Jarred C. Lloyd[1,2]; Wolfgang V. Preiss[1,3]; Alan S. Collins[1]; Georgina M. Virgo[2,1]; Morgan L. Blades[1]; Sarah E. Gilbert[4]; Kathryn J. Amos[2]

1. Tectonics and Earth Systems Group, and Mineral Exploration CRC, Department of Earth Sciences, University of Adelaide, Adelaide, SA 5005, Australia
2. Australian School of Petroleum and Energy Resources, University of Adelaide, Adelaide, SA 5005, Australia
3. Department for Energy and Mining, Geological Survey of South Australia, Adelaide, SA 5000, Australia
4. Adelaide Microscopy, University of Adelaide, Adelaide, SA 5005, Australia

Corresponding author email: jarred.lloyd@adelaide.edu.au

Detrital zircon record of the *Sturtian glaciation*: Adelaide Superbasin

Jarred C. Lloyd[1,2]; Wolfgang V. Preiss[1,3]; Alan S. Collins[1]; Georgina M. Virgo[2,1]; Morgan L. Blades[1]; Sarah E. Gilbert[4]; Kathryn J. Amos[2]

1. Tectonics and Earth Systems Group, and Mineral Exploration CRC, Department of Earth Sciences, University of Adelaide, Adelaide, SA 5005, Australia
2. Australian School of Petroleum and Energy Resources, University of Adelaide, Adelaide, SA 5005, Australia
3. Department for Energy and Mining, Geological Survey of South Australia, Adelaide, SA 5000, Australia
4. Adelaide Microscopy, University of Adelaide, Adelaide, SA 5005, Australia

Abstract

The glaciogenic nature of the Yudnamutana Subgroup was first recognised over a century ago, and their global significance was recognised shortly after, eventually culminating with the pan global *Sturtian glaciation* and Snowball Earth theory. Much debate on the origin and timing of these rocks, locally and globally, has ensued in the years since. A significant corpus of research on the lithology, sedimentology, geochronology, and formal stratigraphy of these sequences globally has attempted to resolve many of these debates. In the type area for the *Sturtian glaciation*, South Australia's Adelaide Superbasin, lithostratigraphy and sedimentology have been well understood; however, formal stratigraphy had remained complicated and contested. Geochronology has also been extremely sparse in this area, with limited advancement in the past few years. The result of these longstanding issues has been disagreement as to whether the sedimentary rocks of the Yudnamutana Subgroup are truly correlative throughout South Australia, and if they were deposited in the same time window now defined for and other *Sturtian glacial* rocks globally, c. 717 Ma to c 660 Ma. In this study we present a large detrital zircon study, summarise and compile existing geochronology, and provide an up-to-date understanding of the formal stratigraphy. We confirm that the rocks of the Yudnamutana Subgroup were deposited within the time globally defined for *Sturtian glaciation*.

1 Introduction

The Neoproterozoic is one of the most pivotal times in Earth's history for earth system changes that led to the Phanerozoic world of extensive macroscopic mineralised life, significantly oxygenated atmosphere and hydrosphere, and a buffered climate devoid of whole-planet glaciations (Halverson et al. 2009; Och & Shields-Zhou 2012; Shields et al. 2022; Tostevin & Mills 2020; Wallace et al. 2017). Within the Neoproterozoic, the Cryogenian Period (derived from the Greek: κρύος, meaning cold), is named for the globally distributed, and long-lasting continental glaciations (Plumb 1991; Plumb & James 1986) characteristic of this time. The record of these glaciations is known on every continent except Antarctica (Arnaud et al. 2011), with notably well studied sections in Australia (Le Heron 2012; Preiss et al. 2011; Virgo et al. 2021), Canada (Hoffman & Halverson 2011; Macdonald et al. 2010; Macdonald et al. 2018), China (Rooney et al. 2020; Wu et al. 2019; Xiao et al. 2020; Xu et al. 2009; Zhang, Q-R et al. 2011; Zhu & Wang 2011), Ethiopia (Park et al. 2019), Namibia (Hoffman et al. 2021; Hoffman et al. 2017b; Nascimento et al. 2017), Scotland (Ali et al. 2018; Fairchild et al. 2018), Svalbard (Halverson et al. 2017; Halverson et al. 2018), and the USA (Le Heron et al. 2018; Lechte et al. 2018; Link & Christie-Blick 2011; Lund et al. 2011; Mrofka & Kennedy 2011; Petterson et al. 2011). While the concept of a Snowball Earth, and even the glaciogenic nature of these some of these formations remains conjectural to this day (e.g., Allen & Etienne 2008; Eyles & Januszczak 2004; Le Heron et al. 2020; Williams & Gostin 2019), two major glacial episodes are indicated; the older *Sturtian glaciation*, and the younger *Marinoan* (Elatina) *glaciation* (Hoffman et al. 2017a). These two major glacial events of the Cryogenian have been invoked to be key drivers of nutrient supply into oceans during the interglacial and post-glacial periods and subsequently the rise of algae/eukaryotic life, leading to the emergence of animals (Brocks 2018; Brocks et al. 2017; Lechte et al. 2019), key control on carbon enrichment of sediments post-glaciation (Xiao et al. 2020), and as a potential explanation for the Laurentian “Great Unconformity” (Keller et al. 2019).

Absolute geochronological constraints have become well established in several of these regions (Rooney et al. 2015) and is ever improving across the globe (e.g, MacLennan et al. 2018; Nascimento et al. 2017; Rud`ko et al. 2020). One notable exception is that of the sequences of Australia where some the thickest and best-preserved Cryogenian glaciogenic formations are found. Until recently (Cox et al. 2018b; Keeman et al. 2020; Lloyd et al. 2020; Rose et al. 2013) radiometric dates of any form for the Cryogenian glaciogenic and interglacial sequences of the Adelaide Superbasin, South Australia, were extremely sparse (Fanning & Link 2006; Ireland et al. 1998; Kendall et al. 2006). This is in part due to the dearth of known volcanogenic horizons within the South Australian Cryogenian sequences, the challenges of dating pre-Cambrian sedimentary rocks (Halverson et al. 2018; Shields et al. 2022), and the general lack of geochronological research conducted on the basin since the marked advancement in laser ablation, and chemical abrasion geochronological techniques during the mid-2000s (Gehrels et al. 2008; Mattinson 2005; Mundil et al. 2004). In this study we address this by presenting 1034 new detrital zircon analyses from fifteen samples [Figure 1] of the Yudnamutana Subgroup (*Sturtian glaciation*), 59 analyses from the thought to be equivalent Yancowinna Subgroup of New South Wales, and an additional 56 analyses from the interglacial Serle Conglomerate. The purpose of this paper is not to debate the environmental aspects of this time, but to provide the base of a geochronological framework for the *Sturtian* glaciogenic rocks of the Adelaide Superbasin, i.e., the true *Sturtian*.

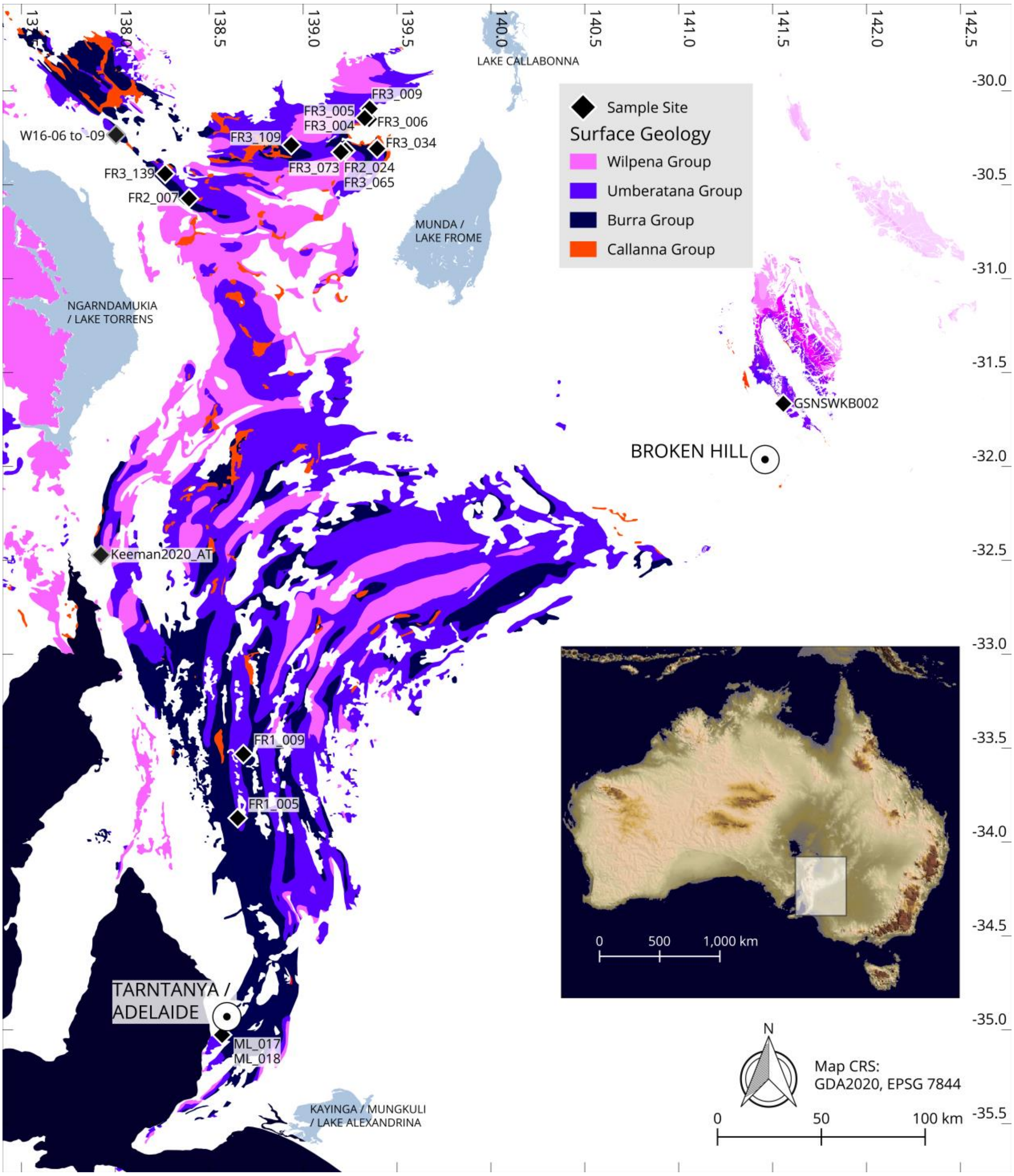

Figure 1 – Sample locality map, showing distribution of Neoproterozoic stratigraphy within the Adelaide Rift Complex of the Adelaide Superbasin. GPS coordinates for samples are provided with the U-Pb data (see data availability).

2 Geological Background

2.1 Adelaide Superbasin

The Adelaide Superbasin (Lloyd et al. 2020) is a large, Neoproterozoic to middle Cambrian sedimentary system at the southeast margin of Proterozoic Australia, which formed as a result of the breakup of the supercontinent Rodinia. The Adelaide

Superbasin consists of several named basins and sub-basins that span the Neoproterozoic to early Cambrian (Lloyd et al. 2020). The largest and oldest of these is the Adelaide Rift Complex that is contiguous with the relatively undeformed rocks of the Torrens Hinge Zone, Stuart Shelf (Sprigg 1952), and Coombalarnie Platform (Callen 1990). Two Cambrian basins, the Arrowie Basin, and the Stansbury Basin, are also considered as part of the Adelaide Superbasin (Lloyd et al. 2020; Preiss et al. 2002). Deposition within the Adelaide Superbasin spans over 300 million years of Earth's history and stretches from the northernmost regions of South Australia, narrowing in the South Mount Lofty Ranges at the Fleurieu Peninsula and extending onto Kangaroo Island. The basin began as an intracontinental rift system that successfully progressed to a passive margin basin in its southeast region, yet remained a failed rift in the north (Lloyd et al. 2022a, preprint). Deposition within the basin ceased during the Delamerian orogeny c. 514–490 Ma (Drexel & Preiss 1995; Foden et al. 2006; Foden et al. 2020; Preiss 2000). Whilst present day exposure of the sedimentary basin is approximately 600 km north to south, the basin spans over 1,100 km from central Australia through to Kangaroo Island. The stratigraphy of the Adelaide Superbasin is divided into three supergroups (Lloyd et al. 2020; Preiss 2000), two for the Neoproterozoic sequences and the third for the Cambrian sequences, with numerous group and subgroup level divisions. The Warrina Supergroup is comprised of the Callanna, Burra, and Poolamacca Groups, and the Heysen Supergroup contains the Umberatana, Wilpena, Torrowangee, and Farnell Groups. Each of these groups are further divided into numerous subgroups. Here we focus on the Yudnamutana Subgroup [Figure 2, Figure 3], which represents the *Sturtian* glaciation, and present an additional sample from the overlying Nepouie Subgroup, both are constituents of the Umberatana Group. One further sample is presented from the thought to be equivalent Yancowinna Subgroup (NSW). The reader is referred to Preiss (1987), Preiss (2000), Counts (2017), Lloyd et al. (2020), Cowley (2020) and references therein for further detail on the geological history of the Adelaide Superbasin.

