Cenozoic volcanic arc history of East Java, Indonesia: The stratigraphic record of eruptions on an active continental margin

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ABSTRACT

The stratigraphic record of volcanic arcs provides insights into their eruptive history, the formation of associated basins, and the character of the deep crust beneath them. Indian Ocean lithosphere was subducted continuously beneath Java from ca. 45 Ma, resulting in formation of a volcanic arc, although volcanic activity was not continuous for all of this period. The lower Cenozoic stratigraphic record on land in East Java provides an excellent opportunity to examine the complete eruptive history of a young, well-preserved volcanic arc from initiation to termination. The Southern Mountains Arc in Java was active from the middle Eocene (ca. 45 Ma) to the early Miocene (ca. 20 Ma), and its activity included significant acidic volcanism that was overlooked in previous studies of the area. In particular, quartz sandstones, previously considered to be terrigenous clastic sedimentary rocks derived from continental crust, are now known to be of volcanic origin. These deposits form part of the fill of the Kendeng Basin, a deep flexural basin that formed in the backarc area, north of the arc. Dating of zircons in the arc rocks indicates that the acidic character of the volcanism can be related to contamination of magmas by a fragment of Archean to Cambrian continental crust that lay beneath the arc. Activity in the Southern Mountains Arc ended in the early Miocene (ca. 20 Ma) with a phase of intense eruptions, including the Semilir event, which distributed ash over a wide area. Following the cessation of the early Cenozoic arc volcanism, there followed a period of volcanic quiescence. Subsequently arc volcanism resumed in the late Miocene (ca. 12–10 Ma) in the modern Sunda Arc, the axis of which lies 50 km north of the older arc.

Keywords: East Java, Indonesia, stratigraphic record, Cenozoic arc volcanism.

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INTRODUCTION

The island of Java lies within the Indonesian archipelago between the landmasses of Eurasia and Australia, on the margin of the Eurasian plate. The southeastern part of this plate is known as Sundaland (Fig. 1), which is the Mesozoic continental core of SE Asia (e.g., van Bemmelen, 1949; Hamilton, 1979). Java is located on Sundaland’s southern margin.

Many studies of volcanic arcs are based on well-exposed areas of arcs active long ago, such as the Cretaceous Allistos Arc in Baja California (Busby et al., 2006) and the Cambrian–Ordovician Lough Nafooey Arc of the Irish Caledonides (e.g., Draut and Clift, 2001). There are few studies of younger arcs in areas where active volcanism continues today. One reason for this is that younger arc products cover older arc sequences. Furthermore, many modern arcs are in tropical areas, such as Indonesia, the Philippines, and the Western Pacific, that are difficult to work in, commonly are not well exposed, and are remote. The modern volcanoes on Java form part of the Sunda Arc, which is well known for volcanic activity, including the famous nineteenth century eruptions of Krakatau and Tambora, and the Pleistocene eruption of Toba. However, despite a long volcanic record in Java, owing to subduction of Indian Ocean lithosphere during the Cenozoic, little is known of its pre-Pleistocene arc history.

Since the middle Eocene (ca. 45 Ma) there has been northward subduction of the Indo-Australian plate at the Java Trench to the south of Java (Hall, 2002). Consequently, Java is essentially a volcanic island, and a long history of arc volcanism is recorded in its Cenozoic stratigraphy. Products of both active and ancient volcanic arcs can be observed. An east-west–trending chain of >30 modern volcanoes, forming part of the Sunda Arc, creates the central spine of the island of Java (Fig. 2). An arc of older, Eocene to Miocene volcanoes is parallel to and south of the Sunda Arc and is known as the Southern Mountains Arc (Smyth et al., 2005).

Exposures of basement rocks are rare in East Java, and before this study the basement was thought to have formed during the Cretaceous, when fragments of arc and ophiolitic material were accreted to the southern margin of Sundaland (Wakita, 2000). There are no continental basement rocks at the surface or reported from drilling in East Java. The basement is often referred to as “transitional,” as to the north and west in Sundaland the basement is continental, and in the east near to Flores, it is oceanic (e.g., Hamilton, 1979).

The Cenozoic stratigraphic record preserved on land in East Java provides an excellent opportunity to examine the eruptive history of a young, well-preserved volcanic arc. The present-day arc, active since the middle to late Miocene (ca. 12–10 Ma; Soeria-Atmadja et al., 1994), is immediately obvious, but the importance of the older Southern Mountains Arc has previously been underestimated. The relatively basic volcanic products of this arc, the “Old Andesites” (van Bemmelen, 1949), are widely known because they are well exposed and form prominent topographic features. However, the acidic products of the arc, which are widespread, have been largely overlooked. As a result of the work reported here, abundant quartz-rich sedimentary rocks in East Java are now known to be the primary and epiclastic products of acidic volcanism but were previously interpreted as continental sediments (e.g., Harahap et al., 2003). The acidic nature of the erupted material is a reflection of the character of the underlying crust, which as a result of new zircon dating is now thought to include a fragment of Archean continental crust.

