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Geochronology and formal stratigraphy of the Sturtian Glaciation in the Adelaide Superbasin

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Abstract

The glaciogenic nature of the Yudnamutana Subgroup was first identified over a century ago, and its global significance was recognised shortly after, eventually culminating with the 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 lithostratigraphy 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 stratigraphic nomenclature has remained complicated and contested. Geochronology has also been extremely sparse in this area. 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 recently defined for 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 global geochronology for the Sturtian Glaciation, and provide an updated formal lithostratigraphy. We show equivalence of the rocks that comprise the revised Sturt Formation of the Yudnamutana Subgroup, and that it was deposited within the time span 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), Siberia (Romanov et al. 2021), 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 contentious for some researchers (e.g., Allen & Etienne 2008; Eyles & Januszczak 2004; Le Heron et al. 2020; Williams & Gostin 2019), most authors accept that two major glacial episodes are indicated; an older Sturtian Glaciation, and a younger Marinoan (Elatina) Glaciation (or "cryochron"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, which has been hypothesised as a cause of the subsequent rise of algae and other eukaryotic life, leading to the emergence of animals (Brocks 2018; Brocks et al. 2017; Lechte 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; Park et al. 2019; Rud`ko et al. 2020; Środoń et al. 2022). 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 Precambrian 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 a new in-situ Rb–Sr shale age and 1034 new detrital zircon analyses from fifteen samples [Figure 1] of the Yudnamutana Subgroup (Sturtian Glaciation), 59 analyses from the Yancowinna Subgroup of New South Wales (that is interpreted as an equivalent unit), 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.

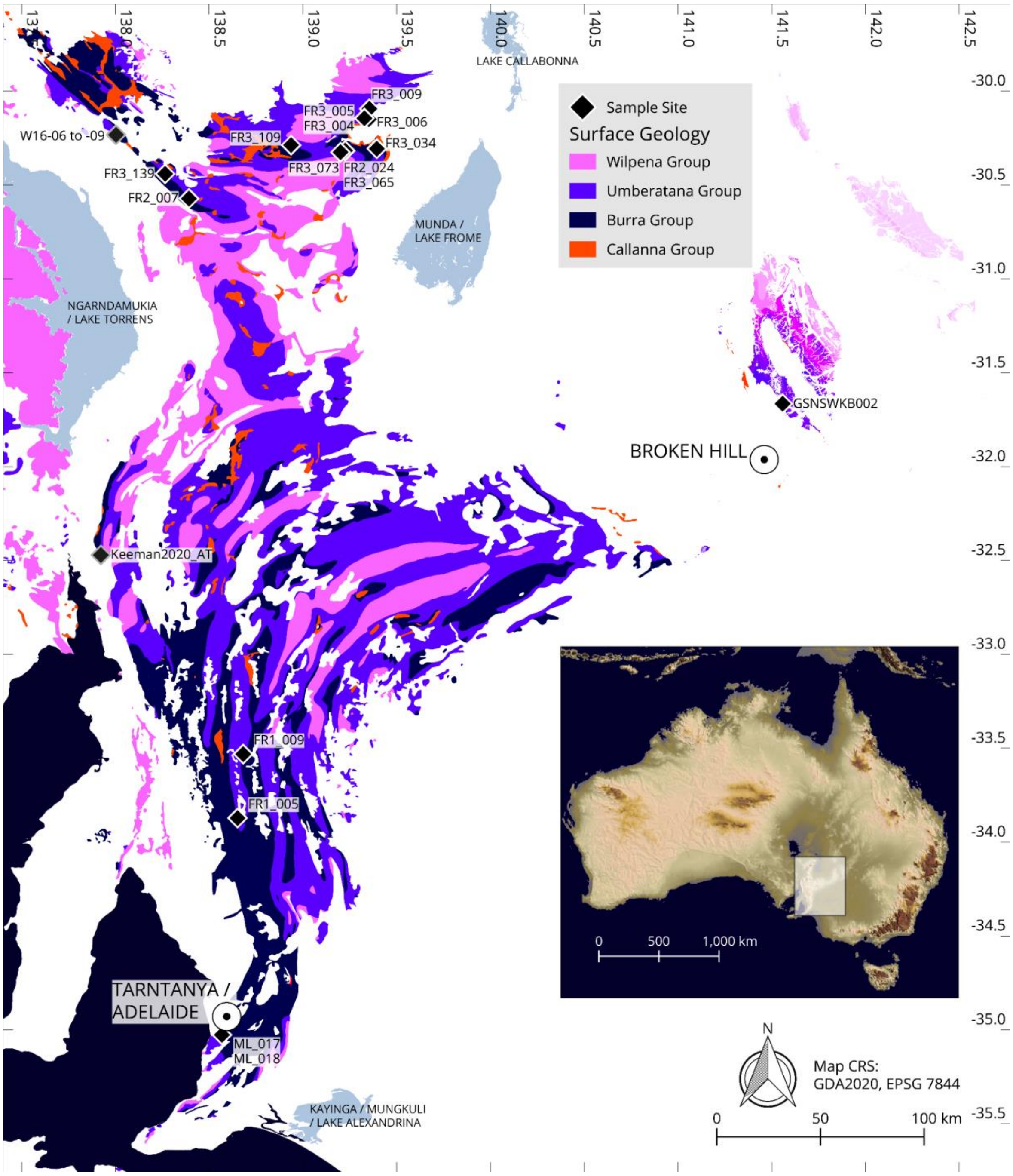

Figure 1 – Sample locality map, showing distribution of Neoproterozoic stratigraphy within the Adelaide Rift Complex of the Adelaide Superbasin. GPS coordinates for samples are provided with the U-Pb data (see data availability).

2 Geological Background

2.1 Adelaide Superbasin

The Adelaide Superbasin (Lloyd et al. 2020) consists of several named basins and sub-basins that form a large, Neoproterozoic to middle Cambrian sedimentary system at the southeast margin of Proterozoic Australia. Formation of the Adelaide Superbasin initiated at c. 890–830 Ma as a result of the breakup of the Rodinia supercontinent (Lloyd et al. 2022a; Powell et al. 1994; Preiss 2000). The Adelaide Rift Complex is the largest and oldest of the basins within the Adelaide Superbasin and includes a number of extensional depocentres, among them the

Yudnamutana Trough (northern Flinders Ranges), Baratta Trough (Olary and eastern Flinders Ranges) and Yancowinna Trough of western New South Wales. The rift complex 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 to Kangaroo Island in the south, and east into western Victoria and New South Wales. 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; 2022b [preprint]; Preiss 2000). 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). Present day exposure of the sedimentary basin is largely restricted to the Flinders and Mount Lofty Ranges of South Australia, and the Barrier Ranges of South Australia and New South Wales. The stratigraphy of the Adelaide Superbasin is divided into three supergroups (Preiss 2000), two for the Neoproterozoic sequences and the third for the Cambrian sequences, with numerous group and subgroup level divisions. The Warrina Supergroup comprises 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 deposits of 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), Cowley (2020), Lloyd et al. (2020), and references therein for further detail on the geological history of the Adelaide Superbasin.

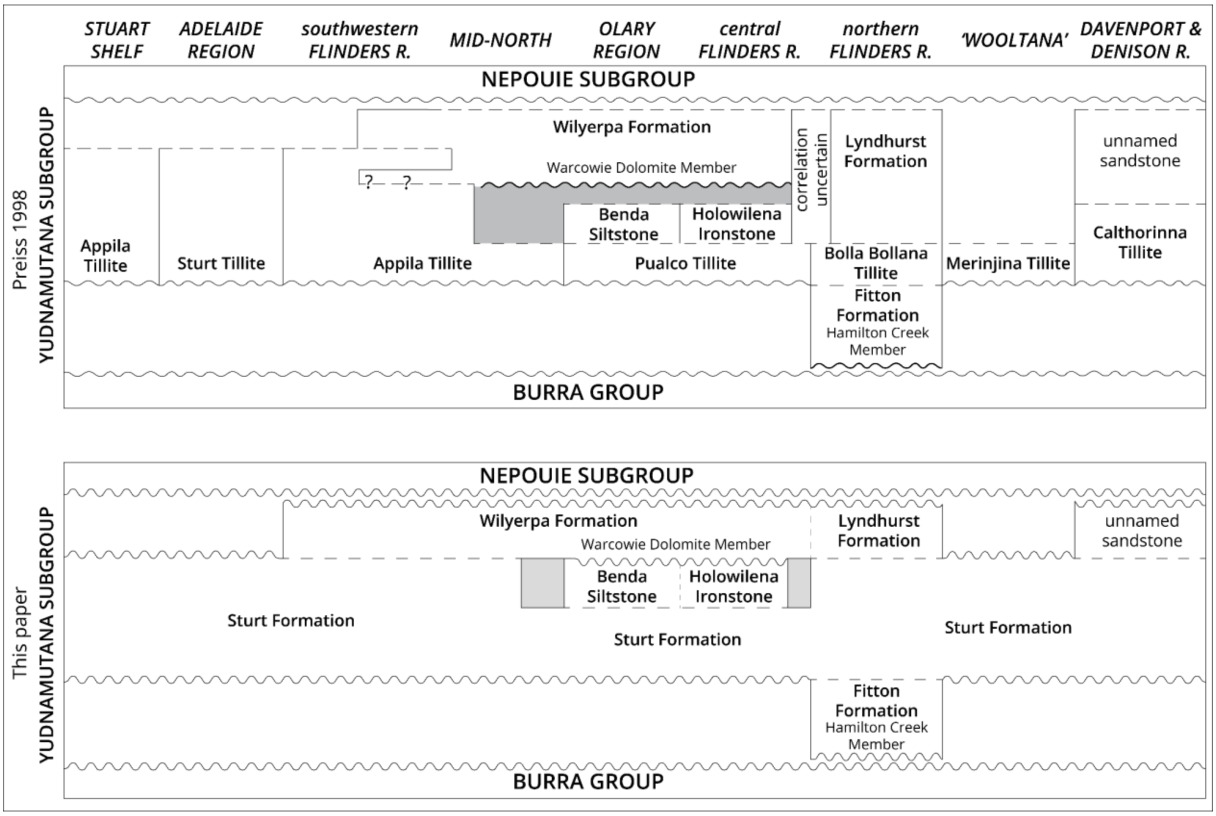

Figure 2 – Stratigraphic table showing past (Preiss et al. 1998) and current correlations (this study) of the Yudnamutana Subgroup.

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 comprises sedimentary rocks that represent the Sturtian glacial event in South Australia. The glaciogenic nature of these rocks was first recognised by Howchin (1901), and these 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; 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 is diamictite, with clasts ranging in size up to boulders and even megaclasts. The matrix varies from mudstone, through to silty sandstone, and carbonate is abundant in some places. Siltstone with lonestones and dropstones are commonly associated with the diamictites, as are sandstones of varying compositions and grain sizes. Non-diamictite conglomerates are a minor, but locally important lithofacies of the Yudnamutana Subgroup (Preiss et al. 2011). Sedimentary ironstones are present but restricted to the Baratta Trough (Preiss 1987; Preiss et al. 2011) in the eastern portion of the Adelaide Superbasin.

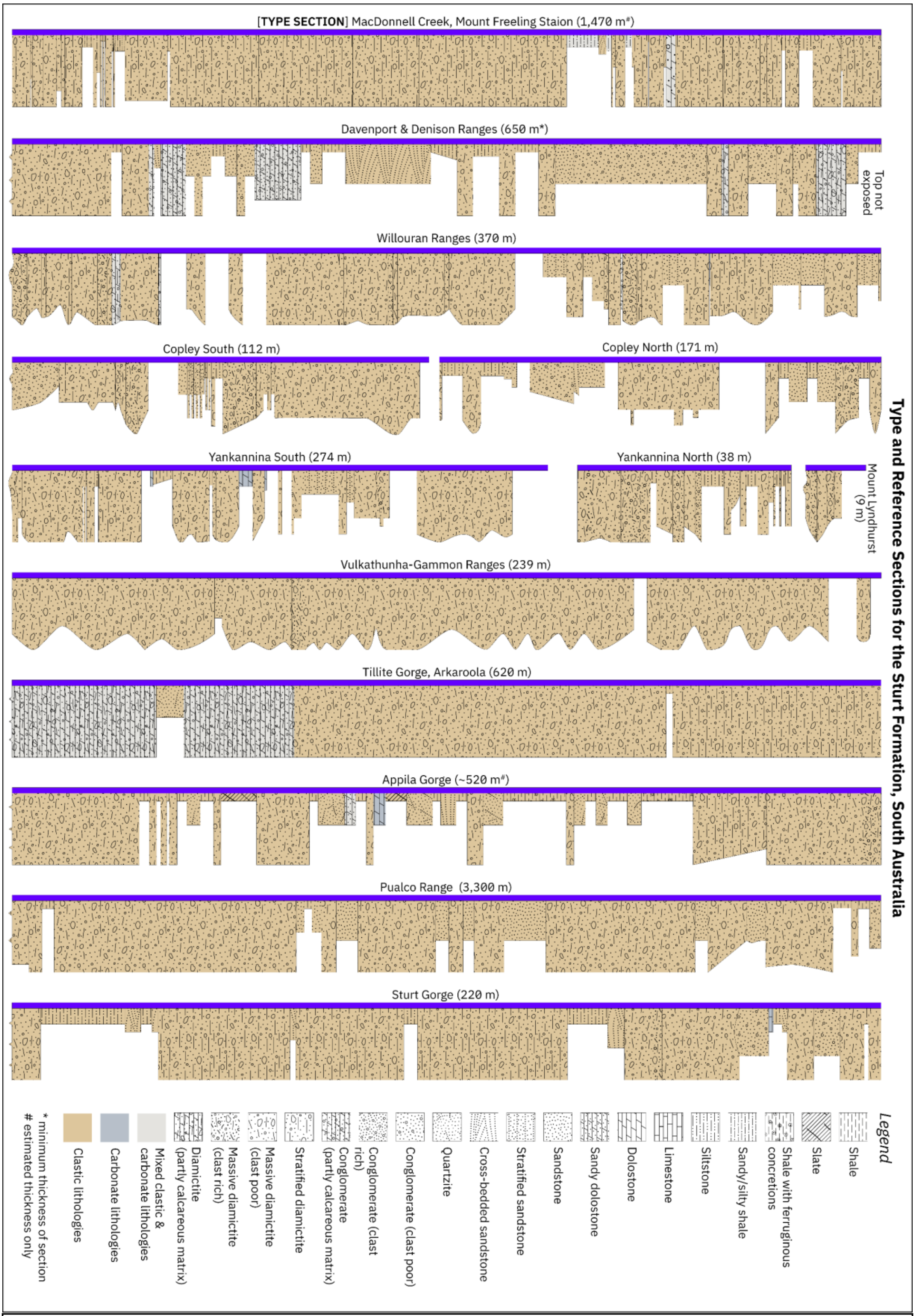

Figure 3 – Generalised stratigraphic logs of the Sturt Formation at its type section, and additional reference sections. For coordinates of locations see the accompanying stratigraphic unit definition (Appendix 1). Copley, Yankaninna, Willouran Ranges, and Vulkathuhna-Gammon Ranges sections are from 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).

The Fitton Formation, the lowermost known glaciogenic rock of the Sturtian Glaciation in South Australia, is only present in the Yudnamutana Trough of the northern Flinders Ranges, where it is overlain by the Bolla Bollana Tillite (Preiss et al. 1998; Young & Gostin 1989b). The latter is one of six currently named diamictite/tillite formations that represent the glacial maximum. These are the Appila Tillite (Thomson et al. 1964) (based on the section of Segnit 1939), the Bolla Bollana Tillite (Coats & Forbes 1977; Thomson et al. 1964), the Calthorinna Tillite (Ambrose et al. 1981), the Merinjina Tillite (Coats & Preiss 1987), the Pualco Tillite (Forbes & Cooper 1976), and the Sturt Tillite (Howchin 1920; Mawson & Sprigg 1950). For reasons outlined later in this publication, the formations representative of the glacial maximum are here combined and renamed the Sturt Formation. The Benda Siltstone, Old Boolcoomata Conglomerate and Holowilena Ironstone overlie the Sturt Formation but are limited in distribution to the Baratta Trough (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 and Tuckwell (1971) presented in further detail by Cooper, PF et al. (1974). It consists of a sequence of coarse poorly sorted and siliciclastics that include arkose, quartzite, sandstone, siltstone, conglomerate, and diamictite (Cooper, PF et al. 1974; Fitzherbert & Downes 2015; Preiss 1987). Diamictite of glacial origin (Tillite) has only been confidently recognised in one area (Cooper, PF 1973), but many of the facies closely resemble probable 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 (Elatina) 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 and not yet confirmed by geochronology.

2.1.3 Nepouie Subgroup

The inter-glacial Nepouie Subgroup (Preiss et al. 1998) most notably includes the basin-wide Tapley Hill Formation. Other formations in the Nepouie Subgroup are the basal Serle Conglomerate, and the Brighton Limestone and Balcanoona Formation at the top, with the latter two overlying and interfingering with 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 composed of well sorted, commonly carbonaceous, calcareous, or dolomitic siltstone, with pyritic shale and dolostone at the base. While extensive in both distribution (basin-wide) and uniformity, there are several minor lithofacies variations 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 defined as a chronostratigraphic unit (Series) in South Australia (Mawson & Sprigg 1950) and was later 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 encompassed 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 global (or near-global) glacial 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 Precambrian glacial sequences, in particular those now attributed to the Sturtian Glaciation, was recognised nearly a century ago (Hoffman 2011; Hoffman et al. 2017a, and references therein); however, their synchroneity was long debated until the advent of reliable and precise geochronology 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). Many of the thickest glacial successions are found in extensional basins associated with the break-up of Rodinia; the very thick Sturt Formation deposits in the Baratta, Yudnamutana, and Yancowinna troughs of the Adelaide Superbasin are typical of these.

3 Methods

3.1 Detrital zircon U–Pb geochronology

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.

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 analysed 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 RESOlution-LR 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 reference material for U–Pb ratios and NIST610 (Jochum et al. 2011) was used as the primary calibration reference material for Pb isotope ratios and trace element data. The internal standard element for trace element data was ^{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 reference materials to check accuracy. 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 used for GJ-1, Plešovice, and 91500 were 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 two-standard error (2SE) 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 uncertainties are quoted at 2SE level. 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.

