University of Wollongong

Research Online

Faculty of Science, Medicine and Health -
Papers: Part B

Faculty of Science, Medicine and Health

1-1-2020

What is underneath the juvenile Ordovician Macquarie Arc (eastern Australia)? A question resolved using Silurian intrusions to sample the lower crust

Qing Zhang

University of Wollongong, qing@uow.edu.au

Allen Phillip Nutman

University of Wollongong, anutman@uow.edu.au

Solomon Buckman

University of Wollongong, solomon@uow.edu.au

Vickie C. Bennett

vickie.bennett@anu.edu.au

Follow this and additional works at: <https://ro.uow.edu.au/smhpapers1>

Publication Details Citation

Zhang, Q., Nutman, A. P., Buckman, S., & Bennett, V. C. (2020). What is underneath the juvenile Ordovician Macquarie Arc (eastern Australia)? A question resolved using Silurian intrusions to sample the lower crust. Faculty of Science, Medicine and Health - Papers: Part B. Retrieved from <https://ro.uow.edu.au/smhpapers1/1126>

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

What is underneath the juvenile Ordovician Macquarie Arc (eastern Australia)? A question resolved using Silurian intrusions to sample the lower crust

Abstract

2020 International Association for Gondwana Research The Ordovician intra-oceanic Macquarie Arc of eastern Australia collided with the eastern Gondwanan margin at ~440 Ma. However, the deep crustal architecture resulting from this assembly is poorly known. This is addressed here by a zircon U-Pb-Hf study of the post-assembly Silurian Browns Creek Intrusive Complex and Davies Creek Granite dykes that intrude into the arc, and not adjacent Gondwanan sedimentary sequences. Zircon U[ϵ]_{Pb} dating integrated with CL imagery indicate two igneous phases at 430-437 Ma and 420-426 Ma and a zircon recrystallisation phase at 395-396 Ma attributed to a late thermal event. The magmatic zircon initial ϵ Hf values vary from -5.1 to +4.7. This signature indicates the source of these granitic rocks is strongly influenced by typical pre-Silurian Gondwanan material. Granitic rock and zircon compositions demonstrate that at the likely temperature of the Silurian granitic magma, especially the Davies Creek Granite dykes, inherited source zircons were mostly dissolved, explaining the absence of pre-Ordovician xenocrysts within the zircon population. The unradiogenic Hf isotopic signatures preserved in the Silurian magmatic zircons demonstrate the contribution of Gondwanan crustal material to the magma source region. These results support the interpretation of the Macquarie Arc as an intra-Panthalassa ocean allochthon, emplaced and resting over the edge of Gondwanan crystalline basement, possibly including the continent-derived sedimentary rocks of the Adaminaby Group.

Publication Details

Zhang, Q., Nutman, A., Buckman, S. & Bennett, V. (2020). What is underneath the juvenile Ordovician Macquarie Arc (eastern Australia)? A question resolved using Silurian intrusions to sample the lower crust. *Gondwana Research*, 81 362-377.

What is Underneath the Juvenile Ordovician Macquarie Arc (Eastern Australia)? A Question Resolved using Silurian Intrusions to Sample the Lower Crust

Qing Zhang ^{a*}, Allen Nutman ^a, Solomon Buckman ^a, Vickie C. Bennett ^b

*Corresponding author: qz576@uowmail.edu.au

a. School of Earth, Atmospheric and Life Sciences, University of Wollongong, 2522,
NSW, Australia

b. Research School of Earth Sciences, Australian National University, 2061, ACT,
Australia

Abstract

The Ordovician intra-oceanic Macquarie Arc of eastern Australia collided with the eastern Gondwanan margin at ~440 Ma. However, the deep crustal architecture resulting from this assembly is poorly known. This is addressed here by a zircon U-Pb-Hf study of the post-assembly Silurian Browns Creek Intrusive Complex and Davies Creek Granite dykes that intrude into the arc, and not adjacent Gondwanan sedimentary sequences. Zircon U-Pb dating integrated with CL imagery indicate two igneous phases at 430-437 Ma and 420-426 Ma and a zircon recrystallisation phase at 395-396 Ma attributed to a late thermal event. The magmatic zircon initial ϵ_{Hf} values vary from -5.1 to +4.7. This signature indicates the source of these granitic rocks is strongly influenced by typical pre-Silurian Gondwanan material. Granitic rock and zircon compositions demonstrate that at the likely temperature of the Silurian granitic magma, especially the Davies Creek Granite dykes, inherited source zircons were mostly dissolved, explaining the absence of pre-Ordovician xenocrysts within the zircon population. The unradiogenic Hf isotopic signatures preserved in the Silurian magmatic zircons demonstrate the contribution of Gondwanan crustal material to the magma source region. These

results support the interpretation of the Macquarie Arc as an intra-Panthalassa ocean allochthon, emplaced and resting over the edge of Gondwanan crystalline basement, possibly including the continent-derived sedimentary rocks of the Adaminaby Group.

Key words: Browns Creek Intrusive Complex, Davies Creek Granite dykes, zircon U-Pb-Hf isotopes, Macquarie Arc, basement

Graphic abstract:

1. Introduction

Intra-oceanic island arcs are key components in the progressive growth of eastern Gondwana, such as the Ordovician Macquarie Arc within the Lachlan Orogen, eastern Australia (Crawford et al., 2007; Glen et al., 2009; Meffre et al., 2007). Thus, understanding the emplacement of the intra-oceanic island arcs is important in any model proposed for the growth and stabilisation of eastern Gondwana. The Macquarie Arc is in faulted contact with coeval quartz-rich turbidites of the Adaminaby Group, which developed as a passive margin sequence along the east Gondwana continental margin (Glen et al., 2002; Meffre et al., 2007) (Fig. 1a, b). Debates exist as to the allochthoneity of the Macquarie Arc with the following three possibilities: (1) a continuously west-dipping subduction zone associated with a retreating

accretionary orogeny, with the Macquarie Arc representing an autochthonous marginal back arc to proximal island arc system (Cawood et al., 2009; Collins, 2002; Glen, 2013), (2) collision of an allochthonous, exotic island arc formed within the Panthalassa Ocean via east-dipping subduction before being obducted onto the passive margin of eastern Gondwana, followed by a subduction flip and continental arc volcanism (Aitchison and Buckman, 2012), or (3) rotation of an arc off-board of Gondwana, leading to its accretion onto the continental margin (Fergusson and Colquhoun, 2018; Gray and Foster, 2004). The first two of these scenarios are summarised in Figure 2, with indication of how they can be differentiated via the U-Pb-Hf zircon study of post accretion assembly Silurian granitic rocks.

A recent study reinforced that the Macquarie Arc was initiated within the Panthalassa ocean remote from Gondwana, as demonstrated by the juvenile zircons (initial ϵ_{Hf} = +12 to +14) from the early arc samples (Zhang et al., 2019a). However, details of the amalgamation of the arc with Gondwana and the resulting deep crustal architecture were unresolved. This study targets the Silurian-Devonian granitic rocks that intrude the Macquarie Arc in order to ‘sample’ their deep crustal source region. This technique is used because granitic magmas carry the isotopic and chemical characteristics from their source regions, which could also be influenced by their surrounding country rocks via assimilation, providing a window to the underlying basement (e.g., Baadsgaard et al., 1986; Chappell et al., 1988; Jeon and Williams, 2018; Moorbath et al., 1981). Integrating whole rock isotopic signatures with U-Pb-Hf zircon studies is providing ever more high-resolution information on the deep crustal sources of granites in eastern Australia (Jeon et al., 2012). This technique, U-Pb-Hf isotopic studies on the post-collision intrusions, could also be widely applied to any exotic terranes, to constrain the emplacement mechanism (e.g., Chappell et al., 1988; Nutman et al., 2008).

Our working hypothesis is that if the Macquarie Arc is allochthonous, it likely represents a vast klippe that overlies the Gondwanan continental margin and is likely to display

continental inheritance within the Silurian granitic bodies cutting it (Fig. 2b). This study focusses on the Browns Creek Intrusive Complex and Davies Creek Granite (dykes) because they intrude the Macquarie Arc and are located at least 10-20 km from exposures of the quartz turbidites of the Gondwanan-sourced Adaminaby Group (Fig. 1c). These two intrusions compositionally plot on the I-, S-type granite transitional line of Chappell et al. (1988). We combine the petrology, zircon U-Pb-Hf isotopes, whole rock geochemistry and previous zircon U-Pb and Sr-Nd studies to establish the deep crustal structure under the Macquarie Arc.

