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GEOLOGICAL NOTE

Did the Delamerian Orogeny Start in the Neoproterozoic?

Simon Turner, Peter Haines,[1] *David Foster,*[2] *Roger Powell,*[3]
Mike Sandiford,[4] *and Robin Offler*[5]

Department of Earth and Planetary Sciences, Macquarie University, Sydney,
New South Wales 2109, Australia
(e-mail: sturner@els.mq.edu.au)

ABSTRACT

Recent studies generally have inferred that the onset of convergence in the Delamerian Orogeny in southeastern Australia commenced at the end of the Early Cambrian (~514 Ma) after the deposition of Kanmantoo Group sediments. Correlative sequences in Antarctica provide evidence that convergent deformation (Ross Orogeny) commenced between 580 and 540 Ma, leading to the interpretation that the locus of deformation migrated or jumped northward along the paleo-Pacific margin of Gondwana. However, the absence of upper Neoproterozoic sequences in the southern Adelaide Rift Complex requires either significant pre-Kanmantoo erosion (for which there is no evidence) or a depositional hiatus due to uplift. New Rb-Sr data from solution cleavage in Brachina Formation sedimentary rocks at Hallett Cove, South Australia, date deformation at 554 ± 10 Ma, while $^{40}Ar/^{39}Ar$ data on white mica in the center of the cleavage yield a relatively flat plateau-like segment with an age of 533 ± 15 Ma. Additional evidence for a pre-514-Ma onset of deformation is provided by a 525 ± 7-Ma $^{40}Ar/^{39}Ar$ age for biotite that developed in a mylonite within a Mesoproterozoic granitic gneiss in the Myponga basement inlier to the south of Hallett Cove. Thus, the data imply that convergence commenced more or less synchronously with contraction during the Ross Orogeny in Antarctica. Deposition of the Cambrian Kanmantoo Group therefore occurred in a synorogenic setting analogous to deposition of the upper Byrd Group in Antarctica.

Online enhancements: appendix tables.

Introduction

During the late Ediacaran (latest Neoproterozoic) to Cambrian periods the paleo-Pacific margin of Gondwana evolved from a passive to a convergent margin (see Drexel and Preiss 1995 for a review). Convergent tectonism is referred to as the Delamerian Orogeny in South Australia and the Ross Orogeny in Antarctica, and strong continuity between the two (see fig. 1*a*) has long been noted (e.g., Flöttmann et al. 1993 and references therein). However, while there is good evidence that contractional deformation had commenced by at least 540 Ma in Antarctica (Rowell et al. 1992, 2001; Goodge et al. 1993, 2004*a*, 2004*b*; Encarnacion and Grunow 1996), in southeastern Australia it is generally interpreted to have started significantly later. The oldest fabric-bearing granite in the Delamerian Orogen of South Australia, the Rathjen Gneiss, has been well dated at 514 ± 4 Ma (Foden et al. 1999). This intrudes Kanmantoo Group sediments placing a minimum age on their deposition. Foden et al. (2006) combined this with the ages of other intrusive rocks to suggest that preorogenic sedimentation (Normanville and Kanmantoo Groups) was ongoing 25 m.yr. after contraction commenced in the

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[1] Geological Survey of Western Australia, 100 Plain Street, East Perth, Western Australia 6004, Australia; e-mail: peter.haines@dmp.wa.gov.au.

[2] Department of Geological Sciences, University of Florida, Gainesville, Florida 32611, U.S.A.; e-mail: dafoster@ufl.edu.

[3] School of Earth Sciences, University of Melbourne, Victoria 3010, Australia; e-mail: powell@unimelb.edu.au.

[4] School of Earth Sciences, University of Melbourne, Victoria 3010, Australia; e-mail: mikes@unimelb.edu.au.

[5] Discipline of Earth Sciences, University of Newcastle, Callaghan, New South Wales 2308, Australia; e-mail: robin.offler@newcastle.edu.au.