3.2 In-situ Rb–Sr geochronology

Two siltstone/shale samples (3404236 & 3404235) were acquired for in-situ Rb–Sr geochronology from the Sturt Formation within drillhole SR13/2 located on the north-eastern margin of the Stuart Shelf, South Australia.

Polished rock blocks in 25mm round epoxy mounts were analysed using an Agilent 8900x ICP-MS/MS coupled to a RESOlution-LR 193 nm ArF excimer LA system house at Adelaide Microscopy, the University of Adelaide. Methods follow Redaa et al. (2021) and Subarkah et al. (2021). Briefly, N_2O was used as the reaction gas to mass separate ^{87}Sr from ^{87}Rb with Sr measured as the reacted $^{87}Sr^{16}O$ product ion mass at 103. A nominal fluence of 3.5 J cm^{-2} with a 67 µm circular spot, a 5 Hz repetition rate, and 40 second ablation time preceded by a 30 second gas blank were used. NIST610 glass (Jochum et al. 2011) was used as the primary calibration reference material for Sr isotope ratios, and the Mica-Mg (Govindaraju 1995) pressed nanopowder pellet was used as the primary calibration reference material for Rb—Sr ratios. Accuracy was checked by analysing MDC (crystalline phlogopite) and Högsbo (crystalline muscovite) (Hogmalm et al. 2017; Redaa et al. 2021) as validation reference materials. Unknowns were bracketed by two analyses of NIST610 and three analyses of Mica-Mg every thirty unknowns.

Data were reduced in LADR (Norris & Danyushevsky 2018) version 1.1.07 and output as “Full Analytical Uncertainty”. Isochrons were calculated using IsoplotR (Vermeesch 2018) using a ^{87}Rb decay constant (λ) of (1.3972 ± 0.0045) x 10^{-11} a^{-1} (Villa et al. 2015). Error correlations (ρ) were calculated in LADR by using a workaround to proxy the Rb–Sr data as U–Pb data. Except for translating headers using a cross-platform PowerShell module from Rb to U and Sr to Pb, all other parameters are the same resulting in identical ratio outputs but allowing for calculation of error correlations. Uncertainties are quoted at 2SE level initially without decay constant uncertainty propagation. The decay constant uncertainty is propagated into the quoted uncertainty during the discussion when comparing to other geochronometric systems.

4 Results

4.1 Detrital zircon geochronology

4.1.1 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].

4.1.2 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). Data from 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 (Spalding area) [Figure 1], 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]. Data from 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). Data from these two samples are 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],

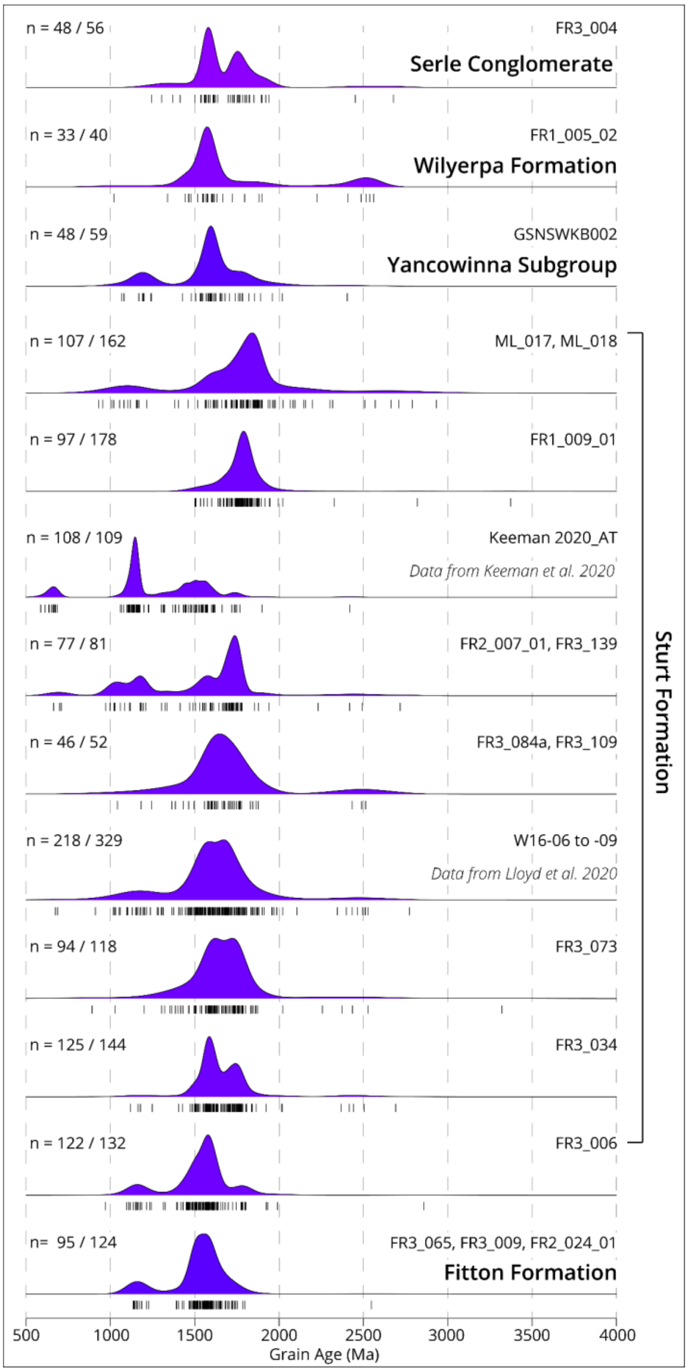

Figure 4 – Kernel density estimates [KDEs] of detrital zircon populations from Yudnamutana, Yancowinna and Nepouie Subgroup samples. Data are from this study unless otherwise denoted. Tick marks below each plot represent an analysis. n = filtered analyses / total analyses. Generated using IsoplotR (Vermeesch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

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].

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, Barrier Ranges (New South Wales) [Figure 1], with 48 passing filtering parameters. Ages range from 1065 ± 18 Ma to 2404 ± 37 Ma [Figure 4].

4.1.3 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].

4.1.4 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].

4.2 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

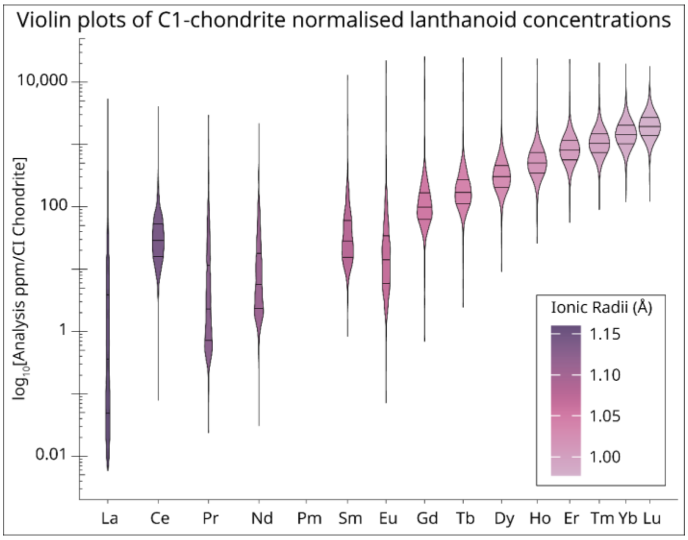

Figure 5 – Violin plots of CI chondrite (O'Neill 2016) normalised lanthanoids for all filtered zircon analysed in this study. X-axis is spaced by ionic radii (Shannon 1976) and ordered by atomic number. Black lines across the fill of each plot represent the 0.25, 0.5, and 0.75 quantiles. Bandwidth of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

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 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.

4.3 In-situ Rb–Sr Geochronology

Of the two siltstone/shale samples analysed for Rb–Sr geochronology, 3404236 (upper Sturt Formation) and 3404235 (lower Sturt Formation), only the latter sample yielded a meaningful result. The analyses on sample 3404236, n = 60, had little spread in Rb/Sr ratios and a low percentage of radiogenic Sr ($^{87}Sr/^{86}Sr < 0.8$), nonetheless a date of 839 ± 235 Ma was obtained with an initial $^{87}Sr/^{86}Sr$ of 0.7030 ± 0.0127 [Figure 6]. For sample 3404235, n= 51, there was reasonable spread in Rb/Sr ratios and a date of 684 ± 37 Ma with an initial $^{87}Sr/^{86}Sr$ of 0.7204 ± 0.0054 was obtained [Figure 6].

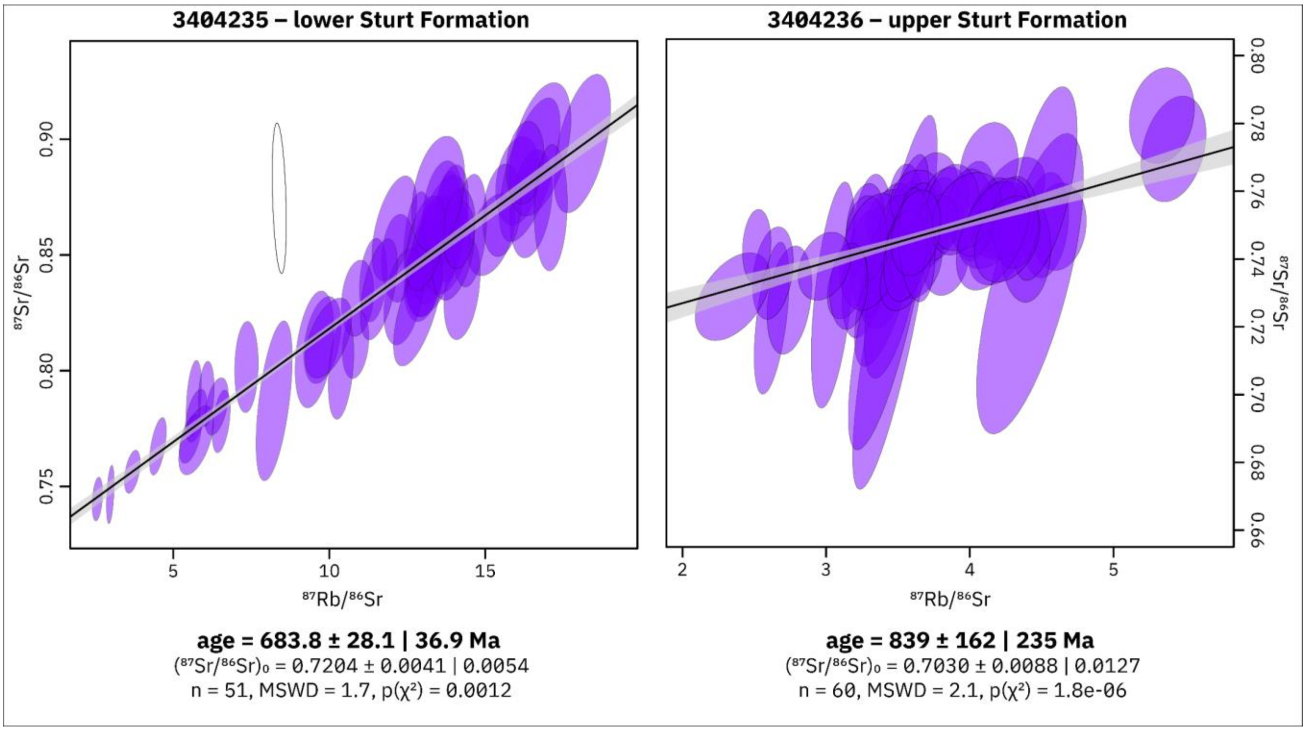

Figure 6 – Rb–Sr isochrons of the two shale/siltstone samples from the Sturt Formation in drillhole SR13/2 analysed in this study. Quoted uncertainty and ellipses are two standard error (2SE). The second uncertainty term accounts for overdispersion. Generated using IsoplotR (Vermeesch 2018), without the decay constant uncertainty propagated. ^{87}Rb decay constant used = (1.3972 ± 0.0045) x 10^{-11} a^{-1}.

5 Discussion

5.1 Zircon trace element geochemistry

Zircons analysed in this study mostly show affinity to generation in continental crust with only a small number of zircons potentially of oceanic affinity [Figure 7], as inferred by the U/Yb against Y plot (Grimes et al. 2007; Grimes et al. 2015). Almost all zircons have a Th/U ratio >0.07 and are inferred to be generated as magmatic rather than metamorphic zircon (Collins et al. 2004; Rubatto 2002). C1 chondrite normalised (O'Neill 2016) lanthanoids concentrations are generally typical for zircon [Figure 5] with a positive pattern slope (increasingly negative λ1 values) from light to heavy lanthanoids, a positive Ce anomaly, and negative Eu anomaly (Hoskin & Ireland 2000; Hoskin & Schaltegger 2003). There is no apparent trend in lanthanoid pattern slope or curvature [Figure 8], 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).

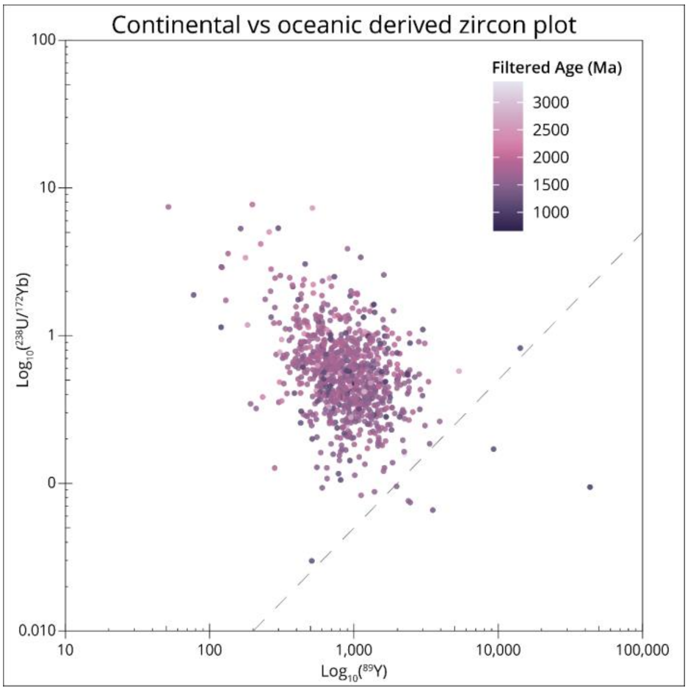

Figure 7 – Plot based on Grimes et al. (2007) used as an indicator of zircon crustal origin. This plots Y against U/Yb, with the dashed reference line dividing the "oceanic" (below line) and "continental" (above line) fields. Most data plot above the reference line, suggesting zircon formation mostly in crust of continental affinity. Coloured by filtered age where light is older and darker is younger.

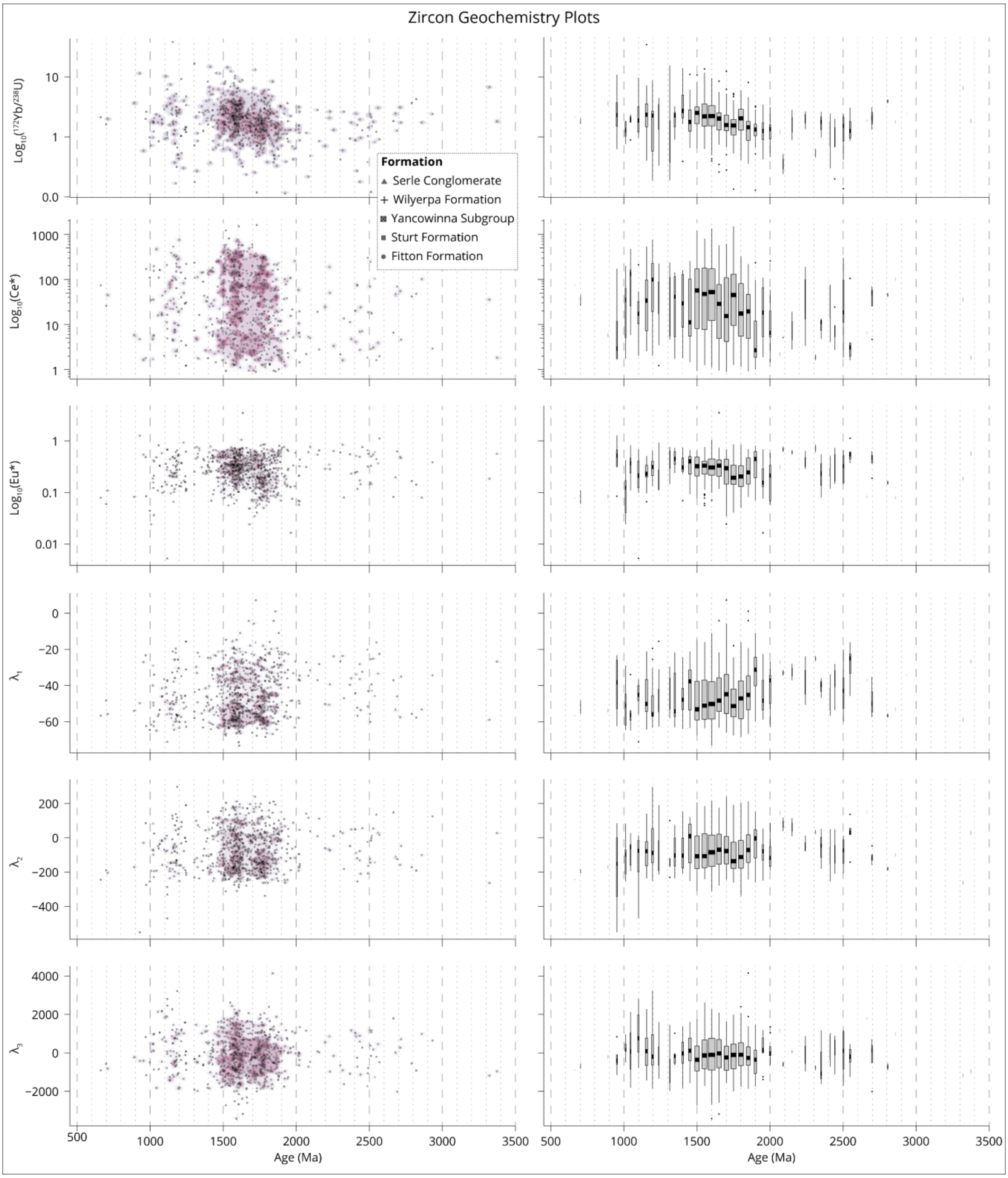

Figure 8 – Key zircon geochemistry plots for zircon analysed in this study. Left: Scatter plots underlain with 2D density estimation. Right: 50-million-year binned boxplots with width scaled by the count of values in the bin. Top to bottom: Yb/U, Ce*, Eu* and λ_{1-3}. λ_{1-3} are measures of lanthanoid pattern shapes, with λ_{1-3} representing the linear slope, quadratic slope and cubic slope respectively. Ce*, Eu* and λ_{1-3} 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 detrital zircon MDAs 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. 2022b [preprint]; van der Wolff 2020). The younger age limit for deposition of the Yudnamutana Subgroup is constrained by a 663.03 ± 0.76 Ma tuff in the Wilyerpa Formation (Cox et al., 2018). The Serle Conglomerate is older than the c. 642 Ma Tapley Hill Shale (Re–Os shale, Kendall et al. 2006) that it 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 4.1.2.

