The deep crust beneath island arcs: Inherited zircons reveal a Gondwana continental fragment beneath East Java, Indonesia

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Abstract

Inherited zircons in Cenozoic sedimentary and igneous rocks of East Java range in age from Archean to Cenozoic. The distribution of zircons reveals two different basement types at depth. The igneous rocks of the Early Cenozoic arc, found along the southeast coast, contain only Archean to Cambrian zircons. In contrast, clastic rocks of north and west of East Java contain Cretaceous zircons, which are not found in the arc rocks to the south. The presence of Cretaceous zircons supports previous interpretations that much of East Java is underlain by arc and ophiolitic rocks, accreted to the Southeast Asian margin during Cretaceous subduction. However, such accreted material cannot account for the older zircons. The age populations of Archean to Cambrian zircons in the arc rocks are similar to Gondwana crust. We interpret the East Java Early Cenozoic arc to be underlain by a continental fragment of Gondwana origin and not Cretaceous material as previously suggested. Melts rising through the crust, feeding the Early Cenozoic arc, picked up the ancient zircons through assimilation or partial melting. We suggest a Western Australian origin for the fragment, which rifted from Australia during the Mesozoic and collided with Southeast Asia, resulting in the termination of Cretaceous subduction. Continental crust was therefore present at depth beneath the arc in south Java when Cenozoic subduction began in the Eocene.

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1. Introduction

The character of the deep crust beneath many volcanic arcs in Southeast Asia is not known. There have been few seismic refraction studies, and the deep crustal rocks are often covered by thick sequences of young volcanic and sedimentary rocks. Xenoliths studies have proven to be extremely useful in other volcanic arcs [1] where they have shown crustal character and magma–crustal interaction but there have been none in Java. In East Java, Indonesia, the basement has long been considered Cretaceous in age and arc and ophiolitic in character. No continental rocks are exposed or reported on East Java. The assumed character of the crust is based on small and isolated exposures of basement rocks and a handful of basement-penetrating exploration wells. U–Pb dating of zircons in this study provides compelling evidence for the presence of a continental fragment of...
Gondwana affinity within the deep crust of East Java. This fragment was sampled by melts feeding Early Cenozoic arc volcanism.

2. Geological background

2.1. Regional setting

The island of Java is located within the Indonesian archipelago between the landmasses of Eurasia and Australia, on the southeast margin of the Eurasian Plate. The southeastern part of the Eurasian Plate is known as Sundaland (Fig. 1), which is the Mesozoic continental core of Southeast Asia [2]. Sundaland is not a single homogenous block of continental crust or a stable continental block; it was formed by the Early Mesozoic through the amalgamation of continental blocks [3,4]. During the late Cretaceous terranes of arc and ophiolitic material of Cretaceous age were accreted to the southern margin of Sundaland along a northeast–southwest trending subduction zone [2]. Subduction moved to its present-day position and east–west orientation, south of Java, along the Java Trench in the Early Paleogene [4]. Cenozoic sequences exposed today on East Java rest unconformably above terranes accreted in the Cretaceous.

2.2. Character of the basement

The interpreted NE–SW orientation of the Cretaceous subduction zone is somewhat speculative, due to limited exposure. The orientation was determined by linking the exposures of subduction complexes in Central Java to those in the Meratus Mountains in SE Kalimantan (Fig. 2) [2,5]. There is no evidence of a relic subduction complex cross-cutting the Java Sea, but this may be due to thick Cenozoic sedimentary cover and lack of publicly available data from deep penetrating seismic surveys.

The character of basement beneath most of East Java is unknown and surmised from spatially limited data. Exposures of basement rocks in Java are rare, and are found only at Ciletuh in West Java, Karangsambung and the Jiwo Hills in the western part of East Java (Fig. 2). These exposures account for less than 1% of the land area. Lithologies exposed are Cretaceous in age and typical of arc and ophiolitic terranes, including basaltic pillow lavas, cherts, limestone, schists, and metasedimentary rocks [5–8]. In addition to those at Karangsambung there are occurrences of high pressure metamorphic rocks such as jadeite–quartz–glaucophane bearing rocks and eclogite interpreted to be diagnostic of subduction zone metamorphism [9]. Cretaceous ages have been determined for the basement rocks at Karangsambung using radiolaria within the cherts [7] and K–Ar dates on muscovite from quartz–mica schist ranging from 110 to 124 Ma [5,9].

