Age and geochemistry of the Boucaut Volcanics in the Neoproterozoic
Adelaide Rift Complex, South Australia

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ABSTRACT
The Adelaide Rift Complex in South Australia records the break-up of Rodinia at a time of great climatic and biological evolution. The Boucaut Volcanics within the Neoproterozoic Adelaide Rift Complex of the Adelaide Superbasin lie at the base of the Burra Group, marking the boundary between the Burra Group and underlying Callanna Group. Despite their significance as one of the few volcanic units within the rift complex, there has been no robust age determination published for the Boucaut Volcanics. We use U–Pb zircon LA-ICP-MS data to determine an age of 788 ± 6 Ma for the eruption of the bimodal Boucaut Volcanics. This has important implications for constraining the timing of stratigraphy within the Adelaide Superbasin. This also has far-reaching implications for plate tectonic reconstructions of Australia and Laurentia, and for correlating global isotope anomalies for the Neoproterozoic.

KEY POINTS
1. New U–Pb zircon data provide a revised age for the Boucaut Volcanics of 788 ± 6 Ma.
2. Whole-rock geochemistry data highlight the bimodality of the Boucaut Volcanics, with both mafic and felsic components present.
3. Boucaut Volcanics potentially correlate with units in the southwest United States, which would support an AUSWUS plate tectonic configuration during the Neoproterozoic.

Introduction
The Adelaide Superbasin in South Australia preserves Tonian to middle Cambrian sedimentary and minor volcanic rocks (Lloyd et al., 2020; Preiss, 2000). They preserve some of the best evidence for the evolving, and sometimes tumultuous, events that characterise this time in Earth’s climatic, biological and geological systems. For example, the earliest known complex multicellular lifeforms are preserved within the Ediacara Hills of the Flinders Ranges, and extensive tillites provide evidence for Earth’s global Cryogenian glaciation events (Hoffman et al., 2017; Le Heron et al., 2011). Of significance to paleogeographic reconstructions, the Adelaide Rift Complex also contains rocks that have been interpreted as forming during the breakup of supercontinent Rodinia (Merdith, Collins et al., 2017; Powell et al., 1994; Preiss, 2000) (Figure 1). Understanding the tectonic and geological evolution of the Adelaide Rift Complex underpins our understanding of these significant Neoproterozoic events, not only in Australia, but globally.

Tectonic overview
The Neoproterozoic to middle Cambrian stratigraphy within the Adelaide Rift Complex formed during at least five major successive rift cycles that led to the breakup of supercontinent Rodinia (Preiss, 2000). In the Adelaide Rift Complex, initiation of the breakup of Rodinia is marked by the 827 ± 6 Ma Gairdner Dyke Swarm (Wingate et al., 1998), which is interpreted to be coeval with the poorly dated (ca 850 Ma based on an Rb–Sr isochron age) Wooltana Volcanics (Compston et al., 1966). The 812 ± 6 Ma Mount Crawford Granite Gneiss intrudes the ca 1600 Ma Barossa Complex basement in the Warren and Oakbank inliers, within the Mount Lofty Ranges (to the south of the Flinders Ranges) (Preiss et al., 2008). The second phase of
Rifting in the Adelaide Rift Complex is marked by the 802 ± 10 Ma Rook Tuff within the Callanna Group (pers. comm. Fanning 1994 in Preiss, 2000). The felsic 798 Ma Oodla Wirra Volcanics (Fabris et al., 2005), which is proximal to the Callanna Group, also constrains the timing of early rifting. The third phase of rifting is marked by the Boucaut Volcanics. This rift phase marks the beginning of extensive syn-rift facies within the Adelaide Superbasin, yet, it has resisted attempts at dating and forms the focus of this study.

According to both the southwest US–East Antarctica (SWEAT; Dalziel, 1991; Moores, 1991) and Australia–western US (AUSWUS; Burrett & Berry, 2000) hypotheses, the Laurentian and East Antarctic–Australian cratons were contiguous during the late Neoproterozoic. This has led to attempted correlations between the stratigraphy of the Adelaide Superbasin and western Laurentia. The SWEAT hypothesis posits a close link between southern Australia and northwest Canada. In this configuration the Boucaut Volcanics have been linked with the Little Dal Group of the Mackenzie Mountains in the Yukon-Northwest Territories of Canada (Milton et al., 2017) (Figure 1, SWEAT reconstruction). Alternatively, in the AUSWUS fit (Figure 1), the Adelaide Superbasin lies adjacent to southwestern US, and correlations with stratigraphy in the Death Valley have been proposed (e.g. Dehler et al., 2017; Mahon et al.,...
An analysis of kinematic data for the different reconstructions in Figure 1 showed that models that put Australia adjacent to southern Laurentia (e.g. AUSWUS, and a more extreme version with Australia adjacent to Mexico-AUSMEX, Wingate et al., 2002) are the easiest to reconcile with Phanerozoic plate kinematic norms (Merdith, Collins et al., 2017).