The full cycle of the Paleogene Southern Mountains Arc, from initiation to termination, can be documented in the stratigraphy of East Java. This paper reports the stages of arc development and the sequence and timing of events within the arc, determined by detailed field investigations accompanied by provenance analysis and isotopic dating. Most of the middle Miocene was marked by a period of volcanic quiescence that followed the termination of Paleogene arc volcanism in the early Miocene (ca. 20 Ma). Near the end of the middle Miocene (ca. 12–10 Ma) the modern Sunda Arc began activity in its present position, 50 km north of the Southern Mountains Arc. Possible explanations for the shift in position of arc volcanism are discussed later in this paper.

PRESENT STRUCTURE OF EAST JAVA

East Java can be subdivided into three parts, broadly parallel to the elongation of the island, representing (1) the early Cenozoic Southern Mountains Arc, (2) a deep basin north of the arc, and (3) a marine shelf north of the basin (Figs. 3 and 4). The modern arc is built mainly on top of the basin north of the early Cenozoic arc. We first summarize the principal features of these components of Java and then go on to discuss the stratigraphy of the Southern Mountains Arc.
There are few exposures of basement rocks in Java, and in East Java they are known only in the western part of the study area. Based upon this limited evidence, the basement has been interpreted to be arc and ophiolitic rocks of Cretaceous age. A volcanic arc was built upon basement rocks from the middle Eocene to the Miocene in southern Java (Smyth, 2005), which is known to extend from East Java into West Java (Soeria-Atmadja et al., 1994). The stratigraphic thickness of the arc...
products is >2500 m, and within this sequence andesites are well known (van Bemmelen, 1949; Soeria-Atmadja et al., 1994), but acidic volcanic rocks have not been previously reported. The zone containing the arc products is 50 km wide. The Southern Mountains Arc is now uplifted and partially eroded. The strata typically dip uniformly toward the south between 20° and 30°.

Kendeng Basin

The Kendeng Basin lies directly behind and to the north of the Southern Mountains Arc (Fig. 2). The deposits of the basin are poorly exposed. The depocenter is marked by a strong negative Bouguer gravity anomaly of more than −580 μm⁻² (Fig. 5). The negative anomaly can be traced eastward into a negative marine free air anomaly (Sandwell and Smith, 1997), which extends from the Straits of Madura eastward to the north of Bali. At the west end of the Kendeng Basin a relatively abrupt change in the character of the anomaly is around the modern volcanoes of Merapi and the Dieng Plateau (Fig. 5). To the west, in West Java, the anomaly is not well defined, as it becomes positive (40 μm⁻²).

No basement rocks are exposed or known from drilling in this region. The basin fill has an age range of middle Eocene to Miocene, similar to the Southern Mountains Arc (de Genevraye and Samuel, 1972). The basin is east-west oriented, at least 400 km long, parallel to the Southern Mountains Arc, and filled with a succession of volcanioclastic turbidites and pelagic mudstones that are reported to be at least 6 km thick (Untung and Sato, 1978). Gravity calculations indicate that the basin may contain as much as 10 km of sediment (C.J. Ebinger, 2005, personal commun.). Based on field observations, seismic sections, and regional gravity interpretation (Smyth, 2005), the basin is estimated to have been ~100–120 km wide during the early Cenozoic. It is now partially exposed at the surface in the Kendeng Fold-Thrust Belt, where there is an estimated 10–30 km of shortening (de Genevraye and Samuel, 1972; Smyth, 2005); de Genevraye and Samuel (1972) report that deformation commenced in the Pliocene.

Figure 3. Structure of East Java in map-and-sketch Eocene to Miocene profile, showing the three structural provinces—Southern Mountains Arc, Kendeng Basin, and the edge of the Sunda Shelf—and the modern Sunda Arc building on top.
Cenozoic volcanic arc history of East Java, Indonesia

Edge of Sunda Shelf

To the north of the Kendeng Basin (Figs. 2 and 4) the hills of North Java and the offshore East Java Sea constitute an area interpreted to be the edge of the early Cenozoic Sunda Shelf (Hamilton, 1979). This region has been the focus of most hydrocarbon exploration. Pre-Cenozoic basement rocks sampled by drilling are known to be ophiolitic and arc rocks, which include chert and basic volcanic and metasedimentary rocks (e.g., Hamilton, 1979). Basin development began in the Eocene. There are between 2000 and 6000 m of Eocene to Pliocene shallow marine clastic and extensive carbonate sedimentary rocks within fault-controlled basins (e.g., Ardhana, 1993; Ebanks and Cook, 1993).

