Emplacement and deformation ages of the Wyangala Granite, Cowra, NSW

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New geochronological data from the Wyangala Granite in the Hill End Trough, Eastern Lachlan Fold Belt, constrain the timing of granite emplacement and subsequent deformation. SHRIMP U–Pb dating of zircon indicates that the granite crystallised in the late Silurian \((425.2 \pm 3.5 \text{ Ma})\). Subsequent west-over-east thrusting resulted in the development of mylonite along its eastern margin and cataclasis of megacrustic and groundmass feldspars, especially in pervasive shear zones within the granite. \(^{40}\text{Ar}/^{39}\text{Ar}\) dating of feldspar from two deformed granite samples yielded ‘plateau’ ages in the range \(375–365 \text{ Ma}\) that are interpreted to reflect the timing of deformation associated with major shearing. These ages broadly overlap with the proposed age range of the late Middle Devonian Tabberabberan event and some biotite K–Ar and Rb–Sr ages in the nearby Sunset Hills Granite.

KEY WORDS: Wyangala Granite, zircon U–Pb, K-feldspar \(^{40}\text{Ar}/^{39}\text{Ar}\), mylonitisation.

INTRODUCTION

The Eastern Lachlan Fold Belt, eastern Australia, contains numerous Ordovician to Devonian composite granite batholiths. Most of these are intruded into lower-middle Paleozoic sedimentary and volcanic rocks, outcropping in north-south trending belts, which were folded about east-west axes and then north-south axes. These episodes of folding are associated with low- to medium-grade regional metamorphism, which together with stratigraphic breaks, define several orogenic events that moulded the fold belt during the early to late Paleozoic (Cas1983; Barron in Pogson & Watkins1998).

The Wyangala Granite encapsulates part of this tectonomagmatic history. It intrudes mainly Ordovician Adataminaby Group turbidites, the Walli Volcanics and the volcaniclastic Coombing Formation (Pogson & Watkins 1998; Johnston et al. 2001; Figure 1). Here we present the first SHRIMP zircon U–Pb data to establish the age of granite emplacement. In addition, as there was some uncertainty with the earlier Ar/Ar work on biotite, we conducted additional Ar/Ar analyses on K-feldspar to understand more about the post-crystallisation deformation history of this granite. These data confirm that biotite \(^{40}\text{Ar}/^{39}\text{Ar}\) ages of \(ca\) 370 Ma reported by Glen et al. (1999) reflect isotopic resetting of igneous biotite during a subsequent tectono-thermal event.

The Wyangala Granite

The Wyangala Granite forms a narrow north-south elongated body exposed over an area of \(\sim 370 \text{ km}^2\) about 20 km SE of Cowra, NSW (Figure 1). It lies within the Hill End Trough, the western margin of which is now considered to be the Frogmore Fault Zone, a major meridional fault system extending ~250 km from near Orange to south of Canberra (Scott 2004; Thomas & Pogson 2012).

The granite is a foliated, porphyritic biotite granite with megacrustic K-feldspar up to 100 mm diameter. In some places, for example at the spillway of Wyangala Dam (Figure 1), it has been mylonitised. The chemical and isotopic characteristics of the granite are consistent with it being S-type (derived from supracrustal source rocks), although its composition has been modified by post-emplacement chemical alteration (Pogson & Watkins 1998). The magma was emplaced along pre-existing faults and foliation planes in the country rocks (Lennox et al. 2005; Lennox & Zwingmann 2007). Zee (1983) suggested that S and C foliations in the granite developed simultaneously or sequentially during the same deformation episode. Morand (1988) proposed that the S surfaces developed during east-west shortening and the C surfaces during east-directed, reverse fault movement possibly related to movement on the Copperhanniwa Thrust 30 km to the east. Glen et al. (1999) used \(^{40}\text{Ar}/^{39}\text{Ar}\) ages, measured on metamorphic biotite, to argue that the C foliation in the Wyangala Granite developed during the late Middle Devonian Tabberabberan event that terminated pre-cratonic development of the fold belt.