2. Geological setting

The Tasmanides represents one sector of the great Terra Australis Orogen that developed as an ~18,000 km long orogen on the Pacific margin (Cawood, 2005), and records Cambrian to Triassic crustal evolution (e.g., Glen, 2005; Rosenbaum, 2018). The Ordovician-Devonian Lachlan Orogen within the southeastern Tasmanides (Fig. 1a) is dominated by massive Ordovician quartz-rich turbidites of the Adaminaby Group, coeval intra-oceanic Macquarie Arc volcanic rocks (Glen, 2005; Meffre et al., 2007; Zhang et al., 2019a), and Silurian-Devonian igneous and sedimentary rocks (Champion, 2016; Fergusson, 2010; Foster and Gray, 2000; Glen, 2005; Rosenbaum, 2018; VandenBerg, 2000). The Macquarie Arc is in faulted contact to the east and west with the quartz-rich turbidites (Fig. 1b, c; Fergusson and Colquhoun, 2018; Meffre et al., 2007).

The Browns Creek Intrusive Complex was originally named as ‘Carcoar Granodiorite’ (Pogson and Watkins, 1998 and references therein), which covers most parts of the intrusive complex, except the more mafic phase ‘Long Hill Diorite’ near Browns Creek (Fig. 1c; Fig.S1; Pogson and Watkins, 1998). This paper uses term ‘Browns Creek Intrusive Complex’, after Kovacs (2000), including the Carcoar Granodiorite, Long Hill Diorite in the north-western part of the intrusion, and the Browns Creek dykes (Ming Dyke Group), some of

which intruded into the Ordovician Cowriga Limestone Member (Figs. 1, 3; Fig. S1). It crops out over ~87 km² and lies to the southwest of Blayney, where it intrudes Ordovician Macquarie Arc units including the Stokefield Metagabbro, Blayney Volcanics, Cowriga Limestone Member and Coombing Formation (Figs. 1, 3; Fig. S1; Pogson and Watkins, 1998). It is faulted against the Late Ordovician Tallwood Monzonite and the Weemalla Formation along the Carcoar Fault to the west (Fig. S1; Fig. 3; Pogson and Watkins, 1998). This intrusion may have experienced up to three deformation events (Lennox et al., 1998).

The Davies Creek Granite occurs to the northeast of Rockley, and includes two plutons with surface expressions of ~70 km² and 15 km², and is cut by a series of north-south striking Carboniferous dolerite dykes (Fig. S1; Colquhoun et al., 2017) and some syn-tectonic granophyre dykes (Fowler and Lennox, 1992). These plutons intrude tightly folded Ordovician Rockley Volcanics of the Macquarie Arc, dominated by greenschist-facies meta-volcaniclastic and volcanic rocks (Fig. S1; Fowler and Lennox, 1992; Pogson and Watkins, 1998).

3. Previous studies and new samples

3.1 Previous studies

The Browns Creek Intrusive Complex including the granodiorite (Carcoar Granodiorite), more mafic part near Browns Creek (Long Hill Diorite) and the dykes, has been dated with a variety of isotopic methods (Table 1). For the granodiorite, the zircon U-Pb dating method gives somewhat older ages of 430-434 Ma than other methods such as Ar-Ar and Rb-Sr at 407-416 Ma (Table 1). It is the same for the dykes which have slightly older U-Pb zircon ages at 436-437 Ma compared with 423-424 Ma using the Ar-Ar method on biotite and hornblende. Microdiorite and skarn near the Browns Creek Mine give ages at 423 Ma and 407 Ma via the K-Ar method on hornblende and Ar-Ar on biotite, respectively (Table 1). To compare with our new zircon U-Pb ages, we replotted the zircon data including samples NH29,

NH43, NH48 and MG5785 (Fig. 4). A dyke sample NH29 from Kovacs (2000) shows a recrystallized age at 420.4 ± 4.4 Ma (2σ) and igneous age at 436.3 ± 5.2 Ma (2σ), and some cores with ages at 2148 Ma and 567 Ma. Dyke sample NH43 has a weighted mean zircon $^{206}\text{Pb}/^{238}\text{U}$ age of 437.1 ± 5.9 Ma with no inherited zircon cores (Kovacs, 2000). A granodiorite sample NH48 has a zircon $^{238}\text{U}/^{206}\text{Pb}$ weighted mean age of 429.8 ± 3.4 Ma with a few inherited zircon cores reported by Kovacs (2000). Using the Pb-evaporation method, Lennox et al. (1998) obtained an age of 426.6 Ma from a Browns Creek granodiorite sample. Sample MG5785 (Lennox et al., 1998) has a weighted mean zircon $^{238}\text{U}/^{206}\text{Pb}$ age of 434.4 ± 5.5 Ma, with two older ages at 450 Ma and 448 Ma which might indicate the inheritance of the Macquarie Arc or the composite ages of the zircon rims and Precambrian cores.

The Davies Creek Granite was dated using the Rb-Sr method on biotite at 327 Ma (Lennox et al., 1998). The ages of surrounding Silurian-Devonian granitic and volcanic rocks intruding/overlying the Adaminaby Group are summarized in Figure 4 and Table 1. The Sunset Hills Granite (Lennox et al., 1998) has a weighted mean zircon $^{238}\text{U}/^{206}\text{Pb}$ age of 430.1 ± 3.7 Ma and has inherited zircon cores with ages of 480 Ma, 486 Ma and 557 Ma. The age of the Canowindra Volcanics is 432.0 ± 5.0 Ma, with inherited cores of 495-1011 Ma detected (Atton, 2013). The Mullions Range Volcanics have a zircon $^{238}\text{U}/^{206}\text{Pb}$ weighted mean igneous age at 433.5 ± 4.7 Ma with evidence of recrystallisation at 421.6 ± 6.7 Ma, and 542-614 Ma inherited cores (Atton, 2013). The Bay Formation has a zircon $^{238}\text{U}/^{206}\text{Pb}$ weighted mean age of 411.3 ± 4.9 Ma with 516-715 Ma cores (Atton, 2013).

3.2 New samples

Representative samples from the Browns Creek Intrusive Complex and Davies Creek Granite dykes were chosen for this study, because they were intruded into the Ordovician Macquarie Arc, which could potentially sample the lower crust below the arc exposed at the surface. The whole rock geochemistry and zircon studies of these samples would indicate

whether these intrusions derived from sources as juvenile as the Macquarie Arc, or less juvenile, due to Gondwanan continental influence. The result could detect what is underneath the Macquarie Arc, the arc itself or the continental basement. For the Browns Creek Intrusive Complex, granodiorite sample 17BC01 (Fig. 5a; Fig. S2a), leucogranite sample 17BC02 (Fig. 5b) and a drill core granodiorite sample (BC06; Fig. 5c) were geochemically analysed. A representative granodiorite sample BC06 was used for zircon studies. To our knowledge, the Davies Creek Granite has no previous zircon U-Pb ages, and no Hf or Nd isotope data reported. In most of the outcrops, only aplite dykes are apparent, but no typical granite country rocks crop out (Fig. 5d; Fig. S2b, c). Therefore, we studied two aplite dyke samples 17DC01, 02 (Fig. 5e; Fig. S2d) using zircon U-Pb-Hf analyses. Sample locations are presented in Figure 1, Figure S1 and Supplementary 2 ds1.

Sample 17BC01 is medium-grained granodiorite (Fig. 5f) with a fine-grained granodiorite xenolith (17BC01i; Fig. S2e). Plagioclase is euhedral, altered and zoned, and quartz shows undulose extinction. Hornblende and plagioclase are interlocked in the xenolith. Sample 17BC02 is medium-fine grained leucogranite dominated by quartz and plagioclase with a small amount of biotite and hornblende (Fig. 5g). Quartz exhibits undulose extinction. Sample BC06 is medium-grained granodiorite with ~40-50% plagioclase, 30% quartz, 15-20% hornblende and biotite, and small amounts of smaller K-feldspar grains (Fig. S2f). Plagioclase is altered with dusty appearance and some of the crystals are zoned. Some quartz grains show corrosion embayment. Hornblende is more common than biotite. A late quartz vein in this sample may indicate a late thermal event superimposed on the granite (Fig. S2g). Sample 17DC01 is fine-grained foliated granite (aplite) with coarser grained quartz and plagioclase at 1-2 mm (Fig. 5h) and it has some granophyric textures. A fabric is given by weak orientation of sericite, representing a late deformation event. Sample 17DC02 is fine-grained foliated

granite (aplite) with granophyric and myrmekite textures (Fig. 5i). Biotite grains show flexure. Muscovite veins indicate a superimposed hydrothermal event (Fig. S2h).

4. Analytical methods

4.1 SHRIMP zircon U-Pb analyses

Zircons were separated by initial rock crushing to fine sand size, sieving, washing and then heavy liquid and magnetic separations. Zircon concentrates were further purified by hand-picking under a binocular microscope at the Institute of Hebei Regional Geological Survey, China. Selected zircons and reference zircons Temora 2 were cast into epoxy resin. After polishing the mounts, cathodoluminescence (CL) images were obtained via the Scanning Electron Microscope JSM-6490 MonoCL4 at the University of Wollongong (UOW).