The sedimentary sequences have been deformed since the late Miocene by numerous open, east-west–oriented folds; northward-verging, east-west–oriented thrusts interpreted to be Pliocene in age; and ENE-WSW normal faults (Chotin et al., 1984; Hoffmann-Rothe et al., 2001).

Modern-Day Volcanic Arc

The active volcanoes of the Sunda Arc are built mainly on the Kendeng Basin (Figs. 3 and 4) but locally overlap the edge of the Southern Mountains Arc. Arc activity commenced in its present position at ca. 10 Ma in the late Miocene (Soeria-Atmadja et al., 1994). The volcanoes exceed 3000 m in elevation and form the central spine of the island (Fig. 2). The average composition of the present-day volcanic products is basaltic andesite (Nicholls et al., 1980), which is much more basic than the average composition of the Southern Mountains Arc products. Most of the active volcanoes are situated ~100 km above the subducting slab (England et al., 2004). There are also a number of unusual K-rich backarc volcanoes (Edwards et al., 1991), which occur to the north of the axis of the arc, including Muria (Fig. 2). The eruptive and epiclastic products of the Sunda Arc cover a significant proportion of the island, contributing to its fertile soils.

STRATIGRAPHIC RECORD OF THE EARLY CENOZOIC SOUTHERN MOUNTAINS ARC

The sedimentary rocks in the Southern Mountains Arc in East Java were deposited on the basement above a poorly dated regional unconformity (Fig. 6). The unconformity separates Upper Cretaceous basement rocks and the Cenozoic succession, suggesting a long period, potentially up to 30 m.y., during which uplift and erosion occurred. The stratigraphic succession above...

Figure 4. Simplified geological map of East Java, showing the main geological provinces and stratigraphic units.
the unconformity in the Southern Mountains Arc and the Kendeng Basin has been subdivided into three “synthems” (Smyth et al., 2005), each representing a different period of arc activity (Fig. 6). The term synthem has been used because much of the work undertaken and published in East Java has been hydrocarbon oriented, and as a result the term sequence is often used with seismic and sequence stratigraphic implications (e.g., Catuneanu, 2006). We have therefore chosen to avoid the term sequence for the major stratigraphic subdivisions and in this study used the term synthem, defined as an unconformity-bounded stratigraphic package (Rawson et al., 2001). The three synthems are:

• Synthem One: records the initiation of arc volcanism and the early stages of arc development during the middle Eocene (ca. 45 Ma) to early Oligocene (ca. 34–28 Ma).

• Synthem Two: records the growth and termination of arc volcanism in the Southern Mountains Arc during the late Oligocene (ca. 28–23 Ma) to the early Miocene (ca. 20 Ma).

• Synthem Three: records widespread carbonate growth, accompanied by the erosion and redeposition of rocks from earlier synthems during the middle Miocene (ca. 20–10 Ma), with no significant volcanic activity.

In the account of the stratigraphy that follows, the stratigraphic ages have been converted to numerical ages, using the Gradstein et al. (2004) time scale.

**Synthem One: Initiation of the Southern Mountains Arc**

Most parts of the Southern Mountains rocks of Synthem One are covered by younger deposits and are exposed only at Karangsambung, Nanggulan, and the Jiwo Hills (Fig. 2). Synthem One is not exposed in the Kendeng Basin but was sampled in blocks brought to the surface by mud volcanoes.

**Southern Mountains Arc**

Basement exposures in East Java are rare and are found only in the western part of the area at Karangsambung and the Jiwo Hills (Fig. 2). The exposed basement rocks are Cretaceous in age (Parkinson et al., 1998; Wakita and Munasri, 1994) and include basaltic pillow lavas, radiolarian cherts, various metasedimentary lithologies, quartz-mica schist, and high-grade metamorphic rocks including jadeite-quartz-glaucophane–bearing rocks and eclogites. Quartz veins are commonly observed within the basement exposures and have not been identified in the overlying Cenozoic rocks. The high-grade metamorphic rocks have been interpreted to indicate subduction zone metamorphism (Miyazaki et al., 1998). The basement rocks are interpreted to represent fragments of arc and ophiolitic material accreted to the margin of Sundaland during the Late Cretaceous. Similar rocks have previously been assumed to extend beneath the rest of East Java, where there is no information from surface exposures or drilling (e.g., Hamilton, 1979; Parkinson et al., 1998).