The aim of the present study was to determine the crystallisation age of the Wyangala Granite and better understand its cooling history. Although the age of the Wyangala Granite has been constrained stratigraphically (Pogson & Watkins 1998), it has not previously been...
dated isotopically. Other S-type granites in the region have yielded zircon ages in the range 435–425 Ma (Lennox et al. 2005; Squire & Crawford 2007; Bodorkos & Simpson 2008, Ickert & Williams 2011). The zircon U–Pb analyses reported here provide a crystallisation age for the granite. ⁴⁰Ar/³⁹Ar dating from the present study shows that the ages of cataclastic K-feldspar in shear zones in the granite record mylonitisation during the period 375–365 Ma. The ⁴⁰Ar/³⁹Ar data clarify whether the regional deformation that affected the granite so profoundly was solely of Tabberabberan age (Foster et al. 1999; Glen et al. 1999), or took place in two episodes, first during the Tabberabberan event, then during the early Carboniferous Kanimblan event as defined by Gray (1997), Gray et al. (1997) or Scheibner & Basden (1998).

Sample selection
Granite samples were taken from two locations within the Wyangala Dam Shear Zone: one from the less deformed granodiorite (PL286) with S and C surfaces (Figures 2, 3a) on the Wyangala to Cowra Road about 1.6 km SW of the

Figure 1 (a) Locality map for NSW, (b) Eastern Lachlan Fold Belt and (c) the Hill End Trough, Wyangala Granite, Wyangala Dam, Copperhannia Thrust and Carcoar, Barry and Sunset Hills granites within the Eastern Lachlan Fold Belt with the other granites forming the Wyangala Batholith shown in outline. The Molong Zone is an abbreviation of the Molong-Wyangala-Jerangle Zone (Scheibner & Basden 1998).

Figure 2 Locality map of the Wyangala Granite at Wyangala Dam, NSW, Australia with the shear zones shown schematically. Sample PL336 is from within a higher strained shear zone within the Wyangala Dam spillway, whereas sample PL286 is located on the Wyangala Dam–Cowra Road about 2 km southwest of the spillway in a lower strained part of the granite. The location in AGD84 is 0677794 mE, 6236930 mN for PL286 and 0679621 mE and 6238053 mN for PL336.
Figure 3 Hand specimen and photomicrographs of PL286. (a) Polished hand specimen showing white K-feldspar megacrysts (top right-hand corner), S and C fabrics defined by elongated black biotite stringers as labelled and grey-coloured groundmass quartz. (b, c) Photomicrographs of the whole thin-section (1.8 × 4.4 cm) under plane-polarised light and crossed nicols showing biotite stringers defining the S and C fabrics wrapping around quartz (Q), plagioclase (P) and K-feldspar (K) phenocrysts.
Figure 4 Field, hand specimen and photomicrographs of PL336. (a) Field photograph looking south of prominent C surface with orientation mark (61 to 250°) and well-defined lineation on the C surface that pitches 70° NNW (i.e. plunges 55° to 288°). (b) Wetted hand specimen oriented normal to the foliations and parallel to the lineation showing disaggregated feldspars within quartz-feldspar mixtures surrounded by biotite-rich stringers aligned either in the S foliation or more prominently up and down the page in the C foliation. (c, d) Scanned complete thin-section (1.8 × 4.4 cm) oriented normal to the foliations and parallel to the lineation in plane polarised light and crossed nicols, respectively. These show the mica-rich S and C planes bending consistent with top to the left movement on the C planes. (d) The euhedral, Carlsbad-albite-pericline twinned plagioclase phenocrysts (P) in the upper middle to right of the thin-section are surrounded by twinned feldspars, quartz phenocrysts showing undulose extinction and peripheral new grain growth and are enclosed within a grossly sigmoidal-shaped body defined by ribbon quartz and mica stringers in C planes (E–W) and S planes (WNW–ESE). The cluster of feldspars above and to the right of the number 5 at the bottom of the figure are broken and disaggregated and twinned feldspar on the left middle of the figure is bent in a kink-like fashion. The quartz shows mortar texture in the sigmoidal body in the upper middle of the figure labelled Q and complete ribbon development around the edges of this body.
Wyangala Dam spillway, and the other from mylonitised granodiorite (PL336) with well-developed C surfaces from within the spillway itself (Figures 1, 4a) (White & Lennox 2010). The aim of this sample selection was not only to date the intrusion of the granite, but also to define the thermal history, and the effects and timing of deformation within the Wyangala Dam Shear Zone.