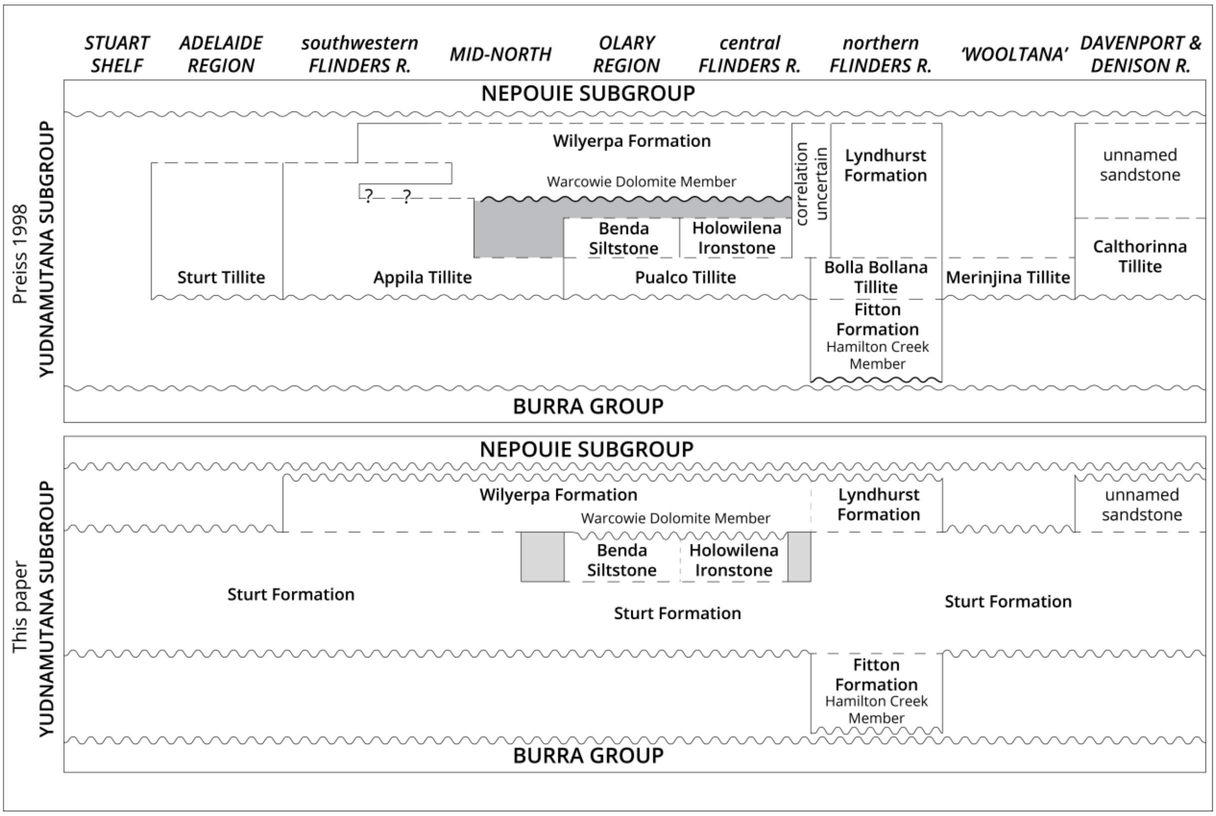

Figure 2 – Stratigraphic table showing past (Preiss et al. 1998) and current correlations (this study) of the Yudnamutana Subgroup.

2.1.1 Yudnamutana Subgroup

The Yudnamutana Subgroup (Coats & Preiss 1987; Preiss et al. 1998; Thomson et al. 1964) is the lowermost subdivision of the Umberatana Group and is comprised of sedimentary rocks that represent the *Sturtian* glacial event in South Australia. The glaciogenic nature of these rocks was first recognised by Howchin (1901), and were traced during the early 20th century throughout the Mount Lofty, Flinders, and Olary Ranges (Preiss et al. 2011). A significant corpus of research has been published of over the past century (e.g., Coats & Forbes 1977; Conor & Preiss 2019; Cox et al. 2013; Cox et al. 2018b; David 1906; Fanning & Link 2008; Forbes & Cooper 1976; Howchin 1901; 1904; 1906; 1908; 1920; Le Heron et al. 2014; Le Heron et al. 2011; Link & Gostin 1981; Mawson & Sprigg 1950; Preiss 1987; 2000; Preiss et al. 1998; Preiss et al. 2011; Preiss et al. 1978; Segnit 1939; Sprigg 1952; Sweet & Preiss 1966; Thomson et al. 1964; Virgo et al. 2021) on the nature of these formations, with the "tillites" quickly rising to international fame (Cooper, BJ 2010; David 1906; Howchin 1908; and references therein). The most characteristic lithofacies of the Yudnamutana Subgroup are the diamictites, which have clasts ranging in size up to boulders. The matrix varies from mudstone, through to silty sands and abundant carbonates in some places. Siltstone with lone-stones and drop-stones are commonly associated with the diamictites, as are sandstones of varying compositions. Non-diamictite conglomerates are a minor lithofacies of the Yudnamutana Subgroup (Preiss et al. 2011). Sedimentary

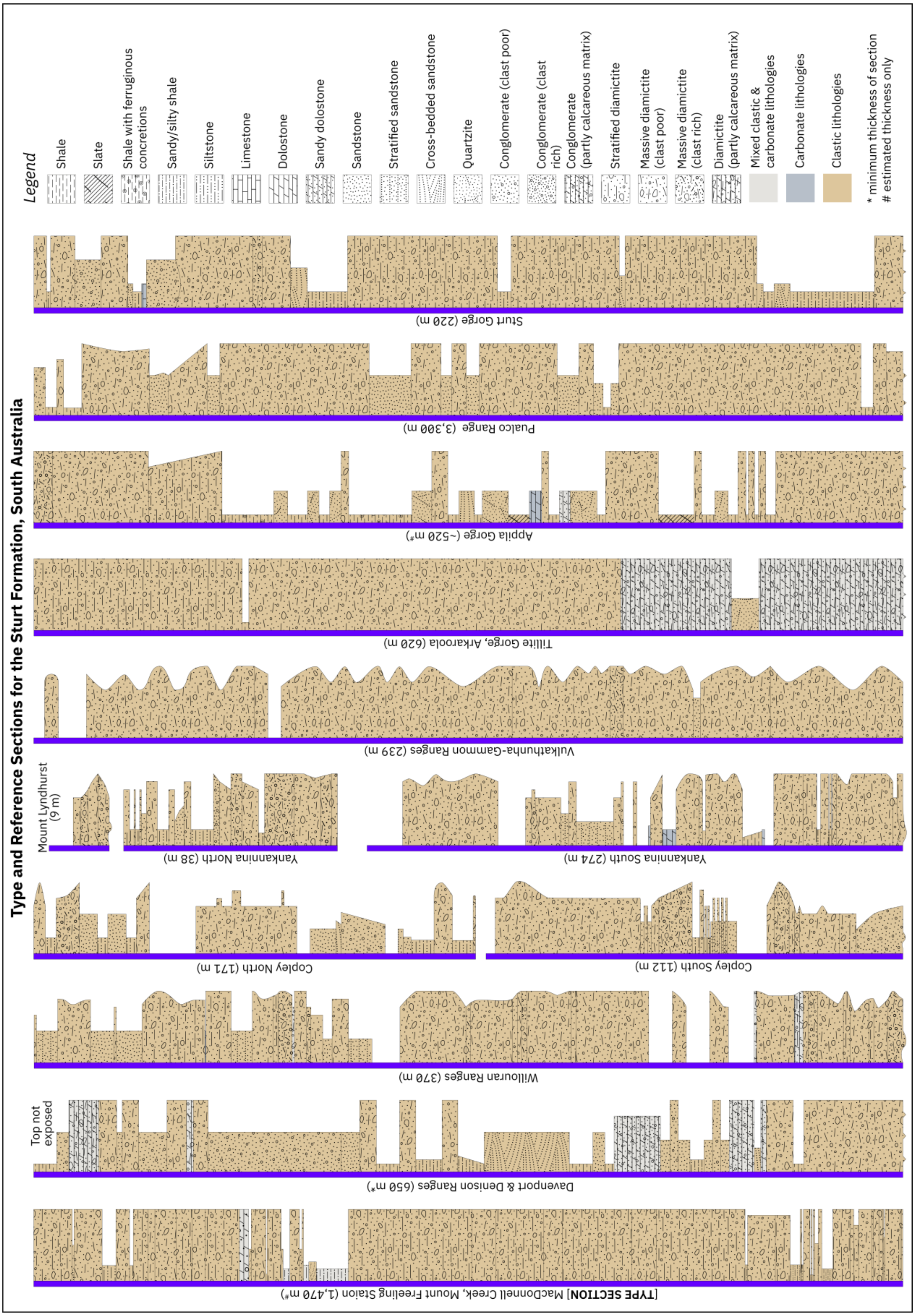

Figure 3 – Generalised stratigraphic logs of the Sturt Formation at its type section, and additional reference sections. For coordinates of locations see the accompanying stratigraphic unit definition (appendix). Copley, Yankaninna, Willouran Ranges, and Vulkathuhna-Gammon Ranges sections are from logging done by authors in this study. Type section is based on data from Belperio (1973) and Young and Gostin (1989b). Other sections are compiled from Segnit (1939), Forbes and Cooper (1976), Coats and Preiss (1987), and Link (1977).

2011) in the eastern portion of the Adelaide Superbasin.

The Fitton Formation, only present in the northern Flinders Ranges, represents glacial advance (Preiss et al. 1998; Young & Gostin 1989b). Currently there are six named diamictite/tillite formations that represent the glacial maximum: the Appila Tillite (Thomson et al. 1964) (based on the section of Segnit 1939), Bolla Bollana Tillite (Coats & Forbes 1977; Thomson et al. 1964), Calthorinna Tillite (Ambrose et al. 1981), Merinjina Tillite (Coats & Preiss 1987), Pualco Tillite (Forbes & Cooper 1976), and Sturt Tillite (Howchin 1920; Mawson & Sprigg 1950). For the reasons outlined later in this publication, the formations representative of the glacial maximum are here renamed the Sturt Formation. The Benda Siltstone, Old Boolcoomata Conglomerate and Holowilena Ironstone overlie the Sturt Formation but are limited in distribution (Conor & Preiss 2019; Lechte & Wallace 2015; Preiss 2006). The exact stratigraphic correlation of these units is still uncertain but are likely partial equivalents of both underlying and overlying stratigraphy. The Wilyerpa Formation (Dalgarno & Johnson 1966; Forbes 1971; Thomson et al. 1964) and Lyndhurst Formation (Thomson et al. 1964; Young & Gostin 1989b) are the uppermost units of the Yudanamutana Subgroup and represent the waning of the *Sturtian* glacial event (Preiss 1987; Preiss et al. 1998).

2.1.2 Yancowinna Subgroup

The Yancowinna Subgroup, Torrowangee Group, of western New South Wales, was defined by (Cooper, PF & Tuckwell 1971) presented in further detail by (Cooper, PF et al. 1974). It consists of a sequence of coarse ill-sorted and clastic material namely arkose, quartzite, sandstone, siltstone, conglomerate, and diamictite (Cooper, PF et al. 1974; Fitzherbert & Downes 2015; Preiss 1987). True tillite has only been recognised in one area (Cooper, PF 1973), but many of the facies closely resemble the possible equivalents in South Australia (Preiss 1987). Its stratigraphic position supports an equivalence with the Yudnamutana Subgroup of South Australia, with the Yancowinna Subgroup overlain by the Euriowie Subgroup (inter-glacial) that is in turn overlain by the Teamsters Creek Subgroup, which is thought to represent the Marinoan glacial event (Fitzherbert & Downes 2015; Preiss 1987). Aside from detailed mapping and the original sedimentological work, there is extraordinarily little research on these sequences, and no geochronology has been published to date. As such the correlations are likely, but uncertain.