Synthem One is ~1000 m thick but is exposed only in the western part of the Southern Mountains Arc in East Java. The oldest sedimentary rocks rest directly on the basement above a regional angular unconformity. They are poorly dated fluvial conglomerates and interbedded sandstones (Figs. 7A and 8) and are at least 50 m thick, but their total thickness is difficult to assess owing to limited and patchy exposures. These are the only rocks
Figure 6. Simplified stratigraphic column of the Southern Mountains Arc. The column shows the three synthems mentioned in the text and indicates the phases of arc development recorded by the sedimentary succession.
exposed onshore that contain no fresh volcanic material (Fig. 9). They are dominated by quartz grains and metamorphic and igneous lithic clasts (Figs. 8 and 9), including vein and metamorphic quartz, chert, phyllite, schist, metasedimentary rock, and basalt. The lithologies identified as clasts are typical of those exposed in the Cretaceous basement (described above) and are interpreted to be the product of erosion and reworking of these basement rocks. The terrestrial conglomerates and sandstones lack palynomorphs and so cannot be directly dated, but they are overlain by a succession of well-dated middle Eocene strata (Lelono, 2000).

The middle Eocene to lower Oligocene of the Southern Mountains Arc is represented by a transgressive succession, from base to top, of coals and conglomerates, sandstones, siltstones, and mudstones (Fig. 8). The middle Eocene age of the lower part of the succession is based on palynomorphs in the coals and organic-rich mudstones (Lelono, 2000), and the occurrence of *Nummulites* and *Discocyclina* higher in the section. The lower part is at least 200 m thick and is a noncalcareous unit of well-bedded coals, conglomerates, quartz-rich sandstones, and organic-rich muds. The coals and conglomerates are restricted to the lower 50 m. The conglomerates are commonly channelized, are ~10–75 cm thick, and contain a range of lithic clasts similar to those identified in the basal section directly overlying the basement. The coals vary laterally in thickness from 5 to >50 cm and have an average vitrinite reflectance of 0.4% $R_o$ (Smyth, 2005). For normal and high geothermal gradients typical
of arc regions this would imply very shallow burial depths of <1 or 2 km (Madon et al., 1997; Watts, 1997).

Above this transgressive succession lie thinly laminated quartz-rich sandstones and organic-rich mudstones that are at least 150 m thick. These sediments were deposited in a terrestrial setting with some marine incursions indicated by the presence of calcareous zones rich in *Nummulites* and *Discocyclina*. In addition to the organic-rich mudstones there are several gray mudstones, which are rich in smectite. The quartz-rich sandstones contain metamorphic lithic clasts, like those of the conglomerates, but also contain volcanic lithic clasts such as pumice and andesite. In addition, a significant proportion of the quartz has a volcanic origin (the identification of volcanic quartz is discussed further below). At the base of the quartz-rich sandstones the quartz is dominated by metamorphic grains, but this content gradually decreases in its relative contribution upsection, and at the top, volcanic quartz is dominant (Fig. 9B). The heavy mineral assemblage contains zircons that yielded spot sensitive high-resolution ion microprobe (SHRIMP) U-Pb ages of 41.8 ± 1.6 and 42.7 ± 1.5 Ma (Smyth, 2005). These ages are the same as the biostratigraphically determined ages for the host rocks, indicating that volcanic activity occurred
as the sediments were deposited. Higher in the section, in the sandstones, a number of *Nummulites*-rich zones mark the onset of fully marine conditions.

Above the nummulitic units the sandstones become increasingly arkosic and rich in fresh laths of plagioclase feldspar (Fig. 9D), volcanic quartz, volcanic lithic fragments, elongate volcanic zircons, and volcanic clays such as smectite and zeolites (Fig. 9A). These sandstones are interbedded with tuffaceous mudstones. Water depth is uncertain but is interpreted to be deeper than that for the nummulitic zones. There are no diagnostic sedimentary structures, but the sandstones contain pelagic foraminifers.

Higher in the section the presence of volcaniclastic turbidites indicates an increase in water depth. Some turbidites are
characterized by Bouma divisions A, C, and E, but more commonly C, D, and E. They are >150 m thick, with individual bed thicknesses ranging from 5 to 50 cm. The turbidites have a diverse planktonic foraminiferal assemblage (Fig. 8E), including Helicosphaera euphratis, H. reticulate, and H. wolcoxonii (P. Lunt, 2002, personal commun.), which provides an age of NP18 (36.8–36.2 Ma) for the lower parts of the succession. The turbidites extend into the lower Oligocene, based on biostratigraphy (P. Lunt, 2002, personal commun.). They are dominated by volcanic debris (Fig. 9) such as laths of plagioclase feldspar, volcanic lithic clasts, and volcanicogenic clays, and there are no metamorphic lithic clasts within the coarser beds. The heavy mineral assemblage is dominated by volcanic zircons, which yielded a weighted mean SHRIMP U-Pb age from 17 grains of 41 ± 1.4 Ma, similar to the biostatigraphic age of the lower part of the section, suggesting some reworking.