Zircon U-Pb analyses were performed using the SHRIMP RG instrument at the Australian National University (ANU), following the methods described by Williams (1998). The primary O₂-ion beam intensity was 4-6 nA. Each site was rastered for 120s prior to analysis and the spot size was ~15-20 µm. ²⁰⁶Pb/²³⁸U was calibrated using the Temora standard (417 Ma, Black et al., 2003), and U abundance was calibrated using the reference zircon SL13 (U = 238 ppm) in a set-up mount. The raw data were reduced using the ANU application *POXI-SC*, and then plotted and assessed using Isoplot 4.1 (Ludwig, 2003). The data are presented in Supplementary 2 ds2 (Mean age calculations are presented at 2σ).

4.2 Zircon Hf isotopes

Zircon Hf isotope analyses were conducted on a ThermoFinnigan Neptune multi-collector ICPMS with 193 nm excimer laser system at ANU, following the protocols by Hiess et al. (2009). The laser was fired at a repetition rate of 5 Hz with the energy density at ~10 J/cm² with a square 42 x 42 µm spot. Analysis of a gas blank and a suite of 6 reference

zircons (Mud Tank, QGNG, 91500, Plesovice, FC-1 and R-33) with varying $^{176}\text{Hf}/^{177}\text{Hf}$ and $^{176}\text{Lu}/^{177}\text{Hf}$ ratios were performed after every 10 unknown sample spots as quality control monitors. The results for all reference zircons are within error of accepted values.

The Hf isotope analytical sites coincided with the U-Pb SHRIMP sites, but with the addition of six more analyses on grains with no age determinations. Complete Lu-Hf isotopic data for all samples and reference zircons along with a detailed method description are presented in Supplementary 2 ds3, 4.

4.3 Whole rock geochemistry

Five representative less altered samples (17BC01, 02, BC01, 17DC01, 02) were crushed using a Cr-Ni TEMA mill, and as a consequence V, Cr, Co and Ni abundances may be compromised, and are not used in interpretations. The major element analyses were carried out on a SPECTRO XEPOS X-ray fluorescence instrument at UOW, following the protocols of Norrish and Chappell (1977). The uncertainties are <3%. The trace element analyses were conducted at the ALS Mineral Division, Brisbane, with a 10% tolerance of error. A prepared sample is digested with four-acid digests (hydrofluoric, perchloric, hydrochloric and nitric acid), and then analysed via Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES) and Inductively Coupled Plasma-Mass Spectroscopy (ICP-MS). In this procedure, accessory phases concentrating the rare earth elements (REEs) may not be totally soluble. The sample results were presented in Supplementary 2 ds5. Further information on standards for quality control monitoring can be obtained from the ALS laboratories.

5. Results

5.1 U-Pb geochronology

From the Browns Creek Intrusive Complex, 25 grains from sample BC06 were analysed, including three analyses on the zircon margins. These zircons display prismatic to

stumpy morphology, with aspect ratio ranging from 1:1 to 3:1 (Fig. 6a). Most of the grains have fine-scale oscillatory zoning and some have banded or patchy internal texture. The Th contents mainly range from 158 to 1195 ppm and U contents range from 42 to 534 ppm, with Th/U ratios ranging from 0.26 to 0.83. The weighted $^{206}\text{Pb}/^{238}\text{U}$ mean age of three zircon margin analyses (#2.1, 3.1, 13.1) is 396.3 ± 5.7 Ma (2σ), representing the timing of recrystallisation. The age of predominant igneous zircon is 426.1 ± 2.2 Ma (2σ) (Fig. 6c, c1).

For the Davies Creek Granite dyke, a total of 28 grains from sample 17DC02 and 7 grains from 17DC01 were analysed. Most grains are prismatic with fine-scale oscillatory zonation and an aspect ratio at $\sim 1:2$. Some of the grains have obvious recrystallised rims (e.g. #1.2 in Fig. 6b). Because in the first analytical session sample 17DC02 had three age peaks based on 23 analyses, a second analytical session was undertaken with 5 more analyses on the same sample and 7 analyses on sample 17DC01. Thorium contents are 38-393 ppm, U contents are 71-606 ppm and Th/U ratios are 0.38-0.76. Although there are only 7 analyses on sample 17DC01, it shows the same age range as sample 17DC02. Thus, the data from both samples are treated together (Fig. 6d, d1). Analysis #10.1 in the middle of the grain with $^{206}\text{Pb}/^{238}\text{U}$ age at 381.3 Ma was deemed as a Pb loss spot based on a second analyses on the margin of the same grain #10.2 with a marginally older age of 393.9 Ma (Fig. 6b). Analysis #2.1 is similar to #10.1 with an age at 385.4 Ma. Therefore, these two analyses are interpreted as displaying ancient loss of radiogenic Pb and were not included in the weighted mean age calculation. Using the Gaussian deconvolution method in Isoplot (Ludwig, 2003), the other 33 analyses display three main components at 394.6 ± 3.4 Ma, 417.4 ± 4 Ma and 434.7 ± 3.0 Ma (2σ) (Fig. 6d, d1). Based on the occurrence of the samples (aplite dyke) and CL images, 394.6 ± 1.7 Ma represents the dyke igneous age (e.g. #1.2) and 434.7 ± 1.5 Ma represents the inherited granite age (Davies Creek Granite age). 417.4 ± 2 Ma may represent a composite age of the dyke and

the Davies Creek Granite, or a separate recrystallization event, which is not possible to resolve from the CL images (e.g. #11.1).

5.2 Hf isotopic composition

Lu-Hf isotope analyses were performed on 22 grains of sample 17DC02. The result shows initial $^{176}\text{Hf}/^{177}\text{Hf}$ values ranging from 0.2824 to 0.2826. Initial $\epsilon_{\text{Hf}}(t)$ values range from -5.1 to +4.7 when calculated by their corresponding weighted mean ages at 394 Ma, 417 Ma and 435 Ma (Figs. 6d, 7; Supplementary 2 ds5).

5.3 Whole rock geochemistry

Three representative samples BC01, 17BC01 and 17BC02 from the Browns Creek Intrusive Complex, and two samples 17DC01 and 17DC02 from the Davies Creek Granite dykes were analysed. Davies Creek dykes and 17BC02 fall in the granite field in the TAS (total alkali silica) diagram (Fig. 8a) with peraluminous affinity (Fig. 8b). Samples 17BC01 and BC06 are granodiorite with metaluminous affinity (Fig. 8a, b). Davies Creek dykes have strong Nb, Sr and Ti negative anomalies, while Browns Creek granites have no obvious Sr anomaly, and less negative Ti anomaly (Fig. 8c). In the REE diagram, Davies Creek dykes have relatively higher ΣREE , stronger Eu negative anomaly and variable Ce content than the Browns Creek Intrusive Complex samples (Fig. 8d). The Ce positive anomaly of sample 17DC02 (Fig. 8c, d) may be due to high monazite (Ce) content. The Davies Creek samples have slightly lower fractionation with La/Yb(N) ranging from 3.0 to 5.1 than the Browns Creek Intrusive Complex with La/Yb(N) at 4.5-7.9 (Supplementary 2 ds5).

In the composition-temperature diagram (Fig. 8e), the zircon saturation temperature of the Davies Creek samples is between 800°C and 850°C. Sample 16BC02 from the Browns Creek Intrusive Complex is between 750°C and 800°C and two other samples are lower than 700°C. Most Davies Creek and Browns Creek samples fall in a volcanic arc field

except sample 17DC02 is on the boundary to oceanic ridge granite (Fig. 8f) or within-plate granite field (Fig. 8g).

6. Discussion

6.1 Zircon U-Pb ages and tectonic setting of the granitic rocks

6.1.1 Zircon U-Pb ages

For these granitic rocks, we conclude that there are two intrusive phases and one thermal/deformation event. Phase1 (430-437 Ma; Fig. 3) is represented by Davies Creek Granite age (17DC01, 02; Fig. 6d) and some Browns Creek samples (NH29, NH43, NH48 and MG5785) including Browns Creek granodiorite and some dykes, which is coeval with the Sunset Hills Granite and Canowindra Volcanics at 430 Ma and 432 Ma respectively (U-Pb age; Table1). Phase 2 is the second intrusive phase at 420-426 Ma (Figs. 3, 6a, 6c), represented by Browns Creek granodiorite (BC06) and some dykes (NH29; Fig. 4a); The Browns Creek granodiorite (BC06) igneous age reported here is 426.1 ± 2.2 Ma which is indistinguishable from 426.6 ± 2.3 Ma obtained by Lennox et al., (2005) using the Pb-evaporation method (Table1). It is the same phase as the 425 Ma Wyangala Granite and the Barry Granodiorite (Lennox et al., 2014; Table 1). Phase 3 is represented by Browns Creek granodiorite recrystallisation age (BC06) and Davies Creek dyke age (17DC01, 02) at 394-396 Ma (Fig. 6c, d; Fig. 3).