On a smaller scale, correlations between the Adelaide Superbasin and northwest Tasmania have also been proposed, for example, between the ca 790 Ma Black River Dolomite of northwest Tasmania (Calver, 1998) and the Skillogalee Dolomite of the Adelaide Superbasin. However, more recent detrital provenance studies suggest that Neoproterozoic stratigraphy in Tasmania differs from the Adelaide Superbasin and instead correlates with rocks in the Death Valley in California and the Transantarctic Mountains (Mulder et al., 2018).

Constraining correlations has important implications for paleogeographic reconstructions of Laurentia-Australia in the Rodinia supercontinent. Unfortunately, many of these correlations rely on old and/or unreliable age data, particularly for the Adelaide Superbasin (Figure 2).

The Boucaut Volcanics

The Boucaut Volcanics lie at the base of the Burra Group and provide an important maximum age constraint for this package. They also constrain the maximum age for the underlying Callanna Group. The age of the Boucaut Volcanics has been most widely reported as 777 ± 7 Ma (pers. comm. Fanning 1994 in Preiss, 2000); however, no isotopic data have been published for this associated age. Confusingly, another source (Drexel et al., 1993) mentions that Fanning (1989) derived an upper intercept age of 783 ± 42 Ma for the Boucaut Volcanics, but the original source of these data is obscure. Regardless, robust isotopic age determinations are needed to constrain the age of this significant unit.

The Boucaut Volcanics are dominated by pale pink to grey rhyolite, with amygdaloidal andesite and basalt also present (Forbes, 1978). These rocks have undergone several phases of deformation and have been metamorphosed to ‘biotite grade’ (Forbes, 1978). The Boucaut Volcanics occur within the southeastern part of the Nackara Arc, and the majority of outcrops are isolated and many are sheared along the northeast-trending Anabma Shear Zone (Preiss, 2000). The Boucaut Volcanics mark a major stage of rifting in the Adelaide Rift Complex that has been interpreted by many as reflecting the separation of Laurentia from Australia and the initiation of the Pacific Ocean basin (Preiss, 2000).

In this contribution, we have collected new U–Pb zircon data from a rhyolite within the Boucaut Volcanics, to provide a robust age constraint on the timing of eruption. Significantly, this new age constrains the base of the Burra Group and the onset of early rifting within the Adelaide Rift Complex, providing important constraints on plate reconstructions for the breakup of the Rodinia supercontinent (e.g. Merdith, Collins et al., 2017; Merdith, Williams et al., 2017).

Analytical methods

Zircon U–Pb and trace-element geochemistry

A rhyolite sample from the Boucaut Volcanics (Sample 050220-12) was crushed and separated for zircons. Zircons were hand-picked and mounted in epoxy resin, and then polished and carbon coated. To identify suitable domains for analysis, zircons were imaged using a Gatan cathodoluminescence (CL) detector attached to a Quanta 600 MLA Scanning Electron Microscope. Zircon U–Pb isotopic and REE/trace-element determination was undertaken at the University of Adelaide using an Agilent 7900x ICP-MS with an attached ASI Resolution excimer 193 nm laser ablation system. A spot size of 29 µm and frequency of 5 Hz was used and isotopes 90Zr, 205Pb, 206Pb, 207Pb, 208Pb, 232Th and 238U were measured. Each analysis comprised a 20 s background and 30 s ablation. GEMOC GJ-1 zircon was used to correct for U–Pb fractionation (TIMS normalising ages 207Pb/206Pb = 206Pb/238U = 707.7 ± 4.3 Ma, 206Pb/238U = 600.7 ± 1.1 Ma and 207Pb/235U = 602.0 ± 1.0 Ma; Jackson et al., 2004). The Plešovice zircon standard was used to assess accuracy over the course of the laser session (ID TIMS 206Pb/238U = 337.13 ± 0.37 Ma; Sláma et al., 2008). Ten Plešovice standard analyses were made and yielded a weighted average 206Pb/238U age of 335.2 ± 4.1 Ma (2σ; MSWD = 0.76), which is within uncertainty of the ID TIMS age. Data were processed using ilolite v3.32 (Paton et al., 2011). U–Pb data and REE data are provided (see data availability statement).