2.1.3 Nepouie Subgroup

The inter-glacial Nepouie Subgroup most notably includes the basin-wide Tapley Hill Formation. Other formations in the Nepouie Subgroup are the Brighton Limestone, Balcanoona Formation, and Serle Conglomerate. The stratigraphic position is well established for the Brighton Limestone and Balcanoona Formation, as both overlie the Tapley Hill Formation. The Balcanoona Formation is coeval with the upper Tapley Hill Formation, forming large palaeo-reef systems above it and passing laterally into it (Wallace et al. 2015). The Tapley Hill Formation itself is primarily comprised of well sorted, often calcareous, dolomitic, or pyritic shale. While extensive in both distribution (basin-wide) and uniformity, there are several minor lithofacies that occur within the Tapley Hill Formation, including arkose, greywacke, siltstone, dolostone, and lenticular conglomerate beds. The latter is attributed to debris flows reworking the underlying glaciogenic sequences (Preiss 1987). The only formation of the Nepouie Subgroup with a still somewhat uncertain stratigraphic position is the Serle Conglomerate, however a position conformably below the Tapley Hill Formation seems likely (Dyson 1996; 2004; Preiss et al. 1998; Young & Gostin 1989a). The Serle Conglomerate is thought to be deposited as part of a submarine fan complex (Young & Gostin 1989a).

2.2 Sturtian glaciation

The term *Sturtian* was originally used to describe a chronostratigraphic sequence in South Australia and proposed for use as a global chronostratigraphic division by Dunn et al. (1971). However, this has since been superseded by international nomenclature (Gradstein et al. 2005; Knoll et al. 2006; Lloyd et al. 2020; Plumb 1991; Preiss et al. 2011; Shields-Zhou et al. 2016; Shields et al. 2022) with the *Sturtian* glaciation wholly within the Cryogenian Period (Plumb 1991; Shields-Zhou et al. 2016). At present, *Sturtian* is informally used by the international community as the name for the older of two s*nowball* (or *slushball*) Earth events (Fairchild & Kennedy 2007; Hoffman et al. 2017a; Hoffman et al. 1998; Hoffman & Schrag 2002) proposed to have occurred during the Cryogenian. In a split from the growing consensus, Le Heron et al. (2020) have advocated that the name "Laurentian Neoproterozoic Glacial Interval" be used in favour of the *Sturtian*, and *Sturtian* be restricted to the formations in Australia, a concept we are not in favour of and will discuss later.

The global distribution of pre-Cambrian glacial sequences, those now attributed to the *Sturtian* glaciation, was recognised nearly a century ago (Hoffman 2011; Hoffman et al. 2017a, and references therein); however, synchroneity has only become evident within the past two decades (e.g., Cox et al. 2018b; Dempster et al. 2002; Hoffman et al. 2017a; Keeman et al. 2020; Kendall et al. 2006; Lamothe et al. 2019; Lloyd et al. 2020; Macdonald et al. 2010; Miller 2013; Park et al. 2019; Rooney et al. 2014; Rooney et al. 2015; Rooney et al. 2020; Shields et al. 2018; Xu et al. 2009). The recognition of global time equivalence led Hoffman et al. (2017a) to propose calling the Cryogenian glacial periods 'cryochrons'. Advancements in the application of geochronology and mass spectrometry have led to tight constraints on the global major onset of glaciation and deglaciation c. 717 Ma and c. 660 Ma respectively (Hoffman et al. 2017a; Rooney et al. 2015).

3 Methods

Fifteen samples [Figure 1] from the Yudnamutana Subgroup (FR1_005_02, FR1_009_01, FR2_007_01, FR2_024_01, FR3_005, FR3_006, FR3_009, FR3_034, FR3_065, FR3_073, FR3_084a, FR3_109, FR3_139, ML_017, & ML_018), one sample from the equivalent Yancowinna Subgroup (GSNSWKB002), and one sample from the lowermost Nepouie Subgroup (FR3_004), were analysed for detrital zircon geochronology.

Methodology is exactly that of (Lloyd et al. 2022a, preprint), with a summary provided here.

Rock samples were prepared for detrital zircon analysis by crushing, sieving, panning and, where necessary due to low zircon yield, heavy liquid separation. Any grain that remotely resembled a zircon was picked to minimise human bias, an issue highlighted by Sláma and Košler (2012) and Dröllner et al. (2021). Where permitted by zircon yields, at least 300 zircons were picked per sample, otherwise all zircons in the sample were picked. Cathodoluminescence images were obtained on either a FEI Quanta 600 scanning electron microscope (for zircon analysed in 2020) or a Cameca SXFive Electron Microprobe (for zircon analysed in 2021). The zircons were using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) to obtain a suite of elemental data for U–Pb geochronology and rare earth element (REE) analysis. All zircons were analysed using a Resonetics M-50 (193 nm ArF excimer) laser ablation system coupled with an Agilent 7900x inductively coupled plasma mass spectrometer. All analytical instruments used are housed at Adelaide Microscopy, University of Adelaide, Australia.

GJ-1 (Horstwood et al. 2016; Jackson et al. 2004), was used as the primary calibration standard for U–Pb ratios and NIST610 (Jochum et al. 2011) was used as the primary calibration standard for Pb isotope ratios and trace element data. The internal standard for trace element data was set to ^{91}Zr with a value of 431,400 ppm (43.14 wt%) assigned to unknowns. Plešovice (Horstwood et al. 2016; Sláma et al. 2008) and 91500 (Horstwood et al. 2016; Wiedenbeck et al. 1995; Wiedenbeck et al. 2004) were used as validation standards. Unknowns were bracketed by two analyses of GJ-1, followed by a combined two to three analyses of Plešovice and 91500, and two analyses of NIST610 every 20–30 unknowns. A 30 second gas blank followed by either a 40 second or 30 second ablation (session on 2021-03-30) time was used with a laser repetition rate of 5 Hz. A spot size of 29 µm and a nominal fluence of 2 Jcm^{-2} was used for zircon, and a spot size of 43 µm using a nominal fluence of 3.5 Jcm^{-2} was used for NIST610. Data were processed using LADR (Norris & Danyushevsky 2018), version 1.1.06 and output as “Full Analytical Uncertainty”. No common Pb corrections were applied to the data. Reference material ratios for GJ-1, Plešovice, and 91500 were set to the Chemical Abrasion Isotope Dilution Thermal Ionisation Mass Spectrometry (CA-ID-TIMS) values (uncorrected for thorium disequilibria and common-Pb) of Horstwood et al. (2016). Weighted averages and dispersion statistics for all standards are available from the link in data availability.

Statistical analysis of the zircon U–Pb data follows the method of Lloyd et al. (2020). Data are considered concordant if within ± 10%, and a “meaningful” age if the 2σ uncertainty is ≤10%—if a datum satisfies both parameters it is termed a *Filtered Age*. Maximum depositional ages are determined from a stricter 2% concordance filter and use the older age of the three isotope ratios ($^{207}Pb/^{235}U$, $^{206}Pb/^{238}U$, $^{207}Pb/^{206}Pb$) for a conservative estimate of the youngest single concordant grain. All ages are quoted with 2σ uncertainty. Kernel density estimates (KDEs), and multidimensional scaling plots (MDS) were generated using IsoplotR (Vermeesch 2018). Key zircon trace element data are presented graphically using methods following Verdel et al. (2021) and additionally lanthanoid data are represented using violin plots and lambda representation (Anenburg 2020; O'Neill 2016).

Metadata for the LA-ICP-MS sessions, data for all analyses, cathodoluminescence images, and R code used to generate plots are available from the links in data and code availability.

4 Results

Fifteen samples [Figure 1] from the Yudnamutana Subgroup (FR1_005_02, FR1_009_01, FR2_007_01, FR2_024_01, FR3_005, FR3_006, FR3_009, FR3_034, FR3_065, FR3_073, FR3_084a, FR3_109, FR3_139, ML_017, & ML_018), one sample from the equivalent Yancowinna Subgroup (GSNSWKB002), and one sample from the lowermost Nepouie Subgroup (FR3_004), were analysed for detrital zircon geochronology. Several samples had naturally low zircon yields (FR3_004, FR1_005_02, GSNSWKB002, FR3_084a, FR3_139, Fitton Formation samples).

4.1 Fitton Formation

A cumulative total of 124 analyses, with 95 analyses passing filtering parameters, were conducted for samples FR3_065 (92/74), FR3_009 (9/1), and FR2_024_01 (23/20). The data for these samples are combined as only two samples yield more than one filtered analysis. These two samples are ~200 m apart (geographically), all three samples are from the broader local area [Figure 1], and there are no discernible differences in the age spectra. Ages range from 1134 ± 24 Ma to 2458 ± 37 Ma, with as primarily population peak c. 1580 Ma, and a secondary peak c. 1160 Ma [Figure 4].

4.2 Sturt Formation and equivalents

A cumulative total of 162 analyses, with 107 analyses passing filtering parameters, were conducted on zircon from samples ML_017 (117/93) and ML_018 (45/14), South Mount Lofty Ranges (Sturt Gorge, Adelaide). The data for these samples are combined as the two sampling sites are ~60 m apart (geographically) [Figure 1] and there are no discernible differences in the age spectra. Ages range from 930 ± 16 Ma to 2933 ± 34 Ma, with a primary population peak c. 1840 Ma, tailing towards 1560 Ma. An additional minor population peak is present c. 1100 Ma [Figure 4].

A total of 178 zircons were analysed from sample FR1_009_01, North Mount Lofty Ranges, with 98 passing filtering parameters. Ages range from 1501 ± 48 Ma to 3374 ± 32 Ma, with a single population peak c. 1790 Ma [Figure 4].

A cumulative total of 81 analyses, with 77 analyses passing filtering parameters, were conducted on zircon from samples FR2_007_01 (31/28) and FR3_139 (50/49), North Flinders Ranges (Copley area) [Figure 1]. The data for these samples are combined as they were sampled from the same stratigraphic interval at approximately the same stratigraphic height. Ages range from 663 ± 11 Ma to 2718 ± 21 Ma, with a primary population peak c. 1740 Ma and secondary population peaks c. 1580 Ma, 1180 Ma, and 1050 Ma [Figure 4].

A cumulative total of 52 analyses, with 46 analysed passing filtering parameters were conducted on zircon from FR3_084a (10/9) and FR3_109 (42/37), North Flinders Ranges (Yankaninna area). The data from these two samples is combined as they are sampled from within 30 metres of each other in the same interval of outcrop [Figure 1]. Ages range from 1042 ± 19 Ma to 2514 ± 48 Ma, with a single primary population peak c. 1640 Ma [Figure 4].

A total of 118 zircons were analysed from sample FR3_073, North Flinders Ranges (Vulkathuhna-Gammon Ranges) [Figure 1], with 94 passing filtering parameters. Ages range from 891 ± 15 Ma to 3322 ± 35 Ma, with a single broad, and slightly bimodal population peak range of c. 1740 Ma to c. 1620 Ma [Figure 4].