The upper boundary of Synthem One is an intra-Oligocene unconformity, which is interpreted to be the result of sea level change, as the sedimentary rocks directly above and below the gap have similar bedding orientations with no indication of deformation. This could be a local sea level change but could also be a global change. Unconformities of this age that record a global intra-Oligocene sea level fall are widely known, from the Haq et al. (1987) curve (30 Ma), the Marshall Paraconformity (32–29 Ma) in the Canterbury Basin, New Zealand (Fulthorpe et al., 1996), and the carbonates of Baldwin County, Alabama, USA (Baum et al., 1994).

Within Synthem One the contribution of volcanic material increases upsection as the proportion of basement-derived material (metamorphic quartz, metamorphic lithic fragments, and illite, chlorite, and serpentinite clays) decreases, and the upper Eocene sedimentary rocks are almost entirely dominated by volcanic debris (Fig. 9A, B). The volcanic centers supplying this material cannot be separately mapped owing to their limited exposure, but they are interpreted to follow the same trend and occupy the same positions as the volcanoes of the Oligocene–Miocene arc (see below).

Kendeng Basin

In the Kendeng Basin there are limited exposures, and Synthem One is not seen at the surface, but blocks of the older lithologies have been brought to the surface by Pleistocene and modern mud volcanoes. These blocks are terrestrial and are composed of shallow marine sandstones and conglomerates (de Genevraye and Samuel, 1972) similar in character to the middle Eocene sedimentary rocks in the Southern Mountains Arc.

Synthem Two: Growth and Catastrophic Termination of Arc Volcanism

Southern Mountains Arc

The upper Oligocene to lower Miocene deposits of Synthem Two are primary volcanic rocks and epiclastic rocks. These rocks are exposed extensively throughout the Southern Mountains Arc (Fig. 4) and within the fold-thrust belt of the Kendeng Basin. The oldest rocks of this synthem in the Southern Mountains Arc are reworked bioclastic tuffaceous mudstones dated biostratigraphically as Oligocene, NP24 (27.3–30 Ma; M. Fadel, 2002, personal commun.).

Throughout the late Oligocene and early Miocene the volcanic activity in the Southern Mountains Arc was extensive, explosive, and intermediate to acidic in composition. The deposits range from andesite to rhyolite, with an average SiO2 content of 67 wt% (Smyth, 2005), and include thick mantling tufts (Fig. 10A), crystal-rich tufts, block and ash flows, pumice-lithic breccias, andesitic breccias (Fig. 10B), silicic lava domes, and lava flows. The Oligocene–Miocene volcanic centers can be mapped (Smyth, 2005) by the occurrence of vent proximal facies, and at least 13 centers are presently exposed (Fig. 2), which show a similar spacing to the volcanoes of the present-day arc. The thickness of the proximal volcanic deposits ranges from 250 to >2000 m.

Thick (>700 m) successions of volcaniclastic sedimentary rocks surround the volcanic centers. These reworked deposits are commonly interbedded with beds of unworked mantling tufts and volcanic breccias >1 m in thickness. The reworked volcaniclastic beds vary in thickness from 5 to >100 cm and are crystal- and volcanic lithic-rich sandstones and tuffaceous mudstones. They commonly contain abundant fragments of charcoal, indicating the presence of vegetated slopes on the terrestrial volcanic centers. Both terrestrial and shallow marine deposits have been identified; the latter do not contain abundant bioclastic material but are weakly calcareous, and their upper bedding surfaces are commonly intensely bioturbated with Cruziana-type facies traces. There are slump folds and mass wasting deposits on the flanks of the volcanic centers.

In the Southern Mountains Arc is a record of a major eruption, the Semilir Eruption, toward the end of the period of arc activity. Extensive deposits of this eruption are widespread to the east of Yogyakarta (Fig. 4). The Semilir and Nglanggran Formations (Fig. 10A, B) are the products of this event, and they were deposited in a short period, possibly during one eruptive phase between 21 and 19 Ma (Smyth, 2005). Based on measured sections, the combined thickness of the two formations varies between 250 and 1100 m. They are well exposed over an area of 800 km², and the total volume of volcanic material is estimated to be at least 480 km³. The Semilir Formation (Fig. 6) is a thick accumulation of dacitic air-fall, pyroclastic surge and flow deposits produced by an explosive eruption. Both terrestrial and shallow marine deposits have been identified, indicating that the erupted material entered the sea from the flanks of the volcanic center. The Nglanggran Formation (Fig. 6) is a series of monomict andesitic volcanic breccias. The individual beds are up to 10 m thick, have flat bases and tops, and can be mapped for tens of kilometers. The breccias contain some blocks >3 m across. They are interpreted as vent proximal facies such as flow breccias or block-and-ash–flow deposits. These deposits mark the end of volcanism in the...
Southern Mountains Arc. There is no significant break within or between the Semilir and Nglanggran Formations, based on zircon dating and biostratigraphic dating of the overlying formations (Smyth, 2005).