- 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 9] 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 glacially derived sediment, the remarkable similarity of most samples' spectra [Figure 4, Figure 9] adds support to unit equivalence, as is strongly suggested by previous mapping of the 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. In addition, many workers have noted that the Sturtian Glaciation deposits often consist of two diamictite packages separated by an argillaceous or arenaceous sequence (Lechte & Wallace 2015; Virgo et al. 2021). It is likely the different regions preserve deposits from different parts of the Sturtian cryochron. The two diamictites may represent different periods of glacial advance, or different phases of the glaciation (Lechte & Wallace 2015; Lechte et al. 2018), which would mean in both cases that they were deposited at different times and therefore may well preserve different MDAs. 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. 2022b [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. Because the older age limit itself is a maximum depositional age for the unconformably underlying Belair Subgroup, the MDA of c. 666 ± 25 Ma is likely close to the true depositional age for the terminal deposits (upper portion) of the Sturt Formation as a whole.

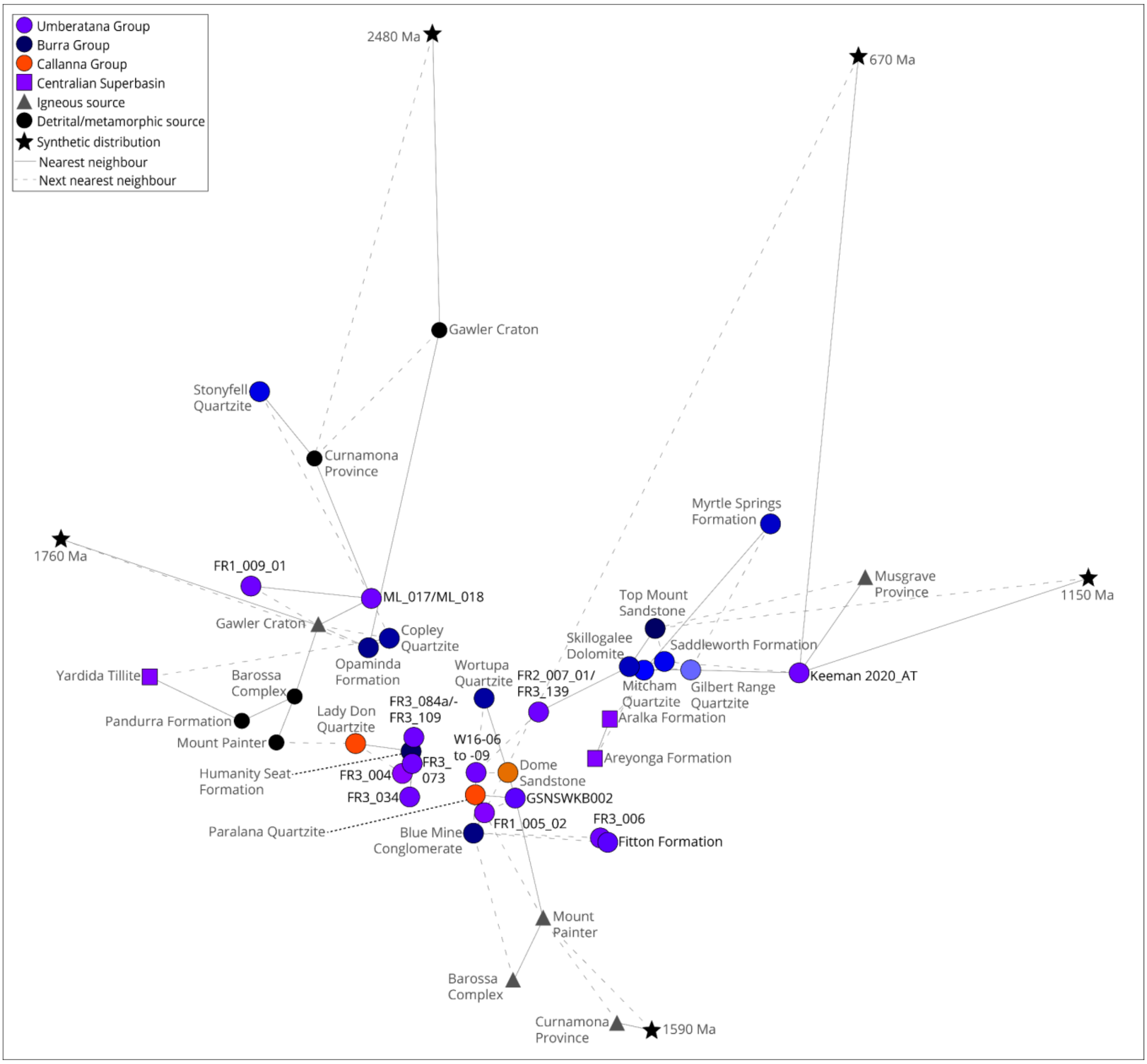

Figure 9 – Non-metric multidimensional scaling plot of samples analysed (n > 30) in this study (purple circles) with data from potential correlative formations of the Centralian Superbasin (purple squares), potential source regions (black and grey circles and triangles), and synthetic distributions (black 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 is a reconnaissance sample collected from undifferentiated Yancowinna Subgroup in the Barrier Ranges of New South Wales to test the general correlation with the Yudnamutana Subgroup of South Australia. This area is the easternmost known 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 from a highly weathered diamictite with clasts ranging up to pebble size, and a silty to fine sand matrix. 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 9]. 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 (i.e. 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 9] 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 detrital zircon populations, c. 1840–1790 Ma and c. 1640–1580 Ma, form major peaks in virtually all samples. The exact age positions and magnitude of the population peaks varies slightly by sample, with broad 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 unconformably 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 9], 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 sourced 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 et al. 2019; Reid & Hand 2012; Reid et al. 2008; Reid et al. 2014a; Reid et al. 2014b; Reid et al. 2017; Reid & Payne 2017; Reid et al. 2021; 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. 1590 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) 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]. Alternative 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, recycling of underlying stratigraphy is a likely source of some of these zircons.

Neoproterozoic zircons with 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 663.03 ± 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 site of the volcanic centre for the ashfall is unknown. Additionally, zircon of this age range (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 10], potentially suggesting this magmatic source was to the west of, or on the western margin of the basin.

Comparison is made with 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 (Preiss et al. 1978). Interestingly, the detrital zircon age spectra of the Yardida Tillite (Georgina Basin, Northern Territory/Queensland) which is likely to be a time correlative of the Sturt Formation, is very similar [Figure 9] to the local basement of South Australia (e.g. Gawler Craton). 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 in the Gawler Craton and Curnamona Province. In addition, palaeomagnetic and geological reconstructions for the time suggest that the South Australian Craton may have been rotated closer to the Georgina Basin at that time (Li, Z-X & Evans 2010; Lloyd et al. 2020). The age spectra in the Areyonga Formation and Aralka Formations (Amadeus Basin, Northern Territory/Western Australia) are similar to the Burra Group and 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 zircons 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.

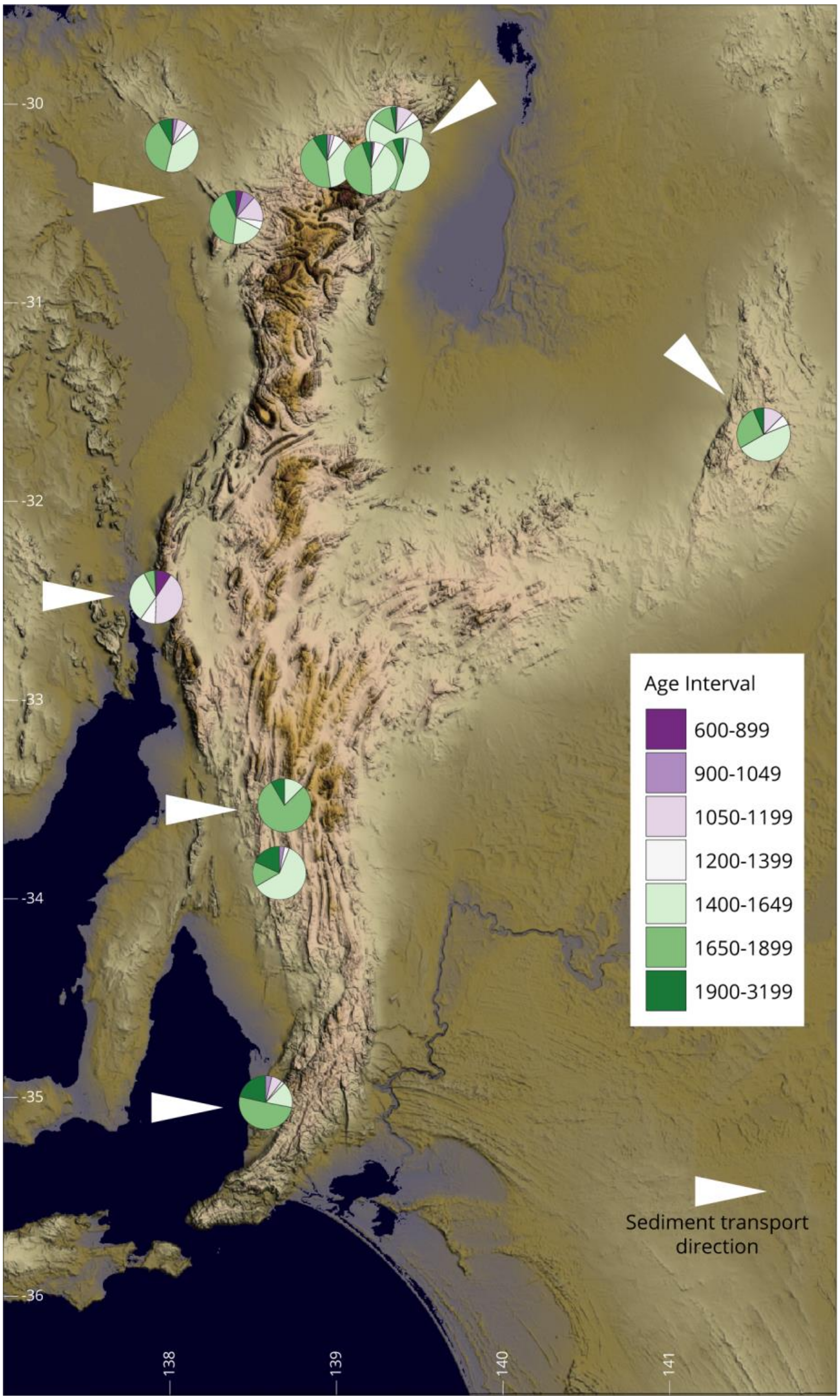

Figure 10 – Schematic map with pie charts at samples locations to highlight the changes in zircon population spectra relative to geographic location. Arrows are generalised schematic indicators of palaeo-sediment transport direction.

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 western edge of the Adelaide Rift Complex (Copley area, south-eastern Willouran Ranges). It is likely that underlying strata have been recycled by sub-glacial erosion, 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) suggest a south, or south-westerly sediment transport [Figure 10] 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 9, Figure 1].

5.3 Rb–Sr geochronology

In-situ Rb–Sr geochronology is a rapidly developing technique that, when applied to shales, can provide information about depositional ages or early diagenetic illite formation (Subarkah et al. 2021). While a powerful although imprecise technique, in shales the Rb–Sr isotopic system is susceptible to low—moderate temperature hydrothermal alteration (Subarkah et al. 2022) and can be influenced by detrital input. These complications mean careful assessment must be done before assigning geological significance to obtained dates. For the two samples analysed in this study, the obtained dates must be between 730 and 663 Ma for them to be representative of depositional age. Uncertainties quoted in this section include propagation of the decay constant uncertainty on ^{87}Rb (~0.32%, Villa et al. 2015) to allow for comparison to other geochronometric systems (e.g. U–Pb).

The date obtained for sample 3404236, 839 ± 241 Ma [Figure 6], is not a meaningful date due to large uncertainty and it likely comprises a significant detrital component pushing the date older than the constraints for the Sturt Formation. These reservations also apply to the former attempts to date the overlying Tapley Hill Formation via traditional whole rock Rb–Sr methods (Webb 1980; Webb et al. 1983). The 684 ± 37 Ma [Figure 6] date obtained for sample 3404235 is consistent with the constrained depositional age for the Sturt Formation and can be considered a meaningful age representing a syn-depositional constraint.

5.4 Tectonic and palaeogeographic implications

While the dataset needs to be expanded in future to cover more of 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, commonly recycling the underlying stratigraphy and/or from the nearby basement geology. This supports the common observation of clasts in diamictites that can be identified as derived from the Burra Group and, locally, the Callanna Group. This finding suggests that the far-field sediment supply to the Burra Group was shut off during deposition of the Yudnamutana Subgroup, with locally derived detritus becoming much more prominent (Lloyd et al. 2020; Preiss 2014). 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 10] suggests that the source was to the west, or along the western margin, of the basin. Of note, there is a basalt conglomerate at the base of the Sturt Formation at the central-western margin (Depot Creek) of the Adelaide Rift Complex (Hopton 1983); however, its origin and age remain enigmatic. 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, consistent with earlier palaeographic interpretations that the Curnamona Province was a topographic high between these two areas that was shedding detrital material to both sides. The data presented here also add 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 clear 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; Preiss et al. 2011; Young & Gostin 1991). The Yudnamutana, Baratta, and Yancowinna troughs are major extensional sub-basins bounded by mappable normal growth faults (Preiss 1985; Preiss & Conor 2001; Preiss et al. 2011). This has been interpreted as the last phase of rifting associated with continental separation (Preiss 2000), although Merdith et al. (2017) considered that the rift-drift transition of the Australia–Laurentia margin occurred earlier at c. 780 Ma.

5.5 Sturtian nomenclature

5.5.1 South Australian Formal Stratigraphy

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 each other (Preiss et al. 1998; Preiss et al. 2011), and both stratigraphic position and geochronology support their equivalence (this study, Cox et al. 2018b; Keeman et al. 2020; Lloyd et al. 2020; Preiss et al. 1998; Young & Gostin 1989b). Considering 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) as the Sturt Formation [Figure 2]. Sturt is retained as the first diamictite formally named was the Sturtian tillite (Howchin 1920; Mawson & Sprigg 1950), and 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 diamictite is the most distinctive lithology, it is not necessarily exclusively of glacial origin, and is not the most volumetrically abundant rock type in all areas (Preiss et al. 2011). Instead, the Sturt Formation comprises numerous lithologies that were deposited under general glacial conditions (Link 1977; Link & Gostin 1981; Preiss 1987; 2000; Preiss et al. 2011). This argument in favour of Formation instead of Tillite was made prior by Murrell et al. (1977) and it follows the international stratigraphic guide. A formal definition card accompanies this paper as Appendix 1, with the generalised stratigraphic logs of the type and reference sections presented in Figure 3. An additional stratigraphic log from drillhole SR13/2 on the Stuart Shelf is provided in supplementary figure S1.

5.5.2 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. They highlight the issue of interpreting results in a model-led approach, a point we agree on, but primarily base this on their interpretation that most Sturtian rocks of Australia chronometrically lie outside of the Sturtian glacial interval, c. 717–660 Ma, defined by Rooney et al. (2015). Only the tuff from near the base of the Wilyerpa Formation (663.03 ± 0.76 Ma, Cox et al. 2018b) was considered to be within this time interval, and this point was reiterated by Kennedy et al. (2020). However, we argue that this interpretation is incorrect, as the interpretation by Le Heron et al. (2020) 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 detrital zircon samples, with FR3_139 yielding an MDA of 666 ± 25 Ma, and a new in-situ Rb–Sr age from the Sturt Formation of 684 ± 37 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. 2022b [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; however, both Fanning and Link (2006) and Cox et al. (2018b) demonstrate that the tuff age is syndepositional, with their age dating volcanism coeval with deglaciation. It provides neither a maximum nor 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. However, this age provides a robust minimum age constraint 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 [Figure 11] (Rooney et al. 2015).

