that each well intersected several tuffs cannot be resolved from our data owing to the inevitable down-hole dispersion of grains and rock fragments during drilling, insufficient resolution of wireline logs and the possibility of higher-density minerals taking longer to reach the surface within the mud system—difficulties perhaps compounded by the amalgamation of individual cuttings samples.

Seven TIMS dates from the Ditji Formation in the Bonaparte Basin that are not obviously reworked span 295.2–292.7 Ma with 2σ errors of 0.12–0.27 Ma, *i.e.* early Sakmarian–late Asselian (Figure 4). Of these dates, the two from Berkley 1 (293.5 and 292.7 Ma) are Sakmarian, whereas those from Barnett 1, Intrepid 1 and Turtle 1 are Asselian (295.2–294.2 Ma). Although the difference implies that at least part of the interval 325–536 m in Berkley 1 could be a younger unit, there are insufficient data to support such an interpretation. The 296.0 Ma date from the upper Ditji Formation in Blacktip 1 seemingly represents reworking. These dates point to a late Asselian age for the base of the Ditji Formation and the base of the associated *P. pseudoreticulata* spore-pollen Zone. A date of 295.25 Ma is suggested for that level based on the cluster of younger TIMS dates from that formation, and thereby supports the Asselian age proposed for the *P. confluens* Zone by Foster and Waterhouse (1988), in contrast to later suggestions of a mid-Sakmarian age (*e.g.* Backhouse, 1991; Mory, 2010; Mory *et al.*, 2008; Mory & Backhouse, 1997).

In the Galilee Basin of northern Queensland, the Edie Tuff Member (upper Joe Joe Group) in OEC Glue Pot Creek 1 has yielded 295.65 ± 0.07 Ma and 296.09 ± 0.07 Ma TIMS dates (Phillips *et al.*, 2018a). By comparison, GSQ Muttaburra 1, 155 km to the west, yielded dates of 294.80 ± 0.12 Ma and 294.91 ± 0.15 Ma from the same unit (Nicoll *et al.*, 2015, p. 215; Phillips *et al.*, 2018a, 2018b). The dates from the latter well come from 38 m below an APP2.1 palynology assemblage (Nicoll *et al.*, 2015, p. 215). The lower part that assemblage equates with the *P. pseudoreticulata* Zone (*e.g.* Laurie *et al.*, 2018), so the TIMS dates from the Queensland sections appear to be consistent with those from the Bonaparte Basin.

Beyond Australia, outcrop of the Ganigobis Shale Member (Dwyka Group) along the Fly River in Namibia yielded SHRIMP dates of 302 ± 3 Ma and 299.2 ± 3.2 Ma (in Bangert *et al.*, 1999) at a level equivalent to the *P. confluens* Zone (Stephenson, 2009). These dates are close to Griffis *et al.*'s. (2021) TIMS date of 299.31 ± 0.35 Ma from a sample collected just over 1 km downstream from Stephenson's (2009) section. Given the low dips along that river, both localities most likely represent much the same stratigraphic level. Unfortunately, the 295.84 ± 0.47 Ma age Griffis *et al.* (2021) obtained from a sample of the Owl Gorge Member (Prince Albert Formation) 320 km farther south has no associated palynology. Similarly, the palynoflora associated with dates of 296.77 ± 0.04 and 296.14 ± 0.09 Ma from volcanic tuffs in the Mengkarang Formation of West Sumatra reported by van Waveren *et al.* (2021) was considered 'unlike those typical of the Asselian–Sakmarian of Gondwanan areas' (Crippa *et al.*, 2014, p. 215). U–Pb dating in the Paraná Basin of Brazil (summarised by Souza *et al.*, 2021) suggests that the *Vittatina costabilis* Zone, which contains *P. confluens*, spans the Gzhelian to mid-Artinskian, but none of the cited TIMS zircon dates are older than Asselian. Kavali *et al.* (2022) indicate that their Palynoassemblage II in Argentina contains species typical of the *P. confluens* Zone in Australia and that it may be as old as 310.63 ± 0.1 Ma (Moscovian) based on a $^{206}Pb/^{238}U$ age reported by Gulbranson *et al.* (2010). It is unclear how this age may be applicable in Australia, given contradictory spore-pollen ranges between the two countries possibly owing to the influence of facies, reworking and preservation issues (Backhouse & Mory, 2020, p. 36).

Although Fang *et al.* (2021) placed the base of the Sakmarian at 294.1 ± 0.2 Ma, the International Commission on Stratigraphy endorses an age of 293.52 ± 0.17 Ma for that level (Gradstein *et al.*, 2020). Nevertheless, there may be some elasticity in the absolute age of this stage boundary, which could diminish the magnitude of the discrepancy in ages assigned to the top of the *P. confluens* Zone in WA based on associated zircon dating and goniatite affiliations.