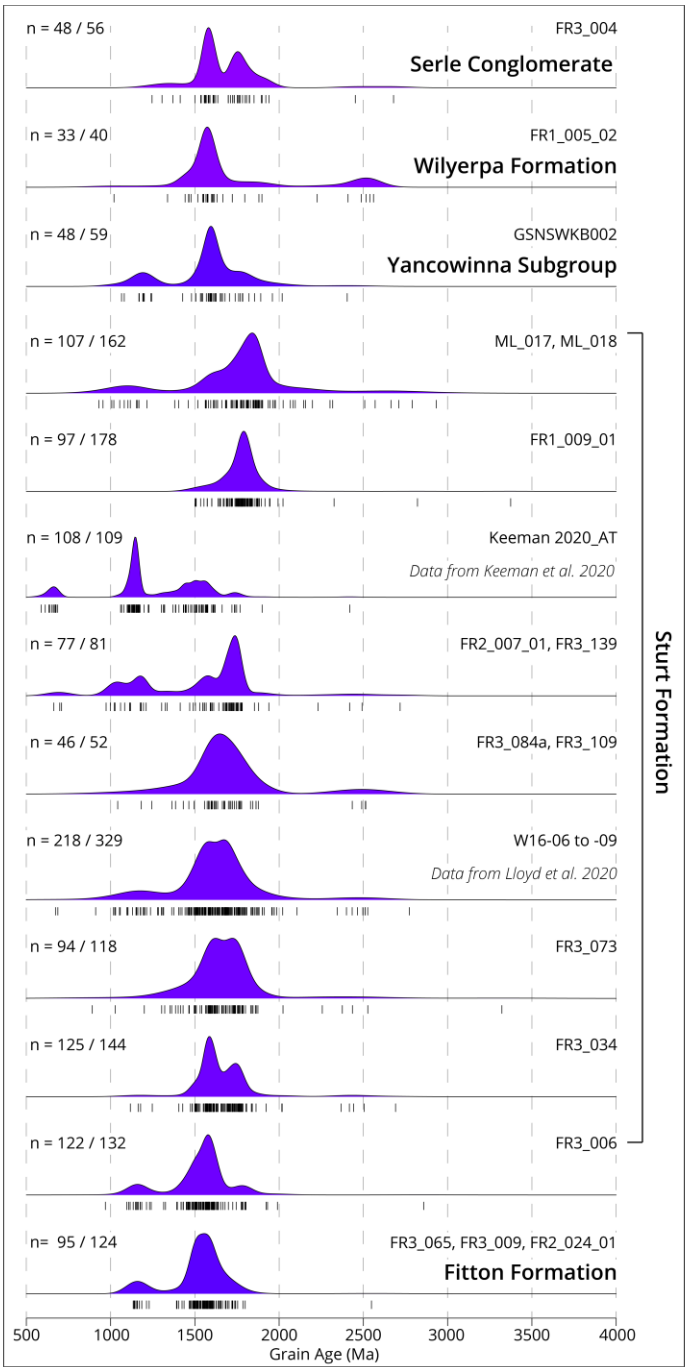

Figure 4 – Kernel density estimates [KDEs] of detrital zircon populations from Yudnamutana, Yancowinna and Nepouie Subgroup samples. Data are from this study unless otherwise denoted. Tick marks below each plot represent an analysis. n = filtered analyses / total analyses. Generated using IsoplotR (Vermeesch 2018).

A total of 144 zircons were analysed from sample FR3_034, North Flinders Ranges (Stubbs Waterhole, Arkaroola), with 125 passing filtering parameters. Ages range from 1117 ± 34 Ma to 2691 ± 42 Ma, with a primary population peak c. 1590 Ma, and a secondary population peak c. 1750 Ma [Figure 4].

A total of 132 zircons were analysed from sample FR3_006, North Flinders Ranges (Stanley Mine, Arkaroola) [Figure 1], with 122 passing filtering parameters. Ages range from 969 ± 16 Ma to 2858 ± 47 Ma, with a primary population peak c. 1580 Ma, and secondary population peaks c. 1790 Ma and 1160 Ma [Figure 4].

A total of 59 zircons were analysed from sample GSNSWKB002, Yancowinna Subgroup, Koonenberry Belt (New South Wales) [Figure 1], with 48 passing filtering parameters. Ages range from 1065 ± 18 Ma to 2404 ± 37 Ma [Figure 4].

4.3 Lyndhurst and Wilyerpa Formations

Sample FR3_005, Lyndhurst Formation, had extremely low zircon yield with only three zircons obtained and analysed. Of those, only two passed filtering parameters, with ages of 1532 ± 24 Ma and 1174 ± 19 Ma [Figure 4].

A total of 40 zircons were analysed from sample FR1_005_02, Wilyerpa Formation, North Mount Lofty Ranges [Figure 1]. Of these, 33 passed filtering parameters with ages ranging from 1020 ± 19 Ma to 2560 ± 79 Ma, with a primary population peak c. 1580 Ma and a secondary population c. 2500 Ma [Figure 4].

4.4 Serle Conglomerate

A total of 56 zircons were analysed from sample FR3_004, Serle Conglomerate, with 48 passing filtering parameters. Ages range from 1246 ± 24 Ma to 2679 ± 65 Ma, with a primary population peak c. 1590 Ma, and a secondary population peak c. 1760 Ma [Figure 4].

4.5 Zircon trace element geochemistry

Most analyses resolved lanthanoid concentrations that are typical for zircons, with several orders-of-magnitude increase in concentration from light to heavy elements, a slight negative deviation in europium (Eu), and a positive deviation in cerium (Ce) [Figure 5]. However, two analyses (FR1_009_01b – 057, and FR1_009_01 - 044) have lanthanoid concentrations atypical of zircon, with overall positive (based on ionic radii) slopes (λ_1 of +7.14, and +1.06) due to highly elevated light lanthanoids (La to Nd). Overall, the

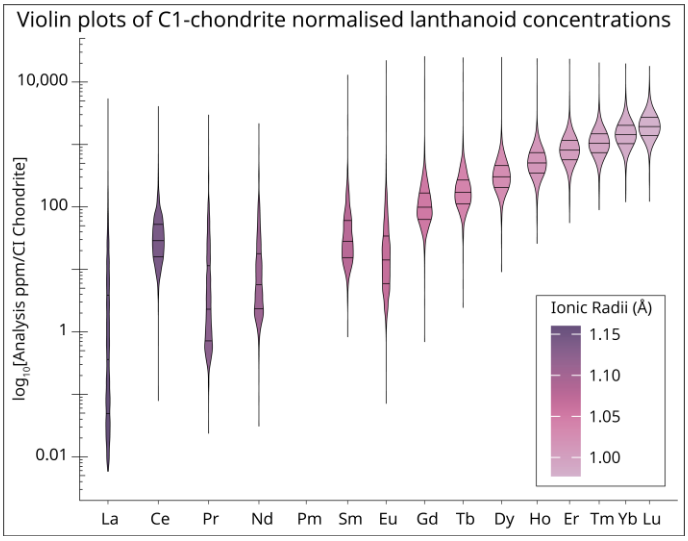

Figure 5 – Violin plots of CI chondrite (O'Neill 2016) normalised lanthanoids for all filtered zircon analysed in this study. X-axis is spaced by ionic radii (Shannon 1976) and ordered by atomic number. Black lines across the fill of each plot represent the 0.25, 0.5, and 0.75 quantiles. Bandwidth of the density estimates is calculated using the Botev algorithm from the Provenance package (Vermeesch et al. 2016).

lanthanoid pattern for both analyses have a concave-up shape with heavy lanthanoid concentration increasing as would normally occur in zircon. Major element percentages, ~14.4 wt% and ~15.6 wt% silicon, suggest these two analyses are zircon, and CL images also support this, although show patchy textures. The ages for these are at the limit of discordance acceptance (90%). It is likely these two analyses have gone through complicated zones of inclusions, altered metamict zones, and/or mineral overgrowths.

5 Discussion

5.1 Zircon trace element geochemistry

A simple U/Yb against Y plot can be used to infer continental or oceanic affinity for zircon generation (Grimes et al. 2007; Grimes et al. 2015). Most zircons analysed in this study are inferred to have been generated in continental crust [Figure 6], with a small number of younger zircons suggesting oceanic affinity. C1 chondrite normalised (O'Neill 2016) concentrations of lanthanoids are generally typical of zircon [Figure 5] with a positive pattern slope (increasingly negative λ_1 values) from light to heavy lanthanoids, a positive cerium anomaly, and negative europium anomaly (Hoskin & Ireland 2000; Hoskin & Schaltegger 2003). Nearly all zircons have a Th/U >0.07 and are generally inferred to be originally generated as magmatic rather than metamorphic zircon (Rubatto 2002). There is no apparent trend in lanthanoid pattern slope or curvature [Figure 7], denoted as λ_1 (linear slope), λ_2 (quadratic slope), and λ_3 (cubic slope) (Anenburg 2020), with time or sample. Both Eu and Ce anomalies (denoted by Eu* and Ce*) show a significant spread through time. The youngest few zircons c. 670 Ma, although limited in number, have out of phase Eu* (low) and Ce* (high) anomalies suggestive of growth in competition with plagioclase, and not reflective of magma oxidation state (Verdel et al. 2021).

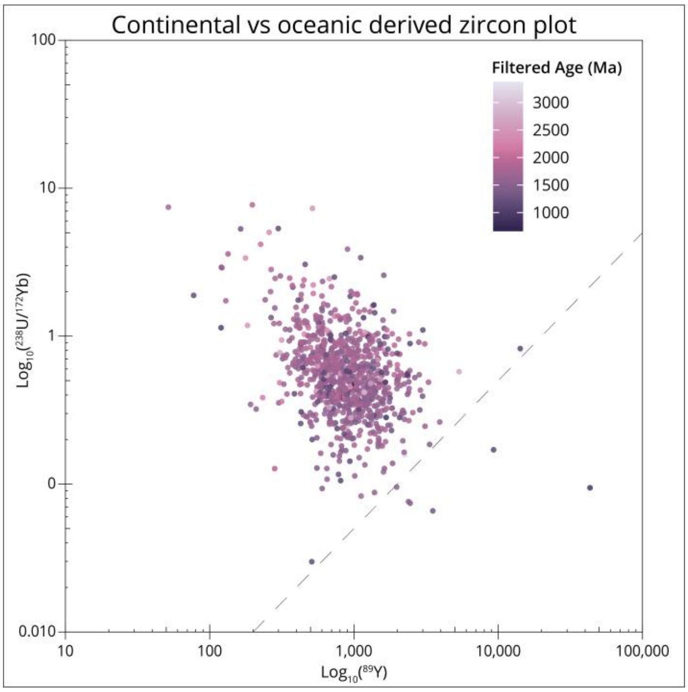

Figure 6 – Plot based on (Grimes et al. 2007) used as an indicator of zircon crustal origin. This plots Y against U/Yb, with the dashed reference line dividing the "oceanic" (below line) and "continental" (above line) fields. Most data plot above the reference line, suggesting zircon formation mostly in crust of continental affinity. Coloured by filtered age where light is older and darker is younger.

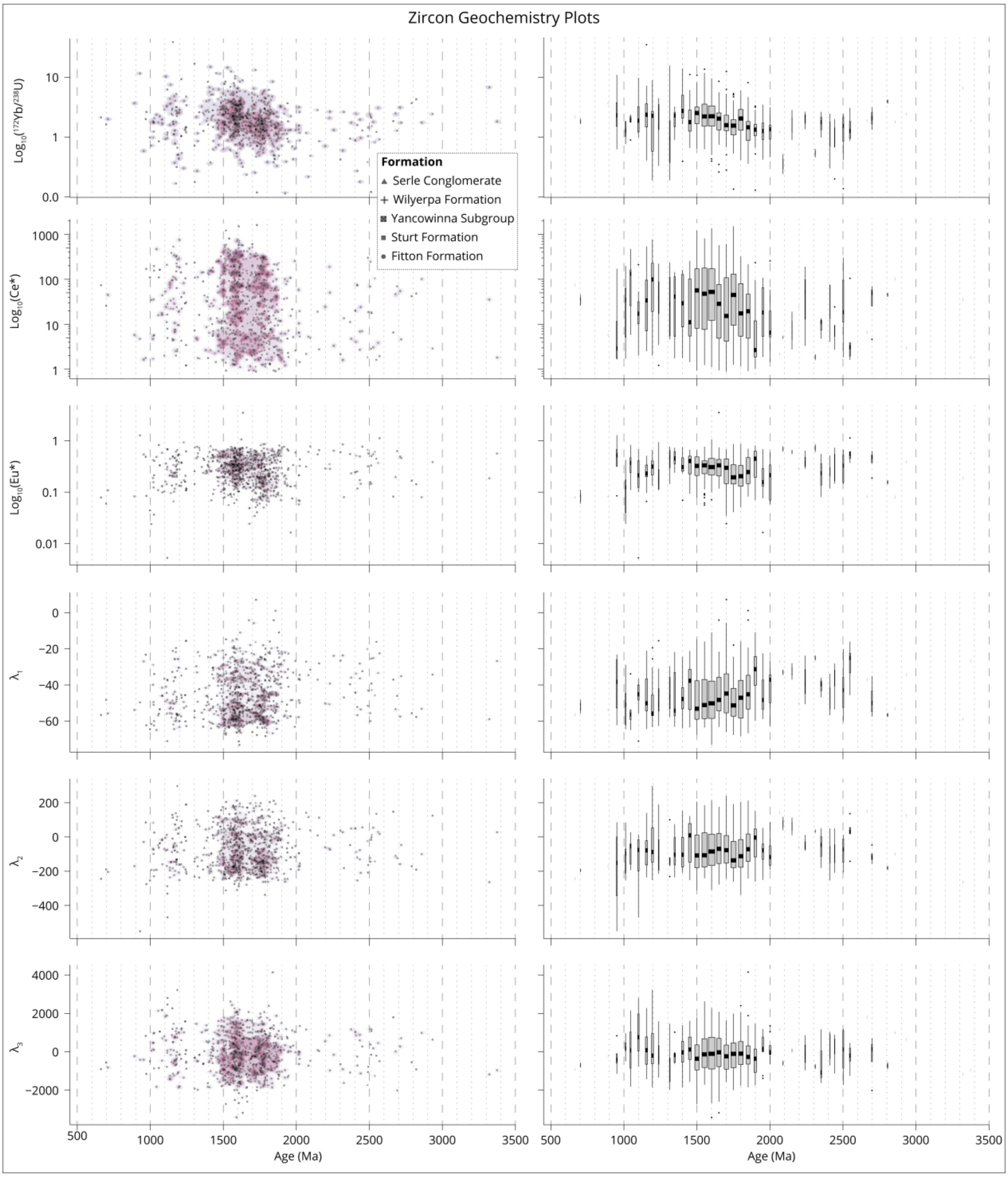

Figure 7 – Key zircon geochemistry plots for zircon analysed in this study. Left: Scatter plots underlain with 2D density estimation. Right: 50 million year binned boxplots with width scaled by the count of values in the bin. Top to bottom: Yb/U, Ce*, Eu* and λ1–3. λ1–3 are measures of lanthanoid pattern shapes, with λ1–3 representing the linear slope, quadratic slope and cubic slope respectively. Ce*, Eu* and λ1–3 are calculated using BLambdaR (Anenburg & Williams 2021).