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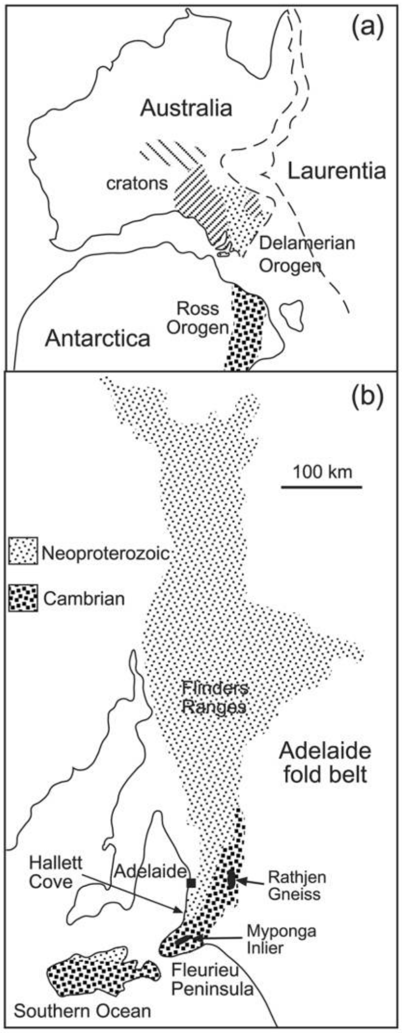

Figure 1. Map of (*a*) Australia–Antarctica and (*b*) enlargement of the southern Adelaide Fold Belt showing the location of Hallett Cove and other key localities referred to in the text.

Ross Orogen. However, magmatic ages only provide a minimum age for deformation, and some studies have suggested much earlier convergent deformation in South Australia (Turner et al. 1994; Offler et al. 1998) and in Tasmania (Foster et al. 2005), based on reconnaissance geochronological results. Additionally, shear-zone fabrics at Broken Hill to the northeast have been dated at 517–497 Ma by (Dutch et al. 2005) but at 540–520 by Hartley et al. (1997). The significance and age of such early Delamerian deformation has been controversial (e.g., Preiss 1995), but here we provide strong support for an earlier start to the Delamerian Orogeny, using both stratigraphic and geochronological observations. The new data provide a more robust framework for regional correlations between the Delamerian and Ross Orogens and associated synorogenic sedimentary sequences such as the Kanmantoo and Byrd Groups.

Stratigraphic Constraints

A hiatus in deposition, such as the one we describe now, can provide important information on changes in basin geometry and tectonics. Figure 2 illustrates a comparison of representative stratigraphic columns from the southern (Fleurieu Peninsula) and northern (Flinders Ranges) Delamerian Orogen in South Australia (see fig. 1*b*) with equivalent sequences in Antarctica. In the northern Delamerian Orogen, a disconformity separates the youngest Neoproterozoic (Ediacaran) strata, belonging to the Wilpena Group, from the Early Cambrian Hawker Group or local Uratanna Formation. This disconformity in the north correlates with a significant unconformity in the southern Delamerian Orogen. In the south, and extending for about 350 km north from the southern coast of South Australia, the upper half of the Wilpena Group (see fig. 2), and locally more of the Neoproterozoic strata, are missing beneath the Lower Cambrian unconformity (Jenkins 1990). Mapped relationships (Thomson 1969; Drexel and Preiss 1995) imply considerable local angularity between Normanville Group and Neoproterozoic strata, particularly in the area east of Adelaide. In the same area there is also a notably angular relationship between the Normanville and Kanmantoo Groups, and the former is locally missing at the northern exposed limit of the Kanmantoo Group. In this area (the Karinya Syncline), the Kanmantoo Group lies with notable angular unconformity directly over Neoproterozoic strata (Brachina Formation equivalent on the western side and pre–Wilpena Group rocks on the eastern side of the syncline). A similar unconformity (see fig. 2) occurs in the central Ross Orogen (Goodge et al. 2004*a*, 2004*b*). Neoproterozoic sedimentary rocks in both orogens are characterized by detrital zircon signatures that indicate derivation from mixed Mesoproterozoic to Archean cratonic material, similar to the basement (Gawler Craton) exposed to the west of the Delamerian Orogen (Ireland et al. 1998; Goodge et al. 2004*b*). Yet, above the unconformities, most sediments of Cambrian age show very different detrital zircon age spectra dominated by young input from the Terra Australis orogenic system (Ireland et al. 1998; Goodge et al. 2004*b*). Sedimentary rocks from the upper Normanville Group on Fleurieu Peninsula seem to show transitional (i.e., contain elements of both end-mem-

