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Detrital zircon U–Pb and $^{40}Ar/^{39}Ar$ hornblende ages from the Aileu Complex, Timor-Leste: provenance and metamorphic cooling history

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Abstract: Geochronological data from the Aileu Complex provide new constraints on the development of the Banda Arc–continent collision. Detrital zircons of the Aileu Complex have major U–Pb age modes at 270–440 Ma, 860–1240 Ma and 1460–1870 Ma, most compatible with a sediment source located in SE Asia as part of the now fragmented Sula Spur. $^{40}Ar/^{39}Ar$ cooling ages of hornblende demonstrate an extended cooling history across the complex, with the eastern parts cooling through hornblende closure temperature by 10 Ma and central parts by 6 Ma, consistent with a variable exhumation history. The onset of cooling by 10 Ma implies that metamorphism was probably coeval with initiation of the Banda Arc. We propose that the Aileu Complex cooling ages record deformation related to fragmentation of the Sula Spur and early development of the Banda Arc, rather than collision between the Australian continent and the Banda Arc.

Supplementary material: Detrital zircon U–Pb analytical results, hornblende argon isotope geochronology sample details, hornblende $^{40}Ar/^{39}Ar$ step heating analytical results and hornblende electron microprobe analytical results are available at www.geolsoc.org.uk/SUP18702.

The Banda Arc of Timor-Leste and eastern Indonesia (Fig. 1) represents one of the youngest arc–continent collision zones, yet the age of onset of collision remains disputed, in part because quantitative geochronological data are limited. A number of observations point to the onset of collision coincident with the *c*. 3 Ma cessation of volcanism north of Timor-Leste (Hall 1996; Elburg *et al*. 2005). An earlier onset of collision has been suggested by some workers to account for the depositional age (*c*. 5.7–3.3 Ma) of post-orogenic strata (e.g. Haig 2012) and the late Miocene (*c*. 8 Ma) cooling ages from the Aileu Complex (Fig. 2) of northern Timor-Leste (Berry & McDougall 1986; Charlton *et al*. 1991; Harris *et al*. 2000; Keep & Haig 2010). Crucial to this debate is the question of the provenance of the Aileu Complex protoliths and, specifically, whether the sediment was derived from the continental margin of northern Australia or elsewhere.

The Aileu Complex comprises an extensive succession of mostly terrigenous sedimentary rocks exposed along the north coast of Timor-Leste (Fig. 2). Owing to the absence of diagnostic faunal assemblages, the biostratigraphic affinity of the Aileu Complex is unclear. Both Australian (Harris *et al*. 2000; Charlton 2002) and Asian (Carter *et al*. 1976; Barber *et al*. 1977) provenances have been suggested.

To better understand the source of the Aileu Complex protoliths, and the evolution of the Banda Arc, this paper presents two new geochronological datasets. The first dataset comprises detrital zircon U–Pb ages from Aileu Complex metasediments. These data provide constraints on the provenance and depositional age of the complex. Together with zircon morphological data, the new results also allow evaluation of the degree of sediment recycling and transport distances. The second dataset comprises new $^{40}Ar/^{39}Ar$ cooling ages from metamorphic hornblende separated from mafic rocks of the Aileu Complex. These data provide cooling ages from regional metamorphism observed in the Aileu Complex and, together with existing $^{40}Ar/^{39}Ar$ data (Berry & McDougall 1986), constrain the timing of orogenesis.

Geology of the Aileu Complex

The Aileu Complex, first described by Audley-Charles (1968), comprises a metamorphosed turbiditic succession with inferred thickness of greater than 1 km (Fig. 2). There is considerable lithological variation within the northeastern parts of the Aileu Complex, including mafic igneous rocks, quartzite, quartz arenite, marble and feldspathic conglomerates. Away from the coast the sequence is more homogeneous, consisting of phyllite and shale. Deformation is also less intense toward the south. The proportion of mafic rocks increases toward the east, where the Aileu Complex is bounded by the Hili Manu amphibolite and ultramafic massifs. Berry & McDougall (1986) considered this amphibolite body to be part of the Aileu Complex, whereas Charlton (2002) suggested that it is part of the Hili Manu lherzolite, which abuts the Aileu Complex along a faulted contact. To the south, the Aileu Complex is bounded by lower metamorphic grade Australian affinity Gondwana Sequence sediments (Harris 2006), with the boundary at least in part defined by the Laclo Fault.

Owing to a paucity of preserved fossil material, the age of the Aileu Complex is poorly constrained. Most researchers have suggested a Permian age (Berry & Grady 1981; Harris *et al*. 2000; Charlton *et al*. 2002), although others have proposed that it may be either older (Barber & Audley-Charles 1976) or younger (Brunnschweiler 1978; Snyder *et al*. 1996), or have been deposited over an extended period of time that spanned the early Permian to the end of the Jurassic, or possibly the early Cretaceous (Audley-Charles & Harris 1990). Charlton *et al*. (2002) concluded that the Aileu Complex is the metamorphosed counterpart of other Permian units in Timor-Leste, including the Maubisse, Atahoc and Cribas formations. This conclusion assumes the Aileu Complex was part of the late Carboniferous to Jurassic Gondwana Sequence, an intracratonic basin of Australian origin deposited prior to the breakup of Gondwana (Harris *et al*. 1998). Assuming the Aileu Complex and Maubisse Formation represent a continuous sedimentary succession (e.g. Barber & Audley-Charles 1976; Berry & Grady 1981; Charlton *et al*. 2002), the recent work of Davydov *et al*. (2013) suggests that the oldest parts of the Aileu Complex could date to the late Carboniferous.

The relationship between the Aileu Complex and adjacent units is crucial, but poorly understood. The Aileu Complex boundary is