The less deformed sample (PL286) is a grey, megacryst granodiorite containing 20–30% K-feldspar megacrysts, 5–10% plagioclase phenocrysts, 40–50% quartz and 5–15% biotite alteration products (Figure 3a). The K-feldspar megacrysts are subhedral to anhedral, white tabular crystals up to 12 × 35 mm in size (Figure 3b, c). Deformation has resulted in some megacrysts being fractured and developing perthitic microcline. The blocky megacrysts commonly have biotite tails. The plagioclase crystals range up to 2–3 mm × 1–2 mm in size and have albite-Ca-carlsbad or albite-Ca-carlsbad-pericline twinning (Figure 3c). The quartz crystals are up to 5–10 mm long, exhibit undulose extinction, mortar texture are often augen-shaped and sometimes form quartz ribbons (Figure 3c). The biotite forms bent or kinked single crystals or clusters of crystals (Figure 3b) that define the trend of the S foliation and with ends bent into the C foliation (Figure 3a).

Sample PL336 was described in the field as a mylonite because the groundmass forms 70–90% of the rock (Figure 4b). The sample is a coarse-grained granodiorite with well-developed S and C foliations (Figure 4c, d). Porphyroclastic remnants of feldspar phenocrysts up to 8–12 mm across are generally not aligned parallel to either the S or C foliation (Figure 4c, d). They are rarely displaced by fractures and are commonly linked by wedge-shaped aggregates of biotite-muscovite. They are commonly 5 × 7 mm in size, form 20–25% of the rock, and are surrounded by grey feldspar (30–35%) that is enclosed in quartz as ribbons or shows partial recrystallisation along surfaces within the crystal (Figures 4b, d). Both quartz and feldspar are wrapped by a biotite–muscovite aggregate in stringers up to 5 mm wide that form 20–25% of the rock (Figures 4b, c). Biotite forms 5–10% of this aggregate. The biotite forms tails on the feldspar phenocrysts (Figure 4b). The biotite is kinked, bent or undeformed, unlike the quartz, which forms prominent ribbons (Figure 4b, d).

In summary, both samples have been deformed and both have large feldspars that pre-date the S-C fabric and small feldspars in the groundmass (Figures 3a, 4b). The large feldspars are up to several tens of millimetres in length (Figures 3a, 4d), while the small feldspars in the groundmass are characteristically < 8 mm (Figures 3a, 4b). The grain sizes of the groundmass feldspars and the large feldspars in both the mylonite and the less deformed sample are similar.

Microstructural analysis shows that the C foliation in the mylonitised granodiorite (PL336) wraps around the large feldspars. Small feldspars occur within this fabric, and quartz characteristically is present as ribbons (Figure 4b). The relationship between the two feldspars is the same in the less deformed granodiorite (PL286) but the fabric is not so strongly developed (Figure 3b). The large feldspars in the mylonitised granodiorite have been affected by cataclasis, with the original magmatic phenocrysts extensively fractured with pervasive formation of sub-grains (Figure 4d). The intensity of cataclasis is greatest at the ends of the sheared augen (Figure 4d). Recrystallisation is evident at the sub-grain boundaries and in the small sub-grains on the outer margins. The groundmass feldspars are caught up in the mylonitic fabric but not obviously cataclasised.

Age determinations

**ZIRCON U–Pb**

Zircon was separated from the less deformed granodiorite sample (PL286) and dated by U–Pb using the SHRIMP II ion microprobe at the ANU and methods based on those described by Williams & Claesson (1987) and Williams (1998). Details are given in Appendix 1. Cathodoluminescence imaging in advance of the dating showed that nearly all of the zircon grains consist of a central core, commonly up to 100 μm in diameter, surrounded by an overgrowth of zircon, up to 100 μm thick at the ends of the grains, with simple concentric igneous growth zoning (Figure 5). The cores are interpreted as unmelted zircon from the source of the granite (restite), and the overgrowths as zircon precipitated from the melt phase of the magma in the period between the start of partial melting and final post-emplacement crystallisation. As the objective of the present study was to date the magmatism, all the spots selected for analysis were on zircon overgrowths.