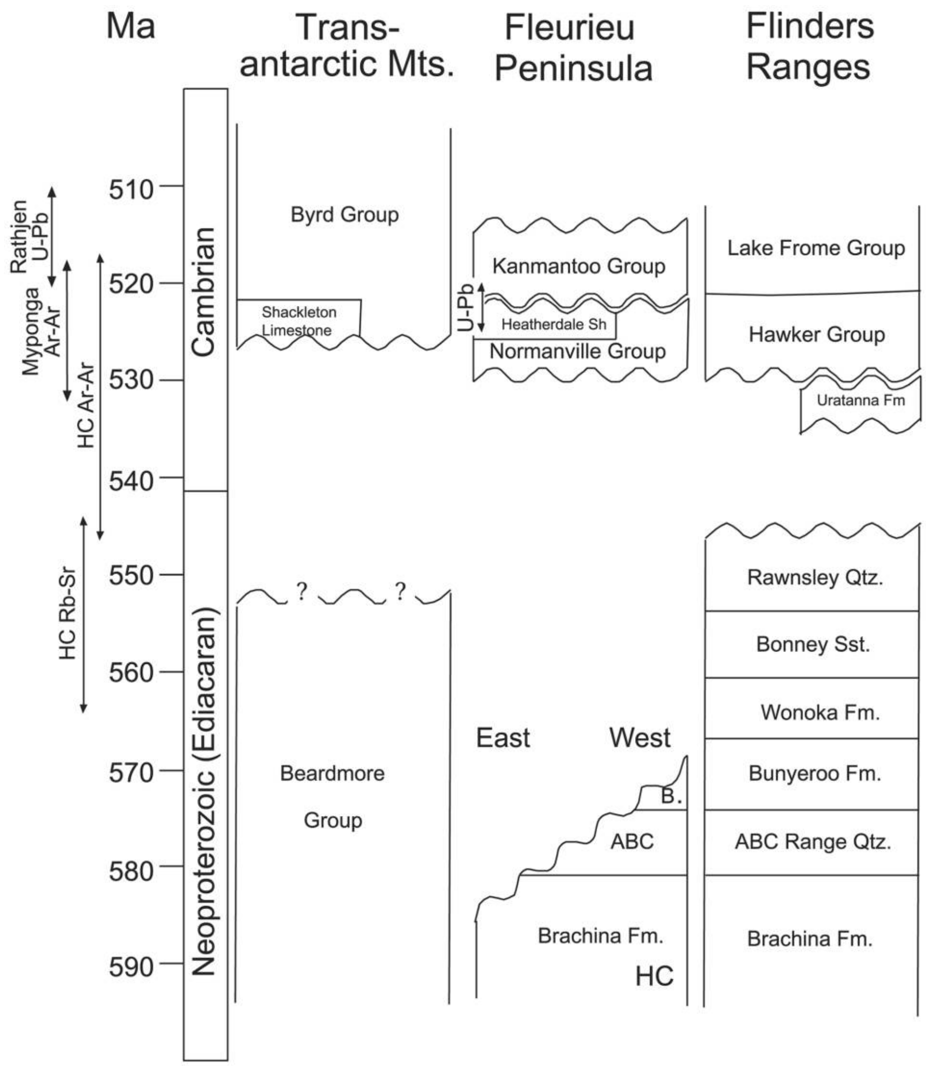

Figure 2. Correlation of stratigraphic units on Fleurieu Peninsula, on Flinders Ranges, and in Antarctica (based on Drexel and Preiss 1995; Goodge et al. 2004*b*). The Wilpena Group comprises the Brachina Formation to the Rawnsley Quartzite. Also shown are the new Rb-Sr and Ar-Ar ages for deformation of the Brachina Formation at Hallett Cove (*HC*), deposition of the Heatherdale Shale (Cooper et al. 1992; Jenkins et al. 2002), and the Rathjen Gneiss (Foden et al. 1999).

bers) detrital zircon patterns. Thus, while the missing Neoproterozoic sequences might, in principle, reflect a period of erosion, no appropriate-age sedimentary rocks have been found, and most of the overlying Cambrian sedimentary rocks require a different provenance. This evidence favors a model of a late Neoproterozoic depositionary hiatus, arguably due to uplift, suggesting that convergence had already commenced by this time. Further, the distinctly different detrital mineral age spectra and the switch to turbiditic fan deposition in the Cambrian Kanmantoo Group suggest rapid and persistent emergence of a new, previously unsourced provenance, consistent with a transition to convergence, at least by the latter part of Early Cambrian time.