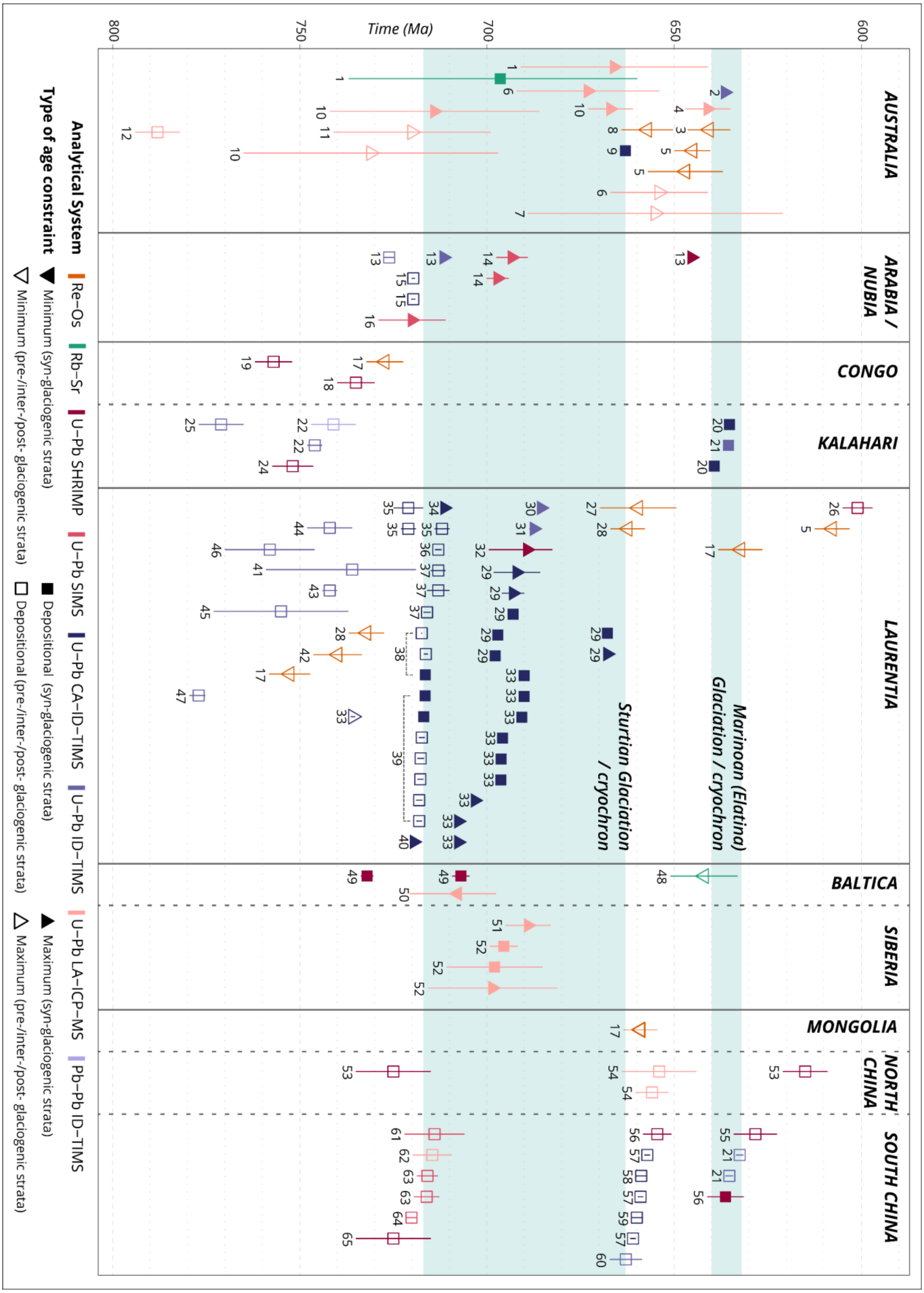

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Figure 11 – Compilation of global geochronologic data for the Sturtian and *Marinoan glaciations*. Symbols are colour coded to reflect analytical method (see figure legend for details). Open symbols are data from pre-, inter-, and post-glaciogenic strata, and closed symbols denote data from syn-glaciogenic strata. Shapes signify age type where squares are considered syn-depositional ages, and triangles denote minimum (tip points older) or maximum (tip points younger) depositional ages. Data sources: **AUSTRALIA:** (1) This study; (2) Calver et al. (2013); (3) Kendall et al. (2009); 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, XH 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:** (48) Zaitseva et al. (2019); (49) Krasnobaev et al. (2019); (50) Środoń et al. (2022) **SIBERIA:** (51) Kochnev et al. (2015); (52) Rud`ko et al. (2020). **MONGOLIA:** (17) Rooney et al. (2015). **NORTH CHINA:** (53) Xu et al. (2009); (54) He et al. (2014). **SOUTH CHINA:** (21) Schmitz (2012); (55) Chongyu et al. (2005); (56) Zhang, S et al. (2005); (57) Rooney et al. (2020); (58) Zhou, C et al. (2019); (59) Zhou, C-M et al. (2020); (60) Zhou, C et al. (2004); (61) Lan et al. (2015); (62) Song et al. (2017); (63) Lan et al. (2014); (64) Lan et al. (2020); (65) Zhang, Q-R et al. (2008)

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 re-evaluated 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) are 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, there is an erosional unconformity between the Yudnamutana Subgroup rocks and the overlying post-glacial transgressive sequences, and the Aralka Formation is demonstrably post-glacial.

Considering the above, we disagree with the proposal of Le Heron et al. (2020) that the use of Sturtian to refer to a globally distributed glaciation can no longer be justified. The available geochronology [Figure 11] 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), Baltica (Środoń et al. 2022), 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 does not discount the possibility of different times 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 11]. However, it must be noted, that while Figure 11 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 methodology. This is an unavoidable limitation of this style of diagram, with size, legibility, and accessibility considerations (e.g., Crameri et al. 2020) all contributing to this. The ideal, and more accurate representation of all these data globally, would be detailed stratigraphic logs of each section with accompanying regional correlations and detailed geochronometric methodology and results. At present, in some regions this information is either unavailable, unreliable, or limited. It would also require significant space and would be best attempted in a global review. To highlight this point, 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 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).

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.
- An in-situ Rb–Sr age from the lower Sturt Formation of 683.8 ± 36.9 | 37.1 Ma (without λSE | with λSE), interpreted to be a syn-depositional age.
- 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 consistent with the common occurrence of clasts derived from the underlying geology.
- Detrital zircon spectra support lithostratigraphic correlation of Yancowinna Subgroup (New South Wales) with 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, Rb–Sr geochronology data, and basic sample metadata.

Zircon and NIST standards data for all analytical sessions: https://doi.org/10.6084/m9.figshare.18131432

Yudnamutana Subgroup detrital zircon data (this study): https://doi.org/10.6084/m9.figshare.19181144

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

Shale Rb–Sr data: https://doi.org/10.6084/m9.figshare.21624162

Code Availability

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

PowerShell module used to adjust headers for rho calculation is available on GitHub at https://github.com/jarredclloyd/PowerShell_LADR_errorcorrelation_workaround

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. **Darwinaji Subarkah:** Investigation, writing - review & editing. **Carmen B. E. Krapf:** Investigation, writing - review & editing, funding acquisition. **Kathryn J. Amos:** Conceptualisation, supervision, writing - review & editing.

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References

Abd El-Rahman, Y, Gutzmer, J, Li, X-H, Seifert, T, Li, C-F, Ling, X-X & Li, J 2020, 'Not all Neoproterozoic iron formations are glaciogenic: Sturtian-aged non-Rapitan exhalative iron formations from the Arabian–Nubian Shield', *Mineralium Deposita*, vol. 55, no. 3, pp. 577-596. doi:10.1007/s00126-019-00898-0.

Aleinikoff, JN, Zartman, RE, Walter, M, Rankin, DW, Lyttle, PT & Burton, WC 1995, 'U-Pb ages of metarhyolites of the Catoctin and Mount Rogers formations, Central and Southern Appalachians; evidence for two pulses of Iapetan rifting', *American Journal of Science*, vol. 295, no. 4, p. 428. doi:10.2475/ajs.295.4.428.

Ali, DO, Spencer, AM, Fairchild, IJ, Chew, KJ, Anderton, R, Levell, BK, Hambrey, MJ, Dove, D & Le Heron, DP 2018, 'Indicators of relative completeness of the glacial record of the Port Askaig Formation, Garvellach Islands, Scotland', *Precambrian Research*, vol. 319, pp. 65-78. doi:10.1016/j.precamres.2017.12.005.

Allen, PA & Etienne, JL 2008, 'Sedimentary challenge to Snowball Earth', *Nature Geoscience*, vol. 1, no. 12, pp. 817-825. doi:10.1038/ngeo355.

Ambrose, GJ, Flint, RB & Webb, AW 1981, *Precambrian and Palaeozoic Geology of the Peake and Denison Ranges*, Bulletin, 50, Geological Survey of South Australia, Adelaide, South Australia.

Anenburg, M 2020, 'Rare earth mineral diversity controlled by REE pattern shapes', *Mineralogical Magazine*, vol. 84, no. 5, pp. 629-639. doi:10.1180/mgm.2020.70.

Anenburg, M & Williams, MJ 2021, 'Quantifying the Tetrad Effect, Shape Components, and Ce–Eu–Gd Anomalies in Rare Earth Element Patterns', *Mathematical Geosciences*. doi:10.1007/s11004-021-09959-5.

Armistead, SE, Collins, AS, Buckman, S & Atkins, R 2020, 'Age and geochemistry of the Boucaut Volcanics in the Neoproterozoic Adelaide Rift Complex, South Australia', *Australian Journal of Earth Sciences*, pp. 1-10. doi:10.1080/08120099.2021.1840435.

Arnaud, E, Halverson, GP & Shields-Zhou, GA (eds) 2011, *The Geological Record of Neoproterozoic Glaciations*, Memoirs, 36, Geological Society, London.

Baldwin, GJ, Turner, EC & Kamber, BS 2016, 'Tectonic controls on distribution and stratigraphy of the Cryogenian Rapitan iron formation, northwestern Canada', *Precambrian Research*, vol. 278, pp. 303-322. doi:10.1016/j.precamres.2016.03.014.

Barovich, KM & Hand, M 2008, 'Tectonic setting and provenance of the Paleoproterozoic Willyama Supergroup, Curnamona Province, Australia: Geochemical and Nd isotopic constraints on contrasting source terrain components', *Precambrian Research*, vol. 166, no. 1, pp. 318-337. doi:10.1016/j.precamres.2007.06.024.

Belousova, EA, Reid, AJ, Griffin, WL & O'Reilly, SY 2009, 'Rejuvenation vs. recycling of Archean crust in the Gawler Craton, South Australia: Evidence from U–Pb and Hf isotopes in detrital zircon', *Lithos*, vol. 113, no. 3-4, pp. 570-582. doi:10.1016/j.lithos.2009.06.028.

Belperio, AP 1973, 'The stratigraphy and facies of the Late Precambrian Lower Glacial sequence, Mt Painter, South Australia', Department of Geology, Honours Thesis, Bachelor of Science (Honours), University of Adelaide, Adelaide, South Australia, <https://hdl.handle.net/2440/131123>.

Borg, G, Kärner, K, Buxton, M, Armstrong, R & Merwe, SWvd 2003, 'Geology of the Skorpion Supergene Zinc Deposit, Southern Namibia', *Economic Geology*, vol. 98, no. 4, pp. 749-771. doi:10.2113/gsecongeo.98.4.749.

Bowring, SA, Grotzinger, JP, Condon, DJ, Ramezani, J, Newall, MJ & Allen, PA 2007, 'Geochronologic constraints on the chronostratigraphic framework of the Neoproterozoic Huqf Supergroup, Sultanate of Oman', *American Journal of Science*, vol. 307, no. 10, pp. 1097-1145. doi:10.2475/10.2007.01.

Brocks, JJ 2018, 'The transition from a cyanobacterial to algal world and the emergence of animals', *Emerging Topics in Life Sciences*, vol. 2, no. 2, pp. 181-190. doi:10.1042/etls20180039.

Brocks, JJ, Jarrett, AJM, Sirantoine, E, Hallmann, C, Hoshino, Y & Liyanage, T 2017, 'The rise of algae in Cryogenian oceans and the emergence of animals', *Nature*, vol. 548, no. 7669, pp. 578-581. doi:10.1038/nature23457.

Callen, RA 1990, *Curnamona*, 1:250 000 Geological Series—Explanatory Notes, Department of Mines and Energy, Adelaide, South Australia.

Calver, CR, Crowley, JL, Wingate, MTD, Evans, DAD, Raub, TD & Schmitz, MD 2013, 'Globally synchronous Marinoan deglaciation indicated by U-Pb geochronology of the Cottons Breccia, Tasmania, Australia', *Geology*, vol. 41, no. 10, pp. 1127-1130. doi:10.1130/g34568.1.

Chongyu, Y, Feng, T, Liu, Y, Gao, L, Yang, Z, Wang, Z, Liu 刘鹏举, P, Xing, YZ & Song, B 2005, 'New U-Pb zircon ages from the Ediacaran (Sinian) System in the Yangtze Gorges: Constraint on the age of Miaohe biota and Marinoan glaciation', *Geological Bulletin of China*, vol. 24, pp. 393-400.

Coats, RP & Forbes, BG 1977, 'Evidence for two Sturtian Glaciations in South Australia', *Quarterly Geological Notes*, vol. 64, pp. 19-20. https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/samref/sarig1/wci/Record?r=0&m=1&w=catno=2041398.

Coats, RP & Preiss, WV 1987, 'Stratigraphy of the Umberatana Group', in WV Preiss (ed.), *Adelaide Geosyncline–late Proterozoic stratigraphy, sedimentation, palaeontology and tectonics*, Geological Survey of South Australia, Adelaide, South Australia, pp. 125-211.

Collins, AS, Reddy, SM, Buchan, C & Mruma, A 2004, 'Temporal constraints on Palaeoproterozoic eclogite formation and exhumation (Usagaran Orogen, Tanzania)', *Earth and Planetary Science Letters*, vol. 224, no. 1, pp. 175-192. doi:10.1016/j.epsl.2004.04.027.

Condon, DJ & Bowring, SA 2011, 'A user's guide to Neoproterozoic geochronology', in E Arnaud, GP Halverson & GA Shields-Zhou (eds), *The Geological Record of Neoproterozoic Glaciations*, Geological Society, London, pp. 135-149.

Conor, CHH & Preiss, WV 2008, 'Understanding the 1720–1640Ma Palaeoproterozoic Willyama Supergroup, Curnamona Province, Southeastern Australia: Implications for tectonics, basin evolution and ore genesis', *Precambrian Research*, vol. 166, no. 1, pp. 297-317. doi:10.1016/j.precamres.2007.08.020.

Conor, CHH & Preiss, WV 2019, 'Cryogenian glaciomarine megaclasts of the MacDonald Corridor, Bimbowrie Conservation Park, Olary Region, South Australia', *Australian Journal of Earth Sciences*, vol. 67, no. 6, pp. 857-872. doi:10.1080/08120099.2018.1553206.

Cooper, BJ 2010, '‘Snowball Earth’: The Early Contribution from South Australia', *Earth Sciences History*, vol. 29, no. 1, pp. 121-145. doi:10.17704/eshi.29.1.j8874825610u68w5.

Cooper, PF 1973, 'Striated Pebbles from the Late Precambrian Adelaidean', *Quarterly Notes - Geological Survey of New South Wales*, vol. 11, pp. 13-15.

Cooper, PF & Tuckwell, KD 1971, 'The upper Precambrian Adelaidean of the Broken Hill area—a new subdivision', *Quarterly Notes - Geological Survey of New South Wales*, vol. 3, pp. 8-16.

Cooper, PF, Tuckwell, KD, Gilligan, LB & Meares, RMD 1974, *Geology of the Torrowangee and Fowlers Gap 1:100,000 Sheets*, Geological Survey of New South Wales, Department of Mines, Sydney, New South Wales.

Counts, JW 2017, *The Adelaide Rift Complex in the Flinders Ranges: geologic history, past investigations and relevant analogues*, Report Book, no. 2017/00016, Geological Survey of South Australia, Department of Premier and Cabinet, Adelaide, South Australia, <https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/samref/sarig1/wcir/Record?r=0&m=1&w=catno=2039731>.

Cowley, WM 2020, 'Geological setting of exceptional geological features of the Flinders Ranges', *Australian Journal of Earth Sciences*, vol. 67, no. 6, pp. 763-785. doi:10.1080/08120099.2020.1748109.

Cox, GM, Halverson, GP, Denyszyn, S, Foden, J & Macdonald, FA 2018a, 'Cryogenian magmatism along the north-western margin of Laurentia: Plume or rift?', *Precambrian Research*, vol. 319, pp. 144-157. doi:10.1016/j.precamres.2017.09.025.

Cox, GM, Halverson, GP, Minarik, WG, Le Heron, DP, Macdonald, FA, Bellefroid, EJ & Strauss, JV 2013, 'Neoproterozoic iron formation: An evaluation of its temporal, environmental and tectonic significance', *Chemical Geology*, vol. 362, pp. 232-249. doi:10.1016/j.chemgeo.2013.08.002.

Cox, GM, Isakson, V, Hoffman, PF, Gernon, TM, Schmitz, MD, Shahin, S, Collins, AS, Preiss, WV, Blades, ML, Mitchell, RN & Nordsvan, A 2018b, 'South Australian U-Pb zircon (CA-ID-TIMS) age supports globally synchronous Sturtian deglaciation', *Precambrian Research*, vol. 315, pp. 257-263. doi:10.1016/j.precamres.2018.07.007.

Cox, GM, Strauss, JV, Halverson, GP, Schmitz, MD, McClelland, WC, Stevenson, RS & Macdonald, FA 2015, 'Kikiktat volcanics of Arctic Alaska—Melting of harzburgitic mantle associated with the Franklin large igneous province', *Lithosphere*, vol. 7, no. 3, pp. 275-295. doi:10.1130/l435.1.

Crameri, F, Shephard, GE & Heron, PJ 2020, 'The misuse of colour in science communication', *Nature Communications*, vol. 11, no. 1, p. 5444. doi:10.1038/s41467-020-19160-7.

Dalgarno, CR & Johnson, JE 1966, *Parachilna map sheet SH54-13*, 1st edn, Geological Atlas of South Australia, 1:250 000 series, Geological Survey of South Australia, Adelaide, South Australia.

David, TWE 1906, 'Australisie: les conditions du climat aux époques géologiques', in *10th International Geological Congress,* Mexico.

Dempster, TJ, Rogers, G, Tanner, PWG, Bluck, BJ, Muir, RJ, Redwood, SD, Ireland, TR & Paterson, BA 2002, 'Timing of deposition, orogenesis and glaciation within the Dalradian rocks of Scotland: constraints from U–Pb zircon ages', *Journal of the Geological Society*, vol. 159, no. 1, pp. 83-94. doi:10.1144/0016-764901061.

Denyszyn, SW, Davis, DW & Halls, HC 2009a, 'Paleomagnetism and U–Pb geochronology of the Clarence Head dykes, Arctic Canada: orthogonal emplacement of mafic dykes in a large igneous province', *Canadian Journal of Earth Sciences*, vol. 46, no. 3, pp. 155-167. doi:10.1139/E09-011.

Denyszyn, SW, Halls, HC, Davis, DW & Evans, DAD 2009b, 'Paleomagnetism and U–Pb geochronology of Franklin dykes in High Arctic Canada and Greenland: a revised age and paleomagnetic pole constraining block rotations in the Nares Strait region', *Canadian Journal of Earth Sciences*, vol. 46, no. 9, pp. 689-705. doi:10.1139/E09-042.