Whole-rock geochemistry

Twenty-one samples from the Boucaut Volcanics were analysed for whole-rock geochemistry (see Figure 2a inset for sample locations). Major-element geochemistry was obtained through the analysis of fused glass discs using X-ray fluorescence at the University of Adelaide. Trace-element and rare earth element (REE) geochemistry was undertaken by Amdel in Adelaide using IC3M and ICM3R. A subsample of up to 0.5 g of the analytical pulp was digested using an HF/multi-acid digest, and the solution obtained through the analysis of fused glass discs using X-ray fluorescence was used and isotopes 90Zr, 205Hg, 204Pb, 206Pb, 207Pb, 208Pb, 232Th and 238U were measured. Each analysis comprised a 20 s background and 30 s ablation. GEMOC GJ-1 zircon was used to correct for U–Pb fractionation (TIMS normalising ages 207Pb/206Pb = 206Pb/238U = 707.7 ± 4.3 Ma, 206Pb/238U = 600.7 ± 1.1 Ma and 207Pb/235U = 602.0 ± 1.0 Ma; Jackson et al., 2004). The Plešovice zircon standard was used to assess accuracy over the course of the laser session (ID TIMS 206Pb/238U = 337.13 ± 0.37 Ma; Sláma et al., 2008). Ten Plešovice standard analyses were made and yielded a weighted average 206Pb/238U age of 335.2 ± 4.1 Ma (2σ; MSWD = 0.76), which is within uncertainty of the ID TIMS age. Data were processed using ilolite v3.32 (Paton et al., 2011). U–Pb data and REE data are provided (see data availability statement).

Results

Sample descriptions

The Boucaut Volcanics crop out near Boucaut East Dam, about 79 km south of Olary (Figure 2). Small isolated outcrops of highly vesicular basalt and rhyolite (Figure 3) are
interbedded with thin beds of mudstone and some cross-bedded sandstones indicating a shallow marine environment during deposition of the basal Burra Group. Strain partitioning has resulted in preservation of undeformed pods of volcanic rock enveloped by strongly foliated equivalents. Minor copper mineralisation is associated with the basalts at Cronje Dam. The rhyolites sampled for this study were relatively fresh, fine-grained, flow-banded rhyolites with small (<1 cm) phenocrysts of quartz and feldspar.

Sample descriptions and locations are provided in Table 1 and shown in Figure 2. Basalts were collected from the type section while rhyolites were collected from surrounding outcrops on the tops of small hills. Examples of outcrop textures are shown in Figure 3.

**Zircon U–Pb geochronology and trace-element geochemistry**

Separated zircons from sample 050220-12 are generally euhedral with preserved facets and pyramidal terminations. Most zircons are banded or have concentric oscillatory zoning in CL images (Figure 4). Forty-four U–Pb and trace-element analyses were obtained from 41 zircons, of which 39 are within 10% of concordance, and 29 are within 5% of concordance (Figure 5). The 29 analyses within 5% concordance yield a $^{206}\text{Pb}/^{238}\text{U}$ weighted average age of $788 \pm 6\text{ Ma}$ (MSWD = 1.08), which we interpret as the crystallisation age of this sample. A $^{207}\text{Pb}/^{206}\text{Pb}$ weighted average of the same analyses yielded an age of $786 \pm 13\text{ Ma}$ (MSWD = 0.29).
Table 1. Sample descriptions, locations and analytical methods applied in this study.