The Ar-Ar (on biotite and hornblende) ages of the Browns Creek basaltic dyke are 424-427 Ma (Table 1) which may correspond with the phase 1 (430-437 Ma), while the Ar-Ar ages (on biotite and hornblende) of the Browns Creek granodiorite at 414-416 Ma (Table 1) are consistent with the Barry Granodiorite Ar-Ar age, and a Rb-Sr (on biotite) age of 407 Ma from skarn near the Brown Creek Mine. This may correspond with the phase 2 (420-426 Ma)

(Table 1; Fig. 3). The Sunset Hills Granite Ar-Ar age (on biotite) of 363-371 Ma might also correspond to the post-magmatic thermal event of recrystallization phase 3 (Fig. 3a). Samples with ages determined using Rb-Sr and Ar-Ar analysis on biotite or hornblende, show younger ages than using the zircon U-Pb dating method. This is because hornblende and biotite have lower closure temperature than the magmatic granite crystallization dated by U-Pb zircon (Ickert and Williams, 2011; Lennox et al., 1998; Lennox et al., 2005), and consequently the ages determined by different methods can vary by 2-28 million years for these rocks (Lennox et al., 2005). Another factor is that the biotite or hornblende may be affected by the late deformation and alteration, especially for the Barry and Sunset Hills Granites which experienced different degrees of deformation (Lennox et al., 1998).

6.1.2 Tectonic setting

Phase 1 (430-437 Ma): Most of the Browns Creek samples fall in the volcanic arc field as also some of the coeval S-type granites (e.g. Cowra Granodiorite; Fig. 8f, g). Because the Browns Creek Intrusive Complex is coeval with the S-type granites, it probably has the same setting as the S-type granite, which is related to crustal thickening associated with the Late Ordovician to Early Silurian Benambran Orogeny (Collins and Hobbs, 2001; Glen et al., 2007). Ickert and Williams (2011) suggested the S-type granites occurred in a supra-subduction zone setting which is the continuation of subduction-related magmatic activity from the Macquarie Arc.

Phase 2 (420-426 Ma) is consistent with the Wyangala Granite crystallisation age at 425 Ma (Lennox et al., 2005). The 417 Ma age apparent in the Davies Creek samples may be a composite age of the dyke and inherited granite. Or it could be related to the isotopic resetting or regional cooling during uplift of the country granites associated with the Bindian event (Lennox et al., 2014; Lennox et al., 2005; Scheibner and Basden, 1998). This 417 Ma event

has also been reported by Lennox et al. (2005) in relation to new biotite growth in the Browns Creek granodiorite.

Phase 3 (~396 Ma) may be a thermal phase, and correlates with a 396 Ma event reported in eastern Tasmania (McClenaghan and Higgins, 1993; Reed, 2001). Other deformation events at 387-363 Ma in this area have been reported based on the mica from the shear zones by the Ar-Ar dating method (Glen et al., 1999; Lennox et al., 2014; Lennox et al., 1998; Packham et al., 1999). As indicated by Lennox et al. (2005), there is a 2-28 million years interval between granite crystallisation and hornblende closure. Therefore, this thermal event may be in the same deformation event related to pre- to syn- Tabberaberan event (Spaggiari et al., 2003; Willman et al., 2002).

6.2 Zircon inheritance and Hf isotope signatures

In this study, zircon populations from the Davies Creek and Browns Creek granitic rocks provided no obvious xenocrysts. However, Kovacs (2000) reported the presence of inherited cores from Browns Creek granodiorite with no ages presented, but also some from the dykes (Mine Dyke Group) with core ages of 567 Ma and 2148 Ma (Fig. 4a). There are some younger inherited ages from the Browns Creek granodiorite reported by Lennox et al. (2005) at 448 Ma and 450 Ma, which may represent inheritance from the Macquarie Arc or the composite age of older zircon core plus the rim. Some Early Ordovician to Cambrian zircon cores are also reported in the surrounding Silurian Sunset Hills Granite which intrudes into the Adaminaby Group (Lennox et al., 2005; Figs. 1, 4e). A similar range of Gondwanan derived zircon cores (495-1011 Ma) are observed in equivalent Silurian-Devonian volcanic units, including the Canowindra Volcanics, Mullions Range Volcanics and the Bay Formation, which unconformably overlie the Ordovician Adaminaby Group and Macquarie Arc (Figs. 1, 4f-h). The inherited cores from the Browns Creek dykes (Mine Dyke Group) may indicate the existence of a Precambrian basement beneath the Macquarie Arc, given that very few if any

Precambrian zircons are present in the Macquarie Arc which displays a distinctly Ordovician-only zircon range (Zhang et al., 2019a).

Although very few inherited zircon xenocrysts occur in the Davies Creek dykes and Browns Creek Intrusive Complex, the Hf, Nd and Sr isotopic compositions suggest the influence of ancient continental crust. The initial ϵHf values (-5.1 to +4.7) of the Davies Creek dykes indicate older continental crust contributed to the magma. If the magma was sourced exclusively from the root of the intra-oceanic Macquarie Arc which has been shown to have very few inherited zircons and mostly juvenile initial ϵHf values in zircons of +8 to +15 (Fig. 7a, b), the initial ϵHf in zircons from Davies Creek dyke would be similar to those in the host Macquarie Arc rocks. Therefore, there must be significantly older continental basement or Gondwana-derived sedimentary units such as the Adaminaby Group underneath the Macquarie Arc, which contributed to the aplite dykes. Comparisons with zircons from the Delamerian and eastern Lachlan granites as well as detrital zircons from the Ordovician Adaminaby Group turbidite, show that the Davies Creek dyke has almost the same range of ϵHf values as Delamerian granite at -6.6 to +4.66, and the Davies Creek dyke zircon Hf isotopic signature is similar to the eastern Lachlan granites that have evolved from early Silurian juvenile monzonites to late Silurian evolved granites (Fig. 7b). Similarly, the Browns Creek Intrusive Complex initial ϵNd isotope values range from -5.9 to +2.44 which are distinctly less radiogenic (less juvenile) than the Macquarie Arc rocks that they intrude, but almost congruent with the Delamerian granites (Fig. 7c). It is also between the juvenile Macquarie Arc and evolved eastern Lachlan granite (Fig. 7c), representing an evolved magma source. The overall initial $^{87}\text{Sr}/^{86}\text{Sr}$ value ranges from 0.7045 to 0.7065 (Kjolle, 1997; Kovacs, 2000), which is consistent with late Delamerian A-type granite $^{87}\text{Sr}/^{86}\text{Sr}$ values at 0.7041-0.7060 (Turner and Foden, 1996), and within the range of typical Lachlan Orogen I-type granite values of 0.7045-0.712, but lower than the S-type granites of 0.709-0.718 (Chappell et al., 1990; King et al.,

1997; McCulloch and Chappell, 1982). This indicates the Browns Creek Intrusive Complex was probably derived from pre-Macquarie Arc felsic sources ultimately of igneous origin. Combining with the rare zircon inheritance of the Browns Creek Intrusive Complex and Hf values of the Davies Creek dykes, both these intrusions may be mainly derived from deep ancient continental crust underneath the Macquarie arc (e.g. Delamerian granite), with possibly some contamination of the Adaminaby Group and Macquarie Arc.

6.3 Geochemistry

The Browns Creek Intrusive Complex and Davies Creek dyke that intrude into the mafic rocks Macquarie Arc contain rare zircon xenocrysts, compared with abundant xenocrysts in the coeval S-type granites (e.g. Cowra Granodiorite, Sunset Hills Granite) and equivalent volcanic rocks (e.g. Canowindra Volcanics) that intrude/overlie the Adaminaby Group. This reflects the fact that they were derived from different source rocks, or the same source (Adaminaby Group) with just higher temperature resulting the melting of the zircon xenocrysts.

The Davies Creek dykes are low in Rb and alumina, has higher $\text{Na}_2\text{O}/\text{K}_2\text{O}$ (0.9-1.5; Supplementary 2 ds5) and largely lacking in inherited zircons, which contrasts with the classic S-type Silurian Cowra Granodiorite and Roseburg and Sunset Hills Granite (Fig. 8g, b). Higher Rb and alumina content in S-type magmas is provided by the incongruous melting of biotite and muscovite originally present in the clay-rich turbidites and shales of the Adaminaby Group source rocks (Offler and Fergusson, 2016). On the other hand, the dykes were sourced from the country rocks of the Davies Creek Granite, as shown by the mixed zircon ages (Fig. 6b, d). Thus, the Davies Creek Granite is possibly from sources with average granitic to tonalite composition, marked by much lower mica content and consequently lower volatile content. This is also shown in the melt composition diagram (Fig. 9) that the Davies Creek Granite

samples from previous studies mainly fall in the tonalite field, and dyke samples from this study are in the granite field. The zircon saturation diagram shows the likely magma temperature of the Davies Creek Granite dykes are around 820°C (Fig. 8f). As shown by experimental work (e.g., Patino Douce, 2004 and references therein), the melting temperature of such sources in the lower crust are high (800-850°C), meaning they can dissolve considerably more zircon until they become saturated in zirconium. Thus, the magma temperatures of the Davies Creek Granite are high, reducing the possibility of preserving inherited zircon from the source rocks. Thus, the Davies Creek Granite is mainly derived from the melting of lower crust with a granitic-tonalite composition.