5.2 Provenance and maximum depositional ages

5.2.1 Maximum depositional ages

The older limit of expected depositional age for samples in this study is constrained by two MDA constraints from the underlying Belair Subgroup, namely the Gilbert Range Quartzite (731 ± 34 Ma, Keeman et al. 2020; Lloyd et al. 2020) and Mitcham Quartzite (c. 730 Ma, Lloyd et al. 2022c, preprint; van der Wolff 2020). The younger age limit for deposition of the Yudnamutana Subgroup is constrained by a 663 ± 0.76 Ma tuff in the Wilyerpa Formation (Cox et al., 2018). The Serle Conglomerate is older than c. 642 Ma Tapley Hill Shale (Re-Os shale, Kendall et al. 2006) which is interpreted to underlie.

A maximum depositional age (MDA) of 1162 ± 49 Ma was obtained for the combined Fitton Formation samples. This is significantly older than the expected depositional age c. 663–730 Ma.

Maximum depositional ages for each of the Sturt Formation samples are presented here according to the combinations outlined in 4.2.

- South Mount Lofty Ranges (Sturt Gorge, Adelaide): 1007 ± 14 Ma
- North Mount Lofty Ranges (Clare Valley): 1774 ± 39 Ma
- North Flinders Ranges (Copley area): 666 ± 25 Ma
- North Flinders Ranges (Yankaninna area): 1186 ± 50 Ma
- North Flinders Ranges (Vulkathuhna-Gammon Ranges): 891 ± 15 Ma
- North Flinders Ranges (Stubbs Waterhole, Arkaroola): 1188 ± 51 Ma
- North Flinders Ranges (Stanley Mine, Arkaroola): 1118 ± 48 Ma

Previous MDAs obtained from detrital zircon studies (Keeman et al. 2020; Lloyd et al. 2020) on the Sturt Formation are:

- South Mount Lofty Ranges (Sturt Gorge, Adelaide): 714 ± 28 Ma
- South Flinders Ranges (Pichi Richi Pass): 667 ± 6 Ma
- North Flinders Ranges (Willouran Ranges): 673 ± 19 Ma

There is significant scatter in the MDAs of individual samples; however, population spectra are similar [Figure 4, Figure 8] across all samples (spanning more than 500 km north–south, Figure 1), and three independent sets of samples over a distance of ~250 km north–south, have MDAs within uncertainty of each other. While detrital zircon population spectra variations occur locally, as is expected across a large basin, and with significant recycling of underlying stratigraphy in glaciogenically derived sediment, the remarkable similarity of most samples' spectra [Figure 4, Figure 8] adds support to unit equivalence, as is strongly suggested by lithostratigraphy. The variation in MDAs also highlights the main challenge in determining depositional ages via detrital zircon studies as it is entirely possible for the MDA to be significantly older than the true age of deposition. This is both a factor of chance (sampling) and dependant on original sediment input—if no zircon of syndepositional ages are present in the detritus being fed into the depocentre, the true age of deposition cannot be determined by this method, hence the need to treat these as maximum depositional ages only. Chronological constraints for the Sturt Formation had been almost non-existent up until recently but are now (Cox et al. 2018b; Fanning & Link 2008; Keeman et al. 2020; Lloyd et al. 2022c, preprint; van der Wolff 2020) robust enough to bracket deposition of the Sturt Formation to between 663.03 ± 0.76 Ma and c. 730 Ma. Considering this, the MDA of c. 666 Ma is likely close to, or representative of true depositional age for the terminal deposits (upper portion) of the Sturt Formation as a whole.

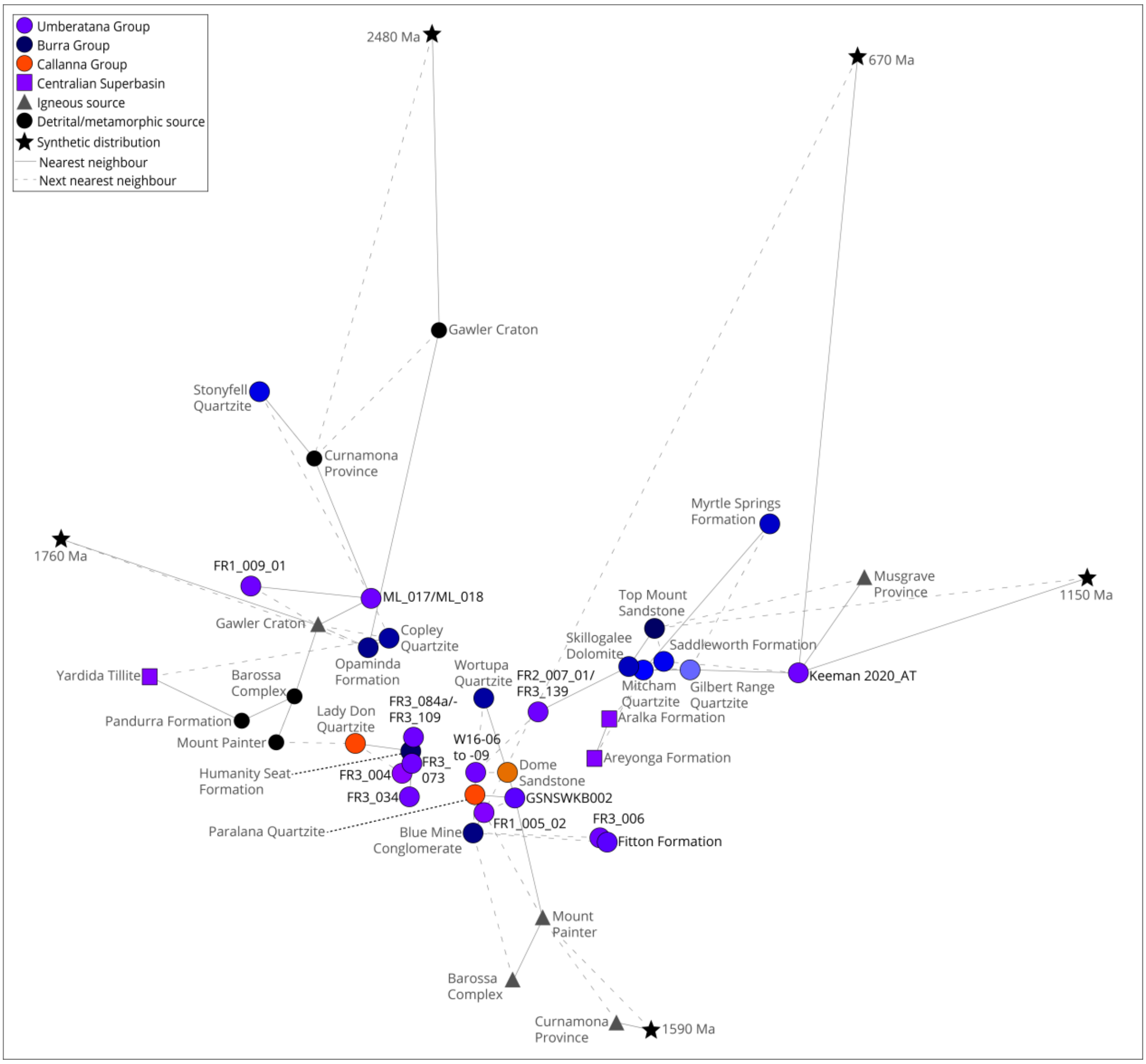

Figure 8 – Non-metric multidimensional scaling plot of samples analysed (n > 30) in this study (purple circles) with data from potential correlative formations of the Centralian Superbasin (purple squares), potential source regions (black and grey circles and triangles), and synthetic distributions (black stars) generated from the primary and secondary peaks of a KDE that combines all new data in this study. This plot shows relative similarity of all data to each other and are intended as a visual guide. Points that closer together suggest greater similarity. Axes are omitted as the algorithm used produces normalised values with no physical meaning and can be safely removed. Produced using IsoplotR (Vermeesch 2018).

GSNSWKB002 was sampled from the undifferentiated Yancowinna Subgroup in the Barrier Ranges of New South Wales. This area is believed to be the easternmost extension of the Adelaide Superbasin during the Neoproterozoic (Cooper, PF 1973; Cooper, PF & Tuckwell 1971; Fitzherbert & Downes 2015; Lloyd et al. 2020; Preiss

1987). The sample is as a highly weathered diamictite with clasts ranging up to pebble size, and a silty to fine sand matrix. This was a reconnaissance sample with the aim to investigate the general correlation of this subgroup to the Yudnamutana Subgroup of South Australia. An MDA of 1075 ± 40 Ma was obtained from the sample, with a detrital zircon population spectrum similar to that of the likely correlatives in South Australia [Figure 4, Figure 8]. This provides limited, but supporting evidence of a shared detrital source and that these two subgroups are correlative as is indicated by the existing lithostratigraphic framework (Lloyd et al. 2020).

An MDA of 1502 ± 70 Ma was obtained from the Wilyerpa Formation (FR1_005_02) sampled in the Clare Valley. This is significantly older than the expected depositional age c. 663 Ma and may be a factor of low zircon yield and/or no zircon close to depositional age being present in the sample.

An MDA of 1291 ± 50 Ma was obtained from the Serle Conglomerate sample (FR3_004). Again, this is significantly older than true depositional age that is expected to be between c. 663 Ma and c. 642 Ma. The detrital zircon population spectrum somewhat differs [Figure 4, Figure 8] from the nearby Sturt Formation sample (FR3_006), although this may partially be an artifact of the much lower zircon yield from the Serle Conglomerate sample.

5.2.2 Provenance

Two broad detrital zircon populations, c. 1840–1790 Ma and c. 1640–1580 Ma, from major peaks in virtually all samples. The exact age positions and magnitude of the population peaks varies slightly by sample, with broad to north–south and east–west variations, generally trending to older Palaeoproterozoic age populations in the west and south. It is likely that there is significant recycling of the underlying stratigraphy due to sub-glacial erosion (Young & Gostin 1989b). The similarity of the detrital zircon spectra within the samples of this study to each other, and to earlier rocks of the Adelaide Superbasin [Figure 8], suggests homogenisation of detrital material over a large area, potentially with extra-basin material, and also supports the notion of intra-basin recycling occurring from sub-glacial erosion of earlier stratigraphy.

Zircons with ages greater than ~1400 Ma are likely locally, from the Gawler Craton/Barossa Complex and Curnamona Province that record numerous zircon generation events and sedimentary sequences known to hold zircon of these ages (Barovich & Hand 2008; Belousova et al. 2009; Conor & Preiss 2008; Fanning et al. 2007; Fraser et al. 2010; Fraser & Neumann 2010; Jagodzinski & Fricke 2010; Jagodzinski & McAvaney 2017; Jagodzinski et al. 2020; Kromkhun et al. 2013; McAvaney 2012; Meaney 2012; 2017; Morrissey et al. 2019; Morrissey et al. 2018; Morrissey et al. 2013; Reid, A et al. 2021; Reid, Anthony J et al. 2019; Reid, Anthony J. & Hand 2012; Reid, Anthony J. et al. 2008; Reid, Anthony J. et al. 2014a; Reid, Anthony J. et al. 2014b; Reid, Anthony J. et al. 2017; Reid, Anthony J. & Payne 2017; Stevens et al. 2008; Swain et al. 2005; Wade, CE 2011). The southernmost samples from Sturt Gorge are dominated by c. 1840 Ma zircons, and northward progression generally sees a shift in dominance of the c. 1840 Ma population to the younger c. 1580 Ma. This observation is likely a result of the variation in local basement geology of the Gawler Craton and Curnamona Province near the sample sites.