| Sample          | Description                                                                 | Analytical methods | Latitude     | Longitude     |
|-----------------|----------------------------------------------------------------------------|--------------------|--------------|---------------|
| 050219-01       | Anabama Mine. Metabasalt chips from RC drilling collar. Strong foliation, silicified, sericite | WR                 | –            | –             |
| 050219-03       | Boucaut Volcanics type section. Fresh basalt with vesicles filled with epidote | WR                 | –32.799685   | 140.295644    |
| 050220-01       | Boucaut Volcanics type section                                             | WR                 | –32.799685   | 140.295644    |
| 050220-02       | Boucaut Volcanics type section                                             | WR                 | –32.799685   | 140.295644    |
| 050220-03       | Boucaut Volcanics type section                                             | WR                 | –32.799685   | 140.295644    |
| 050220-04       | Boucaut Volcanics type section                                             | WR                 | –32.799685   | 140.295644    |
| 050220-05       | Boucaut Volcanics type section                                             | WR                 | –32.799685   | 140.295644    |
| 050220-06       | Boucaut Volcanics type section                                             | WR                 | –32.799685   | 140.295644    |
| 050220-07       | Boucaut Volcanics type section                                             | WR                 | –32.799685   | 140.295644    |
| 050220-08       | Boucaut Volcanics type section                                             | WR                 | –32.799685   | 140.295644    |
| 050220-10       | Boucaut felsic volcanic                                                     | WR                 | –32.808832   | 140.300485    |
| 050220-11       | Boucaut felsic volcanic. Foliated 309/73                                   | WR                 | –32.808832   | 140.300485    |
| 050220-12       | Boucaut felsic volcanic. Fresh undeformed pod surrounded by foliated equivalent | WR + geochronology| –32.809520   | 140.301249    |
| 050220-13       | Boucaut felsic volcanic-tuff?                                              | WR                 | –32.825849   | 140.301249    |
| 050220-14       | Rhyolite with flow banding bedding 179/75                                  | WR                 | –32.825895   | 140.301409    |
| 050220-15       | Rhyolite with flow banding bedding                                         | WR                 | –32.825258   | 140.302055    |
| 050220-16       | Rhyolite. Glassy K-spar rich                                               | WR                 | –32.797221   | 140.329893    |
| 050220-17       | Metabasalt chips from drillcore collar CRD15. Some chalcopyrite mineralisation | WR                 | –32.815613   | 140.335403    |
| 050220-18       | Rhyolite. Round clasts? K-feldspar rind, flow banding. Bedding 335/71       | WR                 | –32.842648   | 140.285837    |
| 050221-01       | Rhyolite with flow banding bedding. Foliation and crenulation in parts. Bedding 335/85 | WR                 | –32.870726   | 140.168623    |
| 050221-02       | Cronje Dam copper prospect. Malachite along foliation                      | WR                 | –32.865131   | 140.160146    |

Figure 3. Field examples of the Boucaut Volcanics: (a) flow-banded rhyolite; (b) flow-banded rhyolite, a fresh undeformed pod surrounded by foliated equivalent (Sample 050220-12); (c) banded intermediate volcanic; and (d) flow-banded or folded volcanic rock.
Trace-element profiles from analyses that are within 10% of concordance are shown in Figure 6 along with their Th/U ratios. Zircons show Th/U values between 0.5 and 1.2 that are consistent with igneous zircons (Belousova et al., 2002). The majority of near concordant zircon divide into two coupled Th/U and REE populations (Figure 6). One population has Th/U ratios >0.8, elevated REEs and moderate positive Ce anomalies. The second population has Th/U ratios <0.8 and a pronounced positive Ce anomaly. Both populations have moderate negative Eu anomalies and positive medium to high REE gradients. The negative Eu anomaly can be caused by the presence of plagioclase in the magma that the zircon grew in and/or by a reducing magma. The latter possibility is discounted, as a positive Ce anomaly is a sign of an oxidising magma (Trail et al., 2012). Additionally, Kirkland et al. (2015) showed that Th/U ratios correlate positively with temperature in a cooling fractionating magma owing to the preferential magma depletion of U as the magma cools. We use these observations to suggest that our analysed zircons reflect growth in a cooling fractionating magma chamber that was becoming progressively more oxidised as it cooled.

Whole-rock geochemistry

Rock samples from the Boucaut Volcanics range from basaltic to rhyolitic compositions, with SiO₂ ranging from 45 to 79 wt% (Figure 7a). Around half of the samples plot within the rhyolite field on a total alkali silica diagram (Le Bas et al., 1986), with the remaining samples plotting within the basalt, andesite and dacite fields. Samples range from ferroan to magnesian for both felsic and mafic samples (Figure 7b).
On the REE diagram of sample/chondrite (Figure 7c), samples are enriched in light REEs relative to heavy REEs, with some exhibiting a negative Eu anomaly, which is more pronounced for the felsic samples. On the sample/primitive mantle trace-element diagram (Figure 7d), samples show a strong negative Sr anomaly and a weak negative Eu anomaly, both of which are more pronounced for the felsic samples. Together, these observations indicate that plagioclase was fractionated as the magma evolved.