Figure 5: Cathodoluminescence images of representative zircon grains showing the common zoning texture; a core discordantly surrounded by an overgrowth of zircon with simple concentric igneous zoning. Ellipses show the areas dated with the measured ages. Uncertainties in the ages are ±1 standard error estimates of precision.
Table 1. U–Th–Pb isotopic analyses of zircon from Wyangala granites.

| Grain.spot | Pb* ppm | U ppm | Th ppm | Th/U | 204Pb | 206Pb | common | 232Th | 238U | 207Pb | 208Pb | 206Pb/238U | Apparent ages (Ma) |
|-------------|---------|-------|--------|------|-------|-------|--------|-------|-------|-------|-------|------------|------------------|
| Wyangala    |         |       |        |      |       |       |        |       |       |       |       |            |                  |
| 1.1         | 35      | 631   | 103    | 0.17 | 3.80E-05 | 1.18E-05 | 0.06 | 0.02/07 | 0.0005 | 0.0653 | 0.0007 | 0.0548 | 0.0006 | 414   | 10  | 408.0  | 4.2         |
| 2.1         | 19      | 338   | 76     | 0.23 | 1.56E-04 | 5.38E-05 | 0.09 | 0.01/82 | 0.0008 | 0.0660 | 0.0007 | 0.0534 | 0.0011 | 367   | 15  | 412.9  | 4.5         |
| 3.1         | 33      | 550   | 64     | 0.12 | 1.76E-05 | 2.12E-05 | 0.07 | 0.02/18 | 0.0008 | 0.0695 | 0.0007 | 0.0558 | 0.0008 | 437   | 16  | 412.9  | 4.5         |
| 4.1         | 48      | 823   | 157    | 0.20 | 5.39E-05 | 9.02E-06 | 0.17 | 0.02/10 | 0.0004 | 0.0683 | 0.0007 | 0.0559 | 0.0005 | 420   | 8   | 425.4  | 4.3         |
| 5.1         | 51      | 866   | 134    | 0.16 | 6.72E-05 | 2.14E-05 | 0.07 | 0.02/12 | 0.0006 | 0.0688 | 0.0007 | 0.0550 | 0.0006 | 426   | 12  | 429.2  | 4.3         |
| 6.1         | 34      | 576   | 96     | 0.17 | 1.10E-04 | 3.48E-05 | 0.18 | 0.02/13 | 0.0007 | 0.0688 | 0.0007 | 0.0553 | 0.0008 | 428   | 14  | 428.8  | 4.4         |
| 7.1         | 32      | 563   | 138    | 0.25 | 8.91E-05 | 1.96E-05 | 0.23 | 0.02/15 | 0.0005 | 0.0669 | 0.0007 | 0.0537 | 0.0007 | 430   | 9   | 417.3  | 4.3         |
| 8.1         | 36      | 614   | 88     | 0.15 | 5.18E-05 | 7.35E-06 | 0.20 | 0.02/18 | 0.0005 | 0.0688 | 0.0008 | 0.0563 | 0.0006 | 437   | 10  | 428.5  | 4.7         |
| 9.1         | 32      | 576   | 79     | 0.13 | 1.08E-04 | 3.36E-05 | 0.35 | 0.01/99 | 0.0008 | 0.0663 | 0.0008 | 0.0563 | 0.0008 | 401   | 16  | 421.9  | 4.7         |
| 10.1        | 29      | 498   | 72     | 0.15 | 1.09E-04 | 2.75E-05 | 0.22 | 0.02/08 | 0.0007 | 0.0679 | 0.0008 | 0.0554 | 0.0008 | 418   | 14  | 423.1  | 4.8         |
| 11.1        | 29      | 512   | 83     | 0.17 | 1.19E-04 | 3.30E-05 | 0.25 | 0.02/00 | 0.0007 | 0.0660 | 0.0007 | 0.0553 | 0.0008 | 403   | 13  | 411.8  | 4.3         |
| 12.1        | 26      | 454   | 83     | 0.19 | 1.75E-04 | 4.67E-05 | 0.01 | 0.01/99 | 0.0008 | 0.0676 | 0.0007 | 0.0528 | 0.0010 | 420   | 15  | 423.0  | 4.5         |
| 13.1        | 33      | 539   | 90     | 0.17 | 9.93E-05 | 3.98E-05 | 0.09 | 0.02/18 | 0.0008 | 0.0689 | 0.0008 | 0.0547 | 0.0009 | 438   | 15  | 429.9  | 4.7         |
| 14.1        | 47      | 799   | 152    | 0.20 | 4.56E-05 | 1.43E-05 | 0.22 | 0.02/18 | 0.0004 | 0.0682 | 0.0007 | 0.0565 | 0.0006 | 437   | 9   | 424.7  | 4.3         |
| 15.1        | 28      | 477   | 85     | 0.18 | 1.11E-04 | 2.16E-05 | 0.31 | 0.02/15 | 0.0006 | 0.0682 | 0.0007 | 0.0562 | 0.0008 | 431   | 11  | 425.0  | 4.5         |
| 16.1        | 30      | 517   | 64     | 0.13 | 1.28E-04 | 3.87E-05 | 0.16 | 0.01/95 | 0.0009 | 0.0788 | 0.0007 | 0.0547 | 0.0009 | 393   | 18  | 423.2  | 4.4         |
| 17.1        | 42      | 694   | 153    | 0.23 | 6.03E-05 | 2.48E-05 | 0.14 | 0.02/22 | 0.0005 | 0.0705 | 0.0007 | 0.0559 | 0.0007 | 444   | 10  | 430.8  | 4.5         |
| 18.1        | 33      | 393   | 72     | 0.19 | 1.36E-04 | 4.10E-05 | 0.17 | 0.02/03 | 0.0007 | 0.0678 | 0.0008 | 0.0546 | 0.0009 | 409   | 14  | 423.2  | 4.1         |
| 19.1        | 37      | 621   | 138    | 0.23 | 1.18E-04 | 4.29E-05 | 0.15 | 0.02/15 | 0.0007 | 0.0688 | 0.0007 | 0.0549 | 0.0009 | 432   | 13  | 429.0  | 4.4         |
| 20.1        | 48      | 826   | 178    | 0.22 | 5.56E-05 | 2.82E-05 | 0.06 | 0.02/10 | 0.0005 | 0.0683 | 0.0008 | 0.0550 | 0.0006 | 420   | 10  | 425.8  | 4.6         |