The generally minor Stenian population of zircon at c. 1160 Ma is suggestive of provenance from the Musgrave Province (Smithies et al. 2008; Smithies et al. 2011; Smits et al. 2014; Wade, BP et al. 2008), but as noted in (Lloyd et al. 2022a, preprint) they may be sourced from an as yet undiscovered but inferred late Mesoproterozoic (c. 1300–1000 Ma) source to the east (Fergusson et al. 2007; Korsch et al. 2012; Mackay 2011; Wysoczanski & Allibone 2004). This population is generally more abundant in samples closer to the eastern and western margins of the basin [Figure 4, Figure 1]. Alternate sources of these late Mesoproterozoic zircon could be the South Tasman Rise (Fioretti et al. 2005), Coompana Province (Pawley et al. 2020) or far-field transport across Antarctica from the Tonian Oceanic Arc Super Terrane (Jacobs et al. 2015). Again, it is highly likely recycling of underlying stratigraphy is also a partial origin of these zircons.

Neoproterozoic zircon of ages between c. 900 Ma and c. 780 Ma are feasibly attributed to early known magmatism in the Adelaide Superbasin (Lloyd et al. 2020); however those younger than 780 Ma are much more difficult to reconcile. It is apparent that some zircon-bearing magmatic crystallisation of zircon was occurring c. 700 Ma to c. 660 Ma, and that these were in the sediment supply of the Sturt Formation. While a 663 ± 0.76 Ma tuff has been dated (Cox et al. 2018b) from within the Wilyerpa Formation, immediately post-dating deposition of the Sturt Formation. The original volcanic centre for the ashfall is unknown. Additionally, zircon of this age (c. 700–660 Ma), within the Sturt Formation has so far, only been found on the far western margin of the Adelaide Rift Complex within the Adelaide Superbasin [Figure 9], potentially suggesting this magmatic source was to the west of, or on the western margin of the basin.

Comparison is made to three correlatives (Edgoose 2013; Kruse et al. 2013; Normington & Donnellan 2020) from the Centralian Superbasin, the syn-glacial Yardida Tillite and Areyonga Formation, and the post-glacial Aralka Formation. Interestingly, the detrital zircon age spectra of the Yardida Tillite (Georgina Basin, Northern Territory/Queensland) which is likely to be a correlative of the Sturt Formation, is very similar [Figure 8] to the local basement of South Australia (e.g., Gawler Craton). However, this is explained by its proximity to the Mount Isa and Aileron Provinces, suggested to be the primary zircon source for the Yardida Tillite (Verdel et al. 2021). These provinces host abundant c. 1640-1850 Ma zircon that are also found the Gawler Craton and Curnamona Province. The age spectra in the Areyonga Formation and Aralka Formations (Amadeus Basin, Northern Territory/Western Australia) are similar to Burra Group formations and the Sturt Formation samples from the western margin of the Adelaide Rift Complex. All of these aforementioned formations are suggested to ultimately source zircon from the Musgrave province where Stenian-aged zircon are abundant, and both basins have abundant nearby sources of pre-Stenian aged zircon. Notably though no zircon younger than c. 800 Ma has been found in the Areyonga and Aralka formations to date.

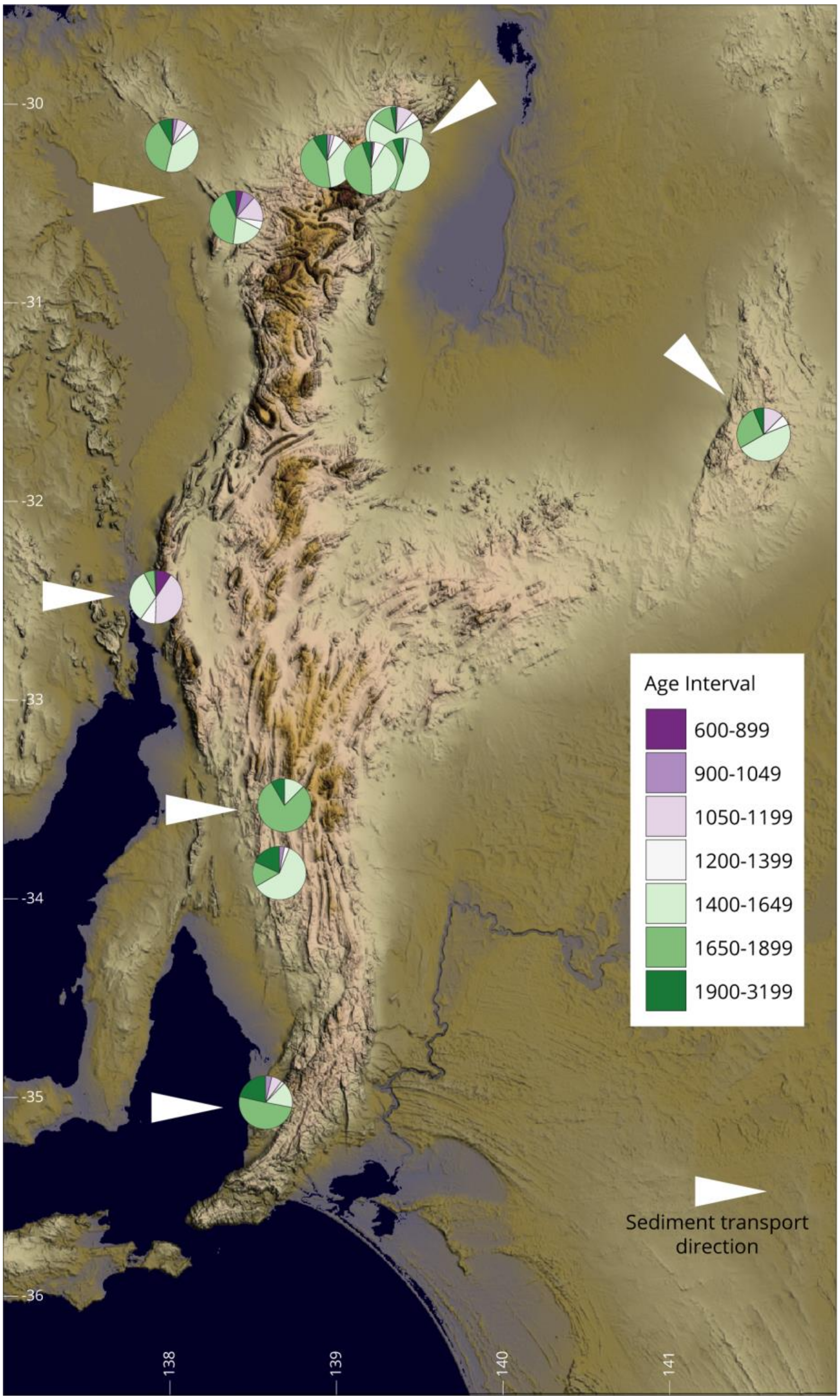

Figure 9 – Schematic map with pie charts at samples locations to highlight the changes in zircon population spectra relative to geographic location. Arrows are generalised and schematic indicators of palaeo-sediment transport direction.

5.2.3 Comparison to Palaeocurrent data

Observations drawn in this study from detrital zircon are generally supportive of existing palaeocurrent data (Link & Gostin 1981; Young & Gostin 1989b; 1991). Palaeocurrent data from the Yudnamutana Subgroup suggest a westerly transport direction in the Mount Painter area and along the Paralana fault system, northerly transport on the northern side of the Gammon syncline and Yankaninna anticline, and north-easterly transport along the eastern edge of the Adelaide Rift Complex (Copley area, south-eastern Willouran Ranges). It is likely that underlying strata have been recycled, making the use of detrital zircon spectra for determining palaeo-transport paths difficult; however, the only area in which the detrital data from this study might potentially differ in transport direction from the existing palaeocurrent data is the Vulkathuhna-Gammon Ranges. Our data (Figure 4: FR3_073, Fitton Formation samples) may suggest a south, or south-westerly sediment transport [Figure 9] direction as the detrital zircon populations are similar to the older stratigraphy of the basin, and to the local basement sources located to the northeast [Figure 8, Figure 1].

5.3 Tectonic and palaeogeographic implications

While the dataset needs to be expanded in future to cover more the basin, particularly to the east (Olary area, and New South Wales) and far northwest (Davenport and Denison Ranges), some points can be made regarding the palaeogeography and tectonics of the Adelaide Superbasin during the *Sturtian glaciation*. Firstly, it is apparent that the detrital zircon spectrum of each sample is highly dependent on local geology, often recycling the underlying stratigraphy and/or from the nearby basement geology. This finding suggests that the far-field sediment supply to the Burra Group (as inferred by Lloyd et al. 2020) was shut off during deposition of the Yudnamutana Subgroup, with locally derived detritus becoming much more prominent (Lloyd et al. 2020). Secondly, active zircon-bearing magmatism occurred at c. 700–660 Ma, although the location and volume of this magmatism remains unknown. The spatial distribution of the samples containing Cryogenian zircon [Figure 9] suggests that the source was to the west, or along the western margin, of the basin. Thirdly, the detrital zircon spectrum of the Yancowinna Subgroup sample supports a shared sediment supply for it and the Sturt Formation samples in the northeast of the basin, allowing for a topographic high (Curnamona Province) in between these two areas that is shedding detrital material to both sides. The data presented here also adds support to the Yancowinna Subgroup being an equivalent of the Yudnamutana Subgroup, as is suggested by the current stratigraphic framework (Cooper, PF 1973; Cooper, PF & Tuckwell 1971; Fitzherbert & Downes 2015; Lloyd et al. 2020; Preiss 1987). In combination with glacial scouring, it is likely that active tectonics played a significant control on the dramatic thickness variations of the Yudnamutana Subgroup sedimentary rocks (Le Heron 2012; Le Heron et al. 2014; Young & Gostin 1991), although this likely post-dates the rift-drift transition of the Australia–Laurentia margin c. 780 Ma (Merdith et al. 2017).

5.4 Sturtian nomenclature

5.4.1 South Australian Formal Stratigraphy

The original correlations of the ‘older’ glacial units across southern Australia (e.g. Sturt

Tillite, Appila Tillite) were originally argued to represent either one or two separate glacial intervals (Coats & Forbes 1977; Coats & Preiss 1987). Subsequent work showed that they were all consistent with only one glacial event (Murrell et al. 1977; Preiss 1993; 2000; Preiss et al. 1998) but representing ice sheet advance-retreat cycles (Le Heron 2012). No significant lithological differentiation (in the sense of formal stratigraphy) can be made to distinguish them from one another (Preiss et al. 1998; Preiss et al. 2011), and both stratigraphic position and geochronology supports their equivalence (this study, Cox et al. 2018b; Keeman et al. 2020; Lloyd et al. 2020; Preiss et al. 1998; Young & Gostin 1989b). In light of this knowledge, we redefine and combine the stratigraphic nomenclature for the outcrops that represent the glacial maximum (e.g., Appila Tillite, Bolla Bollana Tillite, Sturt Tillite) to the Sturt Formation [Figure 2]. *Sturt* is retained as the first diamictite formally named was the *Sturtian tillite* (Howchin 1920; Mawson & Sprigg 1950), as such it takes precedence over all other equivalent formation names, and it has become internationally synonymous with the *Sturtian* glaciation. *Tillite* has been dropped in favour of *Formation* as, while they are the most distinctive lithology, the lithologies are not exclusively diamictites of glacial origin, and they are not the most volumetrically abundant lithologies in all areas (Preiss et al. 2011). Instead, the Sturt Formation is comprised of numerous lithologies that were deposited under general glacial conditions (Link 1977; Link & Gostin 1981; Preiss 1987; 2000; Preiss et al. 2011). A formal definition card accompanies this paper as an appendix, with the generalised stratigraphic logs of the type and reference sections presented in Figure 3.