A number of quartz-rich sandstones (Fig. 10D) are in the upper part of Synthem Two in the Southern Mountains Arc (Smyth, 2005). Volcanic zircons from the sandstones form a single population with ages that are the same as that of the Semilir Formation (Smyth, 2005) and are contemporaneous with the Semilir Eruption. The quartz within these sandstones is entirely of volcanic origin (Fig. 10D). Volcanic quartz grains commonly appear clear and bright in thin section, have
nonundulose extinction, and are monocrystalline (Leeder, 1982). These features and other characteristics, including well-developed crystal faces, bipyramidal shape, melt embayments, and melt inclusions, can be used to distinguish volcanic quartz from other types such as metamorphic, vein, plutonic, and sedimentary quartz. Volcanic crystal-rich sandstones can be produced by primary eruptive mechanisms and/or secondary epiclastic processes. The sandstones and other quartz-rich volcanoclastic rocks in East Java previously were interpreted as continental siliciclastic deposits (Harahap et al., 2003), and it is for this reason that many of the acidic products of the Southern Mountains Arc have been overlooked (as discussed below). Here they are interpreted to have a volcanic origin and to be largely the product of the Semilir Eruption with some subsequent reworking.

**Kendeng Basin**

Synthem Two exposures in the Kendeng Basin are very limited, occurring only in a small thrust-bound sliver. They comprise poorly lithified *Globigerina*-rich tuffaceous mudstones ranging in age from late Oligocene to early Miocene (de Genevraye and Samuel, 1972). The mudstones are at least 85 m thick (de Genevraye and Samuel, 1972) but have limited surface exposure. The mudstones are volcanogenic and apparently lack continental terrigenous material. The volcanic material is fine grained, reworked, and distal in character, very different from that identified within the arc at this time. The abundance of *Globigerina* and other planktonic foraminifers is indicative of pelagic sedimentation in an open marine setting at water depths of a few hundred meters or more. Thick volcanogenic turbidites are reported from wells in this area (P. Lunt, 2002, personal commun.), but no descriptions of the stratigraphy or well log interpretations have been published.

**Edge of the Sunda Shelf**

The offshore Eocene to Pliocene successions in the East Java Sea that have been investigated during hydrocarbon exploration are not reported to contain any volcanic material (e.g., Matthews and Bransden, 1995). Field investigations during this study in northeast Java have identified distal volcanic material on the edge of the Sunda Shelf within carbonates, including thin tuff layers, zones rich in smectite clays, and concentrations of volcanic quartz and zircons. This suggests that there may be more volcanic debris offshore than recognized up to now, and that some of the clay layers may be fine air-fall ash deposits.

The stratigraphic record of Synthem Two within the Southern Mountains Arc and Kendeng Basin accounts for only volcanic and volcanoclastic rocks at this interval. There is no evidence of input of material from basement or other sources. This indicates that the volcanic arc was the only source of sediment at this time. There are no significant exposures of carbonates within Synthem Two in the Southern Mountains Arc or Kendeng Basin, but carbonates do occur farther to the north on the edge of the Sunda Shelf.

**Synthem Three: Reworking of the Southern Mountains Arc**

**Southern Mountains Arc**

In the Southern Mountains, to the south of the Oligocene–Miocene volcanic centers, extensive calcareous volcanogenic turbidites (Fig. 11) occur with Bouma divisions A, C, D, and E. The turbidites are at least 500 m thick and have been dated within nanofossil subzones NN2–NN8 (Kadar, 1986) that correspond to dates between 19 and 10 Ma. Beds vary in thickness from 20 to 75 cm, and upper bedding surfaces are commonly bioturbated with traces of *Cruziana* facies. Flute casts indicate that the flow direction was toward the southeast, and there are slump folds with southeasterly vergence. Thin section examination shows that volcanic crystals and lithic fragments are well rounded, and there is no fresh or unworked volcanic debris present. Dating of zircons (see below) supports the field and petrographic evidence that these are reworked volcanoclastic deposits, as the zircon ages are similar to the age range of rocks in Synthem Two. Synthem Three is therefore interpreted to be the product of reworking of older arc rocks of Synthem Two rather than the product of contemporaneous volcanism.

Several tuff beds have been identified at the top of the turbidite sequence in the Southern Mountains but are not the result of volcanic activity in the Southern Mountains Arc. The tuffs are distal air-fall deposits and yield zircons with ages between 12 and 10 Ma (P.J. Hamilton, 2003, personal commun.). These tuffs are the product of the modern Sunda Arc (Soeria-Atmadja et al., 1994), and the ages mark the initiation of volcanic activity some 50 km to the north of the Southern Mountains Arc.