Some of the Browns Creek samples (e.g. BC06) have much lower Rb and alumina and higher Na₂O/K₂O (e.g. BC06=2.36) compared with the typical S-type Cowra Granodiorite and Roseburg and Sunset Hills Granites (Fig. 8b, g). The melt composition diagram (Fig. 9) shows most of the Browns Creek Intrusive Complex samples falling in the tonalite and granodiorite fields and some in the granite field. However, the likely magma temperature of some granodiorites (e.g. BC06, 17BC01) have similar magma temperature at 600-700°C with the S-type granite and some I-type (e.g. Barry Granite; Fig. 8e), and some (e.g. 17BC02) have a likely magma temperature of 750-800°C (Fig. 8e). According to the melting composition experiments, the lower crust melting starts at ~650°C in metasedimentary rocks (Hermann, 1997 and references therein) but at higher temperature (~800-850°C) for the tonalitic rocks (Patino Douce, 2004) and the widespread melting in middle crust occurs at ~700°C (Harris et al., 1995). Considering some Browns Creek samples have lower magma temperature as the S-type granite (600-700°C) but with rare zircon xenocrysts, the possible source material of the Browns Creek Intrusive Complex is likely from middle to lower crust with a mixed component of granitic-tonalitic crystalline and sedimentary rocks of the Adaminaby Group.

6.4 What lies beneath the Macquarie Arc

Based on the initial zircon Hf and whole rock Nd isotopic compositions of the Browns Creek and Davies Creek intrusions (Fig. 7), the Macquarie Arc is most likely to represent an extensive thrust sheet derived from Panthalassa ocean, which was emplaced onto the Gondwana crust, with geochemical and isotope signatures more like Delamerian crystalline rocks than the Adaminaby Group sedimentary rocks. This thrust sheet was disrupted by later folding and faulting (e.g. Glen and Watkins, 1999). This supports the hypothesis that the Macquarie Arc is not a deeply rooted autochthonous arc but rather more likely to be an allochthonous klippe (Aitchison and Buckman, 2012) (Figs. 2a, 10). Therefore, from this perspective, the Macquarie Arc was much less likely initiated via continually west dipping subduction with back-arc spreading (Cawood et al., 2009; Collins, 2002; Glen, 2013), or amalgamation of the terranes only through the rotation (Fergusson, 2009; Fergusson and Colquhoun, 2018; Glen et al., 2009), because in either cases it would have the root deep into the lithosphere containing only arc crust from its earliest stages. Further, the seismic reflection profile also detected a non-exposed layer at 20-25 km underneath the Macquarie Arc (Glen et al., 2002), which was suggested as Cambrian-Ordovician MORB volcanic rocks.

6.5 Implications

Zircon inheritance studies of post-collision granites have the potential to provide important information relating to the deep structure of the lower crust. It could be widely applied to other proposed exotic terranes to deduce the composition and nature of inaccessible basement. Even in the cases, where there are no inherited zircons being detected, the zircon Hf isotope or whole rock Nd studies can still reveal if the magma has ancient continental contamination or not (e.g., Jeon and Williams, 2018; Nutman et al., 2008).

7. Conclusions

1) The Browns Creek granodiorite from this study has an igneous age of 426.1 ± 2.2 Ma upon which an event caused recrystallization at 396.3 Ma. The Davies Creek dyke has an igneous age of 394.6 ± 3.4 Ma, and Davis Creek Granite age is 434.7 ± 1.5 Ma. These granites have three main phases: Phase 1 is an intrusive event at 430-437 Ma related to widespread extension following the Benambran Orogeny at about the Ordovician-Silurian boundary. Phase 2 is the second intrusive event at 420-426 Ma. Phase 3 is a recrystallization event at 395-396 Ma which is likely related to the pre-Tabberabberan Orogeny.

2) The Browns Creek Intrusive Complex and Davies Creek dyke intrude into the juvenile Macquarie Arc but display significantly low zircon initial ϵ_{Hf} (-5.1 to +4.7) and whole rock initial ϵ_{Nd} values (-5.9 to +2.44; Kjolle, 1997; Kovacs, 2000), and contain rare Cambrian and older zircon xenocrysts. These suggest the Gondwanan continental crust may underlie the Macquarie Arc and contributed to these lower crustal melts. Therefore, the Macquarie Arc is less likely to represent a deeply rooted autochthonous arc but rather an allochthonous island arc that was thrust over the Gondwanan continent.

3) Both studied granites have very rare pre-Ordovician zircon xenocrysts and lower Rb content than the coeval S-type granites, and they have similar evolved Hf and Nd isotope values as the Delamerian granites. These indicate the continental basement underneath the Macquarie Arc is probably dominated by Delamerian granitic-tonalitic crystalline rocks with possibly some sedimentary rocks of the Adaminaby Group which are derived largely from erosion of the Delamerian Orogen.

Acknowledgements

This study is supported by GeoQuest Research Centre, University of Wollongong and the China Scholarship Council (No.201506400054). We give our thanks to

463 Jessica Walsh and Ryan Manton for assistance in the field. Thank you to Chris Fergusson and
464 Lloyd White for helpful discussions. Yang Song assisted with zircon separation of the Davies
465 Creek Granite dyke samples. Tom McMahon assisted with CL imaging on the SEM at UOW
466 Electron Microscopy Centre. Paul Carr and Jose Abrantes assisted with sample preparation and
467 whole rock major element XRF analyses. We thank Dr Robin Offler and an anonymous
468 reviewer providing detailed comments for improvement.

469 Data availability: Analytical data of this study are available in Supplementary 1-2.

470

472
473 Fig. 1. a) Orogenic belts of the Tasmanides in eastern Australia (after Glen, 2005, 2013). b)
474 Location of the Macquarie Arc and Adaminaby Group within the Lachlan Orogen in
475 central New South Wales. c) Simplified lithologic map of the Blayney-Rockley area
476 with sample localities. Maps b, c are after Colquhoun et al. (2017). A detailed map of the
477 study area (Fig. 1b) can be found in Supplementary 1 Fig. S1. Detailed locations of
478 samples from this study are presented in Supplementary 2 ds1. *These ages are from
479 previous studies and detailed references are given in Table 1.

Fig. 2. Two proposed emplacement mechanisms of the Macquarie Arc into the middle of the Adaminaby Group (After Aitchison and Buckman, 2012). a) The Macquarie Arc was thrust onto the passive margin of eastern Gondwana as an allocthonous terrane. In this case, the Macquarie Arc is thin-skinned with no 'root' deep into the lithosphere. The post-collisional granites intruded into the arc would possibly have inherited zircons and less juvenile affinity compared with the juvenile arc via initial ϵ_{Hf} . b) The Macquarie Arc was initiated via continued western subduction in a back-arc setting and ended up with the closure of the back-arc as an autocthonous terrane. In this model, the

489 Macquarie Arc would have the 'root' deep into the lithosphere, and therefore, the
490 granites would have juvenile zircons and almost no pre-Ordovician zircon inheritance.

Fig. 3. a) Simplified stratigraphy of the Lachlan Orogen with orogenic events from Cambrian to Devonian. The orogenic events are after Glen (2013), Glen et al. (2007) and Fergusson (2017). The red intrusion (pluton) symbol represents intrusion phase 1 of this study, the pink intrusion symbol represents phase 2, and intrusion symbols with a white rim represent the phase 3 thermal/deformation and recrystallization event. These symbols are also applicable to Fig. 3b. b) Stratigraphy of the study area. *Browns Creek.-1 represents phase 1, and Browns Creek.-2 means phase 2 intrusion. Data sources: Unit names in red colour indicate the ages are from this study. The Cowra Granodiorite is calculated after Glen et al. (2016). Other Silurian unit ages are from previous study (details are present in Fig. 4 caption and Table 1). The Ordovician unit ages: Weemalla Formation is after Zhang et al. (2019b), the Stokefield Metagabbro and Tallwood Monzonite are after (Pogson and Watkins, 1998), the Coombing Formation is after Meffre et al. (2007).