2.3. Volcanic activity

Java is essentially a volcanic island and two Cenozoic volcanic arcs are preserved on East Java: the modern arc

![Fig. 1. Current plate tectonic setting showing the extent of Sundaland [2] and the location of the study area of East Java. The modern volcanoes of the Sunda Arc are shown in black triangles.](image-url)
which has been active from the Late Miocene and an arc of Early Cenozoic volcanoes known as the Southern Mountains Arc. The two arcs are separated by a distance of 50 km, the modern arc occupying the central spine of the island and the eroded remnants of the Southern Mountains Arc exposed along the southern coast (Fig. 3). The older arc had been thought to be of Oligo-Miocene age [10], but recent studies [6] indicate that the arc was active from the Middle Eocene until the Early Miocene. The erupted products range from andesite to rhyolite and form lava flows and domes, volcanic breccias, and extensive pyroclastic deposits including flow, fall, and surge deposits. The arc rocks are intruded by numerous high-level igneous bodies that range from Eocene to Pliocene in age and basalt to granodiorite in composition. Some of these intrusions are contemporaneous with arc formation.
activity and others post-date it and are associated with the volcanism in the modern arc.

In addition to the volcanic and volcaniclastic rocks exposed in the southern part of East Java, there are thick Cenozoic sedimentary sequences to the north of the arc. The source of these clastic sediments has long been assumed to be Sundaland to the north and west [2,11,12].

As the erupted products of the Southern Mountains Arc are poorly dated a study was designed to utilise SIMS U–Pb dating of zircons to provide age constraints on the development of the arc. In addition it was hoped that the zircons would provide provenance information on the sedimentary rocks exposed within and to the north of the arc, which are commonly assumed to be derived from the continental rocks of Sundaland [2,11,12]. This paper reports the unexpected results of this study.

2.4. Predicted age range

Assuming that the basement of East Java is, as Hamilton [2] suggested, Cretaceous arc and ophiolitic fragments, and knowing the history of Cenozoic arc volcanism on the island, the predicted zircon age range would be Cretaceous to present-day. It was a surprise to discover that in addition to this predicted range there are significant numbers of Cambrian and older zircon grains in many of the samples analysed. Below we document the range and distribution of the old zircon grains identified in the igneous and clastic rocks from East Java, and discuss their potential origin.

3. Methods

3.1. Samples analysed

We report the results of zircon U–Pb SIMS dating of 17 Cenozoic samples of igneous (6 intrusive bodies and 4 extrusive rocks), volcaniclastic (n=3) and sedimentary (n=4) rocks. The samples are listed in Table 1 and their locations shown in Fig. 3. In the samples reported here more than 350 spot dates were measured and of these 290 were Cretaceous and older.

3.2. Analytical method

Zircon grains were analysed for Pb isotope composition and U, Th and Pb concentrations using the SHRIMP facility at Curtin University of Technology. The results are summarised in Table 1 and further details of the samples and analytical methods are given in the Supplementary material. Dates greater than 1250 Ma are calculated from 207Pb/206Pb ratios, and from this group analyses with greater than 15% discordance were excluded from any age plots. Dates less than 1250 Ma are calculated from 206Pb/238U ratios as these yield more reliable results because of uncertainties in common Pb corrections. All grains older than 100 Ma have been corrected for common Pb using 204Pb, and those younger than 100 Ma have been corrected using 208Pb. All errors quoted in the text are 2σm.