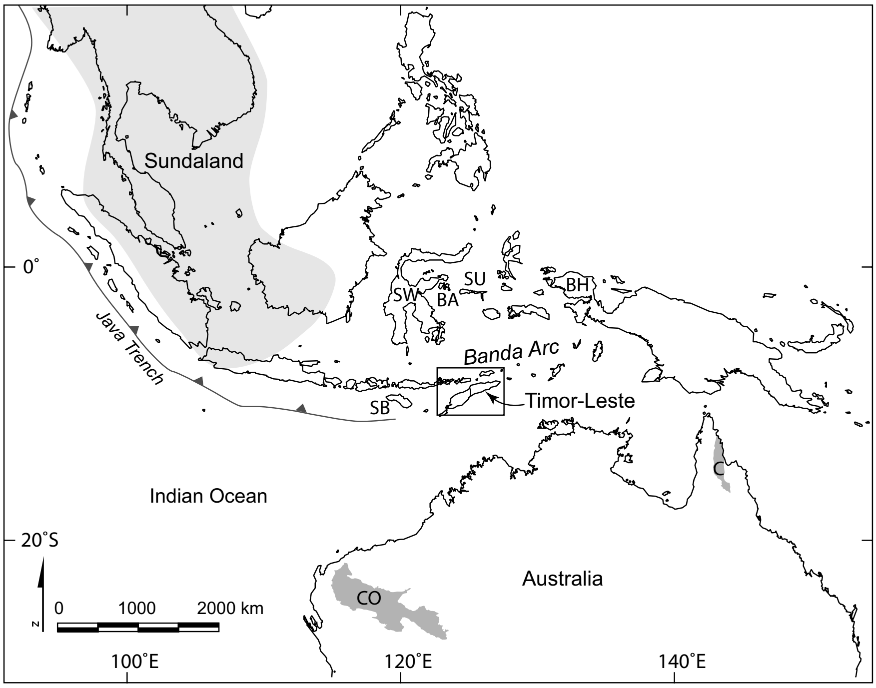

Fig. 1. Timor-Leste occupies the eastern half of the island of Timor in the Banda Arc, SE Asia. Marked locations and features: BA, Banggai Islands; BH, Bird's Head; C, Coen region; CO, Capricorn Orogen; SU, Sula Islands; SB, Sumba; SW, Sulawesi. Area enlarged in Figure 2a is indicated by box. Outline of Sundaland is from Hall & Wilson (2000).

in part defined by the prominent Laclo Fault, but there are no definitive studies that demonstrate continuity of units across this structure. The study by Harris (2006) used ages of detrital zircons from Kisar Island (Fig. 2) to infer an Australian continental source for the Aileu Complex. However, this assumes that the Kisar rocks are correlatives of the Aileu Complex, a conclusion that remains speculative as no previous zircon provenance studies have been undertaken from the Aileu Complex on Timor-Leste to allow for comparison.

In contrast to an Australian origin, Carter *et al.* (1976) and Barber *et al*. (1977) proposed an exotic origin for the Aileu Complex to account for the transition from coarser-grained, quartz-rich metasediments on the north coast to the finer-grained, more distal facies in the southern part of the complex. On this basis Carter *et al.* (1976) argued that the provenance of the Aileu Complex protoliths was probably from the north of Timor, and not from the Gondwanan margin to the south. They suggested Sundaland as a likely provenance (Fig. 1). Barber *et al*. (1977) similarly regarded the juxtaposition of Permian units with contrasting depositional environments to require two distinct source regions, namely the Gondwanan margin to the south and the southern margin of Asia to the north. Based on a structural interpretation, Charlton (2002) argued that the eastern parts of the Aileu Complex formed in a forearc setting. Metcalfe (2006) speculated that the West Burma Block (which now forms part of Sundaland) formed a northern source of sediments for Timor during the Triassic.

Differences in interpretation extend to the tectonic history and structural significance of the Aileu Complex. Harris *et al.* (2000) interpreted the Aileu Complex to be the metamorphosed part of the Gondwana Sequence, and suggested that the Aileu Complex and Maubisse Formation represent a single structural unit. In contrast, Kaneko *et al*. (2007) proposed that the Aileu Complex was tectonically emplaced, along with other metamorphic units of Timor, onto the now structurally underlying Gondwana Sequence. In view of the oblique nature of present-day plate motion across the Banda Arc, there has been surprisingly little attention focused on the role of lateral translations and strike-slip faults in the construction of the Banda orogenic systems. Berry & Grady (1981) noted the potential role of strike-slip faulting, although they did not elaborate in any detail.

The metamorphic grade of the Aileu Complex varies from sub-greenschist facies in the SW to upper amphibolite facies in the NE (Berry & Grady 1981). Previous investigations of the metamorphic history of the Aileu Complex are limited to the work of Berry and co-workers, who described the distribution of metamorphic facies and obtained metamorphic cooling ages from a range of locations (Berry & Grady 1981; Berry & McDougall 1986). Their dataset comprises 13 K–Ar hornblende ages of 7.7–67.9 Ma, five K–Ar biotite and white mica ages of 5.4–6.0 Ma, and $^{40}Ar/^{39}Ar$ ages for six hornblende and one white mica sample. The hornblende $^{40}Ar/^{39}Ar$ results included a single plateau age of 24.1 ± 0.4 Ma (2σ uncertainty) and total gas ages in the range 8.8 ± 1.0 Ma to 69.3 ± 1.2 Ma. Berry & Grady (1981) argued on the basis of the K–Ar data that prograde metamorphism occurred prior to *c.* 11 Ma. Berry & McDougall (1986) interpreted the $^{40}Ar/^{39}Ar$ results as indicating much earlier metamorphism prior to 70 Ma, followed by a reheating event and retrogression during a collision event at *c.* 8 Ma. No tectonic explanation is offered for the 24 Ma plateau age; this age is discounted as the result of a mixed population of new and partially retrogressed hornblende.

Analytical methods

U–Pb detrital zircon ages have been obtained from two quartz-rich metasediments from the Aileu Complex (Fig. 2). Zircons were separated from a sub-354 µm sieve sample using standard heavy liquid and magnetic procedures. Zircon grains were then hand picked, mounted in epoxy on glass slides and polished to reveal a section through the centre of the zircons.

U–Pb ages of single grains were obtained by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) using a 193 nm excimer laser ablation system (32 µm spot size)

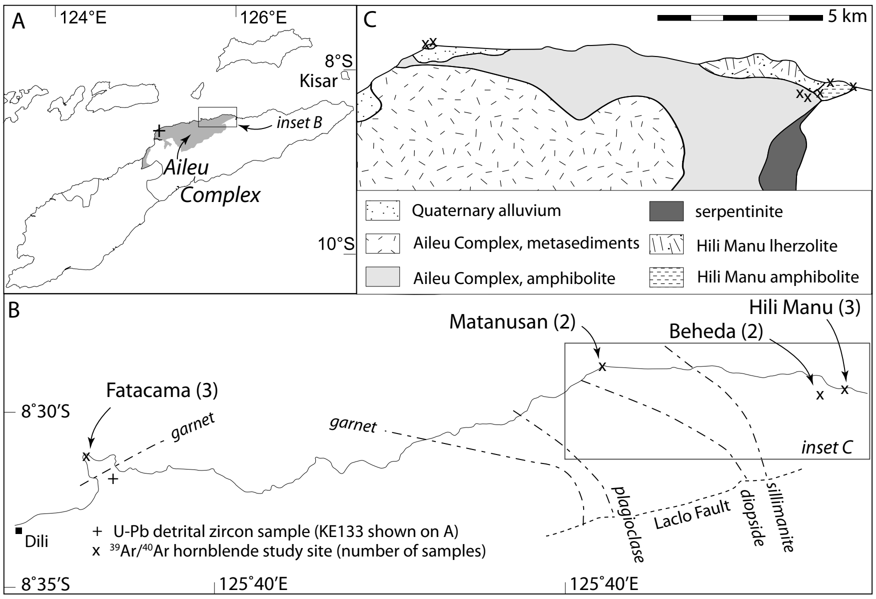

Fig. 2. (**a**) Location of the Aileu Complex in Timor. Geology adapted from Audley-Charles (1968). Location of the western U–Pb sandstone sample indicated by + (KE 133; 8.6428°S, 125.1235°E). (**b**) Location of argon and U–Pb geochronology sampling sites in the eastern Aileu Complex. The number of samples for each site is shown in parentheses. Metamorphic isograds from Berry & McDougall (1986) are shown, along with metamorphic isograds from the same study. (**c**) Detail of the far eastern part of the Aileu Complex, showing geology simplified from Berry & Grady (1981). 'Aileu Complex, metasediments' comprise pelitic and quartz schists with minor amphibolite; 'Aileu Complex, amphibolite' is mostly amphibolite, with minor pelitic and calcareous schist.