Fig. 4. Zircon U-Pb ages from previous studies. a) Sample NH29 has two igneous ages and has pre-Ordovician inheritance. b) For sample NH43 (b), $^{207}\text{Pb}/^{206}\text{Pb}$ ages were used for calculation when zircons have U content >1000 ppm. c) Sample NH48 has a weighted mean age of 429.8 Ma. d) Sample MG5785 has a weighted mean age of 434.4 Ma and possibly has Ordovician inheritance. e) Sample SH2 has a weighted mean age of 430.1 Ma and Ordovician-Cambrian inheritance. f) Sample SCV2 has a weighted mean age of 432.0 Ma and pre-Ordovician inheritance. g) Sample SMU4 has an igneous age at 433.5 Ma, a recrystallisation age at 421.6 Ma (Rex = recrystallisation) and pre-Ordovician inheritance. Data sources: Samples NH29, 43, 48 (a, b, c) are after Kovacs (2000), samples MG5785 (d) and SH2 (e) are after Lennox et al. (2005), samples SCV2, SMU4 and DCB3 (f, g, h) are after Atton (2013).

Fig. 5. a) Browns Creek granodiorite sample (17BC01). b) Browns Creek leucogranite sample (17BC02). c) Browns Creek granodiorite (BC06) from drill core. d) Field occurrence of Davies Creek Granite dyke (17DC02: 33°39'2.00"S, 149°38'46.00"E). e) Davies Creek dyke sample (17DC02). f) Photomicrographs of the Browns Creek granodiorite (17BC01) with xenolith (Fig. S2a). g) Browns Creek leucogranite (17BC02). h-i) Davies Creek dyke samples. i) Granophyre with graphic intergrowths of quartz and plagioclase. Abbreviations: qtz-quartz, hb-hornblende, pl-plagioclase, bi-biotite, mus-muscovite.

Fig. 6. Representative CL images (a, b) and zircon U-Pb age results of the Browns Creek granodiorite and Davies Creek dyke. c, c1) Sample BC06 has an igneous age of 426.1 Ma and recrystallisation age of 396.3 Ma. d, d1) Samples 17DC01, 02 have a dyke igneous age of 394.6 Ma and inherited granite age of 434.7 Ma. Rex-age = recrystallisation age; Ig-age = Igneous age.

Fig. 7. Zircon Hf isotope data for the Davies Creek dyke (red dots in a, b). a, b) Hf isotope comparisons of Eastern Lachlan granites (Kemp et al., 2009), Macquarie Arc volcanic and volcanoclastic rocks (Glen et al., 2011; Zhang et al., 2019a; Zhang et al., 2019b), Adaminaby Group sedimentary rocks (Glen et al., 2017) and Delamerian granites (Kemp et al., 2009). Symbols in (a) are applicable to (b). c) Whole rock Nd isotope comparisons of the Browns Creek Intrusive Complex (Kjolle, 1997; Kovacs, 2000), Eastern Lachlan granites (Kemp et al., 2009), Macquarie Arc (Crawford et al., 2007) and Delamerian granites (Foden et al., 2002; Kemp et al., 2009).

Fig. 8. Whole rock geochemistry of the Browns Creek granodiorite and Davies Creek dyke, and comparisons with nearby Silurian-Devonian granites in the Blayney-Rockley area

including typical S-type granite (e.g. Cowra Granodiorite) and average data of typical I- and A- type granites of the Lachlan Orogen. a) Total alkali vs SiO₂ diagram (Middlemost, 1994), b) aluminous classification diagram (Maniar and Piccoli, 1989), c) spider diagram with Primitive mantle normalised, d) REE diagram with Chondrite normalised. c, d) normalisation values are from Sun and McDonough (1989). e) Zircon saturation diagram (Watson and Harrison, 1983), f-g) tectonic setting diagram (Pearce et al., 1984). The legend is applicable to a, b, c, f, g. *Browns Creek samples = Browns Creek Intrusive Complex samples. Data sources: Browns Creek samples of BC06, 17BC01, 02 and Davies Creek samples 17DC01, 02 are from this study. Average of I-type granite is an average of 1074 samples from Lachlan Fold Belt (Chappell et al., 1992). Barry and some Browns Creek samples (including dykes) are from Kovacs (2000) and references therein. **A-type granites are from the Mumbulla Suite (average of 8 analyses) and Gabo Suite (average of 9 analyses) (Collins et al., 1982). Other Browns Creek, Cowra, Davies Creek, Roseburg and Sunset Hills granitic samples are from Geoscience Data Resources compiled by Geological Survey of NSW.

Fig. 9. Feldspar normative An-Ab-Or diagram after Barker (1979). Samples 17BC01, 02, BC06 and 17DC01, 02 are from this study. The referenced samples are from the same references as Fig. 8.

Fig. 10. Emplacement of the allochthonous Macquarie Arc corresponds with the model 1 in Fig. 2a. The Browns Creek Intrusive Complex and Davies Creek Granite dyke intruding into the Macquarie Arc have some (rare) pre-Ordovician zircon xenocrysts and have similar initial Hf and Nd isotopes as the Delamerian granites. The result indicates the Macquarie Arc has crystalline basement of significant prehistory and possibly also Adaminaby Group as the footwall to the Macquarie Arc which is an allochthonous klippe.

571 Table 1. Summary of previous ages of the Browns Creek Intrusive Complex, Davies Creek
572 Granite and related Silurian-Devonian volcanic rocks in Blayney-Rockley area.

Group	Igneous age (Ma)(2 σ)	Method	Mineral	Data source
Browns Creek Intrusive Complex				
Mine Dyke Group (NH29)	436.2 $\pm$ 5.2*	U/Pb (SHRIMP)	zircon	Kovacs (2000)
Mine Dyke Group (NH43)	437.1 $\pm$ 5.9	U/Pb (SHRIMP)	zircon	Kovacs (2000)
Basaltic dyke	426.9 $\pm$ 0.6	Ar/Ar	alteration biotite	Perkins et al. (1995b)
Basaltic dyke	423.6 $\pm$ 1.0	Ar/Ar	alteration biotite	Perkins et al. (1995b)
Basaltic dyke	424.4 $\pm$ 1.0	Ar/Ar	alteration hornblende	Perkins et al. (1995b)
Microdiorite	423 $\pm$ 12.0	K/Ar	hornblende	Perkins et al. (1995a)
Skarn	~407	Ar/Ar	alteration biotite	Perkins et al. (1995a)
Long Hill Diorite	418.9 $\pm$ 2.8	Ar/Ar	hornblende	Perkins et al. (1995b)
Carcoar Granodiorite	426.6 $\pm$ 2.3	Pb-evaporation	zircon	Lennox et al. (2005)
Carcoar Granodiorite	407 $\pm$ 4.0	Rb/Sr	biotite	Lennox et al. (1998)**
Carcoar Granodiorite	414 $\pm$ 8.0	Ar/Ar	biotite	Perkins et al. (1995b)
Carcoar Granodiorite	413 $\pm$ 8.0	Ar/Ar	biotite	Perkins et al. (1995b)
Carcoar Granodiorite	416 $\pm$ 2.2	Ar/Ar	hornblende	Perkins et al. (1995b)
Carcoar Granodiorite (NH48)	429.8 $\pm$ 3.4	U/Pb (SHRIMP)	zircon	Kovacs (2000)
Carcoar Granodiorite (MG5785)	434.4 $\pm$ 5.5*	U/Pb (SHRIMP)	zircon	Lennox et al. (2005)
Other Groups				
Davies Creek Granite	327 $\pm$ 1.6	Rb/Sr	biotite	Lennox et al. (1998)
Barry Granodiorite	410.2 $\pm$ 11.6	K/Ar	hornblende	Lennox et al. (1998)
Barry Granodiorite	413 $\pm$ 8	Ar/Ar	hornblende	Lennox et al. (1998)
Barry Granodiorite	408.2 $\pm$ 11	K/Ar	hornblende	Lennox et al. (1998)
Barry Granodiorite	425.8 $\pm$ 1.9	Pb-evaporation	zircon	Lennox et al. (2005)
Sunset Hills Granite	371 $\pm$ 4	Ar/Ar	biotite	Lennox et al. (1998)
Sunset Hills Granite	378.8 $\pm$ 8.5	K/Ar	biotite	Lennox et al. (1998)
Sunset Hills Granite	363 $\pm$ 2	Rb/Sr	biotite	Lennox et al. (1998)
Sunset Hills Granite (SH2)	430.1 $\pm$ 3.7	U/Pb (SHRIMP)	zircon	Lennox et al. (2005)
Wyangala Granite	425.2 $\pm$ 3.5	U/Pb (SHRIMP)	zircon	Lennox et al. (2014)
Canowindra Volcanics (SCV2)	432.0 $\pm$ 5.0*	U/Pb (SHRIMP)	zircon	Atton (2013)

Mullions Range Volcanics (SMU2)	421.6±8.7*	U/Pb (SHRIMP)	zircon	Atton (2013)
Bay Formation (DCB3)	411.3±4.9*	U/Pb (SHRIMP)	zircon	Atton (2013)