5.4.2 Sturtian glaciation (Cryochron)/Laurentian Neoproterozoic Glacial Interval

Le Heron et al. (2020) proposed that the name "Laurentian Neoproterozoic Glacial Interval" be used in favour of the *Sturtian*, with the latter name used exclusively for Australian strata. While they highlight the issue of interpreting results in a model-led approach, a point we agree on, Le Heron et al. (2020) primarily base this on their interpretation that most *Sturtian* rocks of Australia chronometrically lie outside of the *Sturtian* glacial interval, c. 720–660 Ma, defined by Rooney et al. (2015), with only the tuff from near the base of the Wilyerpa Formation (663.03 ± 0.76 Ma, Cox et al. 2018b) plotting within this time interval, this is reiterated by Kennedy et al. (2020). However, we argue that this interpretation is incorrect, as Le Heron et al. (2020) interpretation appears to hinge on the previous lack of data from the South Australian Sturtian glacial (Yudnamutana Subgroup) and pre-glacial (Burra Group) sequences. Since publication, even with the challenges associated with constraining deposition by detrital zircon studies, two studies (Keeman et al. 2020; Lloyd et al. 2020) have provided maximum depositional age constraints from the Sturt Formation: South Mount Lofty Ranges, 714 ± 28 Ma; South Flinders Ranges, 667 ± 6 Ma; North Flinders Ranges, 673 ± 19 Ma. This study presents a further ten samples, with FR3_139 yielding an MDA of 666 ± 25 Ma. Importantly, detrital zircon MDA constraints from the underlying Belair Subgroup, namely the Gilbert Range Quartzite (731 ± 34 Ma, Keeman et al. 2020; Lloyd et al.

2020) and Mitcham Quartzite (c. 730 Ma, Lloyd et al. 2022c, preprint; van der Wolff 2020) provide the maximum age estimations for which final deposition occurred within the upper Burra Group. Le Heron et al. (2020) treat the Cox et al. (2018b) tuff age (Wilyerpa Formation, AUS) as a maximum depositional age, although Cox et al. (2018b) demonstrate that the tuff age is syndepositional, with their age dating volcanism coeval with deglaciation. It neither provides a maximum or minimum age limit for the entire Wilyerpa Formation as it occurs part way up section with ~50 additional stratigraphic metres overlying the tuff to the base of the Tapley Hill Formation. This age provides a robust minimum age construction for the underlying diamictite. Thus, these two bracketing constraints require that the *Sturtian* glaciogenic rocks of South Australia (Sturt Formation, Fitton Formation) are deposited c. ≤730 Ma and ≥663 ± 0.76 Ma, thereby constraining the age of the true *Sturtian* (*sensu stricto*) to this time bracket. The initiation of final deglaciation can also be constrained by the data presented here, albeit loosely to between 666 ± 25 Ma and 663.03 ± 0.76 Ma, as samples FR3_139 and FR2_007_01 come from the same stratigraphic interval as the tuff from the Wilyerpa Formation. This independently aligns with the current definition for global timing of the *Sturtian* glaciation, c. 717–660 Ma (Rooney et al. 2015).

By contrast Le Heron et al. (2020) treat the reworked tuff age from the Pocatello Formation, USA (Fanning & Link 2004), as a minimum age estimate. This reworked tuff of Fanning and Link (2004) from the "upper diamictite" (Isakson 2017) of the Pocatello Formation has been revaluated as a maximum depositional age and may actually be a *Marinoan* glacial sequence, unconformably overlying a non-glacial sequence that in turn unconformably overlies a lower *Sturtian* sequence (Isakson 2017). Isakson (2017) had also revised several of the igneous ages presented in the Le Heron et al. (2020) compilation, notably a syn-Sturtian age from the Hogback Rhyolite from 684 ± 4 Ma (Lund et al. 2010; Lund et al. 2003) to 693.03 ± 0.73 Ma. This author also presented two additional ages from volcanics in the lower Scout Mountain Member of the Pocatello Formation of c. 697 Ma, previously interpreted to be 686 ± 4 Ma (Fanning & Link 2008). The data of Keeley et al. (2013) from the lower Scout Mountain member (685 ± 0.4 Ma) is presented as a depositional age by Le Heron et al. (2020), rather than as a maximum depositional age as the original authors and Isakson (2017) present.

Additionally, data from our study refute the Le Heron et al. (2020) suggestion of a short, 2.4 million year, *Sturtian* glacial, 659.6 ± 10.2 Ma to 657.2 ± 5.4 Ma, based on Re-Os ages from the Aralka Formation (Kendall et al. 2006), and Ballachulish Slate (Rooney et al. 2011), as the Australian *Sturtian* deposits are now constrained to be older than this proposed interval.

Considering the above, we disagree with the notion Le Heron et al. (2020) make that the use of *Sturtian* to refer to a globally distributed glaciation can no longer be justified. The available geochronology suggests that deposition of the Neoproterozoic glaciogenic rocks, in at least, Australia (Keeman et al. 2020; Lloyd et al. 2020), Arabia/Nubia (MacLennan et al. 2018; Park et al. 2019), Laurentia (Isakson 2017; Macdonald et al. 2018), South China (Lan et al. 2020; Rooney et al. 2020; Song et al. 2017; Wang et al. 2019), and Siberia (Rud` ko et al. 2020) occurred globally within the c. 717-665 Ma interval. This certainly doesn't discount the possibility of different time for the onset of glaciation, or the presence of glacial advance and retreats. Final deglaciation appears to be relatively synchronous globally at c. 665 Ma [Figure 10]. However, it must be noted, that while Figure 10 and the equivalent diagram in Le Heron et al. (2020) provide brevity for visualisation and assessment of the expanding global geochronologic datasets for the Cryogenian, they lack detailed stratigraphic context and detailed methodology. This is an unavoidable limitation of this style of diagram, with size, legibility, and accessibility (e.g, Crameri et al. 2020) all contributing to this. The ideal, entirely accurate representation of all this data globally, would be detailed stratigraphic logs of each section with accompanying regional correlations and detailed geochronology methodology. At present, in some regions this information is either unavailable, or otherwise unreliable/limited. It would also require significant space and would be best attempted in a global review. To highlight this point though, the apparent diachroneity of glacial onset present in Laurentia may in part be a result of complexity in zircons (post crystallisation Pb loss) that may be slightly older than current determinations suggest, as hinted at by Isakson (2017), and that these dates are from within glaciogenic strata with both over, and underlying portions of glaciogenic strata. The volcanogenic strata and corresponding dates really provide a maximum age for the mid- to upper portions of the glaciogenic formation and do not preclude slightly earlier initiation. Eyster et al. (2018) also highlights how this type of ambiguous interpretation was used to argue for a diachroneity of onset (Baldwin et al. 2016).

Careful scrutiny of geochronologic data, particularly detrital zircon data, as a maximum age constraint rather than as depositional age, stratigraphic position and relationships, and carefully considering the limitations of geochronologic studies and methods, is essential as misinterpretations of either can lead to spurious conclusions e.g., "the Kaigas Formation was previously miscorrelated with glacigenic strata of the Numees Formation" (Rooney et al. 2015).

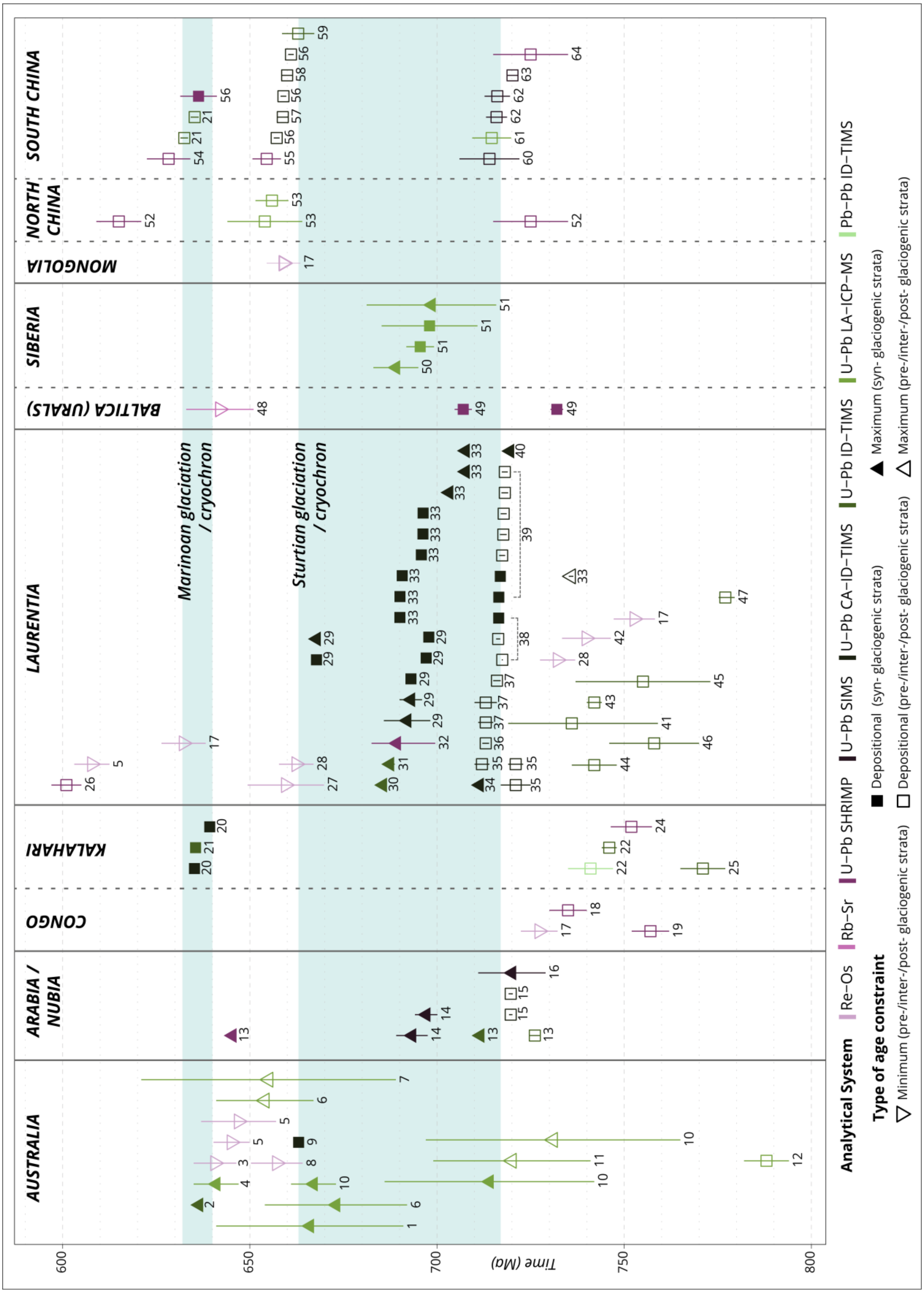

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Figure 10 – Compilation of global geochronologic data for *Sturtian* and *Marinoan glaciations*. Data sources: **AUSTRALIA:** (1) This study; (2) Calver et al. (2013); (3) Kendall et al. (2009); (4) Rose et al. (2013); (5) Kendall et al. (2004); (6) Lloyd et al. (2020); (7) Ireland et al. (1998); (8) Kendall et al. (2006); (9) Cox et al. (2018b); (10) (Keeman et al. 2020); (11) van der Wolff (2020); (12) Armistead et al. (2020). **ARABIA/NUBIA:** (13) Bowring et al. (2007); (14) Abd El-Rahman et al. (2020); (15) MacLennan et al. (2018); (16) Li et al. (2018). **CONGO:** (17) Rooney et al. (2015); (18) Key et al. (2001); (19) Nascimento et al. (2016). **KALAHARI:** (20) Prave et al. (2016); (21) Schmitz (2012); (22) Frimmel et al. (1996); (23) Hoffman et al. (1996); (24) (Borg et al. 2003); (25) Frimmel et al. (2001). **LAURENTIA:** (5) Kendall et al. (2004); (17) Rooney et al. (2015); (26) (Dempster et al. 2002); (27) Rooney et al. (2011); (28) Rooney et al. (2014); (29) Isakson (2017); (30) Keeley et al. (2013); (31) Condon and Bowring (2011); (32) Lund et al. (2003); (33) Eyster et al. (2018); (34) Baldwin et al. (2016); (35) Denyszyn et al. (2009b); (36) Cox et al. (2018a); (37) Denyszyn et al. (2009a); (38) Macdonald et al. (2010); (39) Macdonald et al. (2018); (40) Cox et al. (2015); (41) McDonough and Parrish (1991); (42) Strauss et al. (2014); (43) Fetter and Goldberg (1995); (44) Karlstrom et al. (2000); (45) Ross and Villeneuve (1997); (46) (Aleinikoff et al. 1995); (47) Jefferson and Parrish (1989). **BALTICA (URALS)**: (48) Zaitseva et al. (2019); (49) Krasnobaev et al. (2019). **SIBERIA:** (50) Kochnev et al. (2015); (51) (Rud`ko et al. 2020). **MONGOLIA:** (17) Rooney et al. (2015). **NORTH CHINA:** (52) Xu et al. (2009); (53) He et al. (2014). **SOUTH CHINA:** (21) Schmitz (2012); (54) Chongyu et al. (2005); (55) Zhang, S et al. (2005); (56) Rooney et al. (2020); (57) Zhou, C et al. (2019); (58) Zhou, C-M et al. (2020); (59) Zhou, C et al. (2004); (60) Lan et al. (2015); (61) Song et al. (2017); (62) Lan et al. (2014); (63) Lan et al. (2020); (64) Zhang, Q-R et al. (2008)

6 Conclusions

This research provides an updated chronostratigraphic framework for the Yudnamutana Subgroup of South Australia, i.e., the true *Sturtian glaciation*. Additionally, the lithostratigraphy representing the glacial maximum of the *Sturtian glaciation* in South Australia is consolidated and redefined as the Sturt Formation.