housed at the School of Earth Sciences, University of Melbourne. Analytical procedures were similar to those of Paton *et al*. (2010) and involved ablation and data collection from single zircon grains for up to 50 s, or until the laser penetrated through the zircon into the mounting medium. Zircon standard 91500 (1065.4 ± 0.3 Ma; Wiedenbeck *et al*. 1995) was used as the primary standard, with Temora 1 (416.75 ± 0.24 Ma; Black *et al*. 2003) and Temora 2 (416.8 ± 1.3 Ma; Black *et al*. 2004) used as secondary standards. The zircon standard BR266, also known as z6266 (559.0 ± 2 Ma; Stern & Amelin 2003), was also analysed during each run. Concordia ages for the standards run with samples KE133 and KE342 were 1062.8 ± 3.3 Ma and 1062.6 ± 3.5 Ma for 91500, 401.8 ± 3.4 Ma and 420.4 ± 2.4 Ma for Temora, and 575.2 ± 6.1 and 548 ± 6.9 Ma for BR266, respectively. Each unknown zircon was analysed with a single spot, targeted at inclusion- and crack-free zircon cores. The small size of the crystals (generally in the range 30–100 µm) meant that rims, where present, were not targeted for analysis. Results are presented in Figure 3.

Ten samples for $^{40}Ar/^{39}Ar$ analysis were selected from four sites (Fig. 2). Samples were selected to assess regional trends across the changing metamorphic grade. The Fatacama site has experienced upper greenschist-facies metamorphism, and the Matanusan, Beheda and Hili Manu locations are of higher metamorphic grade and reached upper amphibolite conditions (Berry & McDougall 1986).

Hornblende separates were produced using magnetic and heavy mineral separation techniques followed by handpicking. Samples were packed in foil, and together with flux monitor GA1550 biotite (98.8 ± 0.5 Ma (1σ); Renne *et al*. 1998), were irradiated in position 5C at the McMaster Nuclear Reactor, Ontario, Canada. $^{40}Ar/^{39}Ar$ analyses were conducted at the University of Melbourne Noble Gas Geochronology and Geochemistry Laboratory, using analytical procedures analogous to those described by Phillips *et al*. (2007). The conventions of Steiger & Jäger (1977) were followed for decay constants and $^{40}Ar/^{36}Ar$ air ratio. Step-heating analyses of the hornblende separates were carried out using a tantalum furnace connected to a VG3600 mass spectrometer equipped with a Daly detector. The ^{39}Ar release spectra (Figs 4–7) were plotted using Isoplot/Ex3.04 (Ludwig 2003). Two aliquots of each sample were analysed. All final age results are reported with 2σ uncertainties. Samples were deemed to generate plateau ages if at least 50% of ^{39}Ar gas released, in at least three consecutive steps, generated ages within 2σ error of the weighted mean. Ca/K for each step was calculated by multiplying the corrected $^{37}Ar/^{39}Ar$ by a factor of 1.75, derived from analyses of the hornblende standard Hb3gr, which has known Ca and K values.

The major element composition of hornblende was established using the SX50 electron microprobe housed at University of Melbourne Joint Electron Microprobe (JEM) Facility. Analysis was carried out using wavelength-dispersive spectrometers with an accelerating voltage of 15 kV, a current of 20 nA and a beam diameter of *c*. 3 µm. Matrix corrections and data reduction were undertaken using PAP matrix correction supplied by the manufacturer. For each sample 5–10 spots were analysed, including multiple points within some crystals to establish compositional variation.

Detrital zircon U–Pb age results

Sample KE133 is a fine-grained, weakly foliated quartz arenite sampled from a 10 m thick bed, located on the north coast at Inur Carimbula, 50 km WSW of Dili (8.6428°S, 125.1235°E). The sample comprises mostly fine-grained quartz (0.05–0.2 mm) with interlocking grain boundaries and undulose extinction. A weak foliation is defined by stilpnomelane laths (5%, 0.1–0.2 mm). Plagioclase and finer-grained accessory minerals are also present (<2%) including colourless zircons with a diameter of 40–100 µm, and rarely up to 200 µm. Zircons with elongate grain shapes form 6% of the population, with typical grain sizes of 60 µm wide and 120–200 µm long.

Analysis of 145 zircons from sample KE133 produced 103 concordant (within ±5% of concordia) ages (Fig. 3). Within this concordant dataset major age modes occur at 270–430 Ma, 460–510 Ma, 890–1180 Ma and 1460–1870 Ma. Grains younger than 270 Ma and older than 1900 Ma make up less than 2% and 4% of the population, respectively.

Sample KE342 is a fine-grained, pale grey quartzite sampled from a massive, blocky bed located 6 km NE of Dili (8.5297°S, 125.6212°E). It comprises mostly interlocking quartz grains (0.1–0.3 mm) with randomly oriented biotite (<0.3 mm) and muscovite (<0.2 mm) laths, less common plagioclase and finer-grained

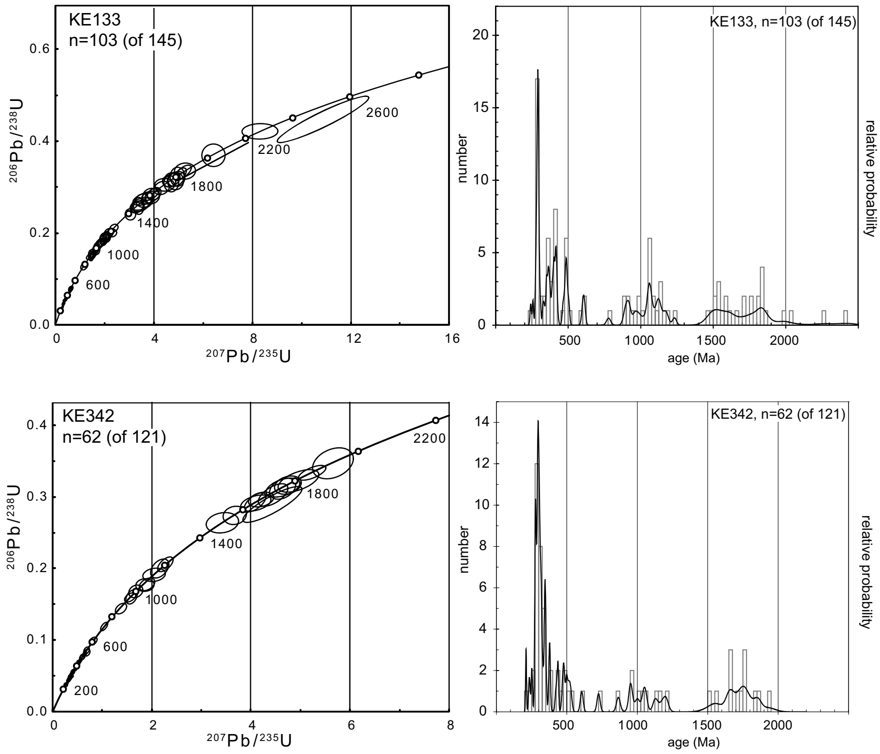

Fig. 3. Detrital zircon U–Pb age results. Concordia, histogram and probability curves of all data with > 95% concordance are shown. Data point error ellipses are 2σ. Plots generated with Isoplot/Ex 3 (Ludwig 2003).

accessory minerals, including colourless zircon mostly with grain widths of 30–80 μm.