Drexel, JF & Preiss, WV (eds) 1995, *The geology of South Australia*, vol. 2, The Phanerozoic, Bulletin, 54, Geological Survey of South Australia, South Australia.

Dröllner, M, Barham, M, Kirkland, CL & Ware, B 2021, 'Every zircon deserves a date: selection bias in detrital geochronology', *Geological Magazine*, vol. 158, no. 6, pp. 1135-1142. doi:10.1017/s0016756821000145.

Dunn, PR, Thomson, BP & Rankama, K 1971, 'Late Pre-Cambrian Glaciation in Australia as a Stratigraphic Boundary', *Nature*, vol. 231, no. 5304, pp. 498-502. doi:10.1038/231498a0.

Dyson, IA 1996, 'Stratigraphy of the Burra and Umberatana Groups in the Willippa Anticline, central Flinders Ranges', *Quarterly Geological Notes*, vol. 129, pp. 10-26.

Dyson, IA 2004, 'Geology of the eastern Willouran Ranges - evidence for earliest onset of salt tectonics in the Adelaide Geosyncline', *MESA Journal*, vol. 35, pp. 46-56. https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/samref/sarig1/wci/Record?r=0&m=1&w=catno=2023965.

Edgoose, CJ 2013, 'Chapter 23: Amadeus Basin', in M Ahmad & TJ Munson (eds), *Geology and mineral resources of the Northern Territory*, Northern Territory Geological Survey, Northern Territory.

Eyles, N & Januszczak, N 2004, ''Zipper-rift': a tectonic model for Neoproterozoic glaciations during the breakup of Rodinia after 750 Ma', *Earth-Science Reviews*, vol. 65, no. 1-2, pp. 1-73. doi:10.1016/s0012-8252(03)00080-1.

Eyster, A, Ferri, F, Schmitz, MD & Macdonald, FA 2018, 'One diamictite and two rifts: Stratigraphy and geochronology of the Gataga Mountain of northern British Columbia', *American Journal of Science*, vol. 318, no. 2, pp. 167-207. doi:10.2475/02.2018.1.

Fairchild, IJ & Kennedy, MJ 2007, 'Neoproterozoic glaciation in the Earth System', *Journal of the Geological Society*, vol. 164, no. 5, pp. 895-921. doi:10.1144/0016-76492006-191.

Fairchild, IJ, Spencer, AM, Ali, DO, Anderson, RP, Anderton, R, Boomer, I, Dove, D, Evans, JD, Hambrey, MJ, Howe, J, Sawaki, Y, Shields, GA, Skelton, A, Tucker, ME, Wang, Z & Zhou, Y 2018, 'Tonian-Cryogenian boundary sections of Argyll, Scotland', *Precambrian Research*, vol. 319, pp. 37-64. doi:10.1016/j.precamres.2017.09.020.

Fanning, CM & Link, PK 2004, 'U-Pb SHRIMP ages of Neoproterozoic (Sturtian) glaciogenic Pocatello Formation, southeastern Idaho', *Geology*, vol. 32, no. 10, pp. 881-884. doi:10.1130/G20609.1.

Fanning, CM & Link, PK 2006, 'Constraints on the timing of the Sturtian Glaciation from Southern Australia; IE for the true Sturtian', in *2006 Philadelphia Annual Meeting*, vol. 7, Geological Society of America, Pennsylvania, p. 115.

Fanning, CM & Link, PK 2008, 'Age constraints for the Sturtian Glaciation; data from the Adelaide Geosyncline, South Australia and Pocatello Formation, Idaho, USA', in SJ Gallagher & MW Wallace (eds), *Neoproterozoic extreme climates and the origin of early metazoan life, Selwyn Symposium of the GSA Victoria Division,* Geological Society of Australia, The University of Melbourne, vol. 91, pp. 57-62.

Fanning, CM, Reid, AJ & Teale, GS 2007, *A geochronological framework for the Gawler Craton, South Australia*, Bulletin, 55, Geological Survey of South Australia, Adelaide, South Australia.

Fergusson, CL, Henderson, RA, Fanning, CM & Withnall, IW 2007, 'Detrital zircon ages in Neoproterozoic to Ordovician siliciclastic rocks, northeastern Australia: implications for the tectonic history of the East Gondwana continental margin', *Journal of the Geological Society*, vol. 164, no. 1, pp. 215-225. doi:10.1144/0016-76492005-136.

Fetter, AH & Goldberg, SA 1995, 'Age and Geochemical Characteristics of Bimodal Magmatism in the Neoproterozoic Grandfather Mountain Rift Basin', *The Journal of Geology*, vol. 103, no. 3, pp. 313-326. doi:10.1086/629749.

Fioretti, AM, Black, LP, Foden, J & Visonà, D 2005, 'Grenville-age magmatism at the South Tasman Rise (Australia): A new piercing point for the reconstruction of Rodinia', *Geology*, vol. 33, no. 10, pp. 769-772. doi:10.1130/G21671.1.

Fitzherbert, JA & Downes, PM 2015, 'A concise geological history of the Broken Hill region', *Quarterly Notes - Geological Survey of New South Wales*, vol. 143, no. 2, pp. 29-43.

Foden, JD, Elburg, MA, Dougherty-Page, J & Burtt, A 2006, 'The timing and duration of the Delamerian orogeny: Correlation with the Ross Orogen and implications for Gondwana assembly', *Journal of Geology*, vol. 114, no. 2, pp. 189-210. doi:10.1086/499570.

Foden, JD, Elburg, MA, Turner, S, Clark, C, Blades, ML, Cox, G, Collins, AS, Wolff, K & George, C 2020, 'Cambro-Ordovician magmatism in the Delamerian orogeny: Implications for tectonic development of the southern Gondwanan margin', *Gondwana Research*, vol. 81, pp. 490-521. doi:10.1016/j.gr.2019.12.006.

Forbes, BG 1971, *Parachilna*, 1:250 000 Geological Series—Explanatory Notes, Department of Mines South Australia, Adelaide, South Australia.

Forbes, BG & Cooper, RS 1976, 'The Pualco Tillite of the Olary Region, South Australia', *Quarterly Geological Notes*, vol. 60, pp. 2-5.

Fraser, GL, McAvaney, S, Neumann, NL, Szpunar, M & Reid, A 2010, 'Discovery of early Mesoarchean crust in the eastern Gawler Craton, South Australia', *Precambrian Research*, vol. 179, no. 1, pp. 1-21. doi:10.1016/j.precamres.2010.02.008.

Fraser, GL & Neumann, NL 2010, *New SHRIMP U-Pb Zircon Ages from the Gawler Craton and Curnamona Province, South Australia, 2008 - 2010*, Record, no. 2010/16, Geoscience Australia, G Australia, Canberra, <http://pid.geoscience.gov.au/dataset/ga/70348>.

Frimmel, HE, Klötzli, US & Siegfried, PR 1996, 'New Pb-Pb Single Zircon Age Constraints on the Timing of Neoproterozoic Glaciation and Continental Break-up in Namibia', *The Journal of Geology*, vol. 104, pp. 459-469. doi:10.1086/629839.

Frimmel, HE, Zartman, RE & Späth, A 2001, 'The Richtersveld Igneous Complex, South Africa: U-Pb Zircon and Geochemical Evidence for the Beginning of Neoproterozoic Continental Breakup', *The Journal of Geology*, vol. 109, pp. 493-508. doi:10.1086/320795.

Gehrels, GE, Valencia, VA & Ruiz, J 2008, 'Enhanced precision, accuracy, efficiency, and spatial resolution of U-Pb ages by laser ablation-multicollector-inductively coupled plasma-mass spectrometry', *Geochemistry, Geophysics, Geosystems*, vol. 9, no. 3. doi:10.1029/2007gc001805.

Govindaraju, K 1995, '1995 WORKING VALUES WITH CONFIDENCE LIMITS FOR TWENTY-SIX CRPG, ANRT AND IWG-GIT GEOSTANDARDS', *Geostandards Newsletter*, vol. 19, no. s1, pp. 1-32. doi:10.1111/j.1751-908X.1995.tb00164.x.

Gradstein, FM, Ogg, JG & Smith, AG (eds) 2005, *A Geologic Time Scale 2004*, Cambridge University Press, Cambridge.

Grimes, CB, John, BE, Kelemen, PB, Mazdab, FK, Wooden, JL, Cheadle, MJ, Hanghøj, K & Schwartz, JJ 2007, 'Trace element chemistry of zircons from oceanic crust: A method for distinguishing detrital zircon provenance', *Geology*, vol. 35, no. 7, pp. 643-646. doi:10.1130/G23603A.1.

Grimes, CB, Wooden, JL, Cheadle, MJ & John, BE 2015, '“Fingerprinting” tectono-magmatic provenance using trace elements in igneous zircon', *Contributions to Mineralogy and Petrology*, vol. 170, no. 5, p. 46. doi:10.1007/s00410-015-1199-3.

Halverson, GP, Hurtgen, MT, Porter, SM & Collins, AS 2009, 'Neoproterozoic-Cambrian Biogeochemical Evolution', in C Gaucher, AN Sial, HE Frimmel & GP Halverson (eds), *Developments in Precambrian Geology*, vol. 16, Elsevier, pp. 351-365.

Halverson, GP, Kunzmann, M, Strauss, JV & Maloof, AC 2017, 'The Tonian-Cryogenian transition in Northeastern Svalbard', *Precambrian Research*, vol. 319, pp. 79-95. doi:10.1016/j.precamres.2017.12.010.

Halverson, GP, Porter, SM & Gibson, TM 2018, 'Dating the late Proterozoic stratigraphic record', *Emerging Topics in Life Sciences*, vol. 2, no. 2, pp. 137-147. doi:10.1042/etls20170167.

He, J, Zhu, W & Ge, R 2014, 'New age constraints on Neoproterozoic diamicites in Kuruktag, NW China and Precambrian crustal evolution of the Tarim Craton', *Precambrian Research*, vol. 241, pp. 44-60. doi:10.1016/j.precamres.2013.11.005.

Hoffman, PF 2011, 'A history of Neoproterozoic glacial geology, 1871–1997', in E Arnaud, GP Halverson & GA Shields-Zhou (eds), *The Geological Record of Neoproterozoic Glaciations*, Geological Society, London, pp. 17-37.

Hoffman, PF, Abbot, DS, Ashkenazy, Y, Benn, DI, Brocks, JJ, Cohen, PA, Cox, GM, Creveling, JR, Donnadieu, Y, Erwin, DH, Fairchild, IJ, Ferreira, D, Goodman, JC, Halverson, GP, Jansen, MF, Le Hir, G, Love, GD, Macdonald, FA, Maloof, AC, Partin, CA, Ramstein, G, Rose, BEJ, Rose, CV, Sadler, PM, Tziperman, E, Voigt, A & Warren, SG 2017a, 'Snowball Earth climate dynamics and Cryogenian geology-geobiology', *Science Advances*, vol. 3, no. 11, p. e1600983. doi:10.1126/sciadv.1600983.

Hoffman, PF & Halverson, GP 2011, 'Neoproterozoic glacial record in the Mackenzie Mountains, northern Canadian Cordillera', in E Arnaud, GP Halverson & GA Shields-Zhou (eds), *The Geological Record of Neoproterozoic Glaciations*, Geological Society, London, pp. 397-412.

Hoffman, PF, Halverson, GP, Schrag, DP, Higgins, JA, Domack, EW, Macdonald, FA, Pruss, SB, Blättler, CL, Crockford, PW, Hodgin, EB, Bellefroid, EJ, Johnson, BW, Hodgskiss, MSW, Lamothe, KG, LoBianco, SJC, Busch, JF, Howes, BJ, Greenman, JW & Nelson, LL 2021, 'Snowballs in Africa: sectioning a long-lived Neoproterozoic carbonate platform and its bathyal foreslope (NW Namibia)', *Earth-Science Reviews*, vol. 219. doi:10.1016/j.earscirev.2021.103616.

Hoffman, PF, Hawkins, D, Isachsen, C & Bowring, SA 1996, 'Precise U–Pb zircon ages for early Damaran magmatism in the Summas Mountains and Welwitschia Inlier, northern Damara belt, Namibia', *Communications of the geological survey of Namibia*, vol. 11, pp. 47-52.

Hoffman, PF, Kaufman, AJ, Halverson, GP & Schrag, DP 1998, 'A Neoproterozoic Snowball Earth', *Science*, vol. 281, no. 5381, p. 1342. doi:10.1126/science.281.5381.1342.

Hoffman, PF, Lamothe, KG, LoBianco, SJC, Hodgskiss, MSW, Bellefroid, EJ, Johnson, BW, Hodgin, EB & Halverson, GP 2017b, 'Sedimentary depocenters on Snowball Earth: Case studies from the Sturtian Chuos Formation in northern Namibia', *Geosphere*, vol. 13, no. 3, pp. 811-837. doi:10.1130/ges01457.1.

Hoffman, PF & Schrag, DP 2002, 'The snowball Earth hypothesis: testing the limits of global change', *Terra Nova*, vol. 14, no. 3, pp. 129-155. doi:10.1046/j.1365-3121.2002.00408.x.

Hogmalm, KJ, Zack, T, Karlsson, AKO, Sjöqvist, ASL & Garbe-Schönberg, D 2017, 'In situ Rb–Sr and K–Ca dating by LA-ICP-MS/MS: an evaluation of N2O and SF6 as reaction gases', *Journal of Analytical Atomic Spectrometry*, vol. 32, no. 2, pp. 305-313. doi:10.1039/c6ja00362a.

Hopton, DL 1983, 'Environmental analysis of the Late Precambrian Appila Tillite equivalent at Depot Flat, southern Flinders Ranges, South Australia', Department of Geology and Mineralogy, Honours Thesis, Bachelor of Science (Honours), University of Adelaide, Adelaide, South Australia, <https://hdl.handle.net/2440/131612>.

Horstwood, MSA, Košler, J, Gehrels, GE, Jackson, SE, McLean, NM, Paton, C, Pearson, NJ, Sircombe, KN, Sylvester, P, Vermeesch, P, Bowring, JF, Condon, DJ & Schoene, B 2016, 'Community-Derived Standards for LA-ICP-MS U-(Th-)Pb Geochronology - Uncertainty Propagation, Age Interpretation and Data Reporting', *Geostandards and Geoanalytical Research*, vol. 40, no. 3, pp. 311-332. doi:10.1111/j.1751-908X.2016.00379.x.

Hoskin, PWO & Ireland, TR 2000, 'Rare earth element chemistry of zircon and its use as a provenance indicator', *Geology*, vol. 28, no. 7, pp. 627-630. doi:10.1130/0091-7613(2000)28<627:REECOZ>2.0.CO;2.

Hoskin, PWO & Schaltegger, U 2003, 'The composition of zircon and igneous and metamorphic petrogenesis', *Reviews in Mineralogy and Geochemistry*, vol. 53, no. 1, pp. 27-62. doi:10.2113/0530027.

Howchin, W 1901, 'Preliminary Note on the Existence of Glacial Beds of Cambrian Age in South Australia', *Transactions of the Royal Society of South Australia*, vol. 25, pp. 10-13.

Howchin, W 1904, 'The geology of the Mount Lofty Ranges: Part I', *Transactions of the Royal Society of South Australia*, vol. 28, pp. 253-280.

Howchin, W 1906, 'The geology of the Mount Lofty Ranges: Part II', *Transactions of the Royal Society of South Australia*, vol. 30, pp. 227-262.

Howchin, W 1908, 'Glacial Beds of Cambrian Age in South Australia', *Quarterly Journal of the Geological Society*, vol. 64, no. 1-4, p. 234. doi:10.1144/GSL.JGS.1908.064.01-04.13.

Howchin, W 1920, 'Past Glacial Action in Australia', in ABo Statistics (ed.), *Year Book*, vol. 13, Australian Bureau of Statistics, Australia, pp. 1133-1146.

Ireland, TR, Flöttmann, T, Fanning, CM, Gibson, GM & Preiss, WV 1998, 'Development of the early Paleozoic Pacific margin of Gondwana from detrital-zircon ages across the Delamerian orogen', *Geology*, vol. 26, no. 3, pp. 243-246. doi:10.1130/0091-7613(1998)026<0243:Dotepp>2.3.Co;2.

Isakson, VH 2017, 'Geochronology of the Tectonic, Stratigraphic, and Magmatic Evolution of Neoproterozoic to Early Paleozoic, North American Cordillera and Cryogenian Glaciation', Department of Geoscience, Dissertation, Doctor of Philosophy, Boise State University, Boise, Idaho, USA.

Jackson, SE, Pearson, NJ, Griffin, WL & Belousova, EA 2004, 'The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology', *Chemical Geology*, vol. 211, no. 1-2, pp. 47-69. doi:10.1016/j.chemgeo.2004.06.017.

Jacobs, J, Elburg, MA, Läufer, A, Kleinhanns, IC, Henjes-Kunst, F, Estrada, S, Ruppel, AS, Damaske, D, Montero, P & Bea, F 2015, 'Two distinct Late Mesoproterozoic/Early Neoproterozoic basement provinces in central/eastern Dronning Maud Land, East Antarctica: The missing link, 15–21°E', *Precambrian Research*, vol. 265, pp. 249-272. doi:10.1016/j.precamres.2015.05.003.

Jagodzinski, EA & Fricke, CE 2010, *Compilation of new SHRIMP U-Pb geochronological data for the Southern Curnamona Province, South Australia, 2010*, Report Book, no. 2010/00014, Geological Survey of South Australia, Department of Primary Industries and Resources, Adelaide, South Australia.

Jagodzinski, EA & McAvaney, SO 2017, *SHRIMP U-Pb geochronology data for northern Eyre Peninsula, 2014–2016*, Report Book, no. 2016/00001, Geological Survey of South Australia, Department of Premier and Cabinet, Adelaide, South Australia, <https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/samref/sarig1/wci/Record?r=0&m=1&w=catno=2039475>.

Jagodzinski, EA, Werner, M, Curtis, S, Fabris, A, Pawley, M & Krapf, C 2020, *SHRIMP Geochronology of the Mt Double area, Southern Gawler Ranges margin*, Report Book, no. 2020/00006, Geological Survey of South Australia, Department for Energy and Mining, South Australia.