Key findings of this research are:

- An MDA for the (upper) Sturt Formation in the Copley area of 666 ± 25 Ma, providing independent support for MDAs obtained by Keeman et al. (2020) and Lloyd et al. (2020) elsewhere in the Adelaide Superbasin.
- Broadly equivalent detrital zircon spectra of all samples, with local variation, and similarity to underlying Burra and Callanna Group rocks suggests recycling of underlying stratigraphy and sourcing of detritus from local basement rocks.
- Detrital zircon spectra provide support to lithostratigraphic correlation of Yancowinna Subgroup (New South Wales) to the Yudnamutana Subgroup (South Australia).
- Support for the continued use of *Sturtian glaciation* or *cryochron* globally.

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Data Availability

Complete data for this publication are freely available for download from figshare at the following links. These datasets contain all the U–Pb geochronology data, trace element data, and basic sample metadata.

Zircon and NIST standards data for all analytical sessions:

https://doi.org/10.6084/m9.figshare.18131432 (Lloyd et al. 2022b)

Yudnamutana Subgroup detrital zircon data (this study): https://doi.org/10.6084/m9.figshare.19181144 (Lloyd et al. 2022d)

Zircon CL images: https://doi.org/10.6084/m9.figshare.19181024

Code Availability

R code used to generate the zircon geochemistry plots is available on GitHub at https://github.com/jarredclloyd/zircon-trace-element-plots

CRediT author statement

Jarred C. Lloyd: Conceptualisation, investigation, writing - original draft, writing - review & editing, methodology, formal analysis, data curation, visualisation. **Wolfgang V. Preiss:** Investigation, writing – review and editing. **Alan S. Collins:** Conceptualisation, funding acquisition, supervision, investigation, writing - review & editing. **Georgina M. Virgo:** Investigation, writing – review and editing. **Morgan L. Blades:** Investigation, writing - review & editing. **Sarah E. Gilbert:** Formal analysis, methodology, investigation, writing - review & editing. **Kathryn J. Amos:** Conceptualisation, supervision, writing - review & editing.

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APPENDIX 1 - DEFINITION CARD

NAME OF UNIT [1.]: Sturt Formation	**STATE(S) [1.]:** South Australia
STATUS OF UNIT: Redefinition	**RANK:** Formation
PROPOSER: Jarred C Lloyd, Wolfgang V Preiss, Georgina M Virgo	**DATE: 2022-02-**

RESERVED IN STRATIGRAPHIC UNITS DATABASE: YES

PROPOSED PUBLICATION: Lloyd, JC, Preiss, WV, Collins, AS, Virgo, GM, Blades, ML & Amos, KJ [in prep], 'Detrital zircon record of the Sturtian glaciation: Adelaide Superbasin', to be submitted to *Geological Magazine,* (EarthArXiv preprint, this publication)

DERIVATION OF NAME [1.]: Sturt River/Warriparri, South Australia

SYNONYMY, UNIT NAME HISTORY (if any) **[1.]:**

Sturt Tillite, Appila Tillite, Pualco Tillite, Merinjina Tillite, Bolla Bollana Tillite, Calthorinna Tillite, Hansborough Tillite (abandoned)

Originally named the Sturtian Tillite (Howchin, 1920)

CONSTITUENT UNITS [3.]: Braemar ironstone facies (informal)

PARENT UNIT: Yudnamutana Subgroup

TYPE LOCALITY *(including Lat. & Long.)* **[2.]:**

CRS for all coordinates is EPSG:7844 (GDA2020); estimations use historical data and modern remote sensing imagery and GIS data to provide locations that are as accurate as possible.

Primary type: SW of Mount Harris, through MacDonnell Creek – base: 139.357, -30.095, top: 139.34021, -30.07363 (GDA2020)

Reference sections:

- Sturt Gorge Recreation Park — base: 138.59633, -35.03398, top: 138.57289, -35.03947 (GDA2020, composite section, estimated from georeferenced map of Link 1977 and current boundaries shown on 100K surface)
- Appila Gorge — base: 138.48247, -33.00312, top: 138.48458, -33.00341 (GDA2020, estimated based on section map from Segnit 1939)
- Pualco Hill — base: 139.64033, -32.97827, top: 139.60483, -32.95732 (GDA2020, composite section, estimated location from map and detail in QGN 60)
- NW of Copley — base: 138.38933, -30.56145, top: 138.39032, -30.5592 (GDA2020)
- Termination Hill — base: 138.01746, -30.21562, top: 138.01387, -30.21756 (GDA2020)
- Yankaninna Station — base: 138.94295, -30.28636, top: 138.9431, -30.28593, (GDA2020, northern section); base: 138.99635, -30.36184, top: 138.9976, -30.36354 (GDA2020, southern section)
- Davenport and Denison Ranges — base: 135.94206, -28.68947, top: 135.93648, -28.70065 (GDA2020, estimated from Ambrose et al. 1981)

- Tillite Gorge, Arkaroola – base: 139.43277, -30.33123, top: 139.40406, -30.34282 (GDA2020)

CONFIDENTIAL TYPE LOCALITY?: No

DESCRIPTION AT TYPE LOCALITY [2.]:

The Sturt Formation comprises characteristic (boulder) diamictites showing evidence for glaciogenic origin, and numerous subsidiary lithologies including poorly sorted sandstones/conglomerates through to finely laminated shales containing a wide variety of lonestones and dropstones.

LITHOLOGY [2.]:

The lithology of the Sturt Formation at its type section defined here is further detailed in Belperio (1973) and Young & Gostin (1989). It is subdivided into four generalised lithologies:

Unit 1: Very poorly sorted conglomerates with sandy matrix to true diamictites with muddy, silty and even very fine sandy matrix. Clasts ranging in size up to boulder (largest observed: 1 m); minor interbeds of laminated siltstone. A higher concentration of larger clasts sizes is present in the lower sections.

Unit 2: Interbedded, well laminated shales and sandy micaceous siltstones. Minor pebbly lenses and silty arenites, crossbedding present, and ripple marked.

Unit 3: Crudely stratified diamictite (lithic wacke, muddy to silty matrix) with clasts ranging up to boulder size (max. observed: 90 cm). Minor interbeds of calcareous shale, and thick interbeds of massive diamictite.

Unit 4: Similar to unit 3, however has a higher mud content in matrix and is mostly massive diamictite. Greater number and size of clasts, ranging up to 1.25 m (observed).

THICKNESS [2.]: ~1,470 m at primary type section

FOSSILS: N/A

DIASTEMS OR HIATUSES (if relevant): N/A

RELATIONSHIPS & BOUNDARY CRITERIA [2.]:

Most commonly overlies Burra Group, less commonly Callanna Group or pre-Neoproterozoic basement. Conformably overlain by Holowilena Ironstone, Benda Siltstone, Wilyerpa Formation, and Lyndhurst Formation. Disconformably overlain by Tapley Hill Formation where Wilyerpa Formation is absent, e.g. Sturt Gorge.

DISTINGUISHING OR IDENTIFYING FEATURES [1.]**:**

Poorly sorted, massive diamictite with clasts ranging up to extremely large boulders. These significantly differ lithologically from the over- and underlying strata. Evidence for glaciogenic origin (dropstones in laminated rocks [lonestones that warp and/or puncture the underlying laminae]; glacial striae and scouring of underlying rock; presence of polished, facetted, striated and grooved clasts) can often be found in outcrop; one glaciated pavement near Merinjina Well.

AGE & EVIDENCE [2.]:

Minimum: 663 ± 0.76 Ma (Tuff near base of overlying Wilyerpa Formation, Cox et al. 2018)

Detrital zircon max depositional age (upper Sturt Formation):

- 667 ± 6 Ma (Pichi Richi Pass, Keeman et al. 2020; data reinterpreted in Lloyd et al. 2020)
- 666 ± 25 Ma (Copley, Lloyd et al. 2022a [pre-print])
- 673 ± 19 Ma (Willouran Ranges, Lloyd et al. 2020)

Maximum age: constrained to younger than 731 ± 34 Ma by detrital zircon in the underlying Gilbert Range Quartzite (Keeman et al. 2020; data reinterpreted in Lloyd et al. 2020) and corroborated by detrital zircon in the Mitcham Quartzite, 734 ± 42 Ma (Lloyd et al. 2022b [pre-print]).

CORRELATION WITH OTHER UNITS [2.]:

Stratigraphic correlative of the Chambers Bluff Tillite (Officer Basin), Areyonga Formation (Amadeus Basin), Naburula Formation (Ngalia Basin), Yardida Tillite (Georgina Basin), and lower units of the Yancowinna Subgroup (NSW). Potential correlatives in Tasmania are the Julius River Member, Red Rock Member, Cotcase Creek Formation, and middle Port Sorrel Formation.

REGIONAL ASPECTS/GENERAL GEOLOGICAL DESCRIPTION:

General lithologic sequence common throughout the basin in complete, or near complete successions of the Sturt Formation is:

- poorly sorted, gravel to boulder conglomerate (diamictite in some areas) with generally sandy matrix; scoured bases are common in areas where the Fitton Formation is not present
- Interbedded fine laminated siltstones and shales to cross-bedded sandstones with few lonestones/dropstones
- boulder diamictite (both massive and stratified)

Regionally, the size, composition, and percentage of clasts in the diamictite lithologies varies. Mega-clasts, ranging up to 1.25 km have been described in the MacDonald corridor north of Olary (Conor & Preiss, 2019).

Arkosic, poorly sorted immature sandstones, and cross-bedded sandstones are predominant in some areas. Iron-rich sections are present in the Sturt Formation underlying the Benda Siltstone and Holowilena Ironstone in the Nackara Arc/South Flinders Ranges.

EXTENT:

Deposited across the entire Adelaide Rift Complex within the Adelaide Superbasin; local areas of non-deposition or subsequent erosion. Deposition on the Stuart Shelf appears to be limited to the eastern most areas and deposition on the Coombalarnie Platform is not known.

GEOMORPHIC EXPRESSION:

THICKNESS VARIATIONS: Thickness varies greatly because of palaeotopography, palaeotectonic activity, and erosion.

Minimum: 9 m, ~2.5 km to the NW of Tower Hill (Mount Lyndhurst station)

Maximum: 3,300 m at Pualco Hill.

STRUCTURE AND METAMORPHISM:

ALTERATION AND MINERALISATION: Iron rich facies present in the Nackara Arc; Talc, Au, Cu, Pb mineralised zones have also been found.

GEOPHYSICAL EXPRESSION:

Iron rich facies show strong anomaly on TMI where the original hematite (as in the Holowilena Ironstone) has been metamorphosed to magnetite (as in Braemar ironstone facies of the Benda Siltstone and the Pualco Range outcrops of the Sturt Formation.

Surface exposure can be readily identified using false colour remote sensing imagery, for LANDSAT 8 specifically using channels 7-5-2 and 5-6-7 for R-G-B.

GEOCHEMISTRY:

GENESIS/DEPOSITIONAL ENVIRONMENT:

Deposited under general glaciogenic conditions: dropstones, lonestones, glacial striae, mega-clasts. Exact environment is dependent on location but encompasses the full range of sub-glacial to pro-glacial terrestrial and glacio-marine sedimentary environments. Mostly massive but contains lithologies showing planar stratification, cross stratification, reverse graded bedding, scour structures, and ripple laminations.
The cast of a glaciated pavement is preserved near Merinjina Well where the Sturt Formation disconformably overlies the Wooltana Volcanics.

COMMENTS:

The “Tillite” portion of the name has been dropped in favour for “Formation” in contrast to the reasoning outlined in Coats & Preiss (1987). This change is done to better reflect the diversity in lithologies present throughout the Sturt Formation. The most prominent of these are the diamictites, many of which are shown to be true tillites, however the formation varies from sub-glacial to grounded ice-margin and glacio-marine facies.

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Definition approved by:

SA Stratigraphic Names Subcommittee

(delete where inapplicable)

Date:

(for registry use only)

Name first published by:

Definition by: