The late Palaeoproterozoic Glyde package across the greater McArthur Basin

Tim J Munson[1,2]

The informally named greater McArthur Basin (Close 2014) is a vast, predominantly sedimentary terrane stretching across the northern half of the Northern Territory from northeastern Western Australia to northwestern Queensland. It includes Palaeo- to Mesoproterozoic successions of the McArthur and Birrindudu basins, and the Tomkinson Province (**Figure 1**). These depositional areas are interpreted to have been continuous at time of deposition and to be interconnected at depth beneath younger cover of Neoproterozoic to Phanerozoic rocks.

The sedimentary successions of the McArthur Basin were subdivided by Rawlings (1999) into five basin-

[1] Northern Territory Geological Survey, GPO Box 4550, Darwin NT 0801, Australia
[2] Email: tim.munson@nt.gov.au

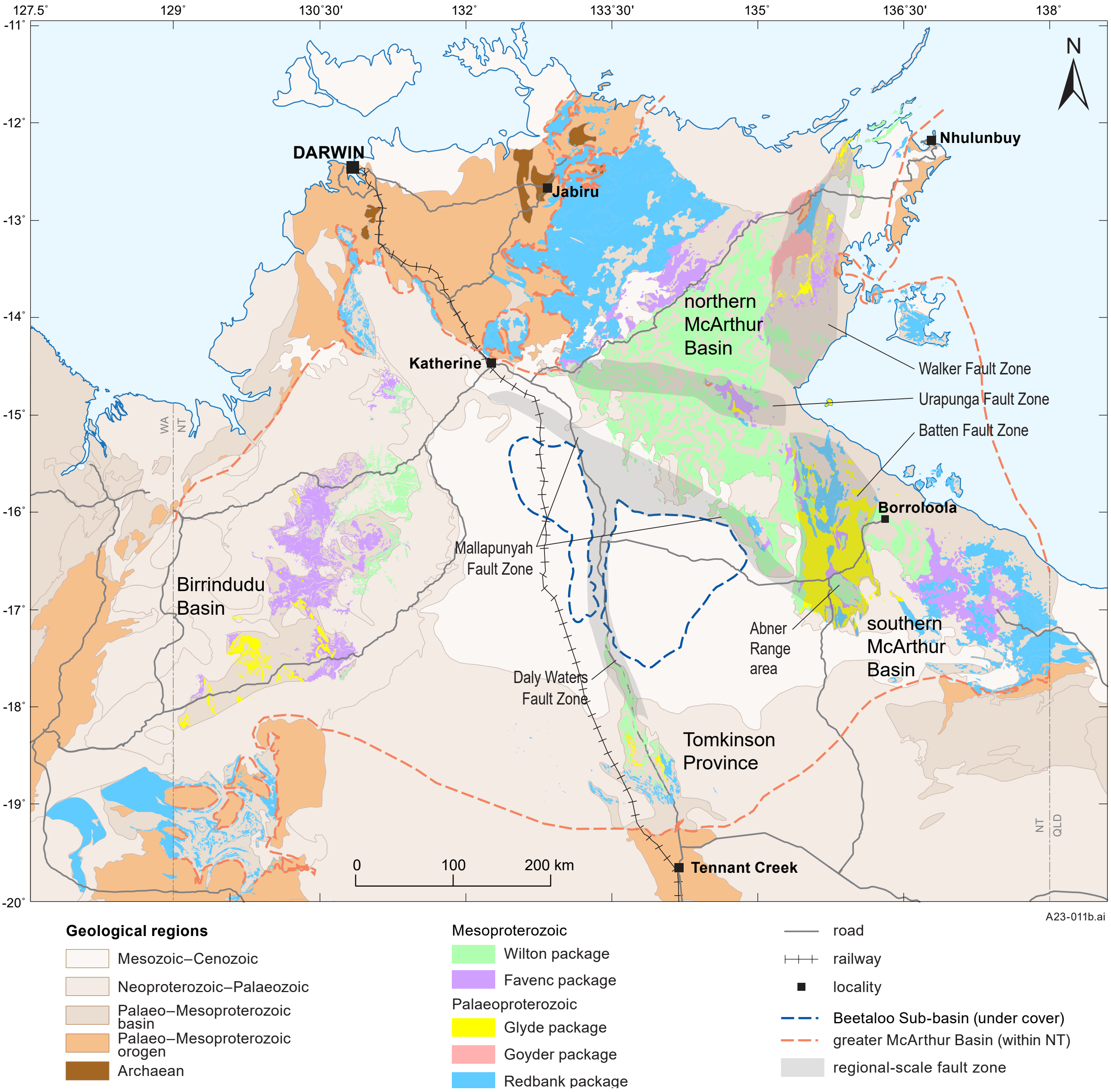


Figure 1. Outcrop distribution of depositional packages of Rawlings (1999, Close 2014) in the NT and bordering areas of WA and Qld (modified from Jarrett *et al* 2022: figure 2). WA polygons from 1:2.5 M-scale GIS dataset downloaded from GSWA website; Qld polygons from WESTMORELAND 1:250 000-scale GIS dataset downloaded from GSQ website. Boundary between Glyde and Favenc packages placed at top Amos Formation in southern McArthur Basin, base Bath Range Formation in northern McArthur Basin, and mid-Shillinglaw Formation in Tomkinson Province. Outline of greater McArthur Basin within NT after Close (2014). Background map is NT geological regions from NTGS 1:2.5 M-scale geological regions GIS dataset with polygons extended into adjacent areas of WA and Qld; polygon colours are modified to highlight packages.

scale, non-genetic depositional ‘packages’: in ascending stratigraphic order, the Palaeoproterozoic Redbank, Goyder, and Glyde packages; and the Mesoproterozoic Favenc and Wilton packages. These were subsequently informally extended by NTGS across the greater McArthur Basin so as to include correlative successions within the Birrindudu Basin and Tomkinson Province (Close 2014, **Figure 1**). The term ‘package’ was originally defined as an ‘amalgamation of lithostratigraphic units with similar ages, stratigraphic position, lithofacies or lithofacies associations, and style and composition of volcanism’ (Rawlings 1999: 705). With the exception of the Goyder package, they are bounded by tectono-eustatic disconformities or unconformities that have regional extent across all, or much of the basin. In general, packages young towards the central sub-surface depocentre (Beetaloo Sub-basin) and towards the Walker and Batten fault zones, where the successions are inverted (**Figure 1**).

The Northern Territory Geological Survey (NTGS) has completed a systematic study (Munson in press) of all sedimentary units of the late Palaeoproterozoic Glyde package, and has previously published a study of the Mesoproterozoic Wilton package (Munson 2016). The main aims of these studies were:

1. to collate and combine historical and new field-based data in order to produce baseline datasets of all stratigraphic units
2. to integrate and interpret geochronological data to constrain the ages of sedimentary units and test proposed intrabasinal correlations
3. to test and refine existing palaeoenvironmental interpretations.

Glyde package

The Glyde package includes the McArthur Group and lower Balbirini Dolostone of the Nathan Group (southern McArthur Basin); Vizard Group (central-western McArthur Basin); Habgood Group and lower Balma Group up to either the medial Baiguridji or medial Yarrawirrie formations (northern McArthur Basin); Limbunya Group (Birrindudu Basin); and lower Namerinni Group up to the medial Shillinglaw Formation (Tomkinson Province; Munson in press, **Figures 2**, **3**). It includes a total of 45 formations as well as a number of

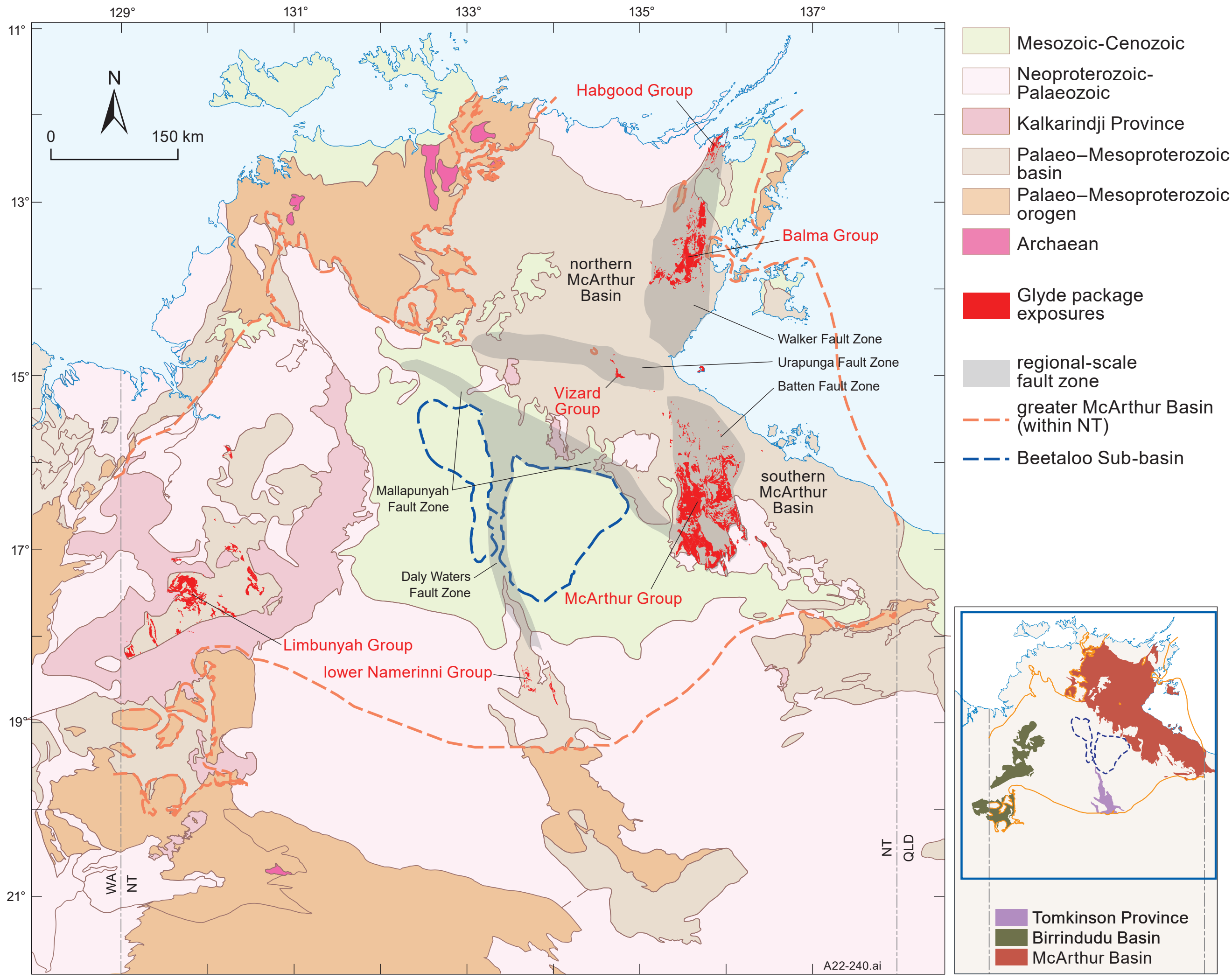


Figure 2. Outcrop distribution of groups included within Glyde package in Birrindudu Basin, McArthur Basin and Tomkinson Province on background map of NT geological regions from NTGS 1:2.5 M-scale geological regions GIS dataset. Extent of greater McArthur Basin, as defined by Close (2014), and subsurface extent of the Beetaloo Sub-basin, as defined by Williams (2019), are also shown.

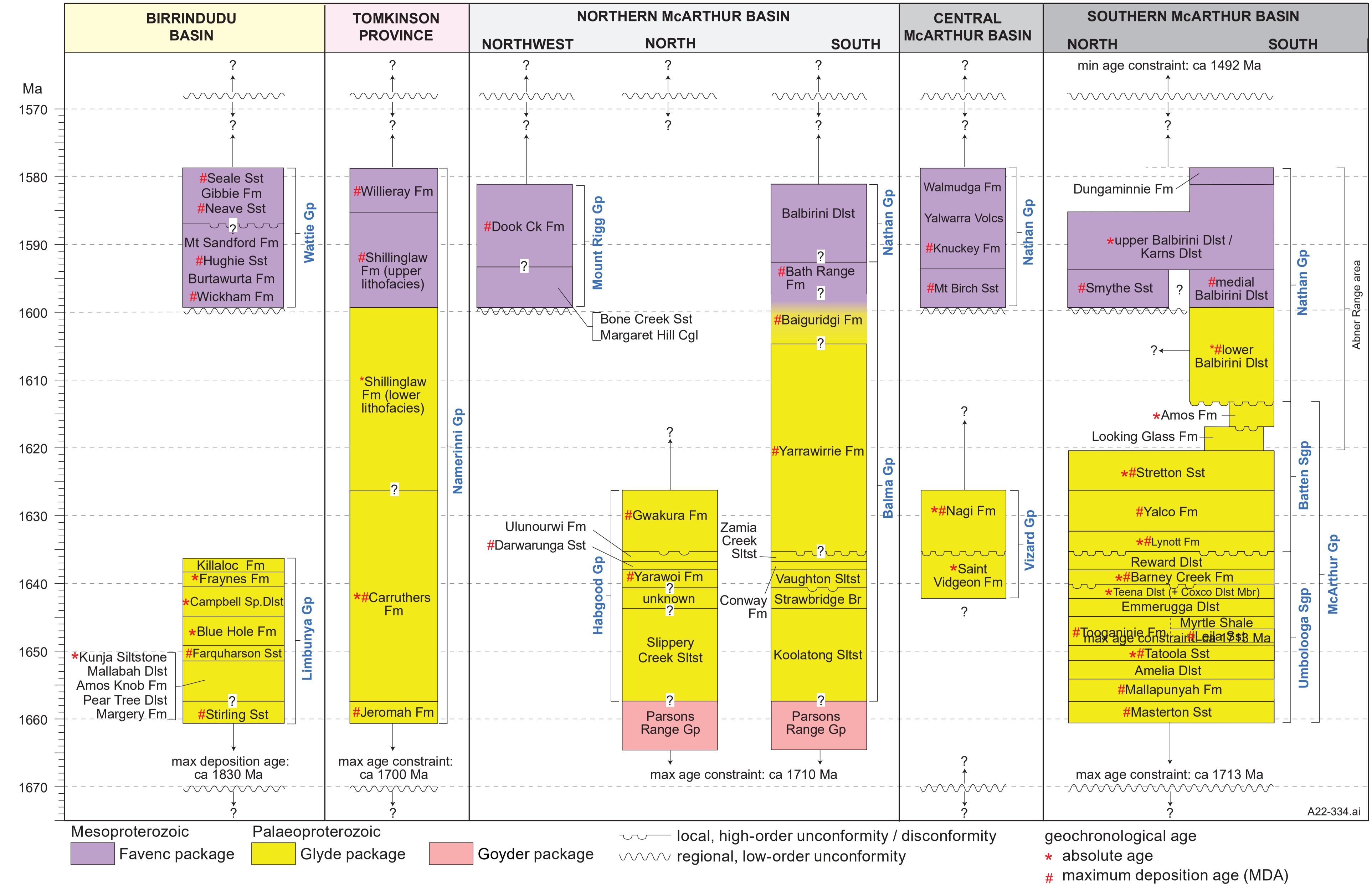


Figure 3. Time-space diagram showing stratigraphic relationships for Glyde and Favenc packages across greater McArthur Basin and units sampled for geochronological analysis. Br = Breccia; Cgl = Conglomerate; Dlst = Dolostone; Fm = Formation; Gp = Group; Mbr = Member; Sgp = Subgroup; Slst = Siltstone; Sst = Sandstone.

formal and informal members. The Glyde package is less widely distributed across the greater McArthur Basin than the underlying Redbank or overlying Favenc packages. In the northern McArthur Basin, it is restricted to the Walker Fault Zone (WFZ, Haines *et al* 1999, **Figure 1**). In the southern McArthur Basin, it outcrops extensively within the Batten Fault Zone (BFZ) and extends to the east in the subsurface for a few tens of kilometres until it is truncated by faults or thins to a zero edge (Blaikie and Kunzmann 2020). To the south of the BFZ, the package is imaged in the L212 Barkly 2D Deep Crustal Seismic Survey as extending in the subsurface as far as the Murphy Province (Southby *et al* 2022). West of the BFZ, the package extends in the subsurface towards the Beetaloo Sub-basin, but it is uncertain as to whether or not it is present at depth within the eastern parts of the sub-basin. Most previous geophysical interpretations (eg Collins 1983, Williams 2019, NTGS and Geognostics Australia Pty Ltd 2021) model the package at depth within the sub-basin over Redbank package basement rocks. However, Garrad (2023) reinterpreted the available seismic data and concluded that the Glyde package is truncated a few tens of kilometres to the west of the BFZ by an angular unconformity at the base of the Favenc package, and that it is absent in the Beetaloo Sub-basin to the east of the Daly Waters Fault Zone (DWFZ) due to either erosion or non-deposition. West of the DWFZ, the Glyde package is imaged in seismic lines (Williams 2019 and references therein) as continuing beneath an erosional unconformity at the base of the Wilton package towards the Birrindudu Basin, where it is continuous with the outcropping Limbunya Group. In the south, the Glyde package (lower Namerinni Group) outcrops in the Tomkinson Province, but the distribution of the package under cover to east and west of this province is unclear.

The Glyde package successions comprise a mix of siliciclastic, carbonate, mixed carbonate/fine-grained siliciclastic rocks, and bedded evaporites that were deposited in the age range ca 1660–1600 Ma in dominantly shallow-marine to emergent palaeoenvironments. It attains a maximum composite thickness of up to about 5000 m in the northern and southern McArthur Basin (Pietsch *et al* 1994, Haines *et al* 1999), up to about 1500 m in the Birrindudu Basin (Cutovinos *et al* 2002), and up to about 2000 m in the Tomkinson Province (Hussey *et al* 2001). The Glyde package is underlain in all areas, except for the northern McArthur Basin, by a regional unconformity that corresponds to a period of uplift and erosion and non-deposition for 30 million or more years (Blaikie and Kunzmann 2020, **Figure 3**). In the northern McArthur Basin, the package is conformably underlain by sedimentary and minor volcanic rocks of the older Palaeoproterozoic Goyder package, which is restricted to the WFZ and its western flanks. The top of the Glyde package is marked by a significant regional tectono-eustatic unconformity that occurs at the base of the Smythe Sandstone (Nathan Group) in the southern McArthur Basin, at the base of the Mount Birch Sandstone (Vizard Group) in the central-western McArthur Basin, and at the base of the Wattie Group in the Birrindudu Basin. This unconformity is interpreted to correspond to the onset of the Isan Orogeny at ca 1600 Ma (eg see Volante *et al* 2022). However, there is no evidence for a significant unconformity at this stratigraphic level in the northern McArthur Basin, Tomkinson Province, or locally in the southern McArthur Basin; in all of these areas, the Glyde–Favenc boundary is concordant and most likely a high-order eustatic disconformity.

McArthur Group

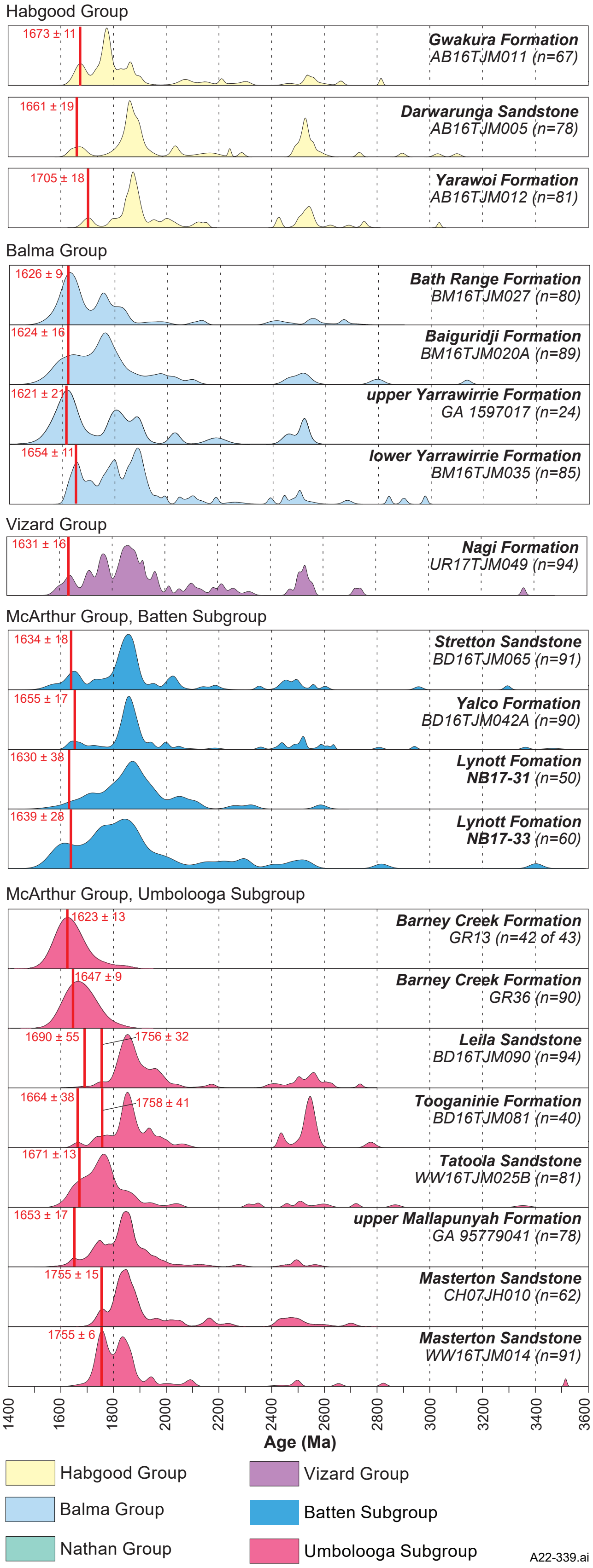
The McArthur Group (**Figures 2**, **3**) is divided into the Umbolooga and overlying Batten subgroups. It is a thick, variably cyclic, heterolithic succession of evaporitic and subaqueous carbonate rocks, mudrock and subordinate sandstone that was deposited in a wide range of environments, from shallow-marine to evaporative platform to fluvial. Carbonate rocks are generally strongly dolomitised, or more rarely silicified. Minor thin beds of fine-grained tuff/tuffaceous mudrock occur throughout the succession but are more abundant and thicker in the medial McArthur Group and towards the south. The group reaches an estimated composite thickness of nearly 4500 m (Pietsch *et al* 1991) in the southern parts of the BFZ (BAUHINIA DOWNS[3], WALHALLOW). It thins to the north to 2500–3000 m in the southeastern parts of MOUNT YOUNG, and continues to thin to the north and west, where only the lowest units of the group are preserved beneath the base-Nathan Group unconformity (Haines *et al* 1993).