Jefferson, CW & Parrish, RR 1989, 'Late Proterozoic stratigraphy, U–Pb zircon ages, and rift tectonics, Mackenzie Mountains, northwestern Canada', *Canadian Journal of Earth Sciences*, vol. 26, no. 9, pp. 1784-1801. doi:10.1139/e89-151.

Jochum, KP, Weis, U, Stoll, B, Kuzmin, D, Yang, Q, Raczek, I, Jacob, DE, Stracke, A, Birbaum, K, Frick, DA, Günther, D & Enzweiler, J 2011, 'Determination of Reference Values for NIST SRM 610–617 Glasses Following ISO Guidelines', *Geostandards and Geoanalytical Research*, vol. 35, no. 4, pp. 397-429. doi:10.1111/j.1751-908X.2011.00120.x.

Karlstrom, KE, Bowring, SA, Dehler, CM, Knoll, AH, Porter, SM, Marais, DJD, Weil, AB, Sharp, ZD, Geissman, JW, Elrick, MB, Timmons, JM, Crossey, LJ & Davidek, KL 2000, 'Chuar Group of the Grand Canyon: Record of breakup of Rodinia, associated change in the global carbon cycle, and ecosystem expansion by 740 Ma', *Geology*, vol. 28, no. 7, pp. 619-622. doi:10.1130/0091-7613(2000)28<619:CGOTGC>2.0.CO;2.

Keeley, JA, Link, PK, Fanning, CM & Schmitz, MD 2013, 'Pre- to synglacial rift-related volcanism in the Neoproterozoic (Cryogenian) Pocatello Formation, SE Idaho: New SHRIMP and CA-ID-TIMS constraints', *Lithosphere*, vol. 5, no. 1, pp. 128-150. doi:10.1130/L226.1.

Keeman, J, Turner, S, Haines, PW, Belousova, E, Ireland, T, Brouwer, P, Foden, J & Wörner, G 2020, 'New UPb, Hf and O isotope constraints on the provenance of sediments from the Adelaide Rift Complex – Documenting the key Neoproterozoic to early Cambrian succession', *Gondwana Research*, vol. 83, pp. 248-278. doi:10.1016/j.gr.2020.02.005.

Kendall, BS, Creaser, RA, Calver, CR, Raub, TD & Evans, DAD 2009, 'Correlation of Sturtian diamictite successions in southern Australia and northwestern Tasmania by Re–Os black shale geochronology and the ambiguity of “Sturtian”-type diamictite–cap carbonate pairs as chronostratigraphic marker horizons', *Precambrian Research*, vol. 172, no. 3-4, pp. 301-310. doi:10.1016/j.precamres.2009.05.001.

Kendall, BS, Creaser, RA, Ross, GM & Selby, D 2004, 'Constraints on the timing of Marinoan “Snowball Earth” glaciation by 187Re–187Os dating of a Neoproterozoic, post-glacial black shale in Western Canada', *Earth and Planetary Science Letters*, vol. 222, no. 3, pp. 729-740. doi:10.1016/j.epsl.2004.04.004.

Kendall, BS, Creaser, RA & Selby, D 2006, 'Re-Os geochronology of postglacial black shales in Australia: Constraints on the timing of “Sturtian” glaciation', *Geology*, vol. 34, no. 9, pp. 729-732. doi:10.1130/g22775.1.

Kennedy, K, Eyles, N & McArthur, A 2020, 'Syn-rift mass flow generated ‘tectonofacies’ and ‘tectonosequences’ of the Kingston Peak Formation, Death Valley, California, and their bearing on supposed Neoproterozoic panglacial climates', *Sedimentology*, vol. 68, no. 1, pp. 352-381. doi:10.1111/sed.12781.

Key, RM, Liyungu, AK, Njamu, FM, Somwe, V, Banda, J, Mosley, PN & Armstrong, RA 2001, 'The western arm of the Lufilian Arc in NW Zambia and its potential for copper mineralization', *Journal of African Earth Sciences*, vol. 33, no. 3, pp. 503-528. doi:10.1016/S0899-5362(01)00098-7.

Knoll, AH, Walter, MR, Narbonne, GM & Christie-Blick, N 2006, 'The Ediacaran Period: a new addition to the geologic time scale', *Lethaia*, vol. 39, no. 1, pp. 13-30. doi:10.1080/00241160500409223.

Kochnev, BB, Pokrovskii, BG & Proshenkin, AI 2015, 'The Upper Neoproterozoic glacial complex in central areas of the Siberian platform', *Doklady Earth Sciences*, vol. 464, no. 2, pp. 1001-1004. doi:10.1134/s1028334x15100049.

Korsch, RJ, Huston, DL, Henderson, RA, Blewett, RS, Withnall, IW, Fergusson, CL, Collins, WJ, Saygin, E, Kositcin, N, Meixner, AJ, Chopping, R, Henson, PA, Champion, DC, Hutton, LJ, Wormald, R, Holzschuh, J & Costelloe, RD 2012, 'Crustal architecture and geodynamics of North Queensland, Australia: Insights from deep seismic reflection profiling', *Tectonophysics*, vol. 572-573, pp. 76-99. doi:10.1016/j.tecto.2012.02.022.

Krasnobaev, AA, Puchkov, VN, Sergeeva, ND & Busharina, SV 2019, 'Nature of zircon clastics in the Riphean and Vendian sandstones of the Southern Urals', *Georesursy*, vol. 21, no. 1, pp. 15-25. doi:10.18599/grs.2019.1.15-25.

Kromkhun, K, Foden, JD, Hore, SB & Baines, G 2013, 'Geochronology and Hf isotopes of the bimodal mafic–felsic high heat producing igneous suite from Mt Painter Province, South Australia', *Gondwana Research*, vol. 24, no. 3-4, pp. 1067-1079. doi:10.1016/j.gr.2013.01.011.

Kruse, PD, Dunster, JN & Munson, TJ 2013, 'Chapter 28: Georgina Basin', in M Ahmad & TJ Munson (eds), *Geology and mineral resources of the Northern Territory*, Northern Territory Geological Survey, Northern Territory.

Lamothe, KG, Hoffman, PF, Greenman, JW & Halverson, GP 2019, 'Stratigraphy and isotope geochemistry of the pre-Sturtian Ugab Subgroup, Otavi/Swakop Group, northwestern Namibia', *Precambrian Research*, vol. 332, p. 105387. doi:10.1016/j.precamres.2019.105387.

Lan, Z, Huyskens, MH, Lu, K, Li, X-H, Zhang, G, Lu, D & Yin, Q-Z 2020, 'Toward refining the onset age of Sturtian glaciation in South China', *Precambrian Research*, vol. 338. doi:10.1016/j.precamres.2019.105555.

Lan, Z, Li, X-H, Zhu, M, Zhang, Q & Li, Q-L 2015, 'Revisiting the Liantuo Formation in Yangtze Block, South China: SIMS U–Pb zircon age constraints and regional and global significance', *Precambrian Research*, vol. 263, pp. 123-141. doi:10.1016/j.precamres.2015.03.012.

Lan, Z, Li, X, Zhu, M, Chen, Z-Q, Zhang, Q, Li, Q, Lu, D, Liu, Y & Tang, G 2014, 'A rapid and synchronous initiation of the wide spread Cryogenian glaciations', *Precambrian Research*, vol. 255, pp. 401-411. doi:10.1016/j.precamres.2014.10.015.

Le Heron, DP 2012, 'The Cryogenian record of glaciation and deglaciation in South Australia', *Sedimentary Geology*, vol. 243-244, pp. 57-69. doi:10.1016/j.sedgeo.2011.09.013.

Le Heron, DP, Busfield, ME, Ali, DO, Al Tofaif, S & Vandyk, TM 2018, 'The Cryogenian record in the southern Kingston Range, California: The thickest Death Valley succession in the hunt for a GSSP', *Precambrian Research*, vol. 319, pp. 158-172. doi:10.1016/j.precamres.2017.07.017.

Le Heron, DP, Busfield, ME & Collins, AS 2014, 'Bolla Bollana boulder beds: A Neoproterozoic trough mouth fan in South Australia?', *Sedimentology*, vol. 61, no. 4, pp. 978-995. doi:10.1111/sed.12082.

Le Heron, DP, Cox, GM, Trundley, A & Collins, AS 2011, 'Two Cryogenian glacial successions compared: Aspects of the Sturt and Elatina sediment records of South Australia', *Precambrian Research*, vol. 186, no. 1, pp. 147-168. doi:10.1016/j.precamres.2011.01.014.

Le Heron, DP, Eyles, N & Busfield, ME 2020, 'The Laurentian Neoproterozoic Glacial Interval: reappraising the extent and timing of glaciation', *Austrian Journal of Earth Sciences*, vol. 113, no. 1, pp. 59-70. doi:10.17738/ajes.2020.0004.

Lechte, MA & Wallace, MW 2015, 'Sedimentary and tectonic history of the Holowilena Ironstone, a Neoproterozoic iron formation in South Australia', *Sedimentary Geology*, vol. 329, pp. 211-224. doi:10.1016/j.sedgeo.2015.09.014.

Lechte, MA, Wallace, MW, Hood, AvS, Li, W, Jiang, G, Halverson, GP, Asael, D, McColl, SL & Planavsky, NJ 2019, 'Subglacial meltwater supported aerobic marine habitats during Snowball Earth', *Proc Natl Acad Sci U S A*, vol. 116, no. 51, pp. 25478-25483. doi:10.1073/pnas.1909165116.

Lechte, MA, Wallace, MW, Hood, AvS & Planavsky, N 2018, 'Cryogenian iron formations in the glaciogenic Kingston Peak Formation, California', *Precambrian Research*, vol. 310, pp. 443-462. doi:10.1016/j.precamres.2018.04.003.

Li, XH, Abd El-Rahman, Y, Abu Anbar, M, Li, J, Ling, XX, Wu, LG & Masoud, AE 2018, 'Old Continental Crust Underlying Juvenile Oceanic Arc: Evidence From Northern Arabian-Nubian Shield, Egypt', *Geophysical Research Letters*, vol. 45, no. 7, pp. 3001-3008. doi:10.1002/2018gl077121.

Li, Z-X & Evans, DAD 2010, 'Late Neoproterozoic 40 intraplate rotation within Australia allows for a tighter-fitting and longer-lasting Rodinia', *Geology*, vol. 39, no. 1, pp. 39-42. doi:10.1130/g31461.1.

Link, PK 1977, 'Facies and palaeogeography of Late Precambrian Sturtian glacial sediments, Copley area, northern Flinders Ranges and in the Sturt Gorge near Adelaide, South Australia', Department of Geology and Mineralogy, Honours Thesis, Bachelor of Science (Honours), University of Adelaide, Adelaide, <https://hdl.handle.net/2440/131122>.

Link, PK & Christie-Blick, N 2011, 'Neoproterozoic strata of southeastern Idaho and Utah: record of Cryogenian rifting and glaciation', in E Arnaud, GP Halverson & GA Shields-Zhou (eds), *The Geological Record of Neoproterozoic Glaciations*, Geological Society, London, pp. 425-436.

Link, PK & Gostin, VA 1981, 'Facies and paleogeography of Sturtian glacial strata (late Precambrian), South Australia', *American Journal of Science*, vol. 281, no. 4, p. 353. doi:10.2475/ajs.281.4.353.

Lloyd, JC, Blades, ML, Counts, JW, Collins, AS, Amos, KJ, Wade, BP, Hall, JW, Hore, S, Ball, AL, Shahin, S & Drabsch, M 2020, 'Neoproterozoic geochronology and provenance of the Adelaide Superbasin', *Precambrian Research*, vol. 350, p. 105849. doi:10.1016/j.precamres.2020.105849.

Lloyd, JC, Collins, AS, Blades, ML, Gilbert, SE & Amos, KJ 2022a, 'Early evolution of the Adelaide Superbasin', *Geosciences*, vol. 12, no. 4, p. 154. doi:10.3390/geosciences12040154.

[Preprint] Lloyd, JC, Collins, AS, Blades, ML, Gilbert, SE & Amos, KJ 2022b, 'Late Tonian development of the Adelaide Superbasin', *EarthArXiv*. doi:10.31223/X5N63H.

Lund, K, Aleinikoff, JN & Evans, KV 2011, 'The Edwardsburg Formation and related rocks, Windermere Supergroup, central Idaho, USA', in E Arnaud, GP Halverson & GA Shields-Zhou (eds), *The Geological Record of Neoproterozoic Glaciations*, Geological Society, London, pp. 437-448.

Lund, K, Aleinikoff, JN, Evans, KV, duBray, EA, Dewitt, EH & Unruh, DM 2010, 'SHRIMP U-Pb dating of recurrent Cryogenian and Late Cambrian–Early Ordovician alkalic magmatism in central Idaho: Implications for Rodinian rift tectonics', *GSA Bulletin*, vol. 122, no. 3-4, pp. 430-453. doi:10.1130/B26565.1.

Lund, K, Aleinikoff, JN, Evans, KV & Fanning, CM 2003, 'SHRIMP U-Pb geochronology of Neoproterozoic Windermere Supergroup, central Idaho: Implications for rifting of western Laurentia and synchroneity of Sturtian glacial deposits', *GSA Bulletin*, vol. 115, no. 3, pp. 349-372. doi:10.1130/0016-7606(2003)115<0349:SUPGON>2.0.CO;2.

Macdonald, FA, Schmitz, MD, Crowley, JL, Roots, CF, Jones, DS, Maloof, AC, Strauss, JV, Cohen, PA, Johnston, DT & Schrag, DP 2010, 'Calibrating the Cryogenian', *Science*, vol. 327, no. 5970, pp. 1241-1243. doi:10.1126/science.1183325.

Macdonald, FA, Schmitz, MD, Strauss, JV, Halverson, GP, Gibson, TM, Eyster, A, Cox, G, Mamrol, P & Crowley, JL 2018, 'Cryogenian of Yukon', *Precambrian Research*, vol. 319, pp. 114-143. doi:10.1016/j.precamres.2017.08.015.

Mackay, WG 2011, 'Structure and sedimentology of the Curdimurka Subgroup, northern Adelaide Fold Belt, South Australia', Doctoral Thesis, Doctor of Philosophy, University of Tasmania, Hobart, Tasmania, <https://eprints.utas.edu.au/12486/>.

MacLennan, S, Park, Y, Swanson-Hysell, N, Maloof, A, Schoene, B, Gebreslassie, M, Antilla, E, Tesema, T, Alene, M & Haileab, B 2018, 'The arc of the Snowball: U-Pb dates constrain the Islay anomaly and the initiation of the Sturtian glaciation', *Geology*, vol. 46, no. 6, pp. 539-542. doi:10.1130/G40171.1.

Mattinson, JM 2005, 'Zircon U–Pb chemical abrasion (“CA-TIMS”) method: Combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages', *Chemical Geology*, vol. 220, no. 1-2, pp. 47-66. doi:10.1016/j.chemgeo.2005.03.011.

Mawson, D & Sprigg, RC 1950, 'Subdivision of the Adelaide System', *Australian Journal of Science*, vol. 13, no. 3, pp. 69-72.

McAvaney, SO 2012, 'The Cooyerdoo Granite: Paleo- and Mesoarchean basement of the Gawler Craton', *MESA Journal*, vol. 65, pp. 31-40. https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/samref/sarig1/wci/Record?r=0&m=1&w=catno=2035289.

McDonough, MR & Parrish, RR 1991, 'Proterozoic gneisses of the Malton Complex, near Valemount, British Columbia: U–Pb ages and Nd isotopic signatures', *Canadian Journal of Earth Sciences*, vol. 28, no. 8, pp. 1202-1216. doi:10.1139/e91-108.

Meaney, KJ 2012, 'The geochronology and structural evolution of the Warren Inlier and Springfield Sequence, Mt. Lofty Ranges: Implications for Proterozoic paleogeographic reconstructions', School of Earth and Environmental Sciences, Honours Thesis, Bachelor of Science (Honours), University of Adelaide, Adelaide, South Australia, <https://hdl.handle.net/2440/95177>.

Meaney, KJ 2017, 'Proterozoic crustal growth in the southeastern Gawler Craton: the development of the Barossa Complex, and an assessment of the detrital zircon method', Department of Geology and Geophysics, Doctoral Thesis, Doctor of Philosophy, University of Adelaide, Adelaide, South Australia, <https://hdl.handle.net/2440/114255>.

Merdith, AS, Williams, SE, Müller, RD & Collins, AS 2017, 'Kinematic constraints on the Rodinia to Gondwana transition', *Precambrian Research*, vol. 299, pp. 132-150. doi:10.1016/j.precamres.2017.07.013.

Miller, RM 2013, 'Comparative Stratigraphic and Geochronological Evolution of the Northern Damara Supergroup in Namibia and the Katanga Supergroup in the Lufilian Arc of Central Africa', *Geoscience Canada*, vol. 40, no. 2, pp. 118 - 140. doi:10.12789/geocanj.2013.40.007.

Morrissey, LJ, Barovich, KM, Hand, M, Howard, KE & Payne, JL 2019, 'Magmatism and metamorphism at ca. 1.45 Ga in the northern Gawler Craton: The Australian record of rifting within Nuna (Columbia)', *Geoscience Frontiers*, vol. 10, no. 1, pp. 175-194. doi:10.1016/j.gsf.2018.07.006.

Morrissey, LJ, Barovich, KM, Hand, M, Howard, KE, Payne, JL & Reid, AJ 2018, 'The final event in the long evolution of the Gawler Craton: new constraints on 1450 Ma metamorphism and magmatism', *MESA Journal*, vol. 88, no. 3, pp. 4-11. https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/samref/sarig1/image/DDD/MESAJ088004-011.pdf.

Morrissey, LJ, Hand, M, Wade, BP & Szpunar, MA 2013, 'Early Mesoproterozoic metamorphism in the Barossa Complex, South Australia: links with the eastern margin of Proterozoic Australia', *Australian Journal of Earth Sciences*, vol. 60, no. 8, pp. 769-795. doi:10.1080/08120099.2013.860623.

Mrofka, D & Kennedy, M 2011, 'The Kingston Peak Formation in the eastern Death Valley region', in E Arnaud, GP Halverson & GA Shields-Zhou (eds), *The Geological Record of Neoproterozoic Glaciations*, Geological Society, London, pp. 449-458.