3.3. Probability of missing a population of ages

As this was the first study of its type in East Java, there was some uncertainty about the expected range of dates. The strategy adopted was to analyse a relatively small number of grains (~15–50) from a large number of samples, rather than the more conventional approach of analysis of a large number of grains from a small number of samples. As a large range of zircon ages was obtained, consideration must be given as to whether the population of zircons has been fully sampled. This problem is discussed in detail in Dodson et al. [13] and Cawood et al. [14] who show that for detrital zircons 60 analyses are necessary to sample the entire population with greater than 95% confidence. For any population of dates that is significant, say greater than 20% of the total population, there is less than a 3.5% chance that it will be missed in a sample set comprising only the smallest number of the grains analysed in this study (n=15 grains). We are thus confident that with 15–35 grains analysed the probability of sampling any population comprising more than 20% is high.

4. Results

4.1. Age range observed

When examining the entire dataset several distinct peaks (Fig. 4A) can be identified in the entire population: a Cenozoic peak (n=55), a Cretaceous peak (n=77), three Cambrian to Proterozoic peaks (n=166) of 500–750 Ma, 900–1250 Ma, 1600–1850 Ma, and an Archean peak of 2500–2800 Ma (n=38). In addition there are 9 zircon ages ranging from Devonian to Jurassic but these do not form a significant peak. This paper details the Cretaceous and older zircon results.

4.2. Lithology and zircon ages

The distribution of zircons of different ages is shown on Fig. 4 and discussed in detail below.
4.2.1. Igneous rocks

The 6 intrusive and 4 extrusive igneous rocks contain a range of Cambrian and older zircons \((n = 155)\). The samples lack Cretaceous zircons (Fig. 4), with the exception of a sample from Central Java (Jhs2AND1) which yielded a single Cretaceous zircon. One sample from a basaltic sill in Central Java (Jhs2KaliS3) yielded a single Carboniferous age. Of the igneous samples, only one extrusive rock from East Java (Jhs2Turen14) failed to yield Archean grains.

4.2.2. Clastic rocks

The 3 volcaniclastic rocks yielded a significant number of Cretaceous zircons \((n = 42)\) but only the westernmost sample (Jhs2KK13) yielded older zircons, a single grain of Mesoproterozoic age \((1079 \pm 36\) Ma). All 4 of the sedimentary rocks analysed were quartz-rich sandstones. These sandstones yielded varied zircon ages. All of the sandstones contain Cretaceous grains \((n = 33)\) (Fig. 4B). The northernmost sandstone sample from the edge of the Sunda Shelf (Jhs1-012) contains a single Jurassic–Triassic grain, but no older grains. The other sandstones from the south contain a range of Cambrian and older grains \((n = 22)\).

4.2.3. Spatial distribution of zircon dates

The samples containing different zircon dates do have a clear geographical pattern. The Archean grains
are found only in rocks of the Southern Mountains Arc (Fig. 4E) and the igneous rocks of this area contain no Cretaceous zircons. Cretaceous zircons are present only in rocks located in the west and north (Fig. 4B). Cretaceous zircons have been identified only in sedimentary and volcaniclastic rocks and one igneous rock from the western part of the study area. This distribution is interpreted to reveal the character of the crust beneath East Java.

5. Discussion

5.1. Origin and incorporation of the zircons into the rocks of East Java

The age range identified in the samples from East Java is much greater than would be predicted whether derived from a Sundaland source or local basement source of Cretaceous arc and ophiolitic rocks.
5.1.1. Possible Sundaland Sources

Sundaland, the continental core of Southeast Asia, is the closest and most obvious source of very old zircons (Fig. 5). Rocks which could have provided abundant zircons are granites of southwest Borneo [2], the Malay Peninsula [15], the Thai–Malay Tin Belt [16] and Sumatra [17,18]. These regions could have been a source of Mesozoic and Paleozoic material, but no Archean rocks are known, nor is there any indication that they are underlain by Archean crust.

There are abundant granites of Cretaceous age located in the Schwaner Mountains and the Thai–Malay Tin Belt which are known to have contributed material to the Paleogene sedimentary sequences of Northern Borneo [19]. If these source regions also provided material to East Java, the zircon populations would be similar. The zircon populations of these regions are dominated by Cretaceous zircons with age peaks different from those in East Java, there are abundant Permian–Triassic zircons (Fig. 6C), which are rare in East Java, and Precambrian zircons are mainly Paleoproterozoic with very rare Archean zircons [19].

In addition to the differences in zircon populations, there are paleogeographic factors to be considered. The island of Java is separated from Borneo by the shallow waters of the Java Sea. Beneath the flat-lying siliciclastic and carbonate Pleistocene deposits of the Sunda Shelf there are numerous broad NE–SW trending ridges.

![Fig. 5. Potential source areas for Cambrian and older zircons in East Java.](image-url)
Fig. 6. Comparison of the Cambrian–Archean data set from East Java with sediments of the Perth Basin Australia and Northern Borneo. A. East Java data set. B. Young placer deposits of the Perth Basin, known to be the product of erosion of the Proterozoic and Archean rocks of Western Australia [34]. C. Range of detrital zircon ages for Paleogene sandstones from Northern Borneo [19]. Bins on the histogram represent 25 Ma and the values are plotted with $2\sigma$ errors.
flanked by narrow deep Cenozoic basins. During the earlier part of the Cenozoic the ridges and basins would have acted as barriers or traps preventing sediment passing to the south and east from Sundaland into East Java. Indeed the ridges themselves may have acted as sediment source areas. One such ridge on the edge of Sundaland, the Karimunjawa Arch (Fig. 5), is reported to have been elevated throughout much of the Late Eocene to Late Miocene [20,21]. The elevation of the arch has been interpreted to be responsible for the different sedimentary environments recorded in the East and West Java Seas. To the east of the arch, the Lower Miocene and Oligocene sediments are marine, but to the west most of the Lower Miocene and all of the Oligocene sediments are non-marine [20,21]. The Karimunjawa Arch is reported to have been a source of sediment to both the East and West Java Sea Basins and potentially provided sediment to the area of present-day Java between the Late Eocene and Late Miocene. There are exposures of metasedimentary rocks on small islands on the arch but none are dated as they are terrestrial. They are interpreted to be pre-Cenozoic in age and part of the continental basement of Sundaland. This basement could be the source of the Cretaceous zircon grains in East Java’s clastic sequences.

5.1.2. Possible Gondwana Sources

The Archean–Cambrian peaks identified coincide with periods of major crustal growth represented by the Pan African and Grenville age orogens and the Archean cratons [22,23]. These peaks are characteristic of much of the Gondwana margin as recorded in the rocks of southern and east India [24], eastern and northern Antarctica [23,25,26], eastern Africa [22,23] and western Australia [14,27–29]. The rocks of Sundaland are not known to share this history. Plate tectonic reconstructions of Gondwanaland prior to and following break-up indicate that it is unlikely that either Antarctic or African material could have contributed to Sundaland [30–32]. The largest and closest area of Archean continental crust is Australia, which formed part of Gondwana until the Cretaceous.

Basement rocks in Western Australia are of Proterozoic and Archean age (Fig. 6B). As these ancient rocks have been the focus of detailed zircon dating studies, many of the basement blocks have age fingerprints [28,29,33,34]. The rocks at the surface in Western Australia are representative of much of the Gondwana margin. A large published dataset [34] from Western Australia was chosen to compare with that obtained from East Java. The dataset [34] focuses on the young placer sediments of the Perth Basin, which are the eroded products of Precambrian basement rocks which are currently exposed in Western Australia. The detrital zircons dated from these placer deposits have three major age peaks and these can be correlated with known source areas [28,29,34]. The Cambrian to Neoproterozoic zircons (500–800 Ma) were produced by the erosion of the Pan African Pinjarra Orogenic Belt, the Mesoproterozoic zircons (1000–1300 Ma) were derived from the Grenvillian Albany Fraser Orogenic Belt, and the Archean zircons (2500–3200 Ma) were eroded from the Yilgarn and Pilbara Cratons. There are also a limited number of dates which correspond to the formation of the Capricorn Orogenic Belt (1600–2000 Ma).

A range of Archean and Proterozoic peaks has also been reported from the Higher Himalayan Gneisses in India [35]. Yoshida and Upreti [35] suggest that these peaks represent terranes derived from a Circum-East Antarctic origin, which could have included part of Greater India. However, the peaks identified do not match those reported in this study.

The Western Australia peaks are remarkably similar to those identified in the Southern Mountains Arc of East Java (Fig. 6). Given this correlation it is plausible that Western Australia or a region with a similar geological history, such as other parts of the Gondwana margin, was the source of material.

5.2. Incorporation of the zircons

Zircon is a highly refractory mineral. Zircon is known to survive numerous sedimentary cycles, metamorphism and diagenesis [36]. The zircon grains identified in the sedimentary rocks of East Java could have been incorporated through erosion and transport of sediment from exposed source areas, such as the local basement, the Karimunjawa Arch or from volcanic sources by air-fall and subsequent reworking. The incorporation of zircons into the igneous rocks requires more explanation. As well as being resistant to weathering, zircon is known to survive episodes of melting [37]. Material of Gondwana origin must have been introduced to the melts feeding the Southern Mountains Arc. There are several mechanisms whereby this introduction could occur.

5.2.1. Subducted sediment

Sediment eroded from western Australia deposited on the Indo-Australian plate could have been carried north to the Java Trench as Australia moved north. However, even today a fan similar in size to the modern Bengal Fan would be required to bring material from Australia to the site of subduction at the Java Trench (Fig. 5). During the Early Cenozoic Australia lay very
far south of its current position (Fig. 7), and at 45 Ma the distance between Australia and East Java would have exceeded 1900 km [4]. If the fan model were correct, the sedimentary sequences on the Indian–Australian plate currently entering the Java Trench would correspond to a relatively proximal position on the Cenozoic fan. However, today there is little sedimentary cover on the Indian–Australian plate south of Java [38]. In addition the modern Bengal Fan is fed by erosion of the Himalayas, and there is no evidence of a similar mountain belt in NW Australia during the Cenozoic.

Sediment of Gondwana origin could have been introduced into the Java Trench by axial transport from the Bird’s Head microcontinent, New Guinea or from the Himalayas via the Bengal Fan, although both are unlikely. The basement rocks of the Bird’s Head microcontinent were not available for erosion as the Bird’s Head was the site of active carbonate sedimentation during most of the Cenozoic and so can be excluded as a source [39]. If sediment was produced by the erosion of the Himalaya it would require transport via the Bengal Fan to the Java Trench and total transport distances would exceed 4000 km. In addition to this significant distance, there were topographic barriers at the Investigator Fracture and the Ninety East Ridge which would have hampered the flow of sediment. The lack of Bengal Fan material today in the Java Trench offshore East Java [38] adds to the argument that this is not a plausible mechanism. It is equally unlikely that sediment from the Himalayan region could travel a distance of over 3500 km from Indochina across Sundaland, by-passing its deep basins, structural highs and ridges [40].

5.2.2. Subducted continental fragment

The subduction of a fragment of continental crust also seems unlikely. Buoyancy forces make subduction of continental crust difficult and even if these were overcome, the fragment is required to have supplied

Fig. 7. Plate tectonic reconstruction of SE Asia and Australia at 45 Ma [4]. The light grey shaded area around Australia shows the approximate extent of continental crust based on present-day bathymetry and mapping of the continental–ocean boundary. The ornamented area west of western Australia indicates the surmised area of continental crust that rifted from Australia in the Jurassic and early Cretaceous. We suggest that the East Java fragment probably originated in the southern part of this area.
melts from the Eocene to the Miocene, a period of around 20 Ma. The fragment either remained stationary beneath the Southern Mountains or was 1500 km in length based on the present subduction rate of 75 mm/yr [41] and Cenozoic plate tectonic reconstructions [4]. Neither of these scenarios is likely.

5.2.3. Collision/accretion of a continental fragment

An alternative, simpler and more plausible explanation is that there is a fragment of continental crust of Gondwana character beneath the Southern Mountains Arc. This fragment must have been in place before subduction began in its current position along the Java Trench. We suggest that the fragment collided with the margin of Sundaland terminating the Late Cretaceous phase of subduction. The origin of this fragment is discussed in detail below. Magmas rising through, or pooling in, the continental crust would lead to partial melting or assimilation of material.

The presence of continental crust is supported by the evolved character of the products of the Southern Mountains Arc and the rocks which intrude them. The volcanic rocks range from andesite to rhyolite (60–77 wt.% SiO₂) with an estimated average SiO₂ content of 67 wt.% [6], and a significant proportion of the high-level intrusive bodies are granodiorites. These rocks are considerably more evolved than the basic-intermediate eruptive products of the present-day volcanoes. The chemistry of the modern arc volcanic rocks in East Java [42–44] indicates they are the products of relatively primitive subduction melts having no significant interaction with underlying crust. The difference in chemistry of the products of the Southern Mountains Arc and the Sunda Arc could be explained in a number of ways: fractional crystallization of basic magma, or contamination by melting of felsic continental basement crust (C. Macpherson, 2006, pers. comm.). The evidence from zircon dating suggests that partial melting of continental basement is the most likely explanation.

The distribution of pre-Cenozoic zircons (Fig. 4) and the character of the arc rocks indicate that the continental fragment is present only beneath the Southern Mountains whereas north of the Southern Mountains there is no continental basement. The deep crust to the north of the arc is probably Cretaceous arc or ophiolitic terranes, as suggested by Hamilton [2], representing material accreted during Cretaceous subduction or underplated during collision.

Sribudiyanti et al. [45] also inferred the presence of a continental fragment beneath East Java. Their interpretation is based on the distribution of quartz-rich sandstones assumed to have a continental origin. A detailed study of the provenance of these sandstones raised doubts about the continental source as many of the sandstones contain considerable acidic volcanic material, probably derived from the Southern Mountains Arc [6]. Thus, although we agree with the interpretation of Sribudiyanti et al. [45] of a continental fragment beneath East Java, we dispute the evidence on which their interpretation is based, and consequently differ on the timing of arrival of the continental fragment.

6. Character and origin of the crust beneath East Java

6.1. Character of the crust

The distribution of pre-Cenozoic zircons in samples from East Java provides new information about the character of the deep crust about which little was previously known. We suggest that the most likely explanation for the zircon age range sampled in East Java is that there is a fragment of continental crust of Archean age, Gondwana affinity and potentially of Western Australian origin at depth beneath the Southern Mountains.

The size of the East Java fragment can be estimated by utilising the spatial distribution of the different zircon age populations and other supporting evidence. Currently none of the data suggests that the continental fragment extends north beneath the modern Sunda Arc. Therefore, the northern boundary must be located north of the Southern Mountains but south of the modern Sunda Arc (Fig. 8). The character of the crust beneath the modern arc is still unclear, but there is no indication of a continental contribution to the magmas feeding the arc [e.g. [42]]. The deep crust is likely to be similar in composition to the Cretaceous arc and ophiolitic fragments known from exposures in Central Java.

The lack of Cretaceous material within the igneous rocks of the Southern Mountains Arc to the west of the Yogyakarta area suggests that a terrane boundary exists in this region between Cretaceous crust and the East Java continental fragment. This boundary is interpreted to coincide with a major northeast–southwest trending structure identified at approximately 110.5°E [6] (Fig. 8B). This lineament links several major features onshore and offshore, a structural high in the Java Forearc, and the aligned centres of three Oligo-Miocene volcanoes [10] in the West Progo Mountains, Mount Merapi and the unusual K-rich back-arc volcano of Mount Muria. In the region close to the boundary between the Cretaceous crust and the older Gondwana fragment mixing of zircons of different ages could easily occur through assimilation or partial melting of the crust during magma ascent, or uplift and erosion of the basement rocks.
Terrane boundaries are rarely straight or uniform features, but are embayed and irregular, and their shape is dictated by original rift morphology and collision tectonics. Therefore the margins of the East Java fragment could be structurally complex.

6.2. Origin and extent of the fragment

Several fragments rifted off the Australian margin during the Mesozoic in a phase of break-up preceding the separation of India from Gondwana \[3,46,47\]. We suggest that one such fragment or fragments collided with the margin of Sundaland during the Late Cretaceous forming the basement to the Southern Mountains Arc. Prior to the collision, arc and ophiolitic terranes were accreted and formed a belt on to the margin of Sundaland (Fig. 8). The ophiolitic blocks may be remnants of Indian Ocean crust which preceded the continental fragment on the northward-moving plate.

The timing of collision of the fragment pre-dates the Middle Eocene as continental crust was already present beneath the arc when subduction began at that time. We suggest that the collision of this fragment resulted in the termination of Cretaceous subduction. Following the renewal of subduction during the Middle Eocene, the Cenozoic melts feeding the Southern Mountains Arc were contaminated by interaction with the continental fragment.

Manur and Barraclough \[48\] indicate the presence of two fragments (Fig. 8B), in the areas of the Bawean Arch and Paternoster Platform, of Pre-Cenozoic continental crust (the shape, orientation and age of which are very poorly constrained) in the Java Sea. These occur between the belt of ophiolitic and arc blocks and the East Java fragment. It is possible that these fragments are a continuation of the East Java fragment, but as there is no evidence of continental crust to the north of the Southern Mountains, beneath the Sunda Arc, it is difficult to envisage how these fragments could be linked.

The eastern extent of the East Java fragment is not known. However, in Sulawesi continental rocks of similar age to those identified in the East Java fragment have been reported \[49\]. Geochemical and zircon dating evidence from the Malino Metamorphic complex of northwest Sulawesi reveals the presence of Archean material with ages up to 3500 Ma \[49,50\]. We suggest that the East Java fragment extends to the northwest, beneath western Sulawesi, forming a large arcuate block on the southeast margin of Sundaland (Fig. 8B). Geochemical analysis of the modern volcanic products on Java \[42–44\] suggests that the magmas are not sampling continental crust. However, the rocks analysed have been basic, and we

![Fig. 8. Character of the crust on the southeastern margin of Sundaland. A. Extent of the continental fragment onshore East Java. B. Map showing the proposed extent of the East Java fragment beneath Sulawesi. C. Sketch cross-section.](image-url)
suggest that a study of the more evolved volcanic rocks would be profitable. Basic rocks are not suitable for a study of the kind reported here as they contain only rare or very small zircons. The study of more evolved volcanic rocks from volcanoes between East Java and northwest Sulawesi could identify the extent of the fragment.

7. Conclusions

This is the first firm evidence of a Gondwana continental fragment in this part of Southeast Asia. Prior to this study little was known about the character of the crust beneath much of Java and in particular nothing was known about the crust beneath the Paleogene arc. The continental fragment beneath the Southern Mountains of East Java was identified by the distribution of ancient zircons in the Cenozoic igneous and sedimentary rocks. U–Pb dating of zircons from East Java has allowed distinct basement types to be mapped. In the north and west there is Cretaceous accreted arc and ophiolitic material and in the south along the Southern Mountains Arc there is compelling evidence for a fragment of Gondwana continental crust. The rising Cenozoic melts feeding the Southern Mountains Arc mixed with the continental crust and picked up ancient zircons through assimilation or partial melting. This fragment could be large and may extend beneath Sulawesi.

The zircons dated in southeast Java are very similar in age to those of the Gondwana terranes of India and Australia. Mesozoic reconstructions of the region show a history of Mesozoic rifting of Gondwana fragments from northwest Australia and this is thought to be the ultimate source of the zircons in the igneous and sedimentary rocks of East Java.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2007.03.044.

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