*C Corrected for laboratory common Pb (204Pb/206Pb = 0.0625; 207Pb/206Pb = 0.962; 208Pb/206Pb = 2.228) using 207Pb.

*a corrected for common Pb using 206Pb, assuming U-Pb concordance.
The analyses showed a relatively narrow range of U (~340–830 ppm) and Th (~65–180 ppm) contents, and low Th/U (0.12–0.25), consistent with a single generation of zircon overgrowth. The isotopic compositions of all 20 analysed spots were concordant within analytical uncertainty (Table 1), but there was a small, but significant, dispersion in radiogenic 206Pb/238U (Figure 6). One analysis (17.1) gave a relatively high age, probably because the primary ion beam contacted the old core in the grain. Three analyses (1.1, 2.1, 11.1) gave low ages because of radiogenic Pb loss. The remaining 16 measurements of radiogenic 206Pb/238U were equal within analytical uncertainty (MSWD = 1.2), giving a weighted mean age of 425.2 ± 3.5 Ma, which is interpreted as the age of zircon crystallisation during and after emplacement of the granite magma. The uncertainty in the age is the 95% confidence limit (t, where t is Student’s t) and includes the uncertainty in the Pb/U calibration for the analytical session (0.3%).

**K-Feldspar 40Ar/39Ar**

Feldspar is the most stable K-bearing mineral used for 40Ar/39Ar geochronology in vacuo step-heating experiments (Lovera et al. 1997). Multi-domain diffusion (MDD) experiments are conducted on K-feldspar to provide temperature-controlled data for modelling thermal and deformational histories (Lovera et al. 1989, 1997; Forster & Lister 2010). K-feldspar crystals commonly contain domains of varying retentivity for argon diffusion, thus preserving the record of older events in more retentive domains of varying retentivity for argon diffusion, thus allowing direct dating of the timing of movement. Groundmass and porphyroclastic K-feldspars from both samples preserved multiple 40Ar/39Ar ages. The different ages obtained from low, intermediate and most retentive domains are remarkably similar (Figure 7).