The McArthur Group unconformably overlies various units of the Palaeoproterozoic Tawallah Group (Redbank package). The contact varies from structurally concordant to angular and is commonly marked by a basal conglomerate. The Mesoproterozoic Nathan group (Favenc package) overlies the McArthur Group, with the contact in most places being a regional unconformity on various formations of both the Batten and Umbolooga subgroups. However, in the vicinity of the Abner Range in the southern BFZ, the contact is concordant, and there is no evidence of a significant unconformity; geochronological evidence indicates that there is also no substantial time gap across the contact (Kositcin and Munson 2020 and references therein). Where the Nathan Group is absent, the McArthur Group is unconformably overlain by the Mesoproterozoic Roper Group (Wilton package), or by Neoproterozoic–Phanerozoic covering rocks.

Umbolooga Subgroup

The Umbolooga Subgroup (Plumb and Brown 1973) is a succession of variably evaporitic and subaqueous carbonate rocks, mudrock, subordinate sandstone and minor tuff/tuffaceous mudrock. Carbonate rocks are generally strongly dolomitised, or rarely silicified. A maximum composite thickness varying from about 2000–3300 m has been estimated for the succession (Jackson *et al* 1987). The subgroup encompasses the lower part of the McArthur Group and is divided into eleven formations (**Figure 3**), several of which have defined members. The upper boundary with the Batten Subgroup is both conformable and locally

[3] Names of 1:250 000 mapsheets are shown in large capital letters eg BAUHINIA DOWNS



unconformable. In most areas, particularly in sub-basins and away from major faults, the contact is gradational with the basal Caranbirini Member of the Lynott Formation (Jackson *et al* 1987, Pietsch *et al* 1991). However, local unconformities occur adjacent to, or within major fault zones, where the Umbolooga Subgroup is unconformably overlain by a range of units, including a number of other formations of the Batten Subgroup, the Mesoproterozoic Nathan and Roper groups, and younger covering rocks.

Basal units of the Umbolooga Subgroup are poorly constrained by a 1713 ± 7 Ma age for the Tanumbirini Rhyolite at the top of the underlying Redbank package (Page and Sweet 1998), and by an estimated age range of 20–40 million years for the intervening, poorly dated Goyder package (Parsons Range Group), which underlies the McArthur Group-equivalent Balma Group in the northern McArthur Basin (Rawlings 1999). Collectively, these provide an inferred maximum age for the basal formation of the Umbolooga Subgroup (Masterton Sandstone) in the range 1690–1670 Ma (Rawlings 1999). Maximum depositional ages of ca 1755 Ma from detrital zircon dating of the Masterton Sandstone (**Figure 4**, **Table 1**) do not improve the age constraint of this unit; however, an interpreted maximum deposition age (MDA) of 1653 ± 17 Ma for a green tuffaceous siltstone from the overlying Mallapunyah Formation implies that the base of the McArthur Group is probably only slightly older. Haines (1994) suggested that the upper part of the Goyder package might be equivalent, at least in part, to the Masterton Sandstone, which would also favour a younger age for the Masterton Sandstone.

The medial McArthur Group from the Tatoola Sandstone (Umbolooga Subgroup) to Lynott Formation (basal Batten Subgroup) is relatively well dated in the age range ca 1648–1636 Ma (**Table 1**), indicating that these units must have been rapidly accumulated and that any time break between the subgroups was relatively short.

Batten Subgroup

The Batten Subgroup is a succession of variably dolomitised or silicified carbonate rocks, mudrock, sandstone and minor tuff/tuffaceous mudrock. It is much thinner than the underlying Umbolooga Subgroup and reaches a maximum thickness ranging from about 150 m to 1000 m (Jackson *et al* 1987). The subgroup encompasses the upper part of the McArthur Group and is divided into five formations and three members (**Figure 3**).

The Batten Subgroup is more sparsely dated than the Umbolooga Subgroup; a tuff from the Stretton Sandstone has returned an age of 1625 ±2 Ma, and the uppermost units of the subgroup were deposited in the age range ca 1614–1609 Ma (**Table 1**).

Figure 4. Comparative relative probability diagram of detrital zircon age data, with formations arranged in stratigraphic order for Umbolooga Subgroup (red polygons), Batten Subgroup (dark blue), Vizard Group (purple), Balma Group (light blue), and Habgood Group (yellow); updated from figure 4 in Munson (2019). Detrital zircon age data for upper Mallapunyah Formation (GA 95779041) and upper Yarrawirrie Formation (GA 1597017) plots are from GA Geochron Delivery. References for all data provided in **Table 1**. Relative probability age spectra are not to scale vertically; associated histograms used to construct the spectra are not shown for clarity; number of concordant and near-concordant (<10%) analyses (n) is shown on right. Red lines indicate interpreted maximum depositional age for each sample; if two lines present, LHS line is youngest concordant zircon(s).

Table 1. Summary of all geochronology results pertaining to Glyde and Favenc packages. Stratigraphic units are arranged in ascending order. Abbreviations: dlst = dolostone; mdst = mudstone; slst = siltstone; sst = sandstone; zrn = zircon.

Unit	Sample	Absolute age (Ma)	MDA (youngest zrn) (Ma)	Source
Mount Rigg Group				
Dook Creek Fm (Jamberline sst Mbr)	sst: LA–ICP–MS U–Pb detrital zrn		1646 ± 44 (1614 ± 78)	Subarkah (2018)
Wattie Group				
Seale Sst	sst: SHRIMP U–Pb detrital zrn		1605 ± 12	Kositcin and Carson (2017)
Neave Sst	sst: SHRIMP U–Pb detrital zrn		1617 ± 39	Carson (2013)
Hughie Sst	sst: SHRIMP U–Pb detrital zrn		1595 ± 22	Kositcin and Carson (2017)
Wickham Fm	sst: SHRIMP U–Pb detrital zrn		1639 ± 16	Carson (2013)
Nathan Group				
upper Balbirini Dlst	tuffaceous sltst: SHRIMP U–Pb zrn	1589 ± 3		Page *et al* (2000)
medial Balbirini Dlst	sst: SHRIMP U–Pb detrital zrn		1607 ± 6	Kositcin and Munson (2020)
lower Balbirini Dlst	tuff: SHRIMP U–Pb zrn	1613 ± 4, 1609 ± 3		Page *et al* (2000)
lower Balbirini Dlst	sst: SHRIMP U–Pb detrital zrn		1625 ± 14	Kositcin and Munson (2020)
Smythe Sst	sst: SHRIMP U–Pb detrital zrn		1605 ± 14	Kositcin *et al* (2017)
Knuckey Fm	sst: SHRIMP U–Pb detrital zrn		1616 ± 7	Kositcin and Munson (2019)
Mount Birch Sst (top)	sst: SHRIMP U–Pb detrital zrn		1615 ± 28	Kositcin and Munson (2019)
Mount Birch Sst (base)	sst: SHRIMP U–Pb detrital zrn		1629 ± 24	Kositcin and Munson (2019)
Namerinni Group				
Willieray Fm	sst: LA–ICP–MS U–Pb detrital zrn		1581 ± 22 (1526 ± 26)	Munson *et al* (2020)
Shillinglaw Fm	sst: SHRIMP U–Pb detrital zrn		1595 ± 10	Kositcin and Munson (2019)
Shillinglaw Fm	tuffite?: SHRIMP U–Pb zrn	1639 ± 27		Nunn (1997)
Carruthers Fm	sst: SHRIMP U–Pb detrital zrn		1688 ± 13	Kositcin and Munson (2019)
Carruthers Fm	tuffaceous mdst: SHRIMP U–Pb zrn	1638 ± 16		Champion *et al* (2020)
Jeromah Fm	sst: LA–ICP–MS U–Pb detrital zrn		1711 ± 16 (1592 ± 46)	Munson *et al* (2020)
Balma Group				
Bath Range Fm	sst: SHRIMP U–Pb detrital zrn		1626 ± 9	Kositcin and Munson (2019)
Bath Range Fm	tuffaceous mdst: SHRIMP U–Pb zrn	1599 ± 11		Pietsch *et al* (1994)
Baiguridji Fm	sst: SHRIMP U–Pb detrital zrn		1624 ± 16	Kositcin and Munson (2019)
Yarrawirrie Fm	sst: LA–ICP–MS U–Pb detrital zrn		1654 ± 11	Munson *et al* (2020)
Yarrawirrie Fm	tuffaceous mdst: SHRIMP U–Pb zrn		1621 ± 21	Pietsch *et al* (1994)
Habgood Group				
Gwakura Fm	sst: LA–ICP–MS U–Pb detrital zrn		1673 ± 11 (1645 ±16)	Munson *et al* (2020)
Darwarunga Sst	sst: SHRIMP U–Pb detrital zrn		1661 ± 19	Kositcin *et al* (2017)
Yarawoi Fm	sst: SHRIMP U–Pb detrital zrn		1705 ± 18	Kositcin *et al* (2017)
Vizard Group				
Nagi Fm	sst: SHRIMP U–Pb detrital zrn		1631 ± 16	Kositcin and Munson (2019)
Nagi Fm	tuffite: SHRIMP U–Pb zrn	1634 ± 4		Page *et al* (2000)
Saint Vidgeon Fm	tuffite: SHRIMP U–Pb zrn	1640 ± 4		Page *et al* (2000)
Limbunya Group				
Fraynes Fm	tuffaceous sltst: TIMS U–Pb zrn	1642.2 ± 3.9		Munson *et al* (2019)
Campbell Springs Dlst	tuffite: SHRIMP U–Pb zrn	1638 ± 9		Armstrong (1998)
Campbell Springs Dlst	tuffite: SHRIMP U–Pb zrn	1639 ± 7		Smith (2001)
Blue Hole Fm	tuffite: SHRIMP U–Pb zrn	1636 ± 5		Smith (2001)
Farquharson Sst	sst: SHRIMP U–Pb detrital zrn		1654 ± 12	Kositcin *et al* (2017)
Kunja Sltst	tuffite: SHRIMP U–Pb zrn	1635 ± 19		Fanning (1991)
Stirling Sst	sst: SHRIMP U–Pb detrital zrn		1830 ± 13	Carson (2013)
McArthur Group				
Amos Fm	tuff: SHRIMP U–Pb zrn	1614 ± 4		Page *et al* (2000)
Stretton Sst	sst: SHRIMP U–Pb detrital zrn		1634 ± 18	Kositcin and Munson (2019)
Stretton Sst	tuff: SHRIMP U–Pb zrn	1625 ± 2		Page *et al* (2000)
Yalco Fm	sst: SHRIMP U–Pb detrital zrn		1655 ± 17	Kositcin *et al* (2017)
Lynott Fm (Hot Spring Mbr)	tuff: SHRIMP U–Pb zrn	1636 ± 4		Page *et al* 2000
Lynott Fm (Hot Spring Mbr?)	sst: LA–ICP–MS U–Pb detrital zrn		1630 ± 38	Zhang *et al* (2020)
Lynott Fm (Hot Spring Mbr?)	sst: LA–ICP–MS U–Pb detrital zrn		1633 ± 27	Zhang *et al* (2020)
Lynott Fm (Hot Spring Mbr?)	sst: LA–ICP–MS U–Pb detrital zrn		1639 ± 28	Zhang *et al* (2020)