In the northern Perth Basin, the stratigraphic association of a limited goniatite assemblage, to which a Sakmarian age is attributed (Leonova, 2011, 2018), with spore-pollen of the *P. confluens* Zone (Backhouse, 1992, 1993a, 1993b) is seemingly at odds with the Asselian TIMS zircon ages from close to the top of this zone in the Bonaparte and Galilee basins. The difference may be a function of facies controls or disparate biogeographic provinces, but the consistency in ages across the north of the continent suggests otherwise. By comparison, the Sakmarian age attributed to goniatites associated with a *P. pseudoreticulata* palynoflora in the Canning Basin by Haig *et al.* (2014 and references therein) is consistent with the 291.62 Ma date from a tuff within the zone in the Gunnedah Basin of New South Wales (Nicoll *et al.*, 2016, p. 35). A reassessment of Australian goniatite affiliations with Russian material, and therefore the global stratotypes, is required for the specimens associated with the *P. confluens* Zone.

The seemingly abrupt end to glacial–deglacial conditions close to the *P. confluens*–*P. pseudoreticulata* spore-pollen datum across WA may not be a coincidence in that land plants are highly susceptible to climatic changes. This level seems tantalisingly close to the Carboniferous–earliest Permian marine Biodiversification Event (placed at 294.8 Ma by Fan *et al.*, 2020; *ca* 294.5 Ma by Shi *et al.*, 2021; and *ca* 294.2 Ma by Macarewich & Poulsen, 2022) when appearances of new marine species peaked in the Asselian.

However, further and more detailed studies are needed within Australia to establish if the events are related.

Sources of Asselian zircons

During the Carboniferous–Permian, the western margin of Australia underwent continental fragmentation with many blocks dispersed into present Southeast Asia (Metcalfe, 2013), but this episode left scant evidence of volcanism in WA. This is unlike the eastern margin of the continent where a subducting continental collision zone generated extended periods of volcanism and deposited tuffs in the subsiding marginal sediments, especially within the developing Bowen–Gunnedah–Sydney basins (Jessop *et al.*, 2019; Rosenbaum, 2018). High atmospheric circulation from such eruptive episodes in eastern Gondwana could have carried detritus, including zircons, to WA basins, even though those volcanic centres lie 2000–3000 km to the east. Major eastern volcanic sequences from Queensland, preserved as the Edie Tuff Member in Muttaburra 1 or within the Jochmus Formation in Glue Pot Creek 1 as well as the Camboon Volcanics (Phillips *et al.*, 2018a), are possible sources for zircons in the Ditji Formation in the Bonaparte Basin and possibly the Grant Formation of the Canning Basin, given the age similarities. Other potential source areas include the Arafura region (Gorter *et al.*, 2008), volcanism along the margins of other blocks that once lay along the northern margin of east Gondwana (Metcalfe, 2013) and Sumatra (van Waveren *et al.*, 2021), or perhaps the Simao Block in southwestern China (Li *et al.*, 2012). Further analyses, notably Lu–Hf, which could confirm such speculation, are beyond the scope of the present study.

Asselian ages from provenance studies of Triassic and Jurassic strata from the Canning and Roebuck basins of the North West Shelf include rare reworked Asselian zircons (Lewis & Sircombe, 2013; Thomas, 2012). However, the origin of these zircons is unclear, and the lower precision of SHRIMP analyses (with errors up to two orders of magnitude greater than TIMS) renders some uncertainty to their significance. Those and other provenance studies (*e.g.* Craddock et al., 2019; Morón *et al.*, 2019; Veevers & Saeed, 2008) show a similar frequency distribution in Precambrian ages from our Bonaparte Basin samples—the so-called 'Gondwanan' zircon signature, which ultimately originated from Antarctica and thereabouts—but there are noteworthy differences from the Paleozoic LA-ICPMS zircon age distribution. In particular, our samples yielded few Devonian or Cambrian–Ordovician zircons (Figure 6). This difference suggests that Silurian and Carboniferous–lowermost Permian zircons came from the edge of the Kimberley Basin, especially as the Treachery Shale sits directly on basement in Intrepid 1 and Berkley 1; however, the ultimate origin of these zircons may have been from well beyond the Bonaparte Basin. By comparison, the paucity of Devonian ages is consistent with the apparent lack of volcanic rocks of that age in other western Australian basins. Transportation by ice during the LPIA best explains the minimal abrasion of our zircons, and probably incorporated several routes from different sediment sources now difficult to pinpoint.