The porphyroblastic K-feldspar grains preserve a 40Ar/39Ar ‘plateaux’ age in the range ca 375–372 Ma; 372.3 ± 0.4 Ma for sample PL286-CX from the less deformed granodiorite (P2, Figure 7c) and 375.1 ± 0.3 Ma for sample PL336-CX from the mylonitised granodiorite (P4, Figure 7d). These ages are consistent with time proposed for the Tabberabberan event (587–570 Ma; Scheibner & Basden 1998) linked to thrusting on west-dipping faults along the eastern margins of several Wyangala Batholith plutons (Paterson et al. 1990). The porphyroclastic K-feldspar lost nearly all its radiogenic Ar during this deformation, with the little that remained recording a relict minimum age of ca 386 Ma.

The groundmass K-feldspars preserve a main 40Ar/39Ar age in the range of ca 372–366 Ma; 365.7 ± 0.4 Ma in the less deformed sample (PL286; Figure 7a) and 371.8 ± 0.8 Ma in the more deformed sample (PL336; Figure 7b). These ages are slightly younger than the deformation ages of the porphyroclastic K-feldspar and lie between the ages proposed for the end of the Tabberabberan event (ca 370 Ma) and the start of the Kanimblan event (ca 350 Ma; Figure 8; Scheibner & Basden 1998). The relict ages in the groundmass feldspars give a minimum age of 386.8 ± 2.6 Ma for PL286-GM (Figure 7a) and a 383.1 ± 1.9 Ma minimum age estimate for PL336-GM (Figure 7b), possibly reflecting resetting during the Tabberabberan event (Figure 8).

**Geological Implications of the age measurements**

Based on its mineralogy, it has been suggested that the Wyangala Granite was emplaced at a depth of 3–9 km (Close 1978) and uplifted to within 2–3 km of the surface during the Tabberabberan, Kanimblan or Hunter–Bowen events. However, biotite aggregates were stable, and feldspars were brittlely deformed during mylonitisation so temperatures at this time must have exceeded 300–400°C. This temperature could be achieved during regional, greenschist metamorphism related to the Tabberabberan event (Figure 8). In turn this makes it more likely that final exhumation took place during the Permian–Triassic Hunter–Bowen events (Lennox et al. 2003).

The granite crystallisation age of 425.2 ± 3.5 Ma is within the range of zircon U–Pb ages measured on other granites from the Wyangala Batholith (Lennox &
Zwingmann 2007; Bodorkos & Simpson 2008), but younger than most of the large volume of S-type granite magma intruded into the Eastern Lachlan Fold Belt at ca 432 Ma (Ickert & Williams 2011). Hornblende and biotite from the Barry, Carcoar and Sunset Hills granites northeast of the Wyangala Granite have been dated by K–Ar, 40Ar/39Ar and Rb–Sr (Figure 1; Lennox et al. 1998). The ages from the Barry and Carcoar Granites are consistently 416–407 Ma, while those from biotites near shear zones within and adjacent to the Sunset Hills Granite are 379–363 Ma. All of these results are significantly younger than the ages measured on the same granites by zircon U–Pb (Barry, 425.8 ± 1.9 Ma; Carcoar, 434.4 ± 5.5 Ma; Sunset Hills, 430.1 ± 3.7 Ma; Lennox et al. 1998). Ages of ca 412 Ma are consistent with isotopic resetting or regional cooling during uplift associated with the Bowning event (410–405 Ma, Gray & Foster 1997 or ca 417–405 Ma for the Bowning-Bindian, Scheibner &

Figure 7 40Ar/39Ar apparent age spectra for the K-feldspar from the (a) groundmass from the less deformed sample PL286; (b) the groundmass from the more strained PL336; (c) for the porphyroclastic feldspar from the less deformed sample PL286; and (d) the porphyroclastic feldspar from the more strained PL336. ‘Plateau’ ages are marked in blue, relict older ages are marked in red. The relict ages have not been completely overprinted by the younger event and are modified substantially; no more can be said other than that they are minimum ages and that the original age may be far older.
The duration of the events is from Scheibner & Basden (1998) who concentrated their studies on the New South Wales section of the Lachlan Fold Belt. The results indicate that the shear zone was active during and probably after the Tabberabberan event. Glen et al. (1999) reported on 40Ar/39Ar spectra for biotite in granites including a total fusion age of 387 Ma for biotite from the foliated Reids Flat Granite and ca. 370 Ma for the biotite lying in the S foliation of the Wyangala Granite. These results are both consistent with the Tabberabberan event deformation. Glen et al. (1999) report a total fusion age of 354 ± 2 Ma consistent with cooling of the biotite within the foliated Sunset Hills Granite at or before ca. 360 Ma. These results are close to the results reported below.

Correlating the ages measured from the Wyangala Granite with particular tectonic events recognised in the stratigraphy of the Lachlan Fold Belt depends upon knowing the age span of those events. The timing of the events is a matter for debate, with ages of 380 Ma (Gray & Foster 2004), 376 Ma (Gray & Foster 1997) and 370 Ma (Scheibner & Basden 1998) having been suggested for the termination of the Tabberabberan event (Figure 8). The ages measured here suggest that the Tabberabberan event lasted longer than previously thought, perhaps until ca. 365 Ma.

CONCLUSIONS

None of the K-feldspar from the Wyangala Granite that was dated using 40Ar/39Ar geochronology records the emplacement/crystallisation of the granite magma at 425.2 ± 3.5 Ma. Some K-feldspar diffusion domains retain relict ages up to 396 Ma, but plateau ages in the range 375–365 Ma are consistent with resetting during mylonitisation. Note that the 40Ar/39Ar spectra require almost complete outgassing of argon at this time during west-over-east thrusting during the Tabberabberan event. Although the Kanimbilan event commenced soon afterwards (at ca. 350 Ma; Figure 8), this deformation appears to have had only minor effects on the K-feldspar K–Ar isotopic system. The principal loss of argon occurred during mylonitisation of the Wyangala Granite, with this apparently resulting from grainsize reduction accompanying cataclasis of K-feldspar during deformation. Similar resetting of biotite K–Ar and Rb–Sr ages in the nearby Sunset Hills Granite in close proximity to shear zones is testament to the effects of fluid activity and relatively high temperatures (~400–500°C).

ACKNOWLEDGEMENTS

This research was supported by a 2012 Faculty Research Grant, UNSW (PS27189), the School of BEES and the Alexander von Humboldt Foundation, Germany to Paul Lennox. M. A. Forster acknowledges the support of an Australian Research Fellowship provided by the Australian Research Council (ARC) and ARC Discovery Grant DP0877274 ‘Tectonic mode switches and the nature of orogenesis.’ Mineral separation was done by L. White and S. Paxton at RSES, ANU. H. de Wall and M. Bestmann facilitated whole-of-thin-section scanning in Erlangen University, Germany. Vince Morand, Evan Leitch and Lloyd White are thanked for reviewing this paper.

SUPPLEMENTAL DATA

Table Ar/Ar data analytical results.

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APPENDIX 1 SHRIMP U–Pb ANALYSIS

A zircon concentrate was prepared using procedures designed to minimise cross-sample contamination. Approximately 500 g of rock was crushed to ~1 cm-sized chips using a jaw-crusher. The chips were washed in water in an ultrasonic bath, dried, then crushed in a tungsten-carbide swing mill to pass a disposable 250 μm screen. Fines were removed by rinsing the crushings in water in a deep glass beaker. A high-density fraction (>2.96 g/cc) was then separated using tetrabromoethane, hand magnetic minerals were removed, and a higher density fraction (~3.3 g/cc) extracted using methylene iodide. Paramagnetic minerals were removed using a Franz isodynamic separator, leaving a relatively non-magnetic zircon concentrate. Final purification was by hand picking.

Approximately 400 selected zircon grains (clear, unaltered) were mounted on double-sided adhesive tape with zircon reference materials SL13 and Temora 1 then cast in Epoxy EpoMount epoxy. The epoxy disc was coarsely ground using 1200 grade SiC paper to expose the...
The measured 204Pb and a Broken Hill galena Pb compositions initially were corrected for common Pb using SQUID 1 software (Ludwig 2000). All analyses were undertaken at the USGS TRIGA reactor, Denver, USA. Irradiated for 40 h in position CT at 1 MWh. Irradiation times are based on the potential natural accumulation of radiogenic 40Ar to the produced 39Ar. A cadmium liner was used to minimise interference from thermal neutrons. Biotite (GA 1550) has been used as the Flux Monitor (Spell & McDougall 2003). Samples and flux monitors were wrapped in aluminium for irradiation. Aluminium foil was removed and samples were rewrapped in tin for analysis in the mass spectrometer, so as to be able to melt the tin wrap and pump away the contaminated gases prior to the analysis of a sample. The 40Ar/39Ar analysis procedures are as described by McDougall & Brown (2006). Grains were analysed using the step-heating method using the furnace technique with temperature control monitored via a thermocouple at the base of a tantalum crucible within a double-vacuum resistance furnace. Analysis was done with liquid nitrogen Cold Trap to reduce contamination into the line and mass spectrometer.

The K-feldspars were analysed on a VG1200 gas source mass spectrometer with a Multiplier operating with sensitivities of approximately 8 × 10−17 mol mV−1. Machine discrimination was determined and used in the data reduction process. Line blanks were measured at different temperatures prior to analysis and backgrounds measured for every step; these were subtracted from final analysis.

Samples were heated prior to analysis with heating up to ~400°C then reduced to 380°C overnight. This is done to outgas contaminants at lower temperatures to minimise mixing contaminants with radiogenic argon released from low-retentivity sites into the initial analytical steps. This contaminated gas was pumped away prior to analysis.

K-feldspars where analysed as diffusion experiments with 41 steps, with two or more isothermal steps throughout the schedule, and with temperatures of the overall schedule rising from 450°C to 1450°C (Lovera et al. 1989). The furnace was decontaminated prior to each sample at 1450°C for 15 min three times prior. The gases from the cleaning process were pumped away and not exposed to the extraction line.

Flux monitors were analysed using a continuous wave laser and the VG1200 Mass Spectrometer, with backgrounds subtracted. Gas released from each step is exposed to Zr–Al getters to remove active gases for 10 min, the purified gas then being isotopically analysed in the mass spectrometer.

40K abundances and decay constants are taken from standard values recommended by the IUGS subcommission on Geochronology (Steiger & Jaeger 1977). Stated precisions for 40Ar/39Ar ages include all uncertainties in the measurement of isotope ratios and are quoted at the 1 sigma level. The method of asymptotes and limits was used in analysis of the data from this study (Forster & Lister 2004) owing to the complex character of the apparent age spectra where a relict age and associated mixing can be recognised to have been preserved in the spectra. There is a notable degree of mixing between the plateau age (in Figure 7 this is marked in blue) and the relict age (in Figure 7 this is marked in red) in each of the spectra.
The method of asymptotes and limits has been automated using a MacOS eArgon (written by G. Lister @ RSES).

Irradiation times, Flux Monitor, Correction Factors

The samples were irradiated at the USGS TRIGA Reactor in Denver, USA, as CAN ANU #10. Irradiated position CT for 40.0 MWh with cadmium shielding.

$^{40}$K abundances and decay constants are taken from Steiger & Jaeger (1977).

Flux monitor: GA1550 biotite @ 98.5 Ma ± 0.8 Ma (Spell & McDougall 2003)

Discrimination Factor: (1 amu) 1.00044 with error 0.380% (calculated using the Power Equation from Renne et al. 2009)

$\lambda_{K40} = 5.5430 \times 10^{-10}$

Corrections for argon produced by interaction of neutrons with K (using K$_2$SO$_4$) and Ca (using CaF$_2$) were made using the following correction factors (see Tetley et al. 1980):

$(^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$ correction factor $2.95 \times 10^{-4}$

$(^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$ correction factor $7.38 \times 10^{-3}$

$(^{39}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ correction factor $6.86 \times 10^{-3}$

$(^{38}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ correction factor $1.19 \times 10^{-4}$

Ca/K conversion factor 1.90

Table A1 List of samples

| Sample | Lithology                       | Sample weight (mg) | Foil No. | Grains   | Comment            |
|--------|---------------------------------|--------------------|----------|----------|--------------------|
| PL286-GM | Leucocratic coarse to rarely megacrystic foliated granodiorite | 9.7          | P1       | Groundmass | Less deformed     |
| PL286-CX | Leucocratic coarse to rarely megacrystic foliated granodiorite | 9.9          | P2       | Phenocryst  | Less deformed     |
| PL336-GM | Leucocratic coarse mylonitic granodiorite     | 11.5          | P3       | Groundmass | More deformed mylonite |
| PL336-CX | Leucocratic coarse mylonitic granodiorite     | 11.3          | P4       | Phenocryst  | More deformed mylonite |