In addition to the turbidites, there are the first widespread carbonates in the Southern Mountains (Fig. 11D). The carbonates range in age from late early Miocene to middle Miocene (Lokier, 2000; Smyth, 2005) and formed isolated reefs and extensive carbonate platforms, which can be observed overstepping the deposits of Synthem Two. The limestones are at least 200 m thick and are the source of the carbonate within the volcanogenic turbidites.

**Kendeng Basin**

Volcanogenic sedimentary rocks identified in the Kendeng Basin include channelized volcanic lithic conglomerates, crystal-rich and volcanic lithic-rich sandstones, tuffaceous mudstones, and *Globigerina* mudstones. A thickness of up to 400 m of rocks is exposed (Smyth, 2005), and hydrocarbon exploration shows there is up to 3000 m in the basin (de Genevraye and Samuel, 1972). The sandstones contain Bouma divisions B, C, and E and are locally cut by the channelized conglomerates. These conglomerates can cut as much as 20 cm into the underlying beds and are up to 1 m thick. Slump folds are common, and most verge toward the northeast. Measurements of scours, grooves, channel structures, flutes, and slumping indicate that sediment was transported from the south toward the north. The *Globigerina* mudstone is similar in character to those of Synthem Two. A sample from the top of the exposed section yielded a biostratigraphic age
of foraminifer subzones N8–N9 (M. Fadel, 2003, personal commun.) corresponding to ages between 17.2 and 14.4 Ma.

**Edge of the Sunda Shelf**

On the edge of the Sunda Shelf are a number of lower to middle Miocene quartz-rich sandstones. They were previously interpreted to have a continental provenance and to have been derived from reworking of basement rocks of Sundaland (e.g., Ardhana, 1993; Sharaf et al., 2005), but new studies (Smyth et al., 2007) have shown that these sandstones contain a significant proportion of volcanic quartz, volcanic zircons, and reworked volcanogenic clays. These volcanic particles are interpreted to have fallen as ash onto the Sunda Shelf, to have been subsequently reworked and mixed with material derived from uplifted basement blocks in the East Java Sea (Bishop, 1980; van Bemmelen, 1949), and redeposited on the edge of the Sunda Shelf.

**INTERPRETATION OF THE EOCENE TO MIocene STRATIGRAPHY**

**Initiation of the Southern Mountains Arc**

The first evidence of arc volcanism in East Java is identified as middle Eocene at ca. 42 Ma with the first occurrence of tuff layers, volcanic lithic fragments, volcanic quartz, laths of plagioclase feldspar, and volcanic zircons. Prior to this, the sedimentary rocks, which are the oldest rocks exposed on East Java, lack evidence of contemporaneous arc volcanism and are the only rocks
exposed on East Java that contain no volcanic debris. This suggests that there was no arc volcanism on Java prior to 42 Ma, which also implies no subduction of the Indian-Australian plate beneath Java at this time.

Growth and Development of the Southern Mountains Arc

Following the initiation of volcanism in the Southern Mountains, the contribution of volcanic debris increased rapidly, and the contribution of basement-derived material decreased. The volcanic centers probably formed an east-west chain of volcanic islands separated by interarc basins, much like the present Izu-Bonin-Mariana and Aleutian Islands Arcs. A narrow volcaniclastic shelf built up around the isolated volcanic islands, where thick sequences of volcanic and epiclastic material were deposited. To the north and directly behind the arc, the Kendeng Basin began to subside, and material was transported from the volcaniclastic shelf into the basin.

No reef carbonates are preserved within Synthem Two near the arc, suggesting that environmental conditions, such as the influx of volcanic detritus, prevented reef growth or, alternatively, that these carbonates were not preserved or exposed. However, some distance to the north, on the edge of the Sunda Shelf, a large area of carbonate platform was developing at this time; the shelf received volcanic debris as air fall, but much less than that deposited close to the arc, and the volcanic material did not substantially inhibit carbonate growth. Wilson and Lokier (2002) showed that volcanic input can influence carbonate development close to active arcs without killing carbonate-producing organisms and causing carbonate deposition to cease.

During the Oligocene to early Miocene, volcanic activity along the Southern Mountains Arc was at its most voluminous and explosive. The volcaniclastic shelf close to the active volcanic centers increased in width and thickness. Material was fed into the Kendeng Basin, and only in the deepest part of the basin was there pelagic sedimentation without a volcanogenic component.

Termination of Volcanism in the Southern Mountains Arc

Following a long period of arc activity between 42 and 18 Ma, volcanism in the Southern Mountains Arc ceased. The final stages of activity were marked by a phase of explosive volcanism, which included a major event, the Semilir Eruption. The age range, thicknesses, area, and estimated volumes of volcanic deposits in the vicinity of the Toba volcanic center (Chesner and Rose, 1991) are similar to those of the Semilir center, and the deposits of the Semilir Eruption may be distributed, like the Youngest Toba Tuffs (Song et al., 2000), over large parts of SE Asia. Work is in progress to assess their distribution.