Mundil, R, Ludwig, KR, Metcalfe, I & Renne, PR 2004, 'Age and timing of the Permian mass extinctions: U/Pb dating of closed-system zircons', *Science*, vol. 305, no. 5691, pp. 1760-1763. doi:10.1126/science.1101012.

Murrell, B, Link, PK & Gostin, VA 1977, 'Evidence for only one Sturtian Glacial Period in the Copley map area', *Quarterly Geological Notes*, vol. 64, pp. 16-19. https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/samref/sarig1/wci/Record?r=0&m=1&w=catno=2041398.

Nascimento, DB, Ribeiro, A, Trouw, RAJ, Schmitt, RS & Passchier, CW 2016, 'Stratigraphy of the Neoproterozoic Damara Sequence in northwest Namibia: Slope to basin sub-marine mass-transport deposits and olistolith fields', *Precambrian Research*, vol. 278, pp. 108-125. doi:10.1016/j.precamres.2016.03.005.

Nascimento, DB, Schmitt, RS, Ribeiro, A, Trouw, RAJ, Passchier, CW & Basei, MAS 2017, 'Depositional ages and provenance of the Neoproterozoic Damara Supergroup (northwest Namibia): Implications for the Angola-Congo and Kalahari cratons connection', *Gondwana Research*, vol. 52, pp. 153-171. doi:10.1016/j.gr.2017.09.006.

Normington, VJ & Donnellan, NC 2020, *Characterisation of the Neoproterozoic succession of the northeastern Amadeus Basin, Northern Territory*, Record, no. 2020-010, Northern Territory Geological Survey, <https://geoscience.nt.gov.au/gemis/ntgsjspui/handle/1/90622>.

Norris, A & Danyushevsky, L 2018, 'Towards Estimating the Complete Uncertainty Budget of Quantified Results Measured by LA-ICP-MS', in *Goldschmidt,* Norris Scientific, Boston.

O'Neill, HSC 2016, 'The Smoothness and Shapes of Chondrite-normalized Rare Earth Element Patterns in Basalts', *Journal of Petrology*, vol. 57, no. 8, pp. 1463-1508. doi:10.1093/petrology/egw047.

Och, LM & Shields-Zhou, GA 2012, 'The Neoproterozoic oxygenation event: Environmental perturbations and biogeochemical cycling', *Earth-Science Reviews*, vol. 110, no. 1, pp. 26-57. doi:10.1016/j.earscirev.2011.09.004.

Park, Y, Swanson-Hysell, NL, MacLennan, SA, Maloof, AC, Gebreslassie, M, Tremblay, MM, Schoene, B, Alene, M, Anttila, ESC, Tesema, T & Haileab, B 2019, 'The lead-up to the Sturtian Snowball Earth: Neoproterozoic chemostratigraphy time-calibrated by the Tambien Group of Ethiopia', *GSA Bulletin*, vol. 132, no. 5-6, pp. 1119-1149. doi:10.1130/B35178.1.

Pawley, MJ, Dutch, RA & Wise, TW 2020, 'The Relationship Between Crustal Architecture, Deformation, and Magmatism in the Coompana Province, Australia', *Tectonics*, vol. 39, no. 12. doi:10.1029/2019tc005593.

Petterson, R, Prave, AR & Wernicke, BP 2011, 'Glaciogenic and related strata of the Neoproterozoic Kingston Peak Formation in the Panamint Range, Death Valley region, California', in E Arnaud, GP Halverson & GA Shields-Zhou (eds), *The Geological Record of Neoproterozoic Glaciations*, Geological Society, London, pp. 459-465.

Plumb, KA 1991, 'New Precambrian time scale', *International Union of Geological Sciences*, vol. 14, no. 2, pp. 139-140. doi:10.18814/epiiugs/1991/v14i2/005.

Plumb, KA & James, HL 1986, 'Subdivision of precambrian time: recommendations and suggestions by the subcommission on precambrian stratigraphy', *Precambrian Research*, vol. 32, no. 1, pp. 65-92. doi:10.1016/0301-9268(86)90031-8.

Powell, CM, Preiss, WV, Gatehouse, CG, Krapez, B & Li, Z-X 1994, 'South Australian record of a Rodinian epicontinental basin and its mid-neoproterozoic breakup (~700 Ma) to form the Palaeo-Pacific Ocean', *Tectonophysics*, vol. 237, no. 3-4, pp. 113-140. doi:10.1016/0040-1951(94)90250-x.

Prave, AR, Condon, DJ, Hoffmann, KH, Tapster, S & Fallick, AE 2016, 'Duration and nature of the end-Cryogenian (Marinoan) glaciation', *Geology*, vol. 44, no. 8, pp. 631-634. doi:10.1130/G38089.1.

Preiss, WV 1985, *Stratigraphy and Tectonics of the Worumba Anticline and Associated Intrusive Breccias*, Bulletin, 52, Geological Survey of South Australia, South Australia.

Preiss, WV 1987, *Adelaide Geosyncline–late Proterozoic stratigraphy, sedimentation, palaeontology and tectonics*, Bulletin, 53, Geological Survey of South Australia, Adelaide, South Australia.

Preiss, WV 1993, 'Neoproterozoic', in JF Drexel, WV Preiss & AJ Parker (eds), *The geology of South Australia*, vol. 1 The Precambrian, Geological Survey of South Australia, South Australia, pp. 171-204.

Preiss, WV 2000, 'The Adelaide Geosyncline of South Australia and its significance in Neoproterozoic continental reconstruction', *Precambrian Research*, vol. 100, no. 1-3, pp. 21-63. doi:10.1016/S0301-9268(99)00068-6.

Preiss, WV 2006, 'Old Boolcoomata Conglomerate Member of the Benda Siltstone', *MESA Journal*, vol. 41, pp. 15-23. https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/samref/sarig1/wci/Record?r=0&m=1&w=catno=2025262.

Preiss, WV 2014, *Geology and mineral resources of Bimbowrie Conservation Park – the MacDonald Corridor and adjacent parts of the Palaeo- to Mesoproterozoic basement*, Report Book, no. 2014/00003, Geological Survey of South Australia, I Department for Manufacturing, Trade, Resources and Energy, South Australia, <https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/samref/sarig1/wci/Record?r=0&m=1&w=catno=2036052>.

Preiss, WV, Alexander, EM, Cowley, WM & Schwarz, MP 2002, 'Towards defining South Australia's geological provinces and sedimentary basins', *MESA Journal*, vol. 27, pp. 39-52. https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/samref/sarig1/wci/Record?r=0&m=1&w=catno=2022981.

Preiss, WV & Conor, CHH 2001, 'Origin and nomenclature of the Wilyama Inliers, Curnamona Province', *MESA Journal*, vol. 21, pp. 47-49. https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/samref/sarig1/wci/Record?r=0&m=1&w=catno=2022263.

Preiss, WV, Dyson, IA, Reid, PW & Cowley, WM 1998, 'Revision of lithostratigraphic classification of the Umberatana Group', *MESA Journal*, vol. 9, pp. 36-42. https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/samref/sarig1/wcir/Record?r=0&m=1&w=catno=2025009.

Preiss, WV, Gostin, VA, McKirdy, DM, Ashley, PM, Williams, GE & Schmidt, PW 2011, 'The glacial succession of Sturtian age in South Australia: The Yudnamutana Subgroup', in E Arnaud, GP Halverson & GA Shields-Zhou (eds), *The Geological Record of Neoproterozoic Glaciations*, Geological Society, London, pp. 701-712.

Preiss, WV, Walter, MR, Coats, RP & Wells, AT 1978, 'Lithological correlations of Adelaidean glaciogenic rocks in parts of the Amadeus, Ngalia, and Georgina Basins', *AGSO Journal of Australian Geology and Geophysics*, vol. 3, pp. 43-53. http://pid.geoscience.gov.au/dataset/ga/80944.

Redaa, A, Farkaš, J, Gilbert, S, Collins, AS, Wade, B, Löhr, S, Zack, T & Garbe-Schönberg, D 2021, 'Assessment of elemental fractionation and matrix effects during in situ Rb–Sr dating of phlogopite by LA-ICP-MS/MS: implications for the accuracy and precision of mineral ages', *Journal of Analytical Atomic Spectrometry*, vol. 36, no. 2, pp. 322-344. doi:10.1039/d0ja00299b.

Reid, AJ, Halpin, JA & Dutch, RA 2019, 'Timing and style of high-temperature metamorphism across the Western Gawler Craton during the Paleo- to Mesoproterozoic', *Australian Journal of Earth Sciences*, vol. 66, no. 8, pp. 1085-1111. doi:10.1080/08120099.2019.1602565.

Reid, AJ & Hand, M 2012, 'Mesoarchean to Mesoproterozoic evolution of the southern Gawler Craton, South Australia', *Episodes*, vol. 35, no. 1, pp. 216-225. doi:10.18814/epiiugs/2012/v35i1/021.

Reid, AJ, Hand, M, Jagodzinski, EA, Kelsey, DE & Pearson, NJ 2008, 'Paleoproterozoic orogenesis in the southeastern Gawler Craton, South Australia', *Australian Journal of Earth Sciences*, vol. 55, no. 4, pp. 449-471. doi:10.1080/08120090801888594.

Reid, AJ, Jagodzinski, EA, Armit, RJ, Dutch, RA, Kirkland, CL, Betts, PG & Schaefer, BF 2014a, 'U-Pb and Hf isotopic evidence for Neoarchean and Paleoproterozoic basement in the buried northern Gawler Craton, South Australia', *Precambrian Research*, vol. 250, pp. 127-142. doi:10.1016/j.precamres.2014.05.019.

Reid, AJ, Jagodzinski, EA, Fraser, GL & Pawley, MJ 2014b, 'SHRIMP U–Pb zircon age constraints on the tectonics of the Neoarchean to early Paleoproterozoic transition within the Mulgathing Complex, Gawler Craton, South Australia', *Precambrian Research*, vol. 250, pp. 27-49. doi:10.1016/j.precamres.2014.05.013.

Reid, AJ, Jagodzinski, EA, Wade, CE, Payne, JL & Jourdan, F 2017, 'Recognition of c. 1780Ma magmatism and metamorphism in the buried northeastern Gawler Craton: Correlations with events of the Aileron Province', *Precambrian Research*, vol. 302, pp. 198-220. doi:10.1016/j.precamres.2017.09.010.

Reid, AJ & Payne, JL 2017, 'Magmatic zircon Lu–Hf isotopic record of juvenile addition and crustal reworking in the Gawler Craton, Australia', *Lithos*, vol. 292-293, pp. 294-306. doi:10.1016/j.lithos.2017.08.010.

Reid, AJ, Tiddy, C, Jagodzinski, E, Crowley, J, Conor, C, Brotodewo, A & Wade, C 2021, *Precise zircon U-Pb geochronology of Hiltaba Suite granites, Point Riley, Yorke Peninsula*, Report Book, no. 2021/00001, Geological Survey of South Australia, Department for Energy and Mining, South Australia.

Romanov, M, Sovetov, JK, Vernikovsky, VA, Rosenbaum, G, Wilde, SA, Vernikovskaya, AE, Matushkin, NY & Kadilnikov, PI 2021, 'Late Neoproterozoic evolution of the southwestern margin of the Siberian Craton: evidence from sedimentology, geochronology and detrital zircon analysis', *International Geology Review*, vol. 63, no. 13, pp. 1658-1681. doi:10.1080/00206814.2020.1790044.

Rooney, AD, Chew, DM & Selby, D 2011, 'Re–Os geochronology of the Neoproterozoic–Cambrian Dalradian Supergroup of Scotland and Ireland: Implications for Neoproterozoic stratigraphy, glaciations and Re–Os systematics', *Precambrian Research*, vol. 185, no. 3-4, pp. 202-214. doi:10.1016/j.precamres.2011.01.009.

Rooney, AD, Macdonald, FA, Strauss, JV, Dudas, FÖ, Hallmann, C & Selby, D 2014, 'Re-Os geochronology and coupled Os-Sr isotope constraints on the Sturtian snowball Earth', *Proceedings of the National Academy of Sciences of the United States of America*, vol. 111, no. 1, pp. 51-56. doi:10.1073/pnas.1317266110.

Rooney, AD, Strauss, JV, Brandon, AD & Macdonald, FA 2015, 'A Cryogenian chronology: Two long-lasting synchronous Neoproterozoic glaciations', *Geology*, vol. 43, no. 5, pp. 459-462. doi:10.1130/G36511.1.

Rooney, AD, Yang, C, Condon, DJ, Zhu, M & Macdonald, FA 2020, 'U-Pb and Re-Os geochronology tracks stratigraphic condensation in the Sturtian snowball Earth aftermath', *Geology*. doi:10.1130/G47246.1.

Rose, CV, Maloof, AC, Schoene, B, Ewing, RC, Linnemann, U, Hofmann, M & Cottle, JM 2013, 'PAUL F. HOFFMAN SERIES The End-Cryogenian Glaciation of South Australia', *Geoscience Canada*, vol. 40, no. 4, pp. 256-293. doi:10.12789/geocanj.2013.40.019.

Ross, GM & Villeneuve, J 1997, *U-Pb geochronology of stranger stones in Neoproterozoic diamictites, Canadian Cordillera: implications for provenance and ages of deposition*, Report, Geological Survey of Canada, Natural Resources Canada.

Rubatto, D 2002, 'Zircon trace element geochemistry: partitioning with garnet and the link between U–Pb ages and metamorphism', *Chemical Geology*, vol. 184, no. 1, pp. 123-138. doi:10.1016/S0009-2541(01)00355-2.

Rud`ko, S, Kuznetsov, N, Shatsillo, A, Rud`ko, D, Malyshev, S, Dubenskiy, A, Sheshukov, V, Kanygina, N & Romanyuk, T 2020, 'Sturtian glaciation in Siberia: Evidence of glacial origin and U-Pb dating of the diamictites of the Chivida Formation in the north of the Yenisei Ridge', *Precambrian Research*, vol. 345. doi:10.1016/j.precamres.2020.105778.

Schmitz, MD 2012, 'Radiometric ages used in GTS2012', in FM Gradstein, JG Ogg, MD Schmitz & GM Ogg (eds), *The Geologic Time Scale*, pp. 1045-1082.

Segnit, RW 1939, *The Precambrian-Cambrian succession - The general and economic geology of these systems, in portions of South Australia*, Bulletin, 18, Department of Mines, Adelaide, South Australia.

Shannon, RD 1976, 'Revised effective ionic radii and systematic studies of interatomic distances in halides and chalcogenides', *Acta Crystallographica Section A*, vol. 32, no. 5, pp. 751-767. doi:10.1107/S0567739476001551.

Shields-Zhou, GA, Porter, SM & Halverson, GP 2016, 'A New Rock-Based Definition for the Cryogenian Period (Circa 720-635 Ma)', *Episodes*, vol. 39, no. 1. doi:10.18814/epiiugs/2016/v39i1/89231.

Shields, GA, Halverson, GP & Porter, SM 2018, 'Descent into the Cryogenian', *Precambrian Research*, vol. 319, pp. 1-5. doi:10.1016/j.precamres.2018.08.015.

Shields, GA, Strachan, RA, Porter, SM, Halverson, GP, Macdonald, FA, Plumb, KA, de Alvarenga, CJ, Banerjee, DM, Bekker, A, Bleeker, W, Brasier, A, Chakraborty, PP, Collins, AS, Condie, K, Das, K, Evans, DAD, Ernst, R, Fallick, AE, Frimmel, H, Fuck, R, Hoffman, PF, Kamber, BS, Kuznetsov, AB, Mitchell, RN, Poiré, DG, Poulton, SW, Riding, R, Sharma, M, Storey, C, Stueeken, E, Tostevin, R, Turner, E, Xiao, S, Zhang, S, Zhou, Y & Zhu, M 2022, 'A template for an improved rock-based subdivision of the pre-Cryogenian timescale', *Journal of the Geological Society*, vol. 179, no. 1. doi:10.1144/jgs2020-222.

Sláma, J & Košler, J 2012, 'Effects of sampling and mineral separation on accuracy of detrital zircon studies', *Geochemistry Geophysics Geosystems*, vol. 13, no. 5. doi:10.1029/2012gc004106.

Sláma, J, Košler, J, Condon, DJ, Crowley, JL, Gerdes, A, Hanchar, JM, Horstwood, MSA, Morris, GA, Nasdala, L, Norberg, N, Schaltegger, U, Schoene, B, Tubrett, MN & Whitehouse, MJ 2008, 'Plešovice zircon — A new natural reference material for U–Pb and Hf isotopic microanalysis', *Chemical Geology*, vol. 249, no. 1, pp. 1-35. doi:10.1016/j.chemgeo.2007.11.005.

Smithies, RH, Howard, HM, Evins, PM, Kirkland, CL, Bodorkos, S & Wingate, MTD 2008, *The west Musgrave Complex - new geological insights from recent mapping, geochronology, and geochemical studies*, Record, no. 2008/19, Geological Survey of Western Australia, Department of Industry and Resources, <http://dmpbookshop.eruditetechnologies.com.au/product/the-west-musgrave-complex-new-geological-insights-from-recent-mapping-geochronology-and-geochemical-studies.do>.

Smithies, RH, Howard, HM, Evins, PM, Kirkland, CL, Kelsey, DE, Hand, M, Wingate, MTD, Collins, AS & Belousova, EA 2011, 'High-Temperature Granite Magmatism, Crust–Mantle Interaction and the Mesoproterozoic Intracontinental Evolution of the Musgrave Province, Central Australia', *Journal of Petrology*, vol. 52, no. 5, pp. 931-958. doi:10.1093/petrology/egr010.

Smits, RG, Collins, WJ, Hand, M, Dutch, R & Payne, J 2014, 'A Proterozoic Wilson cycle identified by Hf isotopes in central Australia: Implications for the assembly of Proterozoic Australia and Rodinia', *Geology*, vol. 42, no. 3, pp. 231-234. doi:10.1130/g35112.1.

Song, G, Wang, X, Shi, X & Jiang, G 2017, 'New U-Pb age constraints on the upper Banxi Group and synchrony of the Sturtian glaciation in South China', *Geoscience Frontiers*, vol. 8, no. 5, pp. 1161-1173. doi:10.1016/j.gsf.2016.11.012.