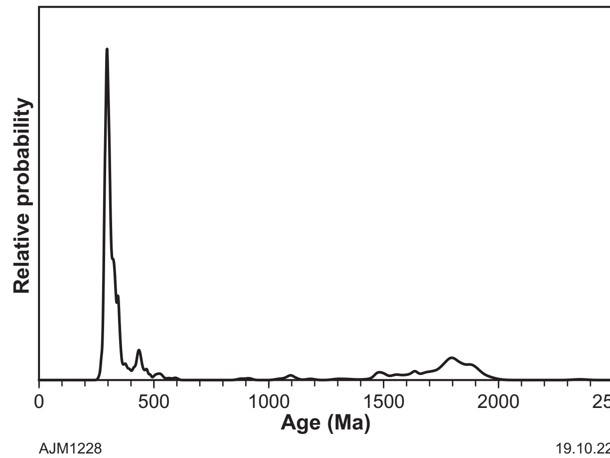

Figure 6. Relative probability (2σ) isoplots of the 370 $^{206}Pb/^{238}U$ LA-ICPMS dates from this study.

Carboniferous–Permian boundary in Australia

The position of the Carboniferous–Permian boundary has not been satisfactorily located in Australia, largely because there are no Middle–Late Pennsylvanian faunas (*e.g.* Jones *et al.*, 2000), and Asselian faunas are of low diversity with highly provincial species (*e.g.* Archbold, 2000). Similarly, palynological assemblages contain species at best endemic to Gondwanan terranes but typically are more restricted in their distribution.

Suggestions that the *M. tentula* Zone spans the Carboniferous–Permian boundary in eastern Australia (*e.g.* Bodorkos *et al.*, 2016; Phillips *et al.*, 2018b) were speculative and conflict with dates from Namibia and possibly some from the Bonaparte Basin. Our samples show that the *P. confluens* Zone seemingly extends into the Gzhelian based on the 300.59 ± 0.17 Ma date within the Quoin Formation at 1285–1295 m in Barnett 1; however, this date is based on just two zircons, and the possibility of reworking/down-hole caving imparts considerable uncertainty. At present, the best evidence relevant to Australia for the position of the Carboniferous–Permian boundary is from zircon dates along the Fly River in Namibia (Bangert *et al.*, 1999, Griffis *et al.*, 2021; Stephenson, 2009), which places it within the *P. confluens* Zone. In Australia, by comparison, this boundary has previously been placed anywhere between the top of this zone (*e.g.* Balme, 1980; Kemp *et al.*, 1977) to somewhere below (Archbold *et al.*, 2004; Backhouse & Mory, 2020), with the most judicious placement being 'at or near the base of Unit II/Stage 2' (Archbold, 1982, p. 267; Archbold, 1984).

Conclusions

The age of the *Pseudoreticulatispora confluens*–*P. pseudoreticulata* spore-pollen datum, which typically coincides with the upper limit of the main phase of glacial sedimentation in WA, is placed close to 295.3 Ma based on zircons dated by TIMS from the Ditji Formation in the Bonaparte Basin, *i.e.* within the Asselian, the earliest stage of the Permian. Although based on petroleum well cuttings, which inherently incorporate material caved from higher stratigraphic levels, the TIMS ages are remarkably consistent (295.2–294.5 Ma with errors generally less than 0.15 Ma) in the five sampled wells spanning almost 400 km along the southern margin of the basin. This age range overlaps with that for the Edie Tuff (296.1–294.8 Ma) in Queensland's Galilee Basin approximately 2000 km to the southeast, which is also considered to lie close to the base of the *P. pseudoreticulata* Zone (Nicoll *et al*., 2016). Previously, there have been few suggestions of Asselian ages in WA based on fossil assemblages, although Glenister *et al*. (1993) did not entirely dismiss this possibility. By comparison, the Asselian age Foster and Waterhouse (1988) suggested for the macrofossils and palynoflora from Calytrix 1 in the Canning Basin largely has been overlooked. Goniatites, which Leonova (1998, 2011) attributes to the Sakmarian, from the Woolaga Limestone Member within the middle of the Holmwood Shale in the northern Perth Basin, are loosely associated with the uppermost *P. confluens* Zone (Backhouse, 1992, 1993a, 1993b)—a reassessment of this material is required.

The position of the Carboniferous–Permian boundary, which lies within the *Pseudoreticulatispora confluens* spore-pollen Zone based on data from Namibia (Griffis *et al*., 2021; Stephenson, 2009), is elusive in Australia and will remain so until more volcanic tuffs with datable zircons are found. Other future work could include Lu–Hf analyses, particularly of the reworked 296.2 Ma zircons from the Bonaparte Basin and the 296.3 Ma zircons from a thin tuff 1000 km to the south within the Grant Group in southern Canning Basin to see if they share a common origin or not.

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ORCID

A. J. Mory http://orcid.org/0000-0003-3541-6172
J. Crowley http://orcid.org/0000-0001-5069-0773
J. Backhouse http://orcid.org/0000-0002-1204-6925
R. S. Nicoll http://orcid.org/0000-0002-6422-6928

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