Analysis of 121 zircons from KE342 yielded 62 concordant (within ±5% of concordia) ages. Major age modes for the concordant data are at 270–530 Ma, 950–1060 Ma and 1650–1780 Ma. Grains younger than 270 Ma make up less than 5% of the population, and a single concordant analysis yielded an age older than 1900 Ma.

Both samples contain a similar range of zircon morphologies, comprising approximately 20% euhedral, 20% rounded, 50% subrounded or subangular and 10% angular grains. Different zircon morphologies are included in all age populations. Rounded zircons yielded both young and old ages, and although euhedral zircons yielded the youngest ages, some are Proterozoic.

Amphibole $^{40}Ar/^{39}Ar$ results

The $^{40}Ar/^{39}Ar$ final ages are reported here with 2σ uncertainties. Both aliquots of sample AH1 from the Hili Manu area generated plateau ages (at least three contiguous steps containing >50% of gas released) within error of one another. The ages obtained were 10.32 ± 0.28 Ma and 9.91 ± 0.42 Ma, with a weighted mean of 10.19 ± 0.23 Ma (Fig. 4).

Samples AH2a and AH2b produced more discordant age spectra with minimum ages of *c.* 12 Ma. The higher temperature steps of AH2b define a plateau age of 17.04 ± 0.20 Ma, including 51.9% of gas released (Fig. 4). Although the higher temperature steps of AH2a are less concordant and do not yield a plateau age, they give an average age of 17.04 ± 0.41 Ma (MSWD = 1.7) from 51.9% of gas released. The saddle-shaped nature of spectra produced by samples AH2a and AH2b suggests the presence of extraneous argon, therefore the plateau and average ages are considered to be maximum cooling ages.

Samples AH5a and AH5b generated similar, discordant age spectra with no plateau ages (Fig. 4). Around 90% of gas release was above 1100 °C, and significant gas was not released until the higher temperature steps at 1200–1300 °C. The weighted average age for five steps from 1130 °C in AH5a is 25.9 ±3.1 Ma (88.5% of gas release, MSWD = 144), and for six steps from 1120 °C in AH5b is 25.8 ± 2.1 Ma (90.9% of gas release, MSWD = 67). Ca/K ratios show limited variation across most temperature steps, and are within the range of the electron microprobe data, suggesting that the disturbance in the age spectrum is not due to mineral contaminants. Hornblende grains from sample AH5 display evidence of recrystallization, with coherent grains surrounded by fine-grained material along grain margins. In addition, large grains are optically discontinuous, suggesting the presence of compositional domains. These features may have resulted in different argon diffusivities, variable cooling ages and/or redistribution of ^{39}Ar owing to recoil effects. The irregular age spectra complicate geological interpretation of these age data, therefore these spectra are considered to indicate a maximum cooling age of *c.* 26 Ma.

Hornblende samples AH3a and AH3b from the Beheda area produced plateau ages within error of one another, of 9.73 ± 0.16 Ma and 9.88 ± 0.15 Ma, with a weighted mean of 9.81 ± 0.11 Ma (Fig. 5).

Samples AH4a and AH4b produced irregular saddle-shaped age spectra with minimum ages of 7.56 ± 1.02 Ma and 10.87 ± 0.16 Ma, respectively (Fig. 5). The Ca/K ratio is higher than obtained from microprobe analyses of the hornblende, suggesting some contamination by a calcium-rich phase. This is likely to be titanite, observed in thin section to be present as rare inclusions within hornblende.

Hornblende from aliquot AH6b, from the Matanusan area, produced a more concordant age spectrum with a pseudo-plateau age (45.5% of gas release) at 6.50 ± 0.09 Ma and a high-temperature flat segment at *c.* 8.4 Ma (Fig. 6). The second aliquot, AH6a, yielded very similar results although with more discordance in the young age steps, which precludes the calculation of a plateau age.