Hallett Cove Revisited

Preliminary geochronological evidence that convergence may have commenced prior to deposition of the Cambrian sequences came from Rb-Sr dating (Turner et al. 1994) of a well-developed pressure solution cleavage at Hallett Cove on Fleurieu Peninsula (fig. 1). The geology at Hallett Cove is well documented (Talbot and Nesbitt 1968). At the southern end of Hallett Cove, the Neoproterozoic

Brachina Formation is well exposed on a wave-cut platform. This formation comprises chocolate brown, fine-grained sandstone and siltstone deposited in a shallow marine storm-dominated environment (Dyson 1995). These rocks have undergone only very low-grade (subgreenschist facies) metamorphism and have been subjected to one major deformation event, producing upright folds that plunge gently south. Approximately axial to these folds is a near vertical cleavage that, within individual beds, is well developed, differentiated and defined by 1–4-cm thick, alternating P (phyllosilicate-rich) and Q (quartz-rich) domains (terminology after Stephens et al. 1979; Waldron and Sandiford 1988). Turner et al. (1994) reported a model 2 Rb-Sr age of 531 ± 32 Ma for this cleavage. Although this was suggestive of an earlier start to the Delamerian Orogeny, the large uncertainty overlapped with published ages for Delamerian granites, suggesting a possible thermal relationship to the granites and precluding a definitive interpretation. The original data were derived from seven different hand specimens, with Rb and Sr concentration data obtained by x-ray fluorescence and the data reduction performed using blanket average errors (Turner et al. 1994). None of these are optimal approaches, and advances in both analytical and statistical techniques encouraged us to revisit this problem (cf. Turner et al. 1995). Furthermore, the presence of fine-grained white micas defining the cleavage (see photomicrographs in Turner et al. 1994) afforded the opportunity to use the $^{40}Ar/^{39}Ar$ method to cross-check the Rb-Sr age using a system that should, in principle, respond very differently to any thermal overprinting and/or mixing effects.

Sample Details and Analytical Techniques

Our new analytical results (tables A1 and A2, available in the online edition or from the *Journal of Geology* office) are based on a slabbed 20-cm block containing a single well-developed ~1-cm-thick cleavage. For the Rb-Sr analyses, a 2-mm dental drill was used to obtain seven 4–16-mg aliquots of powdered rock from across the cleavage, with complete separation of P and Q domains. Samples were spiked with a mixed ^{85}Rb-^{84}Sr spike and dissolved in HF followed by conversion to chloride. Rb and Sr separation was performed on a 100-μL column of EiChrom Sr-specTM resin using HCl, HNO_3, and H_2O as elutants. Rb and Sr fractions were analyzed in static multicollector mode on a Finnigan MAT 261 mass spectrometer at the Open University, and Sr isotopes were corrected for mass fractionation to $^{86}Sr/^{88}Sr = 0.1194$. Analyses of the NBS 987 standard performed over the same period yielded $^{87}Sr/^{86}Sr = 0.710220$ (± 18).

The central (P) zone of the same sample of the cleavage was extracted using dental tools and reduced to 150–250-micron chips, which were then used for $^{40}Ar/^{39}Ar$ analysis. Detrital muscovite has not been observed in the P domains (Turner et al. 1994), and every effort was made to avoid the surrounding (Q) domains when the chips were extracted. Additionally, eight detrital muscovite grains were taken from a bedding plane sample collected in a cliff face ~10 m away. Finally, we extracted neoblastic biotite from a sample from the Myponga inlier to the south of Hallett Cove.

The $^{40}Ar/^{39}Ar$ analyses were performed at the University of Florida. Samples were wrapped in aluminum foil and stacked in a fused silica tube with the neutron flux monitor GA1550 biotite (98.8 ± 0.8 Ma; Renne et al. 1998). Samples were irradiated at the Oregon State University reactor facility. Correction factors for interfering neutron reactions on K and Ca were monitored by analysis of K-glass and optical-grade CaF_2 included in the irradiation, and the following values were used: $(^{40}Ar/^{39}Ar)_K = 2.66 \times 10^{-2}$, $(^{36}Ar/^{37}Ar)_{Ca} = 2.70 \times 10^{-4}$, and $(^{39}Ar/^{37}Ar)_{Ca} = 6.76 \times 10^{-4}$. Following irradiation, the sample was heated using a CO_2 laser with a defocused beam to ensure roughly uniform heating. Step heating of the samples was accomplished by changing the power output of the laser. Reactive gases were removed with two SAES GP-50 getters prior to expansion to a MAP215-50 mass spectrometer. Peak intensities were measured using a Balzers electron multiplier. Mass spectrometer discrimination and sensitivity were monitored by analysis of atmospheric argon aliquots from an online pipette system. The sensitivity of the mass spectrometer was about 6×10^{-17} mol mV^{-1}. The data were also corrected for line blanks analyzed at regular intervals between the unknowns. Ages were calculated using a ^{40}K decay constant of 5.543×10^{-10} yr^{-1} and are reported with 2σ errors.

Rb-Sr Geochronology

The bulk-rock data of Turner et al. (1994) showed a marked contrast in Rb/Sr ratio between the P- and Q-domains but also that the range from one cleavage to another was large ($^{87}Rb/^{86}Sr = 1.95$–9.70). This strongly suggests that the range in Rb/Sr ratios reflects the differential fluid transport of Rb and Sr during solution cleavage development and the different modes of Rb-Sr-bearing minerals developed in the P- and Q-layers (Turner et al. 1994). The new microsampled data come from a cleavage with the highest Rb/Sr ratios yet found, though the range within this cleavage (^{87}Rb/^{86}Sr = 10.88–15.23) is broadly similar to previous analyses. Thus, the new data extend the isotopic range, and on figure 3, the combined data show an eightfold variation in Rb/Sr ratio. Importantly, the Rb/Sr ratios of muscovite never exceed 15 and are typically <5 (Faure and Mensing 2004), making it unlikely that the Rb-Sr data are controlled by the variable presence of detrital muscovite. Moreover, the data form a single linear array, whereas significant scatter would be anticipated if the range in Rb/Sr reflected a random sampling of detrital minerals with different Rb/Sr ratios, or if incomplete Sr isotopic equilibration during cleavage formation was involved. Thus, it is reasonable to suppose that the linear array has age significance with respect to the timing of cleavage formation.

We have used the robust statistics approach of Powell et al. (2002) to interpret the Rb-Sr isotope data. The new data and those published by Turner et al. (1994) are consistent with a single population with an age of 554 ± 10 Ma (95% confidence) and an initial ^{87}Sr/^{86}Sr isotope ratio of 0.71796 (fig. 3). Both are within error of the result obtained from the original data, but the uncertainty is much smaller and similar to that of the 536 ± 7 Ma model 1 isochron of Turner et al. (1994) that had a high MSWD. This highlights the potential problems that can arise from the traditional linear regression and MSWD approach for data with some geological scatter (principally, anticipated small heterogeneities in the Sr isotopic composition of the original fine-grained sediments).

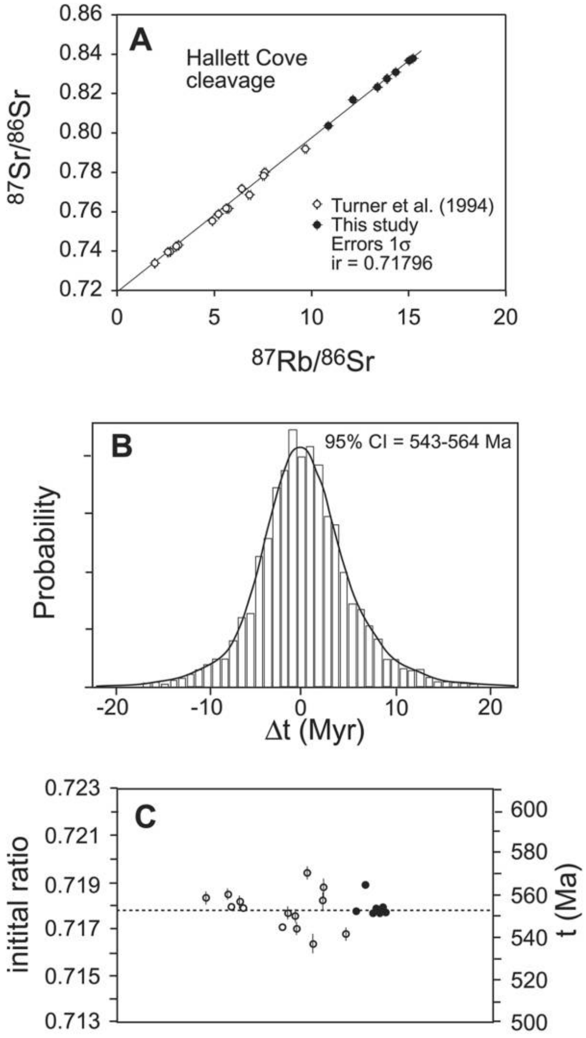

Figure 3. *A*, Conventional Rb-Sr isochron plot with Hallett Cove data from Turner et al. (1994) and this study. *B*, Age confidence range, within 95%, determined from the data in *A* using the method of Powell et al. (2002). *C*, The same data plotted on a Provost diagram (Provost 1990).

^{40}Ar/^{39}Ar Geochronology

The ^{40}Ar/^{39}Ar age spectrum for the P-domain cleavage from the sample used for the Rb-Sr analysis is presented in figure 4*A*. The argon gas released by the sample is almost exclusively from the high percentage of white mica in the P-domain because the quartz does not contain potassium. The age spectrum for sample 01-HC-01 shows an initial step of about 350 Ma followed by a relatively flat plateau-like segment (55% release) with an age of 533 ± 15 Ma. The apparent ages of the final 25% of the age spectra increase to about 850–900 Ma (fig. 4*A*). The total fusion of six single grains of detrital mica from sample 02-HC-02 gives a range of ages between about 980 and 1630 Ma (table A2; fig. 4*B*).

We also completed ^{40}Ar/^{39}Ar analysis of biotite that developed in a mylonite within a Mesoproterozoic granitic gneiss in the Myponga basement inlier. This mylonite formed on the western side of the inlier, where it is in fault contact with overlying Neoproterozoic strata. Biotite grains defining the mylonitic foliation of sample DF02–03 give a plateau age of 525 ± 7 Ma (fig. 5).

The discordance in the age spectrum for 01-HC-01 may be attributed to partial argon loss, argon recoil, and/or mixing. The young apparent age of the initial step is probably due to post-Delamerian argon loss from the finest-grained and least retentive white micas. The fine-grained nature of the white mica in this sample increases the potential for recoil loss of some ^{39}Ar during irradiation (e.g.,

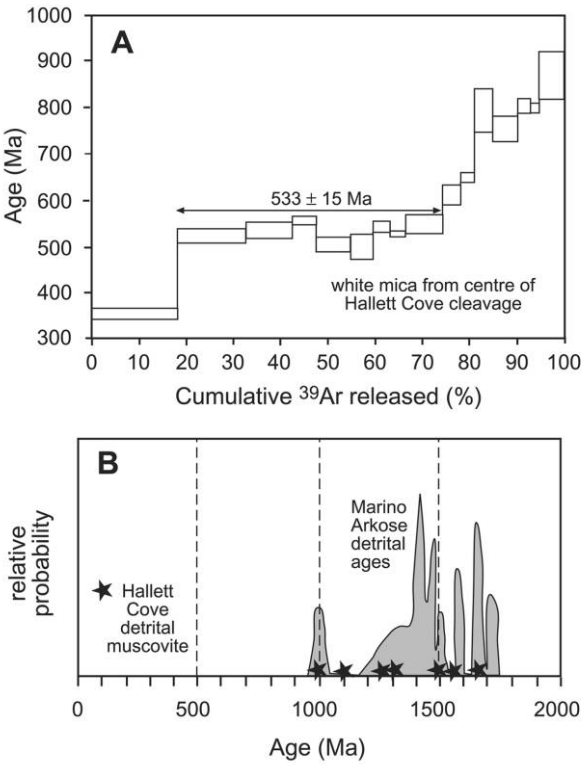

Figure 4. *A*, ^{40}Ar/^{39}Ar age spectrum for laser step heating of white mica from the center of a cleavage zone at Hallett Cove. *B*, Comparison of (total fusion) ages of detrital muscovites from a bedding plane at Hallett Cove (*stars*) with an approximately time-equivalent unit (*gray shading*; data from Haines et al. 2004).

Dong et al. 1997). Recoil loss would tend to increase the relative discordance between adjacent steps and to increase the apparent age. The relatively flat part of the age spectrum suggests that metamorphic white mica dominates about 55% of the gas released. The discordance between adjacent steps is probably due to some recoil exchange, but this would have to be relatively minor, or the spread of apparent ages would be greater. The weighted average age of the plateau-like segment most likely gives the growth age of the metamorphic mica. Elevated ages of the high-temperature steps suggest that an unobserved fraction of detrital mica contributed to the total gas released and that gas was released progressively later in the experiment and was progressively mixed with the gas from the metamorphic mica.

We rule out the potential that the ^{40}Ar/^{39}Ar data from the P-domain cleavage reflect partial resetting of preexisting detrital mica grains during the peak Delamerian thermal event around 505 Ma (Foden et al. 2006) because the Brachina Formation sedimentary rocks at Hallett Cove have, at most, experienced only very low-grade metamorphism (Kübler Index 0.3), well below the temperature required for significant ^{40}Ar loss from detrital white mica (Dunlap 1997). The total fusion ages of the detrital muscovites from 02-HC-02 are entirely consistent with the age distribution of detrital muscovites taken from the Marino Arkose at a stratigraphically lower position nearby (Haines et al. 2004), and there is no evidence for these being systematically displaced to younger ages, as would be anticipated if they had been partially reset (fig. 4*B*).

It cannot be ruled out completely that the argon gas from the precleavage micas that apparently contributed to mixed ages of the highest-temperature mixed steps also elevated the age of the plateau-like segment. It would be remarkably fortuitous, however, if mixing between ^{40}Ar from cleavage and precleavage white mica would lead to concordant ages in both the Rb-Sr and ^{40}Ar/^{39}Ar systems because of the very different ways the two systems react to chemical and physical aspects of cleavage formation and because muscovite does not have sufficiently high Rb/Sr ratios to control the Rb-Sr isochron.

We interpret, therefore, the ^{40}Ar/^{39}Ar data from 01-HC-01 to indicate that the cleavage mica grew at ~533 ± 15 Ma, well before the time of peak metamorphism in the Delamerian Orogen. Independent evidence for a pre-514-Ma onset of deformation is provided by the ^{40}Ar/^{39}Ar age of 525 ± 7 Ma for the biotite from the Myponga inlier mylonite. This biotite age cannot be the result of mix-

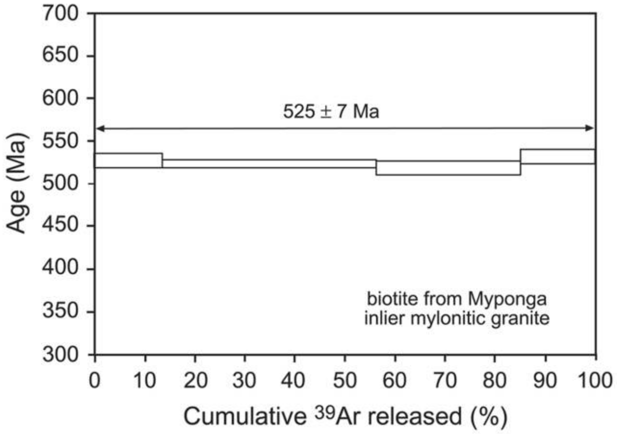

Figure 5. ^{40}Ar/^{39}Ar age spectrum for laser step heating of biotite from retrograde mylonite in Mesoproterozoic granite of the Myponga inlier.

ing with detrital micas, could not have been affected by argon recoil, and shows no evidence of younger resetting.

Discussion and Conclusions

The overlap between the Hallett Cove Rb-Sr and $^{40}Ar/^{39}Ar$ age errors is 547–544 Ma, while the age from the Myponga Inlier is 525 ± 7 Ma (fig. 2). These age constraints indicate that convergent deformation commenced in the latest Neoproterozoic–earliest Cambrian, which brings the time span of the Delamerian Orogeny into much closer agreement with that of the Ross Orogeny in Antarctica (Rowell et al. 1992, 2001; Goodge et al. 1993, 2004*a*, 2004*b*; Encarnacion and Grunow 1996). Thus, the Delamerian cycle of events started at least by 545 Ma and continued to at least 495 Ma, giving a time span of 50 m.yr.

The data also provide supporting evidence that some deformation of the Neoproterozoic sequences of the southern Adelaide Rift Complex significantly predated the emplacement of the Rathjen Gneiss at ~514 Ma (Foden et al. 1999). Clearly, the ages of the orogenic granites can reflect the age of peak thermal conditions in the core of the southern Delamerian Orogen rather than recording the onset of the Delamerian Orogeny. Thus, some Delamerian deformation appears at least 25 m.yr. older than has hitherto been commonly understood. Nevertheless, significant deformation obviously occurred later, between 514 and 495 Ma (Foden et al. 2006), resulting in the main north-south-trending axial folds that dominate the present-day outcrop (Flöttmann et al. 1993; Drexel and Preiss 1995) This later stage of deformation would be anticipated to produce folds with the same style and orientation in the Neoproterozoic and Cambrian sequences unless the far-field stress orientation changed between the Neoproterozoic and the Cambrian (for which there is no evidence).

Deformation in the Neoproterozoic reconciles the dichotomy of having similar stratigraphic observations yet different inferred timing in the contiguous Delamerian and Ross Orogens. In other words, uplift of the southern part of the Delamerian Orogen explains the nondeposition of parts of the youngest Neoproterozoic sequences, in contrast to that observed in the north, and a similar hiatus is observed in Antarctica (fig. 2). Interestingly, this early deformation either predates or overlaps with the age of deposition of the overlying Cambrian sedimentary rocks, including the Heatherdale Shale, that have a deposition age of 522 ± 2 Ma (Cooper et al. 1992; Jenkins et al. 2002). Goodge et al. (2004*b*) argued that, in Antarctica, deposition of the Cambrian Byrd Group occurred in both foreland and forearc basins during the early stages of contractional deformation, during which the young Terra Australis zircon provenance regions were first sourced. The new data presented here suggest that an analogous setting is appropriate for South Australia, implying that Cambrian sequences (Normanville and Kanmantoo Groups) reflect localized deposition in a regime where convergence had already commenced along this segment of the margin. The position of the arc is not well resolved during Delamerian times, but it clearly lay to the east in the incipient Lachlan Fold Belt.

Finally, it has been argued that the alkaline Truro volcanics within the Normanville Group and mafic dikes within the Kanmantoo Group provide evidence of extensional tectonics at the time of sedimentation (e.g., Foden et al. 2002). However, synconvergent mafic magmatism is well documented from other foreland and forearc basins such as in the Himalayan Orogen (Sengupta et al. 1996). In fact, the isotope and trace element characteristics of the Truro volcanics show that they were probably derived from the lithospheric mantle (Foden et al. 2002), not the contemporary asthenosphere, and so they do not provide compelling evidence for decompression melting and, by implication, extensional tectonics. Rather, many of the dikes postdate the main deformational fabrics and yield zircon ages of 510 ± 2 Ma (e.g., Chen and Liu 1996), clearly indicating that mafic magmatism can persist during convergent deformation. The occurrence of this (not uncommon) style of mafic magmatism in convergent tectonic belts is yet to be fully understood, but it may reflect compression melting of amphibole-bearing peridotite in the lithospheric mantle. This is predicted as a consequence of the negative dT/dP slope of the amphibole peridotite solidus at low temperatures (e.g., Iwamori 1997).

In summary, the age data presented here imply that convergence commenced in the latest Neoproterozoic–earliest Cambrian in South Australia more or less synchronously with contraction in the Ross Orogeny in Antarctica. In this framework, deposition of the Cambrian Kanmantoo Group occurred in a synorogenic setting analogous to deposition of the Byrd Group in Antarctica.

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