573 Note: *samples have inherited zircons, **S. Shaw in Lennox et al., 1998

574 References

- 575 Aitchison, J.C., Buckman, S., 2012. Accordion vs. quantum tectonics: Insights into continental growth
576 processes from the Paleozoic of eastern Gondwana. *Gondwana Research* 22, 674-680.
- 577 Atton, H., 2013. Tectono-metallogenic evolution of Silurian to Devonian felsic volcanics of the
578 Lachlan Orogen, Orange region, School of Earth and Environmental Sciences. University of
579 Wollongong, p. 158.
- 580 Baadsgaard, H., Nutman, A., Bridgwater, D., 1986. Geochronology and isotopic variation of the early
581 Archaean Amitsoq gneisses of the Isukasia area, southern West Greenland. *Geochimica et*
582 *Cosmochimica Acta* 50, 2173-2183.
- 583 Barker, F., 1979. Trondhjemite: definition, environment and hypotheses of origin, *Developments in*
584 *petrology*. Elsevier, pp. 1-12.
- 585 Black, L.P., Kamo, S.L., Allen, C.M., Aleinikoff, J.N., Davis, D.W., Korsch, R.J., Foudoulis, C.,
586 2003. TEMORA 1: a new zircon standard for Phanerozoic U–Pb geochronology. *Chemical*
587 *Geology* 200, 155-170.
- 588 Cawood, P.A., 2005. Terra Australis Orogen: Rodinia breakup and development of the Pacific and
589 Iapetus margins of Gondwana during the Neoproterozoic and Paleozoic. *Earth-Science*
590 *Reviews* 69, 249-279.
- 591 Cawood, P.A., Kröner, A., Collins, W.J., Kusky, T.M., Mooney, W.D., Windley, B.F., 2009.
592 *Accretionary orogens through Earth history*. Geological Society, London, Special
593 *Publications* 318, 1-36.
- 594 Champion, D.C., 2016. *Geodynamic synthesis of the phanerozoic of eastern Australia*, Second ed.
595 Geoscience Australia, Canberra.
- 596 Chappell, B., Williams, I., White, A., McCulloch, M., 1990. *Granites of the Lachlan Fold Belt*. ICOG
597 7 Field Guide Excursion A-2, Seventh International Conference on Geochronology,

598 Cosmochronology and Isotope Geology. Bureau of Mineral Resources, Geology and
 599 Geophysics, Australia, Canberra, p. 96.

600 Chappell, B.W., White, A.J.R., Hine, R., 1988. Granite provinces and basement terranes in the
 601 Lachlan Fold Belt, southeastern Australia. *Australian Journal of Earth Sciences* 35, 505-521.

602 Collins, W., Beams, S., White, A., Chappell, B., 1982. Nature and origin of A-type granites with
 603 particular reference to southeastern Australia. *Contributions to Mineralogy and Petrology* 80,
 604 189-200.

605 Collins, W., Hobbs, B., 2001. What caused the Early Silurian change from mafic to silicic (S-type)
 606 magmatism in the eastern Lachlan Fold Belt? *Australian Journal of Earth Sciences* 48, 25-41.

607 Collins, W.J., 2002. Hot orogens, tectonic switching, and creation of continental crust. *Geology* 30,
 608 535-538.

609 Colquhoun, G.P., L.Deyssing, Ballard, J.C., Hughes, K.S., Troedson, A.L., 2017. New South Wales
 610 zone 55 East Seamless Geology, version 1 [Digital Dataset], Geological Survey of New South
 611 Wales, Maitland.

612 Crawford, A.J., Meffre, S., Squire, R.J., Barron, L.M., Falloon, T.J., 2007. Middle and Late
 613 Ordovician magmatic evolution of the Macquarie Arc, Lachlan Orogen, New South Wales.
 614 *Australian Journal of Earth Sciences* 54, 181-214.

615 Fergusson, C.L., 2009. Tectonic evolution of the Ordovician Macquarie Arc, central New South
 616 Wales: arguments for subduction polarity and anticlockwise rotation. *Australian Journal of*
 617 *Earth Sciences* 56, 179-193.

618 Fergusson, C.L., 2010. Plate-driven extension and convergence along the East Gondwana active
 619 margin: Late Silurian–Middle Devonian tectonics of the Lachlan Fold Belt, southeastern
 620 Australia. *Australian Journal of Earth Sciences* 57, 627-649.

621 Fergusson, C.L., 2017. Mid to late Paleozoic shortening pulses in the Lachlan Orogen, southeastern
 622 Australia: a review. *Australian Journal of Earth Sciences* 64, 1-39.

623 Fergusson, C.L., Colquhoun, G.P., 2018. Ordovician Macquarie Arc and turbidite fan relationships,
624 Lachlan Orogen, southeastern Australia: stratigraphic and tectonic problems. *Australian*
625 *Journal of Earth Sciences*, 1-31.

626 Foden, J., Elburg, M.A., Turner, S., Sandiford, M., O'Callaghan, J., Mitchell, S., 2002. Granite
627 production in the Delamerian orogen, South Australia. *Journal of the Geological Society* 159,
628 557-575.

629 Foster, D.A., Gray, D.R., 2000. Evolution and Structure of the Lachlan Fold Belt (Orogen) of Eastern
630 Australia. *Annual Review of Earth and Planetary Sciences* 28, 47-80.

631 Fowler, T., Lennox, P., 1992. Low-pressure deformation of a small high-level pluton: the syn-tectonic
632 Davys Creek Granite from the southeastern Lachlan Fold Belt, NSW. *Tectonophysics* 214,
633 293-309.

634 Glen, R., Lennox, P., Foster, D., 1999. ⁴⁰Ar–³⁹Ar dating of deformation west of the Hill End Trough,
635 Lachlan Orogen. New South Wales. *Quarterly Notes of the Geological Survey of New South*
636 *Wales* 110, 13-22.

637 Glen, R.A., 2005. The Tasmanides of eastern Australia. *Geological Society, London, Special*
638 *Publications* 246, 23-96.

639 Glen, R.A., 2013. Refining accretionary orogen models for the Tasmanides of eastern Australia.
640 *Australian Journal of Earth Sciences* 60, 315-370.

641 Glen, R.A., Belousova, E., Griffin, W.L., 2016. Different styles of modern and ancient non-collisional
642 orogens and implications for crustal growth: a Gondwanaland perspective. *Canadian Journal*
643 *of Earth Sciences* 53, 1372-1415.

644 Glen, R.A., Fitzsimons, I.C.W., Griffin, W.L., Saeed, A., 2017. East Antarctic sources of extensive
645 Lower–Middle Ordovician turbidites in the Lachlan Orogen, southern Tasmanides, eastern
646 Australia. *Australian Journal of Earth Sciences* 64, 143-224.

647 Glen, R.A., Korsch, R.J., Direen, N.G., Jones, L.E.A., Johnstone, D.W., Lawrie, K.C., Finlayson,
648 D.M., Shaw, R.D., 2002. Crustal structure of the Ordovician Macquarie Arc, Eastern Lachlan

649 Orogen, based on seismic-reflection profiling. *Australian Journal of Earth Sciences* 49, 323-
650 348.

651 Glen, R.A., Meffre, S., Scott, R.J., 2007. Benambran Orogeny in the Eastern Lachlan Orogen,
652 Australia. *Australian Journal of Earth Sciences* 54, 385-415.

653 Glen, R.A., Percival, I.G., Quinn, C.D., 2009. Ordovician continental margin terranes in the Lachlan
654 Orogen, Australia: Implications for tectonics in an accretionary orogen along the east
655 Gondwana margin. *Tectonics* 28, 1-17.

656 Glen, R.A., Saeed, A., Quinn, C.D., Griffin, W.L., 2011. U–Pb and Hf isotope data from zircons in
657 the Macquarie Arc, Lachlan Orogen: Implications for arc evolution and Ordovician
658 palaeogeography along part of the east Gondwana margin. *Gondwana Research* 19, 670-685.

659 Glen, R.A., Watkins, J.J., 1999. Implications of Middle Devonian deformation of the eastern part of
660 the Hill End Trough, Lachlan Orogen, New South Wales. *Australian Journal of Earth
661 Sciences* 46, 35-52.

662 Gray, D., Foster, D., 2004. Tectonic evolution of the Lachlan Orogen, southeast Australia: historical
663 review, data synthesis and modern perspectives. *Australian Journal of Earth Sciences* 51, 773-
664 817.

665 Harris, N., Ayres, M., Massey, J., 1995. Geochemistry of granitic melts produced during the
666 incongruent melting of muscovite: implications for the extraction of Himalayan leucogranite
667 magmas. *Journal of Geophysical Research: Solid Earth* 100, 15767-15777.

668 Hermann, J., 1997. Experimental constraints on phase relations in subducted continental crust.
669 *Contributions to Mineralogy and Petrology* 143, 219-235.