(Table continued next page)

Table 1. Summary of all geochronology results pertaining to Glyde and Favenc packages. Stratigraphic units are arranged in ascending order. Abbreviations: dlst = dolostone; mdst = mudstone; slst = siltstone; sst = sandstone; zrn = zircon. Table continued from previous page.

Unit	Sample	Absolute age (Ma)	MDA (youngest zrn) (Ma)	Source
McArthur Group (continued)				
Barney Creek Fm	tuffaceous dlst, tuffaceous shale: SHRIMP U–Pb zrn	1638 ± 7, 1639 ± 3, 1640 ± 3		Page and Sweet (1998)
Barney Creek Fm	sst: LA–ICP–MS U–Pb detrital zrn		1623 ± 13	Zhang *et al* (2020)
Barney Creek Fm	sst: LA–ICP–MS U–Pb detrital zrn		1647 ± 9	Zhang *et al* (2020)
Teena Dlst (Coxco Dlst Mbr)	tuff: SHRIMP U–Pb zrn	1639 ± 6		Page *et al* (2000)
Leila Sst	sst: SHRIMP U–Pb detrital zrn		1756 ± 32 (1690 ± 55)	Kositcin and Munson (2019)
Tooganinie Fm	sst: SHRIMP U–Pb detrital zrn		1758 ± 41 (1664 ± 38)	Kositcin and Munson (2019)
Tatoola Sst	sst: SHRIMP U–Pb detrital zrn		1671 ± 13.	Kositcin and Munson (2019)
Tatoola Sst	tuffaceous sltst: SHRIMP U–Pb zrn	1648 ± 3		Page *et al* (2000)
Mallapunyah Fm (upper)	tuffaceous sltst: SHRIMP U–Pb zrn		1653 ± 17	GA geochron delivery, Page *et al* (2000)
Mallapunyah Fm	sst: LA–ICP–MS U–Pb detrital zrn		1740 ± 28	Cruz (2019)
Masterton Sst	sst: LA–ICP–MS U–Pb detrital zrn		1709 ±28	Cruz (2019)
Masterton Sst	sst: SHRIMP U–Pb detrital zrn		1755 ± 15	Hollis *et al* (2010)
Masterton Sst	sst: SHRIMP U–Pb detrital zrn		1755 ± 6	Kositcin *et al* (2017)

lower Balbirini Dolostone (Nathan Group)

The Nathan Group is a dolostone-dominated succession with minor siliciclastic and bedded evaporitic rocks that was deposited in a range of environments from transgressive/fluvial to shallow-marine to evaporative platform (Jackson *et al* 1987, Pietsch *et al* 1991, Haines *et al* 1993, 1999). The group outcrops widely in the southern, central and northern McArthur Basin and is generally included within the early Mesoproterozoic Favenc package of Rawlings (1999).

In the southern McArthur Basin, the Nathan group includes a basal siliciclastic and often conglomeratic unit, the Smythe Sandstone, overlain by thicker carbonate and siliciclastic rocks of the Balbirini Dolostone and Dungaminnie Formation (Jackson *et al* 1987, Pietsch *et al* 1991). In most areas, the boundary between the Glyde and Favenc packages is a major tectono-eustatic unconformity underlying the Smythe Sandstone. However, where the Smythe Sandstone is absent in the vicinity of the northern and western Abner Range (**Figures 1**, **2**), the boundary between the Glyde and Favenc packages is not marked by a significant unconformity and its stratigraphic position is not clearly defined. In this area, Jackson *et al* (1987) divided the Balbirini Dolostone into three informal units: in ascending stratigraphic order, a lower 'evaporitic unit', a medial 'stromatolitic unit', and an upper 'recrystallised unit'. The contact between the 'evaporitic unit' and the underlying Amos Formation at the top of the McArthur Group is generally concordant or a local erosional surface with stratigraphic relief of up to 2 m (Pietsch *et al* 1991). Well-dated, pink tuff/tuffaceous rocks on either side of the contact in the western Abner Range area have returned interpreted magmatic crystallisation ages of 1614 ± 4 Ma and 1613 ± 4 Ma for the Amos Formation and lower Balbirini Dolostone respectively (Page *et al* 2000, **Table 1**). These ages are indistinguishable from one another and indicate that there is no significant time break across the contact. Dolostones of the upper Amos Formation are interpreted as subaqueous and are overlain by redbeds of the lower Balbirini Dolostone, indicating that the surface is a high-order eustatic, subaerial disconformity. Additional SHRIMP U–Pb detrital zircon dating and remapping of the area (Kositcin and Munson 2020 and references therein; Munson in press; **Table 1**) suggests that the Glyde–Favenc package boundary is most likely between the lower 'evaporitic unit' and medial 'stromatolitic unit', although the succession is concordant throughout and there is no obvious stratigraphic level where the boundary might be positioned. The available evidence supports the suggestion of Haines and Rawlings in Haines *et al* (1999) that the lower Balbirini Dolostone might be more appropriately included within the Glyde package as part of the McArthur Group.

Vizard Group

The Vizard Group outcrops in the central-western McArthur Basin within the broadly east-trending Urapunga Fault Zone (UFZ; **Figures 1**, **2**), which is a series of reverse faults related to a late-stage north–south shortening event that juxtaposed various Palaeo- to Mesoproterozoic stratigraphic levels of the McArthur Basin and underlying basement rocks (Betts *et al* 2015). The group is a succession of mostly fine-grained dolomitic rocks, stromatolitic dolostone, mudrock, sandstone, and minor tuff/tuffaceous mudrock that were deposited in a range of shallow- to very shallow-marine to occasionally emergent environments (Abbott *et al* 2001). The succession attains a thickness of about 330 m and is subdivided into the Saint Vidgeon and overlying Nagi formations, each of which is further subdivided into several informal numbered units.

The Vizard Group is the oldest exposed unit in the central-western part of the McArthur Basin. The base of the group is not exposed and has not been intersected in drillholes; the stratigraphically lowermost intervals are either concealed beneath regolith, or are structurally truncated (Abbott *et al* 2001). It is not known whether underlying units of the lower

Glyde and Redbank packages are present in this part of the basin, although a basement inlier (Urapunga Inlier) of older Palaeoproterozoic (Orosirian) granite and felsic volcanic rocks, which predates the McArthur Basin, is exposed in the core of an anticline about 25 km northwest of the main outcrop tract, to the north of the Roper River. These basement units are unconformably overlain by Mesoproterozoic Nathan Group rocks (Abbott and Sweet 2001); intervening Palaeoproterozoic successions of the McArthur Basin, including the Vizard Group, are not present in this area. The apparent absence of these successions might indicate either a substantial period of non-deposition for much of the Palaeoproterozoic prior to accumulation of the Vizard and Nathan groups, or the complete erosion of several kilometres of section corresponding to the Redbank package and much of the Glyde package. Both scenarios would suggest that the UFZ might have been a significant structural feature that influenced basin development in the Palaeoproterozoic, with a longer history of activity prior to the late-stage north–south shortening event described by Betts *et al* (2015).

In the vicinity of the main outcrop tract in southeast URAPUNGA, the Vizard Group is overlain by the Mount Birch Sandstone, the basal formation of the Nathan Group in this area, above a regional unconformity. A lenticular basal or near-basal conglomerate within the Mount Birch Sandstone marks the contact.

Balma Group

The Balma Group outcrops in the central and central-northern WFZ in the northern McArthur Basin (**Figures 1**, **2**). The group is a thick succession of mudrock, mostly silicified carbonate rocks, sandstone, and minor tuff/tuffaceous mudrock that were mostly deposited in a range of subtidal to intertidal environments, with evidence for local evaporitic conditions and surface exposure in a few intervals (Plumb and Roberts 1992, Haines 1994, Rawlings *et al* 1997, Haines *et al* 1999). Compared to equivalent rocks of the McArthur Group in the southern McArthur Basin, the succession contains a greater proportion of siliciclastic mudrock and sandstone relative to carbonate rocks. Evaporitic rocks are also much less abundant in the Balma Group in comparison to the McArthur Group. The Balma Group is subdivided into eight formations (**Figure 3**). There are no complete sections through the group and the succession is essentially undrilled. A maximum composite thickness estimate in the range 4500–5000 m has been derived by combining thicknesses for formations determined at various localities (Rawlings *et al* 1997, Haines *et al* 1999).

The Balma Group conformably overlies the Fleming Sandstone of the Parsons Range Group (Goyder package). The nature of the upper contact with the purported Balbirini Dolostone of the Nathan Group (Favenc package) is unclear. The contact is not exposed in areas where it is above the Bath Range Formation at the top of the Balma Group, but there is no evidence of an angular relationship or of any significant erosive down-cutting in these areas, so the contact might be disconformable or even conformable. A discordant relationship is present in some areas where purported Balbirini Dolostone is juxtaposed against the Yarrawirrie Formation, which is stratigraphically lower in the Balma Group, but it is uncertain as to whether the contact is structural or an angular unconformity due to poor outcrop and silicification (Haines *et al* 1999). In some areas, the Balma Group is unconformably overlain by Cretaceous strata and Cenozoic deposits (Plumb and Roberts 1992).

Geochronological analyses have been performed on several formations from the Balma Group (**Figure 4**, **Table 1**), but only one of these can be considered to be close to an absolute age determination. This is a tuff from the base of the Bath Range Formation at the top of the group, which returned a robust age maximum at 1599 ± 21 Ma plus a few scattered older detrital zircons (Pietsch *et al* 1994). The peak at ca 1599 Ma was considered to be 'the magmatic age of these euhedral zircons, and a good stratigraphic age for the tuff' by the analyst (R Page, GA Geochron Delivery[4]; GA sample 1496323 metadata, 1996). Haines *et al* (1999) noted that the age is within statistical error of ages determined for both the uppermost units of the McArthur Group and the upper Balbirini Dolostone of the Nathan Group (see above). However, it is still an interpreted MDA, which favours a younger Nathan Group-age for this formation.

Detrital zircon age spectra have also been determined for samples from the base and top of the Yarrawirrie Formation, and for the upper Baiguridji and upper Bath Range formations (**Table 1**). The detrital zircon age spectrum for the lower Yarrawirrie Formation has a similar modal distribution to those of the Nagi Formation (Vizard Group) and units of the Batten Subgroup; therefore, a broad correlation between these units is supported by these data (Munson 2019, **Figure 4**). Age spectra and interpreted MDAs for the upper Yarrawirrie Formation, and the upper Baiguridji and Bath Range formations, are very similar to one another and indicate that these units might be related in terms of depositional age and provenance. They more closely resemble age spectra of the Nathan Group (**Figure 5**) than those of other groups of the Glyde package (**Figure 4**), particularly in having prominent, relatively young modes and a similar spread of ages. This suggests that some or all of this interval might be better included within the Nathan Group rather than their current placement at the top of the Balma Group.

All formation contacts are concordant between the Yarrawirrie Formation and the Balbirini Dolostone in areas where there are no potential structural complications (Haines *et al* 1999). There is little evidence for a major angular unconformity within this succession, such as exists in the southern McArthur Basin beneath the Smythe Sandstone, although it is possible that one or more significant disconformities might be present. The boundary between the Glyde and Favenc packages, which equates to this unconformity, is inferred to be somewhere within this succession but is very difficult to place on available data. It is probably below the Bath Range Formation and most likely also below the sandstone-rich upper part of the Baiguridji Formation; these units have a very similar and distinctive detrital zircon spectral signature, which indicates a common provenance and a close relationship (Munson 2019).

[4] https://www.ga.gov.au/geochron-sapub-web/geochronology/shrimp/search.htm

Sandstone-rich intervals in these units might correlate with the Smythe and Mount Birch sandstones at the base of the Nathan Group in the southern McArthur Basin, at least in part; this possible relationship is depicted in **Figure 3**. It is also possible that the Glyde-Favenc boundary is located even lower in the succession. There are significant differences between the detrital zircon age spectra from the base and top of the Yarrawirrie Formation (**Figure 4**), which indicate a major change in provenance and/or sediment pathways up-section through the formation. This change might be related to the early Isan Orogeny in which case the Glyde-Favenc boundary could be located somewhere within this interval.

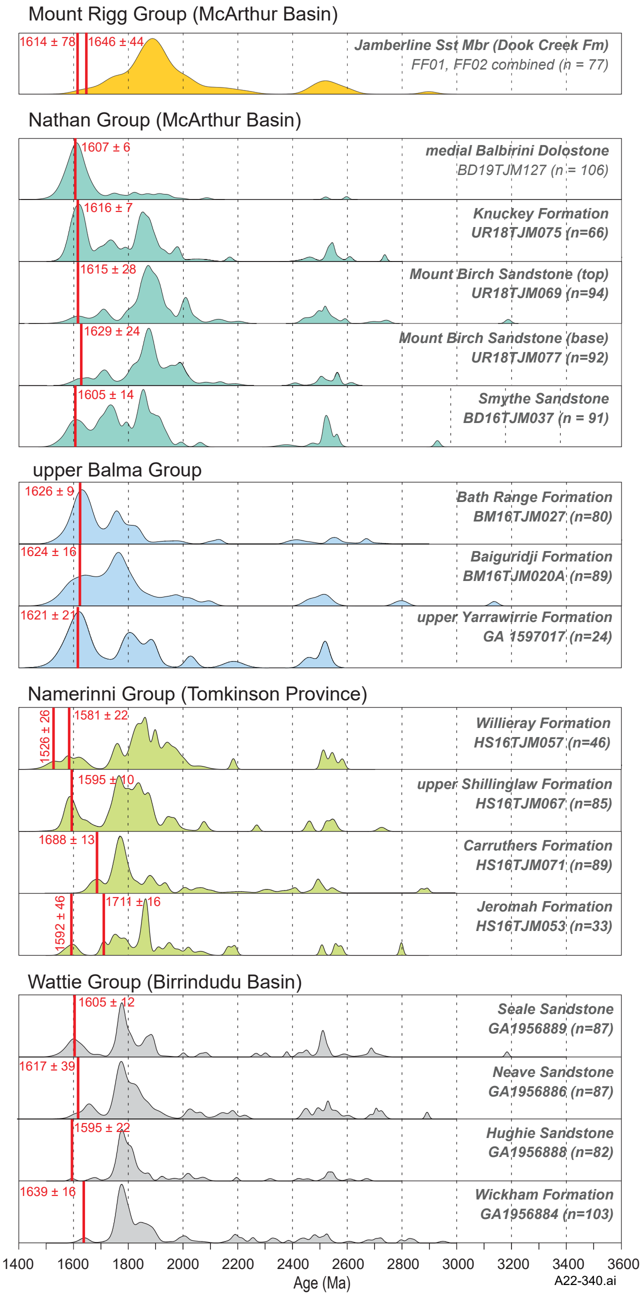


Figure 5. Comparative relative probability diagram of detrital zircon age data, with formations arranged in stratigraphic order for Wattie Group (grey polygons), Namerinni Group (lime green), upper Balma Group (blue), Nathan Group (green) and Mount Rigg Group (orange); updated from figure 7 in Munson (2019). References for all data provided in **Table 1**. Relative probability age spectra are not to scale vertically; associated histograms used to construct the spectra are not shown for clarity; number of concordant and near-concordant (<10%) analyses (n) is shown on right. Red lines indicate interpreted maximum depositional age for each sample; LHS red lines for Jeromah and Willieray formations are youngest concordant zircons, but these dates have low confidence due to possible analytical issues (see Munson *et al* 2020). Data for Dook Creek Formation replotted from analytical dataset supplied by D Subarkah (University of Adelaide).

Habgood Group

The Habgood Group outcrops in the northern WFZ in the northern McArthur Basin (Haines 1994, Rawlings *et al* 1997, **Figure 2**) and like the Parsons Range and Balma groups, is only recognised within this major structural feature and depocentre. Correlatives of the succession in adjacent areas to east and west of the WFZ are either very attenuated or absent (Haines 1994, Rawlings *et al* 1997, Haines *et al* 1999). The Habgood Group comprises five formations (**Figure 3**). Fine-grained siliciclastic sedimentary rocks dominate the succession, but bedded sandstones form a significant component of both the Darwarunga Sandstone and Gwakura Formation. Dolostone is a minor constituent of all units. The group was deposited in a range of subtidal to intertidal environments, and a few formations show some evidence of evaporitic conditions and periodic exposure. Structural complexities preclude determinations of the thickness of several formations; as the top of the succession is not exposed, the thickness of the group as a whole is not accurately known. However, it is considered to be several kilometres thick and of a similar order of magnitude as the Balma and McArthur groups (Rawlings *et al* 1997).

The Habgood Group conformably overlies the Kurala Sandstone of the Parsons Range Group with a relatively sharp contact, interpreted to indicate rapid deepening and a probable marine flooding surface (Rawlings *et al* 1997). The top of the Habgood Group is eroded and is unconformably overlain by the Neoproterozoic Buckingham Bay Sandstone, the basal unit of the Wessel Group (Arafura Basin), and by Cenozoic sediments. No younger Mesoproterozoic units of the McArthur Basin are in contact with the group.

The medial to upper Habgood Group units Yarawoi Formation, Darwarunga Sandstone, Ulunourwi Formation and Gwakura Formation have previously been directly correlated with the Balma Group units Vaughton Siltstone, Yarrawirrie Formation, Baiguridji Formation and Bath Range Formation respectively, based on their apparently equivalent stratigraphic positions and limited lithostratigraphic criteria (eg Haines 1994). However, detrital zircon age spectra obtained from a number of sandstone samples of these formations (**Figure 4**) provide little or no support for these correlations (Munson 2019).

Spectra from three formations of the Habgood Group (Yarawoi Formation, Darwarunga Sandstone and Gwakura Formation) have appreciably older interpreted MDAs (ca 35–80 million years) than those of upper Balma Group units, which have prominent young modes in the age range ca 1626–1621 Ma. The Habgood spectra also have significant older modes at ca 1870 Ma that are not present in the upper Balma Group. These features collectively suggest that there were significant dissimilarities in sediment provenances and/

or sediment pathways between the two groups. Habgood Group detrital zircon age spectra have some similarities with those of both the Batten and upper Umbolooga subgroups of the McArthur Group, particularly in the amplitudes and distribution of older modes (**Figure 4**). However, interpreted MDAs that are >ca 1660 Ma suggest that all three Habgood Group formations might be older than previously interpreted and might be equivalent to units lower in the Balma and McArthur groups as depicted in **Figure 3**.

Namerinni Group

The Namerinni Group is a heterolithic succession of siliciclastic and carbonate rocks that outcrops within the Tomkinson Province in the central-southern part of the greater McArthur Basin (**Figure 2**). In ascending stratigraphic order, the group is divided into four formations (**Figure 3**), two of which (Carruthers and Shillinglaw formations) are further subdivided into a number of informal unnamed units ('lithofacies' of Hussey *et al* 2001). The Namerinni Group forms a conformable, predominantly shallow-marine to fluviatile succession of sandstone, siltstone and carbonate rocks, with a maximum thickness of about 2800 m (Hussey *et al* 2001, Donnellan 2013). There is a cyclicity on a number of scales between more siliciclastic-dominated and more carbonate-dominated lithologies, both within the group and within individual formations. The Namerinni Group unconformably overlies the Palaeoproterozoic Tomkinson Creek Group (Redbank package) with a subtle angular unconformity. The Mesoproterozoic Renner Group (Wilton package) unconformably overlies all formations of the Namerinni Group (Hussey *et al* 2001). The subsurface extent of the Namerinni Group under Phanerozoic cover to the east and west of the Tomkinson Province is unknown.

The age of the Namerinni Group has not been well constrained previously. The base of the group is now constrained by a ca 1710 Ma interpreted MDA obtained from the Short Range Sandstone of the underlying Tomkinson Creek Group (McArthur Linkage Team 2020). The top is poorly constrained by a SHRIMP U–Pb baddeleyite age of 1295 ± 14 Ma for an unnamed dolerite sill that intrudes the overlying Renner Group (Melville 2010) and by the interpreted age of the Renner Group, which is correlated with the <ca 1500 Ma Roper Group of the McArthur Basin (eg Munson 2016). Ward (1983) correlated the group in general with the McArthur Group (and in particular the Umbolooga Subgroup) of the southern McArthur Basin on the basis of lithological similarities, and this has been followed in most subsequent studies. However, Munson (2019) correlated the entire group with the overlying Mesoproterozoic Wattie and Nathan groups based on detrital zircon geochronological results reported in Kositcin and Munson (2019) and a preliminary interpreted MDA of 1592 ± 46 Ma for the basal Jeromah Formation, which was subsequently revised to a much more conservative age of 1711 ± 16 Ma by Munson *et al* (2020, **Figure 5**) because of possible analytical issues.

Two SHRIMP zircon ages have previously been reported from purported tuffaceous layers within the group (**Table 1**). Nunn (1997) reported a SHRIMP U–Pb zircon age of 1639 ± 27 Ma from the Shillinglaw Formation, obtained from an altered, green illitic tuffaceous unit in Key Resources Pty Ltd drillhole Hunter 2DD (**Figure 6**). Hussey *et al* (2001) reported that this sample was obtained from near the top of the lower of two lithofacies recognised within the formation. Nunn commented that the analyses were done on 'primary magmatic grains', inferring that this is an absolute age, and used it as evidence to correlate the Shillinglaw Formation with the Barney Creek Formation of the McArthur Group, which is reliably dated at about this age. The report for the SHRIMP analysis is no longer available, so it is not possible to query the original data to determine the nature of the ca 1639 Ma age; it should therefore be treated with caution, and Hussey *et al* (2001) preferred to consider it to be a maximum depositional age. Champion *et al* (2020) subsequently reported a SHRIMP U–Pb zircon age of 1638 ± 16 Ma for an interpreted tuffaceous layer in a unit they identified as Carruthers Formation in drillhole Clifford Minerals Willieray 3DD (**Figure 6**). This sample was collected from 138–146 m depth and is near the top of the formation as noted from relogging of the drillhole (Munson in press). The age is based on nine analyses from only four euhedral zircon grains but is consistent with a detrital zircon interpreted MDA of 1688 ± 13 Ma for the Carruthers Formation reported by Kositcin and Munson (2019). Champion *et al* (2020) commented that there is no evidence of significant sedimentary reworking of the grains and that this increases confidence that the sampled layer had a magmatic origin and is tuffaceous. If the age interpretations of Nunn (1997) and Champion *et al* (2020) are correct, this would indicate that the lower Namerinni Group (Jeromah and Carruthers formations, and lower lithofacies of the Shillinglaw Formation) are all equivalent to the McArthur Group and can probably be referred to the Glyde package (**Figure 3**).

Detrital zircon geochronological analyses of sandstone samples from the upper two formations of the Namerinni Group have both returned interpreted MDAs under 1600 Ma (Kositcin and Munson 2019, Munson *et al* 2020; **Table 1**); a sample from the lower part of the upper lithofacies of the Shillinglaw Formation has an interpreted MDA of 1595 ± 10 Ma (n=14), and one from the overlying Willieray Formation has an interpreted MDA of 1581 ± 22 Ma (n=3). These interpreted MDAs are the same, within error, as those for the Wattie and Nathan groups of the Favenc package. There is also a relatively high degree of correspondence of zircon age modes from the three groups (**Figure 5**), suggesting that these units are correlatives.

Collectively, the above results indicate that the Glyde–Favenc package boundary, which equates to the unconformity beneath the Smythe Sandstone in the McArthur Basin, occurs within the medial to upper part of the Namerinni Group. It is probably above the altered tuffaceous unit dated at 1639 ± 27 Ma by Nunn (1997) near the top of the lower lithofacies, but below the sandstone with the interpreted MDA of 1595 ± 10 Ma in the lower part of the upper lithofacies; the stratigraphic interval between these sample points is of unknown thickness. The age data suggest the package boundary might correspond a time break of unknown duration. If so, this is likely to be a disconformity as Hussey *et al* (2001) did not recognise

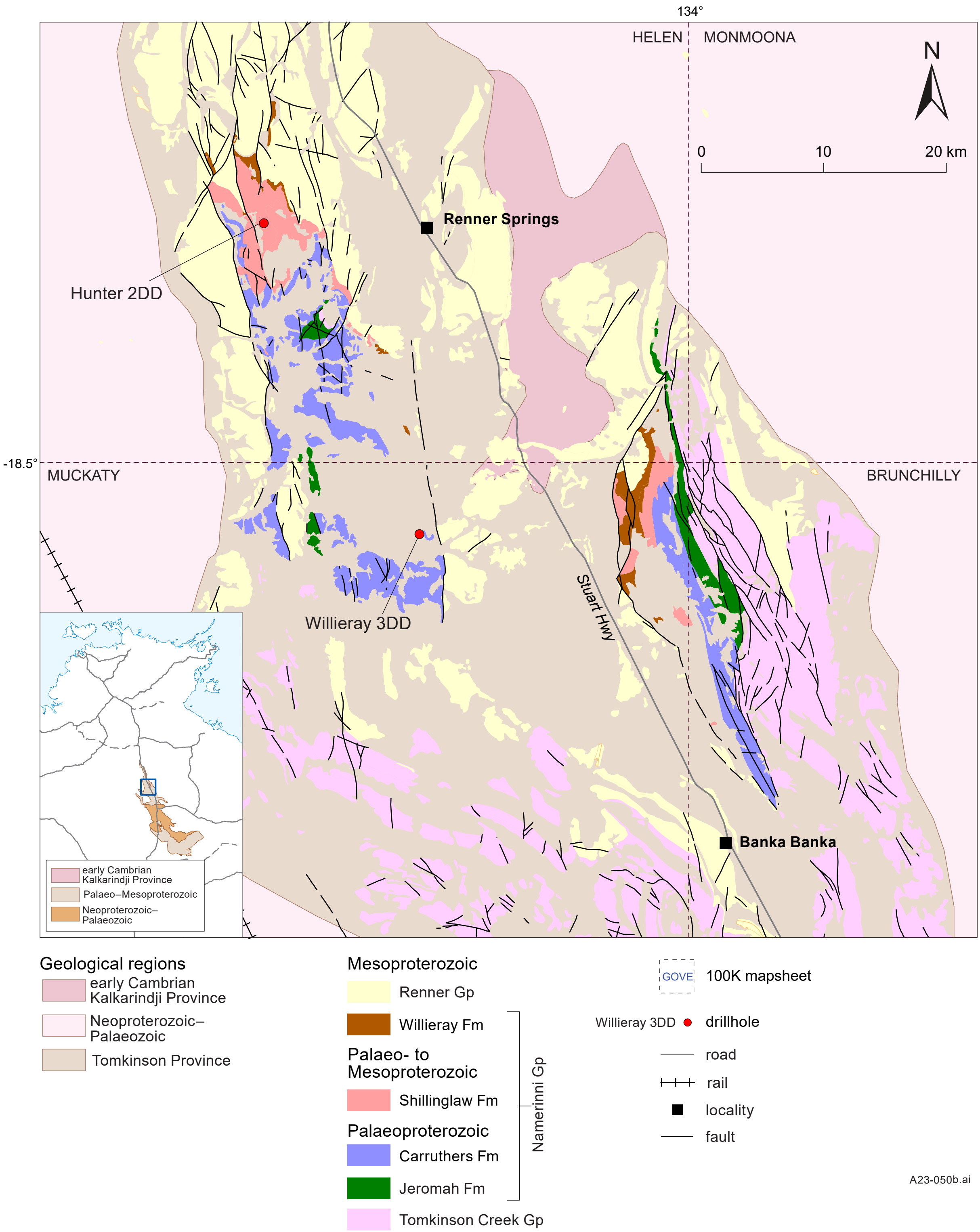


Figure 6. Simplified geological map of Namerinni Group in Tomkinson Province showing locations of drillholes referred to in the text, slightly modified from 1:250 000 geological mapsheet polygons in NTGS GIS database. Faults after HELEN SPRINGS 1:250 000-scale NTGS GIS dataset. Background map is NT geological regions from NTGS 1:2.5 M-scale GIS dataset. Inset map shows location within NT.

a significant unconformity at any stratigraphic level within the Namerinni Group during regional mapping, with all formation contacts being described as conformable. The most likely position of the boundary is at or near the contact between the lower and upper lithofacies of the Shillinglaw Formation, which Hussey *et al* (2001) described as variably transitional to sharp and conformable to possibly disconformable (**Figure 3**).

Limbunya Group

The Limbunya Group is a succession of cyclical carbonate and mostly fine-grained siliciclastic rocks that outcrops within the Birrindudu Basin in the western part of the greater McArthur Basin (**Figure 2**). In the subsurface, Limbunya Group-equivalent strata are interpreted as continuing beneath younger Proterozoic and Phanerozoic cover into the western Beetaloo Sub-basin at least as far as the Daly Waters Fault Zone (DWFZ; Hoffman 2014, Williams 2019, Garrad 2023). The group is divided into eleven concordant and probably conformable formations (**Figure 3**). All of these units, other than the Stirling and Farquharson sandstones, are dolomitic; some formations contain thick intervals dominated by bedded dolostone. Interbeds of siltstone and shale are common and are the predominant lithologies in the Kunja Siltstone. Coarse-grained siliciclastic rocks are comparatively rare. Sweet *et al* (1974) estimated the thickness of the group to be probably greater than 1300 m. The Limbunya Group is interpreted to have been deposited in mostly shallow-marine to emergent environments (Sweet *et al* 1971, 1974; Sweet 1977, Dunster *et al* 2000, Cutovinos *et al* 2002, Dunster and Ahmad 2013).

The Limbunya Group unconformably overlies greenschist-facies metamorphic basement rocks of the Inverway Metamorphics. It is also generally considered to be unconformable on older Palaeoproterozoic sedimentary rocks of the Birrindudu and Tolmer groups (Cutovinos *et al* 2002, Dunster and Ahmad 2013), although there are no exposed contacts with either of these groups, which respectively outcrop well to the south and north of exposures of the Limbunya Group. The inferred unconformable relationship is based on:

1. an interpreted intercorrelation of the Birrindudu and Tolmer groups and the inclusion of both groups within the Redbank package, which unconformably underlies the Glyde package (eg Dunster and Ahmad 2013 and references therein)
2. the presence of a subsurface unconformable contact in some drillholes between the Stirling Sandstone at the base of the Limbunya Group and underlying rocks regarded as being equivalent to the Birrindudu Group. However, the age and affinities of these 'Birrindudu Group' rocks are yet to be confidently established; it is also possible that they might be equivalent to the older Inverway Metamorphics (Munson in press). Various formations of the Limbunya Group are unconformably overlain by Mesoproterozoic rocks of the Wattie Group (Favenc package) and by Neoproterozoic to Phanerozoic cover rocks.

A number of tuffaceous rocks from the upper part of the Limbunya Group (Kunja Siltstone to Fraynes Formation) have been dated by SHRIMP U–Pb and CA–IDTIMS U–Pb methods (**Table 1**). These span the age range ca 1642–1635 Ma and are indistinguishable, within error, from ages returned from the medial McArthur Group (Teena Dolostone to Lynott Formation), which range from ca 1641 Ma to 1636 Ma. These data strongly support a general correlation of the Limbunya Group with the Umbolooga Subgroup of the McArthur Group (**Figure 3**) as proposed by Dunster (1998) and subsequent studies as summarised in Munson (2019). Correlations of formations from the lower part of the Limbunya Group are more uncertain due to a paucity of effective age controls. Dunster (1998) tentatively correlated the Farquharson Sandstone with the Tatoola Sandstone; the Margery Formation to Kunja Siltstone interval with the Mallapunyah Formation and Amelia Dolostone; and the Stirling Sandstone at the base of the Limbunya Group with the Masterton Sandstone at the base of the McArthur Group.

Carson (2013) and Kositcin *et al* (2017) produced detrital zircon age spectra for two units of the Limbunya Group: the basal Stirling Sandstone and medial Farquharson Sandstone respectively. These are compared to spectra from the medial McArthur Group, Depot Creek Sandstone (basal Tolmer Group) and Mount Charles Formation (ungrouped, Tanami Region) in **Figure 7**.

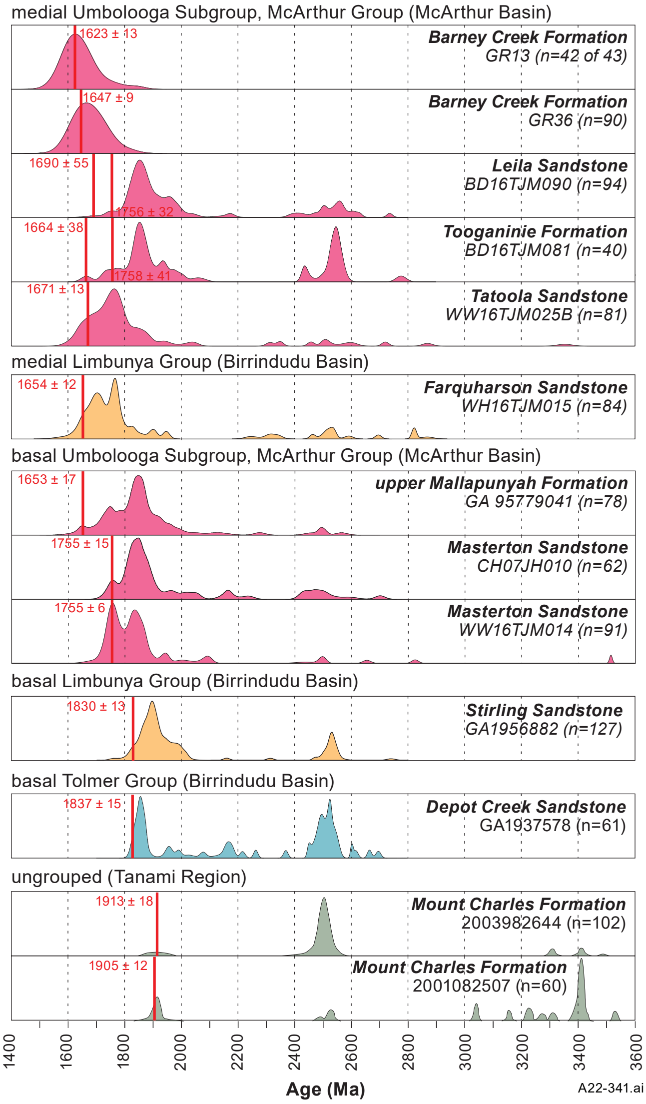


Figure 7. Comparative relative probability diagram of detrital zircon age data, with formations arranged in stratigraphic order for Mount Charles Formation (blue-green polygons), Depot Creek Sandstone (blue), Limbunya Group (orange) and Umbolooga Subgroup (McArthur Group; red), updated from figure 8 in Munson (2019). References for Limbunya and McArthur group data provided in **Table 1**. Mount Charles Formation plots redrawn after Cross and Crispe (2007: figure 17). Depot Creek Sandstone plot redrawn after Carson *et al* (2011: figure 17). Relative probability age spectra are not to scale vertically; associated histograms used to construct the spectra are not shown for clarity; number of concordant and near-concordant (<10%) analyses (n) is shown on right. Red lines indicate assigned maximum depositional age for each sample; if two lines present, LHS line is youngest concordant zircon(s).

The Farquharson Sandstone has a very similar detrital zircon age spectrum to that of the Tatoola Sandstone (Munson 2019, **Figure 7**); the interpreted MDAs for the two formations overlap within error, and the major age modes are closely comparable. This supports the correlation of these units and other formations of the Limbunya Group, both above and below the Farquharson Sandstone, with formations of the Umbolooga Subgroup above and below the Tatoola Sandstone respectively, as suggested by Dunster (1998, **Figure 3**). However, the age spectrum from the Stirling Sandstone is markedly dissimilar to that of the Masterton Sandstone. The interpreted MDA is appreciably older (ca 1830 Ma as compared to ca 1755 Ma) and the spread of age modes shows that these units had very different provenances and sediment pathways. Although these data do not exclude equivalence of these units as younger zircons might not have been present in source areas that provided detritus to the Stirling Sandstone, it does not support their correlation. Carson (2010) proposed that the Stirling Sandstone may represent a lateral stratigraphic equivalent of contemporaneous, although probably discontinuous, <ca 1830 Ma basal sandstones unconformably overlying Proterozoic metamorphosed basement across the northern part of the North Australian Craton, which is based on lithostratigraphic comparisons and detrital zircon suite ages. These units include the Depot Creek Sandstone (basal Tolmer Group, Birrindudu Basin; see Carson *et al* 2011), Mamadawerre Sandstone (basal Kombolgie Subgroup, northern McArthur Basin; see Zhang *et al* 2020) and Westmoreland Conglomerate (basal Tawallah Group, southern McArthur Basin; see Carson *et al* 2011). All have interpreted MDAs of ca 1830 Ma, similar to that of the Stirling Sandstone; the spread of age modes for analysed sandstones from these formations is also comparable (eg compare spectra of Stirling and Depot Creek sandstones in **Figure 7**). Carson (2013) suggested another possible correlation of the Stirling Sandstone with the older Palaeoproterozoic Mount Charles Formation of the Tanami Region based on similarities in the detrital zircon age spectra. The Mount Charles Formation spectra have modes at about 1900 Ma and 2500 Ma that are similar in age to the two larger modes of the Stirling Sandstone, but they also have significant populations of older Archaean zircons that are not present in the latter formation (**Figure 7**). For both possible correlations, a sizeable hiatus of up to 200 million years would need to be invoked between deposition of the Stirling Sandstone and the overlying Margery Formation. The relationship between these units is concordant and has been previously described as conformable (Sweet *et al* 1974) and as gradational over a few centimetres (Cutovinos *et al* 2002); however, it would be expected to be discordant if the depositional age of the Stirling Sandstone is close to its interpreted MDA.

The upper part of the Glyde package in the McArthur Basin (Batten Subgroup and its correlatives) has no known equivalents in the Birrindudu Basin. Hoffman (2015) reported that Batten Subgroup units can be mapped seismically from the western Beetaloo Sub-basin to the west towards the Birrindudu Basin, but these strata have not been recognised in outcrop or drillholes in the vicinity of the Limbunya Group. Hoffman attributed this to either an erosional unconformity at the base of the overlying Wattie Group, non-deposition, or a lack of exposure at this stratigraphic level.

References

Abbott ST and Sweet IP, 2001. Measured sections and drillcore logs from the Urapunga and Roper River 1:250 000 mapsheets, Northern Territory. *Northern Territory Geological Survey, Technical Report* 2001-004.

Abbott ST, Sweet IP, Plumb KA, Young DN, Cutovinos A, Ferenczi PA, Brakel A and Pietsch BA, 2001. *Roper Region: Urapunga and Roper River Special, Northern Territory (Second Edition). 1:250 000 geological map series and explanatory notes, 53-10, 11.* Northern Territory Geological Survey and Australian Geological Survey Organisation (National Geoscience Mapping Accord).

Armstrong RA, 1998. Ion Microprobe (SHRIMP) U-Pb dating of zircons from the Northern Territory Part III. *Precise Radiogenic Isotope Services (PRISE), Job #A98-030.* Research School of Earth Sciences, Australian National University, Canberra.

Betts P, Armit R and Ailleres L, 2015. Potential-field interpretation mapping of the greater McArthur Basin, PGN Geoscience Report 15/2014: in *'Geophysical and structural interpretation of the greater McArthur Basin'. Northern Territory Geological Survey, Digital Information Package* DIP 015.

Blaikie TN and Kunzmann M, 2020. Geophysical interpretation and tectonic synthesis of the Proterozoic southern McArthur Basin, northern Australia. *Precambrian Research* 343. https://doi.org/10.1016/j.precamres.2020.105728.

Carson CJ, 2010. The Victoria and Birrindudu basins: A UPb SHRIMP study and review of resource potential: in *'Annual Geoscience Exploration Seminar (AGES) 2010. Record of abstracts'. Northern Territory Geological Survey, Record* 2010-002, 24–26.

Carson CJ, 2013. The Victoria and Birrindudu Basins, Victoria River region, Northern Territory, Australia: a SHRIMP U-Pb detrital zircon and Sm-Nd study. *Australian Journal of Earth Sciences* 60, 175–196.

Carson CJ, Hollis JA, LM Glass, Close DF, Whelan JA and Wygralak A, 2011. Summary of results. Joint NTGS-GA geochronology project: Pine Creek Orogen, eastern Arunta Region, Murphy Inlier and Amadeus Basin, July 2007–June 2009. *Northern Territory Geological Survey, Record* 2010-004.

Champion D, Huston D, Cross A, Jarrett A, Bastrakov E and Thorne J, 2020. Geochemistry and age of the greater McArthur Basin: Base line geochemical studies and implications for basin-hosted mineral systems: in *'Annual Geoscience Exploration Seminar (AGES) Proceedings, Alice Springs, Northern Territory 24–25 March 2020'.* Northern Territory Geological Survey, Darwin, 105–116.

Close DF, 2014. The McArthur Basin: NTGS's approach to a frontier petroleum basin with known base metal prospectivity: in *'Annual Geoscience Exploration Seminar (AGES) 2014. Record of abstracts'. Northern Territory Geological Survey*, *Record* 2014-001, 85–88.

Collins C, 1983. Crustal structure of the southern McArthur Basin, northern Australia, from deep seismic-sounding. *BMR Journal of Australian Geology & Geophysics* 8(1), 19–34.