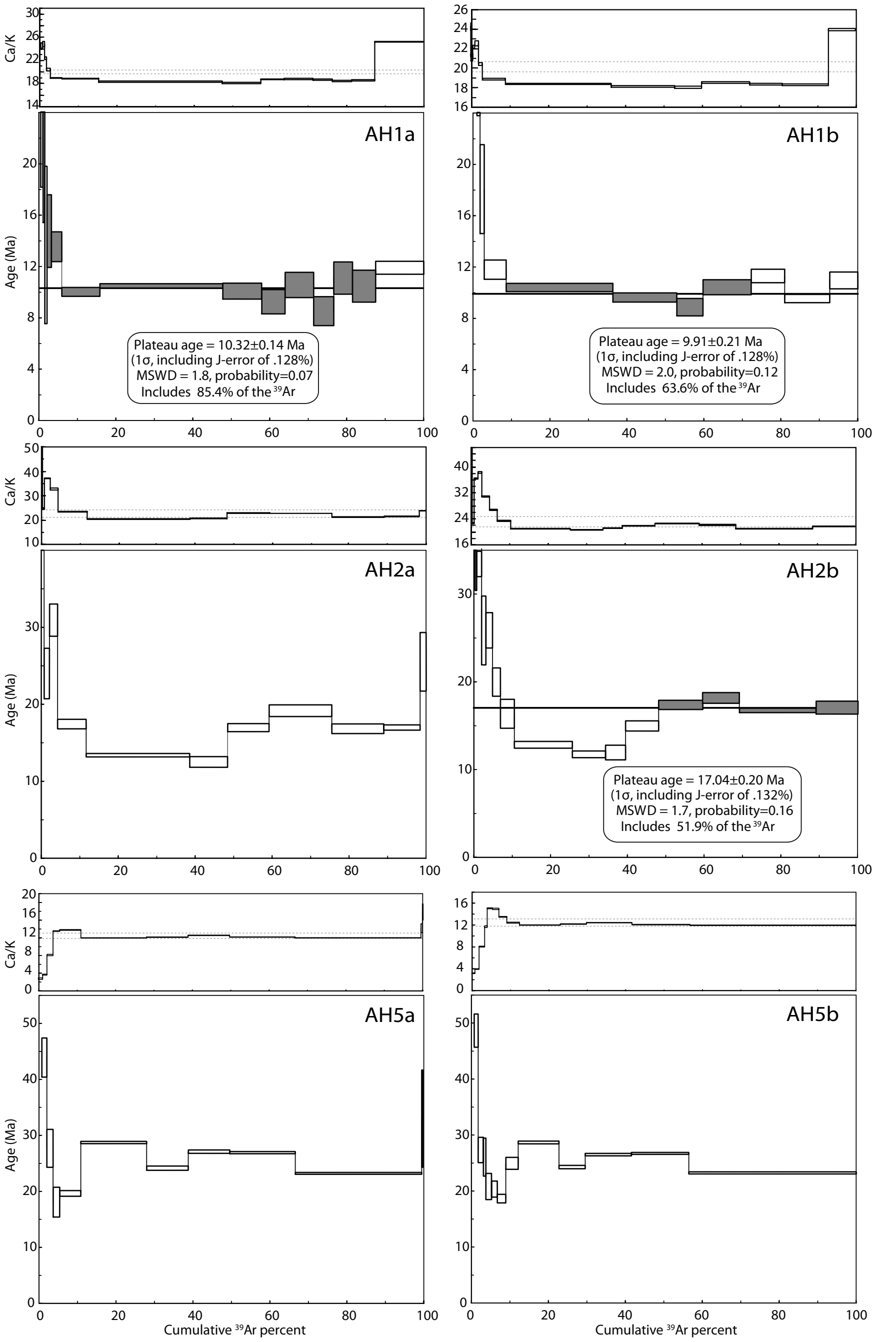

Fig. 4. Argon release spectra and apparent Ca/K ratios for the Hili Manu hornblende samples. Box heights are ±1σ. Shaded steps are included in plateau ages.

The saddle-shaped age spectra obtained from hornblende aliquots AH7a and AH7b are characterized by relatively large uncertainties as a result of low levels of gas release (Fig. 6). The minimum age measured is 3.88 ± 1.86 Ma. The increase in age with increasing temperature correlates with an increase in Ca/K ratios, from 18 at the youngest age step (1000 °C), to 39 in the higher temperature steps. Electron microprobe analysis of hornblende yielded Ca/K ratio values of 26–30, suggesting that this hornblende separate was contaminated with a high-potassium phase that outgassed at low temperatures and a high-calcium phase that outgassed at high temperature. The hornblende grains contained numerous quartz and magnetite inclusions, but no obvious K- or Ca-bearing minerals were observed. The variation in Ca/K ratios might be due to undetected compositional variations within some hornblende grains or undetected contaminant phases such as biotite or titanite.

From the Fatacama area, aliquots AH8a, AH8b, AH9a and AH9b all produced similar irregular age spectra, with the youngest ages generated in the lowest temperature steps before increasing during intermediate temperature steps (Fig. 7). Ages then decrease to those generated at the lowest temperatures before increasing again at the highest temperature steps. Ca/K ratios also reflect this pattern, and are mostly lower than microprobe analyses of hornblende from these samples, suggesting contamination by a high-potassium

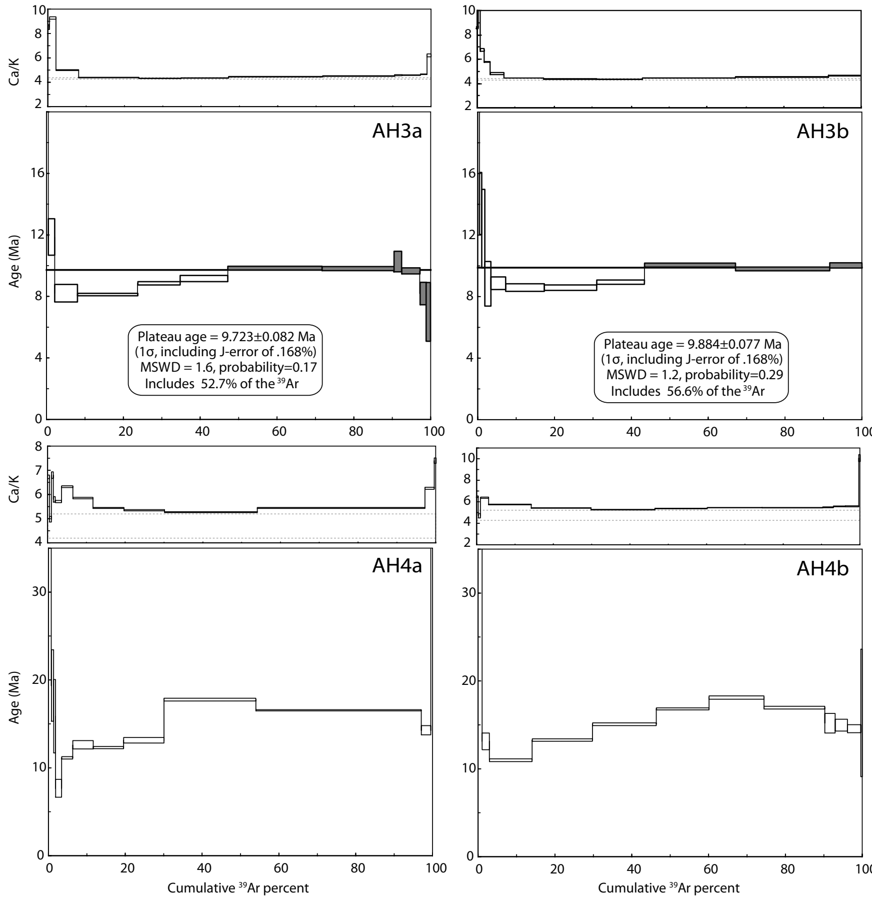

Fig. 5. Argon release spectra and apparent Ca/K ratios for the Beheda hornblende samples. Box heights are ±1σ. Shaded steps are included in plateau ages.

phase, most probably stilpnomelane. These disturbed spectra all include at least several steps at *c*. 6–7 Ma, interpreted to be the hornblende closure age.

The final Fatacama sample, AH10, yielded a mean plateau age of 6.13 ± 0.05 Ma. Aliquot AH10a generated a plateau age of 6.01 ± 0.06 Ma from 83.9% of released gas over eight steps, and AH10b produced a plateau age of 6.24 ± 0.05 Ma from 72.8% of the gas release over four steps (Fig. 7).

Discussion of results

Interpretation of detrital zircon age results

The detrital zircon age distributions from the two Aileu Complex samples are almost identical, with major age modes occurring at 270–425 Ma (40% of grains), 860–1180 Ma (14%) and 1460–1870 Ma (20%). Grains younger than 270 Ma make up 3% of the population, as do grains older than 1900 Ma. No Archaean zircons were identified. The similarities between the detrital zircon age spectra of the two samples suggest a common history that may be considered to be representative of at least the northern parts of the Aileu Complex. Th/U ratios of 97% of zircons analysed are within the range 0.1–1.6, considered normal for felsic igneous zircons (Williams & Claesson 1987) and consistent with the zircon age modes representing igneous rather than metamorphic events.