670 Hiess, J., Bennett, V.C., Nutman, A.P., Williams, I.S., 2009. In situ U–Pb, O and Hf isotopic
671 compositions of zircon and olivine from Eoarchaeon rocks, West Greenland: New insights to
672 making old crust. *Geochimica et Cosmochimica Acta* 73, 4489-4516.

673 Ickert, R.B., Williams, I.S., 2011. U–Pb zircon geochronology of Silurian–Devonian granites in
674 southeastern Australia: implications for the timing of the Benambran Orogeny and the I–S
675 dichotomy. *Australian Journal of Earth Sciences* 58, 501-516.

676 Jeon, H., Williams, I.S., 2018. Trace inheritance—Clarifying the zircon O-Hf isotopic fingerprint of I-
677 type granite sources: Implications for the restite model. *Chemical Geology* 476, 456-468.

678 Jeon, H., Williams, I.S., Chappell, B.W., 2012. Magma to mud to magma: Rapid crustal recycling by
679 Permian granite magmatism near the eastern Gondwana margin. *Earth and Planetary Science*
680 *Letters* 319-320, 104-117.

681 Kemp, A., Hawkesworth, C., Collins, W., Gray, C., Blevin, P., 2009. Isotopic evidence for rapid
682 continental growth in an extensional accretionary orogen: The Tasmanides, eastern Australia.
683 *Earth and Planetary Science Letters* 284, 455-466.

684 King, P., White, A., Chappell, B., Allen, C., 1997. Characterization and origin of aluminous A-type
685 granites from the Lachlan Fold Belt, southeastern Australia. *Journal of Petrology* 38, 371-391.

686 Kjolle, I., 1997. The setting and genesis of the Browns Creek gold-copper skarn deposit, New South
687 Wales, Australia. Australian National University, p. 193.

688 Kovacs, N.J., 2000. Magmatic and hydrothermal evolution of the Browns Creek intrusive complex
689 and associated gold mineralisation. Australian National University, p. 202.

690 Lennox, P., Forster, M., Williams, I., 2014. Emplacement and deformation ages of the Wyangala
691 Granite, Cowra, NSW. *Australian Journal of Earth Sciences* 61, 607-618.

692 Lennox, P., Fowler, T., Foster, D., 1998. Barry Granodiorite and Sunset Hills Granite: Wyangala-
693 style intrusion at the margin of a regional ductile shear zone, northern Lachlan Fold Belt, New
694 South Wales. *Australian Journal of Earth Sciences* 45, 849-863.

695 Lennox, P., Trzebski, R., Armstrong, R., Siebel, W., 2005. Structural evolution and granite
696 chronology of the central Molong Zone, eastern Lachlan fold belt, Australia. *Australian*
697 *Journal of Earth Sciences* 52, 79-99.

698 Ludwig, K.R., 2003. User's manual for isoplot 3.00, a geochronological toolkit for microsoft excel.
699 Berkeley Geochronology Center, Special Publication 4, 25-32.

700 Maniar, P.D., Piccoli, P.M., 1989. Tectonic discrimination of granitoids. *Geological Society of*
701 *America Bulletin* 101, 635-643.

702 McClenaghan, M., Higgins, N., 1993. The age and intrusive relationships of granitoids of the Blue
 703 Tier Batholith, north-east Tasmania. Mineral Resources Tasmania Report 33.
 704 McCulloch, M.T., Chappell, B.W., 1982. Nd isotopic characteristics of S-and I-type granites. Earth
 705 and Planetary Science Letters 58, 51-64.
 706 Meffre, S., Scott, R.J., Glen, R.A., Squire, R.J., 2007. Re-evaluation of contact relationships between
 707 Ordovician volcanic belts and the quartz-rich turbidites of the Lachlan Orogen. Australian
 708 Journal of Earth Sciences 54, 363-383.
 709 Middlemost, E.A., 1994. Naming materials in the magma/igneous rock system. Earth-Science
 710 Reviews 37, 215-224.
 711 Moorbath, S., Taylor, P.N., Goodwin, R., 1981. Origin of granitic magma by crustal remobilisation:
 712 Rb-Sr and Pb/Pb geochronology and isotope geochemistry of the late Archaean Qôrqu
 713 Granite Complex of southern West Greenland. Geochimica et Cosmochimica Acta 45, 1051-
 714 1060.
 715 Norrish, K., Chappell, B.W., 1977. X-ray fluorescence spectrometry, Physical Methods in
 716 Determinative Mineralogy, 2nd Edition ed. Academic Press, London, pp. 201-272.
 717 Nutman, A.P., Dawes, P.R., Kalsbeek, F., Hamilton, M.A.J.P.R., 2008. Palaeoproterozoic and
 718 Archaean gneiss complexes in northern Greenland: Palaeoproterozoic terrane assembly in the
 719 High Arctic. 161, 419-451.
 720 Offler, R., Fergusson, C.L., 2016. Proto-Pacific-margin source for the Ordovician turbidite submarine
 721 fan, Lachlan Orogen, southeast Australia: Geochemical constraints. Sedimentary Geology
 722 334, 53-65.
 723 Packham, G., Percival, I., Bischoff, G., 1999. Age constraints on strata enclosing the Cadia and
 724 Junction Reefs ore deposits of central New South Wales, and tectonic implications, In: Wales,
 725 G.S.o.N.S. (Ed.), Quarterly Notes, pp. 1-20.
 726 Patino Douce, A.E., 2004. Vapor-absent melting of tonalite at 15–32 kbar. Journal of Petrology 46,
 727 275-290.
 728 Pearce, J.A., Harris, N.B., Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic
 729 interpretation of granitic rocks. Journal of Petrology 25, 956-983.

730 Perkins, C., McDougall, I., Walshe, J.L., 1995a. Metallogenic epochs of the Tasman Orogen, eastern
731 Australia. AMIRA Project P334A, Annual Report.

732 Perkins, C., Walshe, J.L., Morrison, G., 1995b. Metallogenic episodes of the Tasman fold belt system,
733 eastern Australia. *Economic Geology* 90, 1443-1466.

734 Pogson, D.J., Watkins, J.J., 1998. Bathurst 1: 250 000 Geological Sheet SI/55-8: Explanatory Notes.
735 Geological Survey of New South Wales.

736 Reed, A., 2001. Pre-Tabberabberan deformation in eastern Tasmania: A southern extension of the
737 Benambran Orogeny. *Australian Journal of Earth Sciences* 48, 785-796.

738 Rosenbaum, G., 2018. The Tasmanides: Phanerozoic Tectonic Evolution of Eastern Australia. *Annual*
739 *Review of Earth and Planetary Sciences* 46, 291-325.

740 Scheibner, E., Basden, H., 1998. *Geology of New South Wales-Synthesis. Volume 2 Geological*
741 *Evolution-5*.

742 Spaggiari, C.V., Gray, D.R., Foster, D.A., McKnight, S., 2003. Evolution of the boundary between
743 the western and central Lachlan Orogen: implications for Tasmanide tectonics. *Australian*
744 *Journal of Earth Sciences* 50, 725-749.

745 Sun, S.-S., McDonough, W.-S., 1989. Chemical and isotopic systematics of oceanic basalts:
746 implications for mantle composition and processes. *Geological Society, London, Special*
747 *Publications* 42, 313-345.

748 Turner, S., Foden, J., 1996. Magma mingling in late-Delamerian A-type granites at Mannum, South
749 Australia. *Mineralogy and Petrology* 56, 147-169.

750 VandenBerg, A., 2000. The Tasman Fold Belt system in Victoria: geology and mineralisation of
751 Proterozoic to Carboniferous rocks. Geological Survey of Victoria, Melbourne, Victoria.

752 Watson, E.B., Harrison, T.M., 1983. Zircon saturation revisited: temperature and composition effects
753 in a variety of crustal magma types. *Earth and Planetary Science Letters* 64, 295-304.

754 Williams, I.S., 1998. U-Th-Pb geochronology by ion microprobe. *Reviews in Economic Geology* 7,
755 1-35.

756 Willman, C., VandenBerg, A., Morand, V., 2002. Evolution of the southeastern Lachlan fold belt in
757 Victoria. *Australian Journal of Earth Sciences* 49, 271-289.

758 Zhang, Q., Buckman, S., Bennett, V.C., Nutman, A., 2019a. Inception and early evolution of the
759 Ordovician Macquarie Arc of Eastern Gondwana margin: Zircon U-Pb-Hf evidence from the
760 Molong Volcanic Belt, Lachlan Orogen. *Lithos* 326, 513-528.

761 Zhang, Q., Buckman, S., Bennett, V.C., Nutman, A., Song, Y., 2019b. Lachlan Orogen, Eastern
762 Australia: Triangle Formation records the Late Ordovician arrival of the Macquarie Arc
763 terrane at the margin of eastern Gondwana. *Tectonics*.

764

765