**Discussion and implications**

Here, we present a revised age for the eruption of the Boucaut Volcanics at 788 ± 6 Ma along with whole-rock geochemistry for a range of samples from the Boucaut Volcanics. This age is older than a poorly documented age of 777 ± 7 Ma that was based on a personal communication with no associated isotopic data. The new age presented here provides important constraints on early rifting in the Adelaide Rift Complex and provides a piercing point for plate tectonic reconstructions. The revised age of 788 ± 6 Ma constrains the onset of the third phase of rifting in the Adelaide Rift Complex (Figure 2c) to be as early as 788 ± 6 Ma, earlier than previously suggested (Preiss, 2000), but more consistent with kinematic constraints on the timing of the Australia–Laurentia rift-drift transition as central Rodinia began to break up at ca 800 Ma (Merdith, Williams et al., 2017).

This new age of the Boucaut Volcanics constrains the base of the Burra Group to 788 ± 6 Ma. The underlying Callanna Group, has a reported maximum age of 802 ± 10 Ma (Fanning et al., 1986), which, however, is only documented in an abstract with no isotopic data. The Callanna Group appears not to contain the ca 810 Ma Bitter Springs carbon isotope anomaly (Macdonald et al., 2010; Stüeken et al., 2019), which may be used as a minimum age constraint. More work is needed to confirm that the basin waters had compositions similar to the contemporaneous ocean waters. Our new data now provide a revised minimum age for the deposition of the Callanna Group of 788 ± 6 Ma.

Several intrusive and extrusive magmatic suites are present within the Adelaide Superbasin. Owing to the scarcity of robust age constraints, these have been challenging to place within a tectonostratigraphic framework, and to correlate with other units across the region. The Kooringa Member within the Skillogalee Dolomite contains an intrusive porphyry that has been dated at 794 ± 4 Ma (Preiss et al., 2009). This is within uncertainty of the Boucaut Volcanics and may represent an intrusive equivalent.

Potential correlations exist between the Boucaut Volcanics and southwest Laurentia and northwest Laurentia. The Little Dal Basalts form part of Gunbarrel magmatic event that affected western North America during the breakup of the Rodinia supercontinent and have a well-constrained CA-ID-TIMS age of 775.10 ± 0.54 Ma (Milton et al., 2017). This age is younger and not within uncertainty. 

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**Figure 6.** Trace-element profile of zircons within 10% concordance (n = 39/44), coloured by Th/U. Normalised to chondrite (Sun & McDonough, 1989).
of our newly reported age of 788 ± 6 Ma for the Boucaut Volcanics, so we do not consider these volcanic rocks to be equivalent.

In the Death Valley region of the southwest United States, the ca 787 Ma Horse Thief Springs Formation overlies a ca 300 m.y. unconformity, separating it from the >ca 1080 Ma Crystal Spring Formation (Mahon et al., 2014b). The Horse Thief Springs Formation comprises siltstone and dolomite, and has a maximum depositional age of 787 ± 11 Ma (Mahon et al., 2014b). This is indistinguishable from our new age of 788 ± 7 Ma for the Boucaut Volcanics. Furthermore, these ages are indistinguishable from a new maximum depositional age constraint for the Skillogalee Dolomite within the Adelaide Superbasin of 787 ± 9 Ma (Lloyd et al., 2020). Similar age constraints on sedimentary units exist in the Grand Canyon in the United States. For example, the Chuar Group, which has been proposed to correlate with the Death Valley, has a maximum depositional age of ca 782 Ma (Dehler et al., 2017).

Further comparative studies of the sedimentology, volcanic and detrital geochronology between the Adelaide Superbasin and different regions of western North America are required to better constrain the tectonic links. The new age of 788 ± 6 Ma for the Boucaut Volcanics presented here suggests a possible link with the Death Valley and Grand Canyon of southwest United States. Combined with plate tectonic modelling of kinematic data (Merdith, Williams et al., 2017), this supports an AUSWUS plate tectonic configuration (Figure 1) during the Neoproterozoic.

Acknowledgements
Jarred Lloyd and Claire Wade are thanked for providing regional overview data and context. A. S. Collins acknowledges the MinEx CRC, and his contribution forms MinEx CRC output #2020/46. Sarah Gilbert and Ben Wade at Adelaide Microscopy are thanked for help obtaining analytical data. Wolfgang Preiss and an anonymous reviewer are thanked for reviews, their feedback greatly improved this manuscript.

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