Using the method described by Vermeesch (2004), where the probability of analysing a sample component of a certain frequency is a function of the number of analyses undertaken, the probability of analysing a sample component that forms 5% of the zircon age population is greater than 95% for each of these samples. When the two samples are combined ($n = 165$), a reasonable pooling of data given the similarity of the samples, this probability increases to 99.9%, giving confidence that all significant zircon age populations have been analysed.

The age of the youngest detrital zircons establishes a maximum age for sediment deposition. Although the youngest zircon analysed is often used to constrain this maximum age, a more robust approach is to use the age of the youngest coherent zircon population (e.g. Bruguier *et al*. 1999; Tyler *et al*. 1999; Williams 2001; Van Wyck & Williams 2002). Both sediment samples yield uncommon Triassic zircons, with concordant ages of 211 ± 6 Ma and 234 ± 12 Ma (sample KE342) and 242 ± 10 Ma (sample KE133). For both samples the youngest zircon population is Permian, with statistically indistinguishable ages of 273 ± 9 Ma (KE342) and 275 ± 10 Ma (KE133). We are confident therefore that the depositional age of at least some parts of the Aileu Complex protoliths is no greater than *c*. 275 Ma. The presence of uncommon Triassic zircons suggests that a younger deposition age is also possible.

Several characteristics of the Aileu Complex detrital zircon population are important to consider in the context of a depositional setting. The most significant age peak, at 290 Ma, is also the youngest, which demonstrates the importance of sediment contributions from early Permian source rocks. The inclusion of many euhedral zircons in the Aileu Complex suggests a proximal source rather than prolonged transportation and/or multiple sedimentary cycles. This is consistent with the immature nature of some feldspathic sandstones and conglomerate with feldspathic volcanic clasts, such as those exposed at Buku Fatossidi, located 1 km north of the KE342 sampling site.

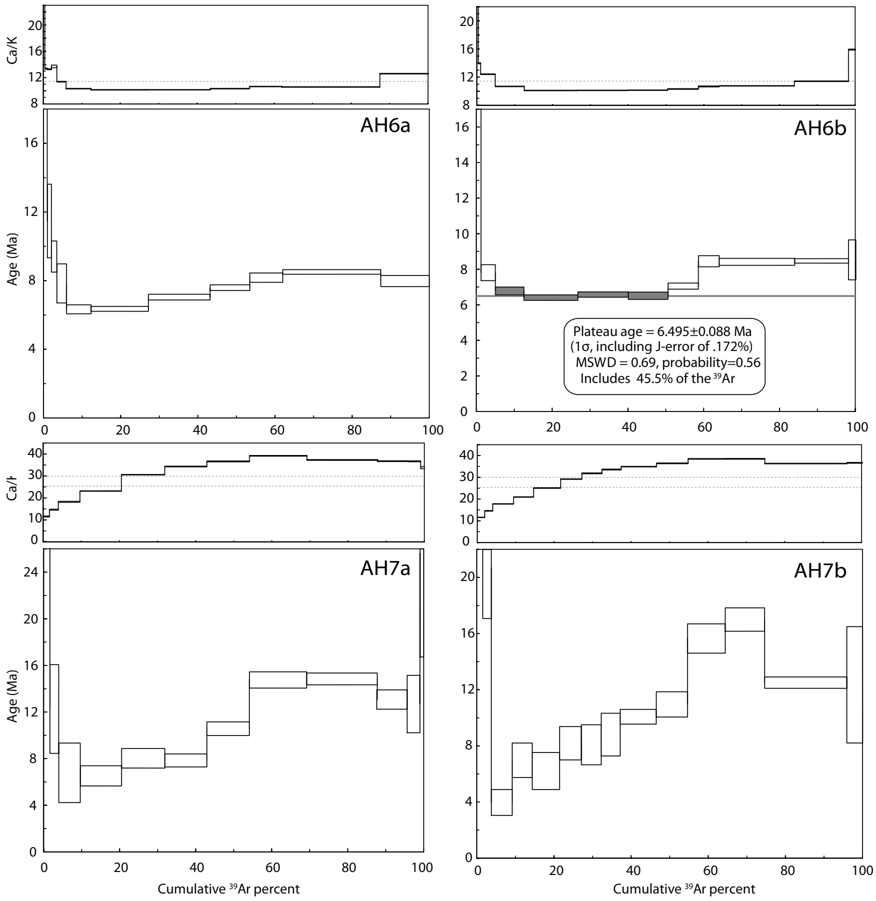

Fig. 6. Argon release spectra and apparent Ca/K ratios for the Matanusan hornblende samples. Box heights are ±1σ. Shaded steps are included in plateau ages.

Metamorphism and cooling history

The range of $^{40}Ar/^{39}Ar$ cooling ages recorded in metamorphic hornblende across the Aileu Complex suggests variable exhumation across the complex. Cooling ages vary from 6 to 10 Ma, with the oldest ages generated from the highest metamorphic grade samples.

Hili Manu, the highest metamorphic grade sample site, cooled through the hornblende closure temperature at 10.2 ± 0.2 Ma. Although not all Hili Manu samples in this study produced plateau ages, there is no evidence of a Late Cretaceous cooling age, which was suggested by Berry & McDougall (1986) as minimum age for prograde metamorphism based on a total gas age from a highly discordant $^{40}Ar/^{39}Ar$ age spectrum.

Hornblende from the Aileu Complex in the Beheda region, adjacent to Hili Manu, records an average cooling age of 9.8 ± 0.1 Ma. This age cannot be differentiated from that obtained from Hili Manu when compositional differences in the hornblende are taken into account; the more Mg-rich compositions of Hili Manu (Mg-number 40–46 compared with 28–30 for Beheda) are expected to yield slightly older apparent ages owing to greater argon retention (Dahl 1996). The data suggest that, although Hili Manu is separated from the Beheda region by a faulted contact, these areas shared a common metamorphic cooling history, at least since the Late Miocene. An important implication, if the Hili Manu amphibolite and adjacent lherzolite share a common history, is that this complex underwent exhumation by 10 Ma. This may have occurred either prior to or in the early stages of metamorphism of the Aileu Complex.

The cooling history of Matanusan is not tightly constrained by the new data; however, pseudo-plateau ages of 6.5 and 8.4 Ma are consistent with the K–Ar age of 7.7 Ma obtained from the same region (Berry & Grady 1981). For the Fatacama region near Dili, a new cooling age of 6.1 ± 0.1 Ma is presented in this study. The partial metamorphic overprint of igneous fabrics in these greenschist-facies rocks suggests a simple, single-stage metamorphic history.

Closure temperature and cooling rates

The amphibole $^{40}Ar/^{39}Ar$ age data from both this study and that of Berry & McDougall (1986) suggest that there is some variability in the thermal history across the Aileu Complex. The new data confirm cooling from the late Miocene as suggested by Berry & McDougall (1986) and indicate cooling through the hornblende closure temperature by 10 Ma in the eastern Aileu Complex and by 6 Ma in the central Aileu Complex near Dili (Fatacama samples of this study). Although 500 °C is commonly used as the closure temperature for hornblende, there is considerable variability associated with closure temperatures. Dahl (1996) showed closure temperature to vary systematically across 60 °C with increasing magnesium content. The variation of Mg-number within the Aileu amphiboles indicates an expected closure temperature range of (490–515) ± 50 °C, with the easternmost samples having the highest closure temperatures. This reconciles the age difference recorded between Hili Manu (10.2 ± 0.2 Ma, Mg-number 40–46) and Beheda (9.8 ± 0.1 Ma, Mg-number 28–30) but cannot account for the 4 myr age difference between samples from the eastern Aileu Complex and those from farther west near Dili. Thus, a minimum cooling rate for the eastern Aileu Complex of *c.* 50 °C Ma^{-1} is indicated; faster cooling or a variable cooling history may have occurred but cannot be further

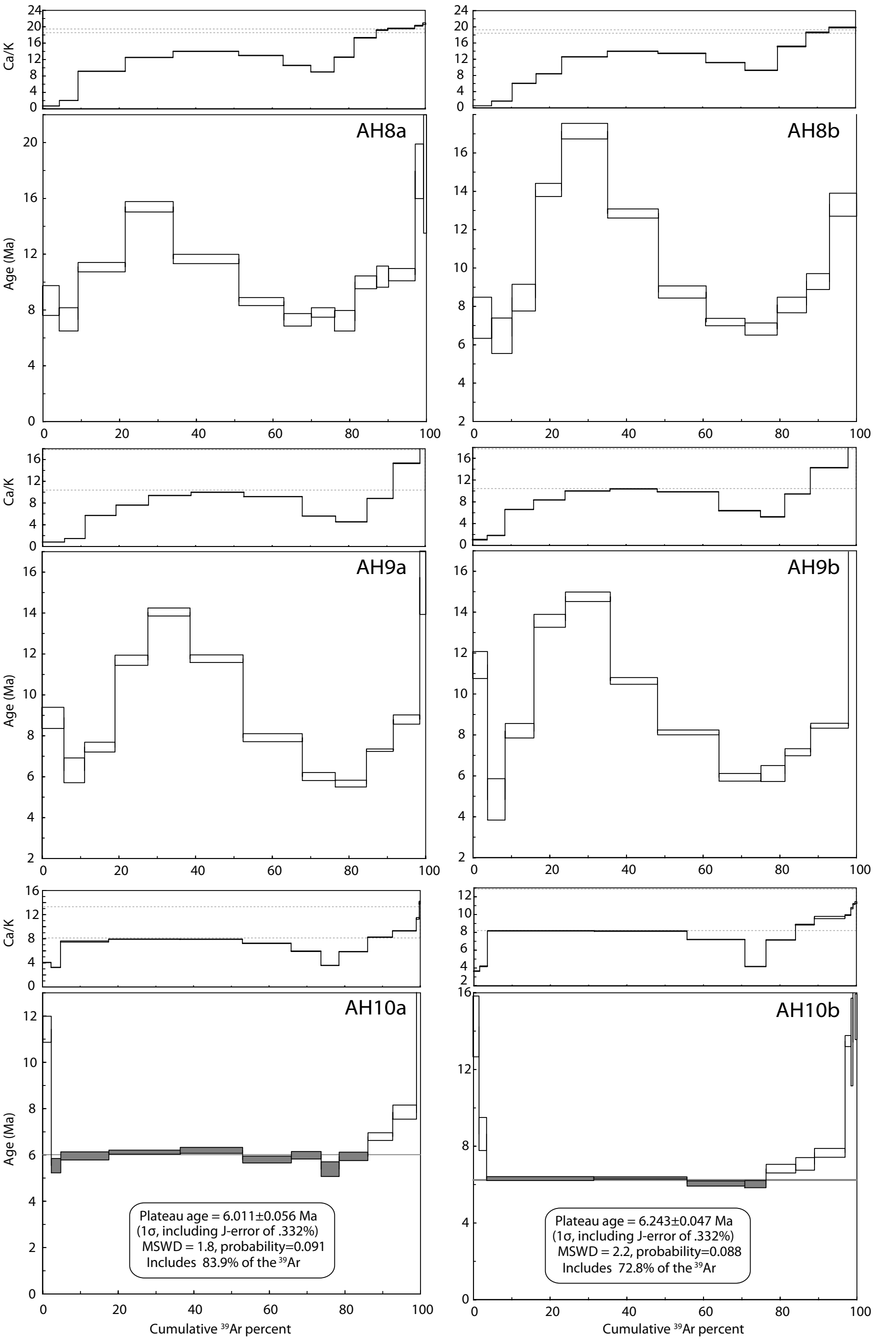

Fig. 7. Argon release spectra and apparent Ca/K ratios for the Fatacama hornblende samples. Box heights are ±1σ. Shaded steps are included in plateau ages.

constrained by the available data. Faster cooling would be consistent with the minimum cooling rate inferred from the Fatacama samples, of *c.* 80 °C Ma^{-1}. Mica cooling ages of 5.5 Ma from samples 5–10 km west of Beheda (Fig. 2), reported by Berry & McDougall (1986), fit best into the cooling history of the eastern Aileu Complex.

Cooling of the Aileu Complex through *c.* 500 °C by 10 Ma requires attainment of peak metamorphic conditions sometime prior to this time. A cooling rate of 50–80 °C Ma^{-1} implies that the Hili Manu and Beheda regions reached peak metamorphic temperatures of 650 °C (Berry & Grady 1981) by *c.* 12 Ma, if not even earlier. We therefore conclude that metamorphism probably commenced prior to this, possibly by several million years.

Tectonic implications

Sediment source

Assessment of potential sediment source terranes requires consideration of both the zircon age populations identified as well as those age ranges that are not present. At the same time, unique characterization of the provenance is not straightforward. Some of the challenges pertain to the extensive tectonic rearrangement of SE Asia since the time of Aileu Complex deposition. Uncertainties in the palaeogeography make for considerable ambiguity in assigning significance to particular zircon age populations within the detrital mix. Moreover, the coverage and sampling density of existing zircon age population data for Australia and SE Asia vary widely, limiting the scope for a consistent assessment of each potential source region.

Carter *et al.* (1976) and Barber *et al.* (1977) proposed that the sediments of the Aileu Complex were sourced from Sundaland, the shelf region now forming the Malay Peninsula and Borneo. Subsequent studies have established the detrital zircon characteristics of sediments in this region. For example, the Triassic sediments of the Khorat Basin in Thailand are characterized by detrital zircon age peaks at 255 and 455 Ma (Carter & Moss 1999). On the Malay Peninsula, modern river sediments yield mostly Triassic zircons, sourced from the extensive granite provinces (Sevastjanova *et al.* 2011). These zircon populations overlap in age with the youngest zircons observed in the Aileu Complex; however, the older zircon ages present in the Aileu Complex are rare or absent. Various interpretations have been presented of the arrangement during the Permian of the terranes that now form Sundaland. Charlton (2001) suggested that connection with Gondwana persisted until the late Triassic, a scenario that would allow sediments shed from terranes that now form Sundaland to be deposited in a location proximal to the future Banda Arc. In contrast, Metcalfe (2006) proposed that these terranes rifted from Gondwana in the early Permian, making transport of late Permian sediments from such a distal location problematic. Both geochronological and tectonic arguments suggest that Sundaland is not likely to be the source of sediment for the Aileu Complex.