Cross AJ and Crispe AJ, 2007. SHRIMP U–Pb analyses of detrital zircon: a window to understanding the Paleoproterozoic development of the Tanami Region, northern Australia. *Mineralium Deposita* 42, 27–50.

Cruz CJ, 2019. *Geochronological analysis of the McArthur and Tawallah Groups, McArthur Basin: age constraints, provenance and implications for basin evolution*. BSc (Hons) thesis, Department of Earth Sciences, University of Adelaide, Adelaide.

Cutovinos A, Beier PR, Kruse PD, Abbott ST, Dunster JN and Brescianini RF, 2002. *Limbunya, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SE 52-07.* Northern Territory Geological Survey, Darwin.

Donnellan N, 2013. Chapter 16 – Tomkinson Province: in Ahmad M and Munson TJ (compilers). *'Geology and mineral resources of the Northern Territory'. Northern Territory Geological Survey, Special Publication* 5.

Dunster JN, 1998. Reconnaissance of the Proterozoic Rocks of the Victoria River Region. North Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1998-0082.

Dunster JN and Ahmad M, 2013. Chapter 17 – Birrindudu Basin: in Ahmad M and Munson TJ (compilers). *'Geology and mineral resources of the Northern Territory'. Northern Territory Geological Survey, Special Publication* 5.

Dunster JN, Beier PR, Burgess JM and Cutovinos A, 2000. *Auvergne, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SE 52-15.* Northern Territory Geological Survey, Darwin.

Fanning CM, 1991. *Ion microprobe U-Pb zircon dating of a tuffaceous horizon within the Kunja Siltstone, Victoria River Basin, Northern Territory. Report for Pacific Oil and Gas Pty Ltd*. Australian National University, Research School of Earth Sciences.

Garrad D, 2023. A new interpretation sheds light on the evolution of the Beetaloo Sub-basin and its surrounds: in *'Annual Geoscience Exploration Seminar (AGES) Proceedings, Alice Springs, Northern Territory 18–19 April 2023'.* Northern Territory Geological Survey, Darwin (this volume).

Haines PW, 1994. The Balma and Habgood Groups, Northern McArthur Basin, Northern Territory: stratigraphy and correlations with the McArthur Group: in Hallenstein CP (editor). *'Australian mining looks north – the challenge and choices. 1994 AusIMM Annual Conference, Darwin, Australia, August 5–9, 1994.' Australasian Institute of Mining and Metallurgy, Publication Series* 5/94, 147–152.

Haines PW, Pietsch BA, Rawlings DJ, and Madigan TLA, 1993. *Mount Young, Northern Territory (Second Edition). 1:250 000 geological map series and explanatory notes, SD 53-15.* Northern Territory Geological Survey, Darwin.

Haines PW, Rawlings DJ, Sweet IP, Pietsch BA, Plumb KA, Madigan TLA and Krassay AA, 1999. *Blue Mud Bay, Northern Territory (Second Edition). 1:250 000 geological map series and explanatory notes, SD 53-07.* Northern Territory Geological Survey, Darwin and Australian Geological Survey Organisation, Canberra.

Hoffman TW, 2015. Recent drilling results provide new insights into the western Palaeoproterozoic to Mesoproterozoic McArthur Basin: in *'Annual Geoscience Exploration Seminar (AGES) 2015. Record of Abstracts.' Northern Territory Geological Survey, Record* 2015-002, 50–54.

Hollis JA, Beyer EE, Whelan JA, Kemp AIS, Scherstén A and Greig A, 2010. Summary of results. NTGS laser U-Pb and Hf geochronology project: Pine Creek Orogen, Murphy Inlier, McArthur Basin and Arunta Region, July 2007–June 2008. *Northern Territory Geological Survey, Record* 2010-001.

Hussey KJ, Beier PR, Crispe AJ, Donnellan N and Kruse PD, 2001. *Helen Springs, Northern Territory. 1:250 000 geological map series and explanatory notes, SE53-10 (Second Edition)*. Northern Territory Geological Survey, Darwin.

Kositcin N and Carson CJ, 2017. New SHRIMP U–Pb zircon ages from the Birrindudu and Victoria Basins, Northern Territory: July 2016–June 2017. *Geoscience Australia, Record* 2017/16.

Kositcin N and Munson TJ, 2019. Summary of results. Joint NTGS–GA geochronology project: greater McArthur Basin, July 2017–August 2018. *Northern Territory Geological Survey, Record* 2019-002.

Kositcin N and Munson TJ, 2020. Summary of results. Joint NTGS–GA geochronology project: Balbirini Dolostone, southern McArthur Basin, June 2019–September 2019. *Northern Territory Geological Survey, Record* 2020-002.

Kositcin N, Munson TJ and Whelan JA, 2017. Summary of results. Joint NTGS – GA geochronology project: greater McArthur Basin, July 2016–June 2017. *Northern Territory Geological Survey, Record* 2017-012.

McArthur Linkage Team, 2020. Age constraints and provenance of the Tomkinson Province – the southernmost greater McArthur Basin (poster): in Northern Territory Geological Survey, 2020. Annual Geoscience Exploration Seminar (AGES). Presentations and posters. *Northern Territory Geological Survey, Record* 2020-003.

Melville PM, 2010. Geophysics and drilling collaboration final report for drilling program, Lake Woods Project, EL23687, EL24520, EL25631, EL27317, EL27318. *Northern Territory Geological Survey, Open File Company Report* CR2010-0226.

Munson TJ, 2016. Sedimentary characterisation of the Wilton package, greater McArthur Basin, Northern Territory. *Northern Territory Geological Survey, Record* 2016-003.

Munson TJ, 2019. Detrital zircon geochronology investigations of the Glyde and Favenc packages: Implications for the geological framework of the greater McArthur Basin, Northern Territory: in '*Annual Geoscience Exploration Seminar (AGES) Proceedings, Alice Springs, Northern Territory, 19–20 March 2019'*. Northern Territory Geological Survey, Darwin, 33–43.

Munson TJ, in press. Stratigraphic characterisation of the Glyde package, greater McArthur Basin, Northern Territory. *Northern Territory Geological Survey, Record.*

Munson TJ, Denyszyn SW, Simmons JM and Kunzmann M, 2019. A 1642 Ma age for the Fraynes Formation, Birrindudu Basin, confirms correlation with the economically significant Barney Creek Formation, McArthur Basin, Northern Territory. *Australian Journal of Earth Sciences* 67(3), 321–330.

Munson TJ, Thompson JM, Meffre S and Orth K, 2020. NTGS laser ablation ICP–MS U–Pb geochronology project: Habgood and Balma groups (McArthur Basin), Namerinni Group (Tomkinson Province), and unnamed units from drillholes NDW12-01 and Jamison-1, July 2016–May 2019. *Northern Territory Geological Survey, Record* 2020-009.

Northern Territory Geological Survey and Geognostics Australia Pty Ltd, 2021. Northern Territory SEEBASE® and GIS – Gravity and Magnetics. *Northern Territory Geological Survey, Digital Information Package* DIP 031.

Nunn T, 1997. Second annual report for the period 2 June 1996 to 1 June 1997 for ELs 9022-9025, 9325-9327, 9570 Helen Springs project. *Northern Territory Department of Mines and Energy, Open File Company Report* CR1997-0444.

Page RW, Jackson MJ and Krassay AA, 2000. Constraining sequence stratigraphy in north Australian basins: SHRIMP U–Pb zircon geochronology between Mt Isa and McArthur River. *Australian Journal of Earth Sciences* 47(3), 431–459.

Page RW and Sweet IP, 1998. Geochronology of basin phases in the western Mt Isa Inlier, and correlation with the McArthur Basin. *Australian Journal of Earth Sciences* 45(2), 219–232.

Pietsch BA, Plumb KA, Page RW, Haines PW, Rawlings DJ and Sweet IP, 1994. A revised stratigraphic framework for the McArthur Basin, NT: in Hallenstein CP (editor). *'Australian mining looks north – the challenges and choices.' 1994 AusIMM Annual Conference, Darwin 5–9 August 1994, Technical Program Proceedings.* The Australasian Institute of Mining and Metallurgy, Melbourne, 135–138.

Plumb KA and Roberts HG, 1992. The geology of Arnhem Land, Northern Territory. Mineral Provinces 15. *Bureau of Mineral Resources, Record* 1992/55.

Rawlings DJ, 1999. Stratigraphic resolution of a multiphase intracratonic basin system: the McArthur Basin, northern Australia. *Australian Journal of Earth Sciences* 46, 703–723.

Rawlings DJ, Haines PW, Madigan TLA, Pietsch BA, Sweet IP, Plumb KA and Krassay AA, 1997. *Arnhem Bay-Gove, Northern Territory (Second Edition). 1:250 000 geological map series and explanatory notes, SD 53-3, 4*. Northern Territory Geological Survey and Australian Geological Survey Organisation (National Geoscience Mapping Accord).

Smith J, 2001. Summary of results. Joint NTGS-AGSO age determination program 1999-2001. *Northern Territory Geological Survey, Record* 2001-007.

Southby C, Carson CJ, Fomin T, Rollet N, Henson PA, Carr LK, Doublier MP and Close D, 2022. Exploring for the Future – The 2019 Barkly Reflection Seismic Survey (L212). *Geoscience Australia, Record* 2022/009. http://dx.doi.org/10.11636/Record.2022.009

Subarkah D, 2018. *The forgotten Mesoproterozoic of Northern Australia: a chemostratigraphy and detrital zircon study of the greater McArthur Basin.* BSc (Hons) thesis, Department of Earth Sciences, University of Adelaide, Adelaide.

Sweet IP, 1977. The Precambrian geology of the Victoria River region, Northern Territory. *Bureau of Mineral Resources, Australia, Bulletin* 168.

Sweet IP, Mendum JR, Bultitude RJ and Morgan CM, 1974. The geology of the southern Victoria River region, Northern Territory. *Bureau of Mineral Resources, Australia, Report* 167.

Volante S, Collins WJ, Barrote V, Nordsvan AR, Pourteau A, Li Z-X, Li J and Beams S, 2022. Spatio–temporal evolution of Mesoproterozoic magmatism in NE Australia: A hybrid tectonic model for final Nuna assembly. *Precambrian Research* 372, 106602. https://doi.org/10.1016/j.precamres.2022.106602

Ward DF, 1983. Report on geological mapping and geochemical survey on EL2835 and 3607, and drill testing targets in EL3607, Helen Springs. Esso Australia Ltd. *Northern Territory Geological Survey, Open File Company Report* CR1983-0299A, B.

Williams B, 2019. Definition of the Beetaloo Subbasin. *Northern Territory Geological Survey, Record* 2019-015.

Zhang Shuanhong, Pei Junling, Hu Guohui, Liu Jianmin and Munson TJ, 2020. Detrital zircon U-Pb geochronology of drill core sandstone samples, McArthur Basin, northern Australia. *Northern Territory Geological Survey, Core Sampling Report* CRS0512.