Sprigg, RC 1952, 'Sedimentation in the Adelaide Geosyncline and the formation of the continental terrace', in MF Glaessner & RC Sprigg (eds), *Sir Douglas Mawson Anniversary Volume*, The University of Adelaide, South Australia, pp. 153-159.

Środoń, J, Gerdes, A, Kramers, J & Bojanowski, MJ 2022, 'Age constraints of the Sturtian glaciation on western Baltica based on U-Pb and Ar-Ar dating of the Lapichi Svita', *Precambrian Research*, vol. 371. doi:10.1016/j.precamres.2022.106595.

Stevens, BPJ, Page, RW & Crooks‡, A 2008, 'Geochronology of Willyama Supergroup metavolcanics, metasediments and contemporaneous intrusions, Broken Hill, Australia', *Australian Journal of Earth Sciences*, vol. 55, no. 3, pp. 301-330. doi:10.1080/08120090701769456.

Strauss, JV, Rooney, AD, Macdonald, FA, Brandon, AD & Knoll, AH 2014, '740 Ma vase-shaped microfossils from Yukon, Canada: Implications for Neoproterozoic chronology and biostratigraphy', *Geology*, vol. 42, no. 8, pp. 659-662. doi:10.1130/G35736.1.

Subarkah, D, Blades, ML, Collins, AS, Farkaš, J, Gilbert, S, Löhr, SC, Redaa, A, Cassidy, E & Zack, T 2021, 'Unraveling the histories of Proterozoic shales through in situ Rb-Sr dating and trace element laser ablation analysis', *Geology*. doi:10.1130/G49187.1.

Subarkah, D, Nixon, AL, Jimenez, M, Collins, AS, Blades, ML, Farkaš, J, Gilbert, SE, Holford, S & Jarrett, A 2022, 'Constraining the geothermal parameters of in situ Rb–Sr dating on Proterozoic shales and their subsequent applications', *Geochronology*, vol. 4, no. 2, pp. 577-600. doi:10.5194/gchron-4-577-2022.

Swain, G, Woodhouse, A, Hand, M, Barovich, K, Schwarz, M & Fanning, CM 2005, 'Provenance and tectonic development of the late Archaean Gawler Craton, Australia; U–Pb zircon, geochemical and Sm–Nd isotopic implications', *Precambrian Research*, vol. 141, no. 3, pp. 106-136. doi:10.1016/j.precamres.2005.08.004.

Thomson, BP, Coats, RP, Mirams, RC, Forbes, BG, Dalgarno, CR & Johnson, JE 1964, 'Precambrian Rock Groups in the Adelaide Geosyncline: A new subdivsion', *Quarterly Geological Notes*, vol. 9, pp. 1-20.

Tostevin, R & Mills, BJW 2020, 'Reconciling proxy records and models of Earth's oxygenation during the Neoproterozoic and Palaeozoic', *Interface Focus*, vol. 10, no. 4, p. 20190137. doi:10.1098/rsfs.2019.0137.

van der Wolff, EJ 2020, 'Detrital Provenance and Geochronology of the Burra, Umberatana and Wilpena Groups in the Mount Lofty Ranges', Department of Earth Sciences, Honours Thesis, Bachelor of Science (Honours), University of Adelaide, Adelaide, South Australia.

Verdel, C, Campbell, MJ & Allen, CM 2021, 'Detrital zircon petrochronology of central Australia, and implications for the secular record of zircon trace element composition', *Geosphere*. doi:10.1130/ges02300.1.

Vermeesch, P 2018, 'IsoplotR: a free and open toolbox for geochronology', *Geoscience Frontiers*, vol. 9, no. 5. doi:10.1016/j.gsf.2018.04.001.

Vermeesch, P, Resentini, A & Garzanti, E 2016, 'An R package for statistical provenance analysis', *Sedimentary Geology*, vol. 336, pp. 14-25. doi:10.1016/j.sedgeo.2016.01.009.

Villa, IM, De Bièvre, P, Holden, NE & Renne, PR 2015, 'IUPAC-IUGS recommendation on the half life of 87Rb', *Geochimica et Cosmochimica Acta*, vol. 164, pp. 382-385. doi:10.1016/j.gca.2015.05.025.

Virgo, GM, Collins, AS, Amos, KJ, Farkaš, J, Blades, ML & Subarkah, D 2021, 'Descending into the “snowball”: High resolution sedimentological and geochemical analysis across the Tonian to Cryogenian boundary in South Australia', *Precambrian Research*, vol. 367. doi:10.1016/j.precamres.2021.106449.

Wade, BP, Kelsey, DE, Hand, M & Barovich, KM 2008, 'The Musgrave Province: Stitching north, west and south Australia', *Precambrian Research*, vol. 166, no. 1, pp. 370-386. doi:10.1016/j.precamres.2007.05.007.

Wade, CE 2011, 'Definition of the Mesoproterozoic Ninnerie Supersuite, Curnamona Province, South Australia', *MESA Journal*, vol. 62, pp. 25-42.

Wallace, MW, Hood, Av, Shuster, A, Greig, A, Planavsky, NJ & Reed, CP 2017, 'Oxygenation history of the Neoproterozoic to early Phanerozoic and the rise of land plants', *Earth and Planetary Science Letters*, vol. 466, pp. 12-19. doi:10.1016/j.epsl.2017.02.046.

Wallace, MW, Hood, AvS, Woon, EMS, Giddings, JA & Fromhold, TA 2015, 'The Cryogenian Balcanoona reef complexes of the Northern Flinders Ranges: Implications for Neoproterozoic ocean chemistry', *Palaeogeography, Palaeoclimatology, Palaeoecology*, vol. 417, pp. 320-336. doi:10.1016/j.palaeo.2014.09.028.

Wang, D, Zhu, X-K, Zhao, N, Yan, B, Li, X-H, Shi, F & Zhang, F 2019, 'Timing of the termination of Sturtian glaciation: SIMS U-Pb zircon dating from South China', *Journal of Asian Earth Sciences*, vol. 177, pp. 287-294. doi:10.1016/j.jseaes.2019.03.015.

Webb, AW 1980, *Geochronology of stratigraphically significant rocks from South Australia. Progress Report No. 30*, no. Env 01689, Amdel Ltd, South Australia, <https://sarigbasis.pir.sa.gov.au/WebtopEw/ws/samref/sarig1/wcir/Record?r=0&m=1&w=catno=2021979>.

Webb, AW, Coats, RP, Fanning, CM & Flint, RB 1983, 'Geochronological Framework of the Adelaide Geosyncline', in *Adelaide Geosyncline Sedimentary Environments and Tectonics Settings Symposium*, Geological Society of Australia, Sydney, New South Wales, pp. 7-9.

Wiedenbeck, M, Allé, P, Corfu, F, Griffin, WL, Meier, M, Oberli, F, Quadt, AV, Roddick, JC & Spiegel, W 1995, 'Three Natural Zircon Standards for U-Th-Pb, Lu-Hf, Trace Element and REE Analyses', *Geostandards Newsletter*, vol. 19, no. 1, pp. 1-23. doi:10.1111/j.1751-908X.1995.tb00147.x.

Wiedenbeck, M, Hanchar, JM, Peck, WH, Sylvester, P, Valley, J, Whitehouse, M, Kronz, A, Morishita, Y, Nasdala, L, Fiebig, J, Franchi, I, Girard, JP, Greenwood, RC, Hinton, R, Kita, N, Mason, PRD, Norman, M, Ogasawara, M, Piccoli, PM, Rhede, D, Satoh, H, Schulz-Dobrick, B, Skår, O, Spicuzza, MJ, Terada, K, Tindle, A, Togashi, S, Vennemann, T, Xie, Q & Zheng, YF 2004, 'Further Characterisation of the 91500 Zircon Crystal', *Geostandards and Geoanalytical Research*, vol. 28, no. 1, pp. 9-39. doi:10.1111/j.1751-908X.2004.tb01041.x.

Williams, GE & Gostin, VA 2019, 'Late Cryogenian glaciation in South Australia: Fluctuating ice margin and no extreme or rapid post-glacial sea-level rise', *Geoscience Frontiers*. doi:10.1016/j.gsf.2019.02.002.

Wu, L, Guan, S, Ren, R, Zhang, C & Feng, X 2019, 'Neoproterozoic glaciations and rift evolution in the northwest Tarim Craton, China: new constraints from geochronological, geochemical, and geophysical data', *International Geology Review*, pp. 1-20. doi:10.1080/00206814.2019.1700399.

Wysoczanski, RJ & Allibone, AH 2004, 'Age, Correlation, and Provenance of the Neoproterozoic Skelton Group, Antarctica: Grenville Age Detritus on the Margin of East Antarctica', *Journal of Geology*, vol. 112, no. 4, pp. 401-416. doi:10.1086/421071.

Xiao, W, Cao, J, Luo, B, He, Y, Zhou, G, Zuo, Z, Xiao, D & Hu, K 2020, 'Marinoan glacial aftermath in South China: Paleo-environmental evolution and organic carbon accumulation in the Doushantuo shales', *Chemical Geology*, vol. 555, p. 119838. doi:10.1016/j.chemgeo.2020.119838.

Xu, B, Xiao, S, Zou, H, Chen, Y, Li, Z-X, Song, B, Liu, D, Zhou, C & Yuan, X 2009, 'SHRIMP zircon U–Pb age constraints on Neoproterozoic Quruqtagh diamictites in NW China', *Precambrian Research*, vol. 168, no. 3, pp. 247-258. doi:10.1016/j.precamres.2008.10.008.

Young, GM & Gostin, VA 1989a, 'Depositional environment and regional stratigraphic significance of the Serle Conglomerate: A Late Proterozoic submarine fan complex, South Australia', *Palaeogeography, Palaeoclimatology, Palaeoecology*, vol. 71, no. 3, pp. 237-252. doi:10.1016/0031-0182(89)90052-7.

Young, GM & Gostin, VA 1989b, 'An exceptionally thick upper Proterozoic (Sturtian) glacial succession in the Mount Painter area, South Australia', *Geological Society of America Bulletin*, vol. 101, no. 6, pp. 834-845. doi:10.1130/0016-7606(1989)101<0834:Aetups>2.3.Co;2.

Young, GM & Gostin, VA 1991, 'Late Proterozoic (Sturtian) succession of the North Flinders Basin, South Australia; An example of temperate glaciation in an active rift setting', in JB Anderson & GM Ashley (eds), *Glacial marine sedimentation; Paleoclimatic significance*, vol. 261, Geological Society of America, pp. 207–222.

Zaitseva, TS, Kuznetsov, AB, Gorozhanin, VM, Gorokhov, IM, Ivanovskaya, TA & Konstantinova, GV 2019, 'The Lower Boundary of the Vendian in the Southern Urals as Evidenced by the Rb–Sr Age of Glauconites of the Bakeevo Formation', *Stratigraphy and Geological Correlation*, vol. 27, no. 5, pp. 573-587. doi:10.1134/s0869593819050083.

Zhang, Q-R, Chu, X-L & Feng, L-J 2011, 'Neoproterozoic glacial records in the Yangtze Region, China', in E Arnaud, GP Halverson & GA Shields-Zhou (eds), *The Geological Record of Neoproterozoic Glaciations*, Geological Society, London, pp. 357-366.

Zhang, Q-R, Li, X-H, Feng, L-J, Huang, J & Song, B 2008, 'A New Age Constraint on the Onset of the Neoproterozoic Glaciations in the Yangtze Platform, South China', *The Journal of Geology*, vol. 116, no. 4, pp. 423-429. doi:10.1086/589312.

Zhang, S, Jiang, G, Zhang, J, Song, B, Kennedy, MJ & Christie-Blick, N 2005, 'U-Pb sensitive high-resolution ion microprobe ages from the Doushantuo Formation in south China: Constraints on late Neoproterozoic glaciations', *Geology*, vol. 33, no. 6. doi:10.1130/g21418.1.

Zhou, C-M, Huyskens, MH, Xiao, S & Yin, Q-Z 2020, 'Refining the termination age of the Cryogenian Sturtian glaciation in South China', *Palaeoworld*, vol. 29, no. 3, pp. 462-468. doi:10.1016/j.palwor.2020.04.002.

Zhou, C, Huyskens, MH, Lang, X, Xiao, S & Yin, Q-Z 2019, 'Calibrating the terminations of Cryogenian global glaciations', *Geology*, vol. 47, no. 3, pp. 251-254. doi:10.1130/g45719.1.

Zhou, C, Tucker, R, Xiao, S, Peng, Z, Yuan, X & Chen, Z 2004, 'New constraints on the ages of Neoproterozoic glaciations in south China', *Geology*, vol. 32, no. 5, pp. 437-440. doi:10.1130/G20286.1.

Zhu, M & Wang, H 2011, 'Neoproterozoic glaciogenic diamictites of the Tarim Block, NW China', in E Arnaud, GP Halverson & GA Shields-Zhou (eds), *The Geological Record of Neoproterozoic Glaciations*, Geological Society, London, pp. 367-378.

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: 2022-03-31**

RESERVED IN STRATIGRAPHIC UNITS DATABASE: YES

PROPOSED PUBLICATION: Lloyd, JC, Preiss, WV, Collins, AS, Virgo, GM, Blades, ML & Amos, KJ [submitted to Geological Magazine], 'Geochronology and formal stratigraphy of the Sturtian Glaciation in the Adelaide Superbasin', (EarthArXiv preprint doi:10.31223/X50G9N)

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 lithofacies)

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 is comprised of (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 lithofacies:

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

Lithofacies 2: Interbedded, well laminated shales and sandy micaceous siltstones. Minor pebbly lenses and silty arenites, cross-bedding present, and ripple marked.

Lithofacies 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.

Lithofacies 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: 663.03 ± 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. Parts of the Benda Siltstone and Holowilena Ironstone may be correlative of the upper part of the Sturt 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: Ranging from undeformed to strongly sheared. Locally metamorphosed up to amphibolite grade.

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.

The exact (chrono)stratigraphic relationship of the Holowilena Ironstone and Benda Siltstone to the entirety of the Sturt Formation is uncertain. They may be upper members of the Sturt Formation, or an intervening sequence between the Sturt and Wilyerpa formations.

REFERENCES (if any) [1]: **This is not exhaustive, as many are already in ASUD. These are the key resources for this definition card.**

Ambrose, GJ, Flint, RB & Webb, AW 1981, ‘Precambrian and Palaeozoic Geology of the Peake and Denison Ranges’, *Bulletin* (50), Geological Survey of South Australia

Belperio, AP 1973, ‘The stratigraphy and facies of the Late Precambrian Lower Glacial sequence, Mt Painter, South Australia’, Department of Geology, Honours Thesis, Bachelor of Science (Honours), University of Adelaide, Adelaide, South Australia, https://hdl.handle.net/2440/131123

Coats RP & Preiss WV 1987, ‘Stratigraphy of the Umberatana Group’, IN: WV Preiss (compiler), ‘The Adelaide Geosyncline – Later Proterozoic Stratigraphy, Sedimentation, Palaeontology and Tectonics’, *Bulletin* (53), pp. 125–210, Geological Survey of South Australia

Conor, CHH & Preiss, WV 2019, ‘Cryogenian glaciomarine megaclasts of the MacDonald Corridor, Bimbowrie Conservation Park, Olary Region, South Australia’, *Australian Journal of Earth Sciences*, vol. 67 (6), pp. 857-872. doi:10.1080/08120099.2018.1553206

Cox, GM, Isakson, V, Hoffman, PF, Gernon, TM, Schmitz, MD, Shahin, S, Collins, AS, Preiss, WV, Blades, ML, Mitchell, RN & Nordsvan, A 2018, 'South Australian U-Pb zircon (CA-ID-TIMS) age supports globally synchronous Sturtian deglaciation', *Precambrian Research*, vol. 315, pp. 257-263. doi:10.1016/j.precamres.2018.07.007

Forbes, BG & Cooper RS 1976, ‘The Pualco Tillite of the Olary Region, South Australia’, *Quarterly Geological Notes*, vol. 60, pp. 2–5, Geological Survey of South Australia

Howchin, W 1920, 'Past Glacial Action in Australia', IN: Year Book (13), Australian Bureau of Statistics, Australia, pp. 1133-1146

Keeman, J, Turner, S, Haines, PW, Belousova, E, Ireland, T, Brouwer, P, Foden, J & Wörner, G 2020, 'New UPb, Hf and O isotope constraints on the provenance of sediments from the Adelaide Rift Complex – Documenting the key Neoproterozoic to early Cambrian succession', *Gondwana Research*, vol. 83, pp. 248-278. doi:10.1016/j.gr.2020.02.005

Link, PK 1977, ‘Facies and palaeogeography of Late Precambrian Sturtian glacial sediments, Copley area, northern Flinders Ranges and in the Sturt Gorge near Adelaide, South Australia’, Honours Thesis, University of Adelaide, https://hdl.handle.net/2440/131122

Lloyd, JC, Blades, ML, Counts, JW, Collins, AS, Amos, KJ, Wade, BP, Hall, JW, Hore, S, Ball, AL, Shahin, S & Drabsch, M 2020, 'Neoproterozoic geochronology and provenance of the Adelaide Superbasin', *Precambrian Research*, vol. 350, p. 105849. doi:10.1016/j.precamres.2020.105849.

[Pre-print] Lloyd, JC, Preiss WV, Collins, AS, Virgo, GM, Blades, ML, Gilbert, SE & Amos, KJ 2022a, 'Geochronology and formal stratigraphy of the Sturtian Glaciation in the Adelaide Superbasin', *EarthArXiv*, doi:10.31223/X50G9N

[Pre-print] Lloyd, JC, Collins, AS, Blades, ML, Gilbert, SE & Amos, KJ 2022b, 'Late Tonian development of the Adelaide Superbasin', *EarthArXiv*, doi:10.31223/X5N63H

Segnit, RW 1939, ‘The Precambrian-Cambrian succession — The general and economic geology of these systems, in portions of South Australia’, *Bulletin* (18), Geological Survey of South Australia

Young, GM & Gostin, VA 1989, ‘An exceptionally thick upper Proterozoic (Sturtian) glacial succession in the Mount Painter area, South Australia’, *Geological Society of America Bulletin*, vol. 101 (6), ppp. 834-845. doi:10.1130/0016-7606(1989)101<0834:Aetups>2.3.Co;2

(for subcommittee use only)
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SA Stratigraphy Subcommission
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Name first published by:

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Supplementary Figure S1