On the basis of the transitional nature of the southern contact of the Aileu Complex with the Maubisse Formation, the rocks of the Aileu Complex are considered by many workers to represent part of the Australian continental shelf (Berry & Grady 1981; Harris *et al*. 1998; Harris 2006; Keep & Haig 2010). The currently exposed basement of northern Australia is dominated by terranes that yield Palaeoproterozoic zircons, with an Archaean component in some regions, both of which are under-represented in the detrital zircon populations obtained from the Aileu Complex. Based on a small dataset of late Carboniferous and Palaeoproterozoic zircons from Kisar, Harris (2006) suggested the Capricorn Orogen of Western Australia as a sediment source (Fig. 1). Consideration of the larger dataset of detrital zircon age data now available for the Aileu Complex shows that this proposal is highly unlikely, as sediments derived from this terrane would not contain the predominance of Palaeozoic zircons observed in the Aileu Complex.

The dominance of a detrital zircon age peak of *c*. 290 Ma, together with the common preservation of euhedral zircons, suggests the presence of a nearby, magmatic source region of early Permian age. Permian rocks in Australia are relatively scarce; Adams *et al*. (2007) identified northern Queensland as the sole potential supplier of Permian zircons from the east coast of Australia. However, although Permian igneous rocks are exposed in the Coen and Cairns regions (Fig. 1), available zircon data (Edgecombe *et al*. 2002) suggest that sediment shed from these regions would lack zircons with the other major zircon age modes found in the Aileu Complex. In addition, the great distance of these regions from the Banda Arc makes this an unlikely source for the immature sediments found in the Aileu Complex without a mechanism for tectonic transport.

Klompé (1954) recognized the Sula Spur as a terrane extending west of New Guinea and including the Banggai and Sula islands, which have a Palaeozoic granite and metamorphic basement (Hamilton 1979). Permian granites have been documented in the Banggai and Sula islands (Garrard *et al*. 1988) and the Bird's Head Peninsula (Fig. 1), along with Siluro-Devonian sedimentary sequences that contain Mesoproterozoic granodiorite clasts (Pieters *et al*. 1983). Although geochronological data in this region are limited, the available data do suggest that sediments shed from the Sula Spur basement rocks could provide appropriately aged zircons to match the observed age spectra from the Aileu Complex sediments.

The Sula Spur was separated from the northern margin of the Australian continent by the Banda Embayment from the mid-Mesozoic (Hall 2012). Miocene reconstructions show fragments of the Sula Spur being distributed west of the Bird's Head to eastern Sulawesi along left lateral strike-slip fault systems (Hamilton 1979; Silver *et al*. 1985), accounting for the current positions of the Sula and Banggai islands. More recent detailed tectonic reconstructions of the Banda Arc region show extension of the Sula Spur from the Middle Miocene, then fragments being transported to the southern Banda Arc as the strongly curved arc developed through extension and rollback through the Late Miocene to Pliocene (Spakman & Hall 2010; Hall 2012). Such a scenario provides a suitable mechanism for transport of the Aileu Complex from the Sula Spur to the north coast of Timor.

Significance of Aileu Complex metamorphism

Metamorphism of the eastern Aileu Complex, constrained here as occurring prior to 10 Ma, precedes the cessation of subduction along the Banda Arc north of Timor, which was active until at least 3 Ma (Abbot & Chamalaun 1981; Ely *et al*. 2011). Cooling by 10 Ma is also consistent with the Aileu Complex metamorphism having commenced prior to the major phase of Banda Arc volcanism during the late Miocene (Hall & Smyth 2008).

Two scenarios may be envisaged for metamorphism of the Aileu Complex, each of which has implications for the mechanism of cooling. In the first scenario, metamorphism took place in a convergent orogenic wedge, analogous perhaps to the region south of the modern Sumba Ridge (Shulgin *et al*. 2009). In this case, metamorphic cooling would have been driven by erosion, with the resultant detritus recorded by significant deposition of synorogenic sediments. Alternatively, metamorphic cooling may have occurred in an extensional realm associated with tectonic unroofing beneath a detachment, without the requirement for synorogenic sedimentation. Given the tectonic complexity of the eastern Indonesian region, both scenarios are considered possible.

A key question relating to the palaeogeographical setting of the Aileu Complex metamorphism is whether there is a record of synorogenic sediments at the time of Aileu Complex cooling. The stratigraphy of Australian margin sequences in southern Timor-Leste described by Haig & McCartain (2007) shows that no such synorogenic deposits are preserved on Timor. Rather, the period 10–6 Ma coincides with a stratigraphic hiatus, which those researchers have interpreted to reflect incipient collision in a convergent tectonic environment rather than an extensional setting. The lack of late Miocene synorogenic sedimentation on Timor at this time is critical, as it implies that Aileu Complex denudation did not take place in a part of the orogen contiguous with the sequence described by Haig & McCartain (2007).

It is conceivable that both convergence and extension operated during orogenesis of the Aileu Complex, with metamorphism in a convergent setting preceding extensional denudation. This scenario is consistent with recent tectonic reconstructions (Hall & Smyth 2008; Spakman & Hall 2010; Hall 2012) and evidence that rapid back-arc spreading in the North Banda Sea commenced at around 12.5 Ma (Hinschberger *et al*. 2005). The reconstruction of Hall (2012) shows that the first contact of the Sula Spur with the Asian margin occurred soon after 25 Ma, with the collision of the Sula Spur with the Sulawesi North Arm volcanic arc. The $^{40}Ar/^{39}Ar$ cooling age of 24.1 ± 0.4 Ma reported by Berry & McDougall

(1986) from the eastern Aileu Complex may record this event. Initiation of subduction into the Banda Embayment at 15 Ma coincided with breakup of the Sula Spur, with fragments transported south towards Timor during the late Neogene (Hall 2012). The new $^{40}Ar/^{39}Ar$ Aileu Complex cooling ages of 10–6 Ma reported in this study are compatible with an origin for the complex as part of the fragmented Sula Spur.

The sediment provenance and cooling history demonstrated here for the Aileu Complex clearly establish a geological history separate from that of the Australian affinity Gondwana Sequence, but compatible with a Sula Spur origin as described above. It follows that metamorphism of the Aileu Complex does not need to be accounted for as part of the collision of the northern margin of the Australian continent with the Banda Arc. This further supports a Pliocene collision event, as suggested by the emergence of Timor from 3.4 Ma (Haig & McCartain 2007) and cessation of volcanism by 3 Ma (Abbot & Chamalaun 1981; Ely *et al*. 2011), rather than an extended or stepwise collision process that accounts for Miocene metamorphism (Keep & Haig 2010).

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