Lull and Resurgence of Volcanic Activity

Following the termination of volcanism, there was widespread erosion of the deposits of Synthem Two and extensive reef growth. Volcanogenic turbidites built out as thick aprons northward from the inactive arc into the Kendeng Basin. Sedimentation was rapid and on an unstable northward-dipping slope, and the deposits began to fill the accommodation space within the basin. Material also traveled southward from the eroding arc into the Java forearc. On fault-bounded highs or in the shelter of the extinct volcanoes, reefs and carbonate platforms developed, marking the first period of extensive carbonate growth within the Southern Mountains during the middle Miocene (ca. 20–10 Ma).

Arc volcanism resumed in the late Miocene, after a lull of ~8 m.y., 50 km to the north of the extinct Southern Mountains Arc at the position of the modern Sunda Arc.

Character of the Crust Beneath the Southern Mountains Arc

Little is known of the crust beneath many young arcs, especially in Indonesia, and East Java is no exception. However, study of the stratigraphy of the Southern Mountains Arc has provided some new and surprising insights into the character of the deep crust beneath the arc.

As discussed above, exposures of basement rocks in East Java are limited and are restricted to the west of the study area. These rocks have been interpreted to be fragments of arc and ophiolitic material accreted to the continental margin of Sunda-land during the Late Cretaceous (Hamilton, 1979; Wakita, 2000). It has been generally considered that these rocks are typical of the basement beneath the whole of East Java. This is supported by oil company drilling on land in East Java and farther to the north in the East Java Sea, where deep wells penetrate a varied basement, including basic and acidic volcanic rocks, slaty metasedimentary rocks, quartzites, and cherts (e.g., Hamilton, 1979; Matthews and Bransden, 1995). However, the abundance of acidic volcanism in the Southern Mountains Arc and the dating of zircons indicate that the crust beneath much of the southern part of East Java is very different, and is much older.

Volcanism

The intermediate to acidic volcanic rocks of the Southern Mountains Arc range in composition from andesite to rhyolite (60–77 wt% SiO₂), with an estimated average SiO₂ content of 67 wt%. In addition, many of the high-level intrusive bodies exposed within the Southern Mountains Arc are granodiorites. These rocks are considerably more evolved than the basic to intermediate eruptive products of the present-day volcanoes. The chemistry of the modern arc volcanic rocks in East Java (Handley, 2006; Nicholls et al., 1980; Wheller et al., 1987) indicates that they are the products of relatively primitive subduction melts, which reveal 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 more basic magma, interaction of more basic magma with felsic crust, and partial melting of
felsic crust. Evidence from zircons (discussed below) suggests that involvement of continental basement in petrogenesis is the most likely explanation.

**Ancient Zircons**

At the beginning of this study there were very few good dates for volcanic rocks of the older arc on Java (50 analyses), and all published ages were K-Ar dates (Ben-Avraham and Emery, 1973; Soeria-Atmadja et al., 1994). No acidic rocks had been dated. During this study, zircons from 16 Cenozoic samples of igneous (9), volcanioclastic (3), and sedimentary rocks (4) were dated by the SHRIMP U-Pb method at Curtin University of Technology, Australia, using the methods described in Smyth et al. (2005, 2007). More than 453 spot ages were measured, and 270 of these were Cretaceous and older.

Prior to SHRIMP dating, the expected age range of the zircon samples was Cenozoic to Cretaceous. This reflects the age of arc activity known from Java, and a contribution from the Cretaceous arc and ophiolitic terranes interpreted to form the basement of East Java. However, in addition to the expected ages, an unexpected range of Archean–Cambrian grains was identified in a large number of samples (Smyth, 2005, 2007). The samples containing Cretaceous ages and those containing Cambrian and older zircons occur in distinct areas of East Java.

**Lithology and Zircon Age Range**

The five intrusive and four extrusive igneous rocks analyzed contain a range of Cambrian and older zircons (n = 155) but lack Cretaceous zircons. In contrast, the three volcanioclastic rocks analyzed yielded a significant number of Cretaceous zircons (n = 42) but only one Cambrian or older zircon. The four quartz-rich sandstones analyzed yielded varied zircon ages. All of these sandstones contain Cretaceous grains (n = 33). Three sandstones from the Southern Mountains and Kendeng Basin contain a range of Cambrian and older grains (n = 22). One sandstone from the edge of the Sunda Shelf contains a single Jurassic–Triassic grain but no older grains.

**Age Ranges and Spatial Distribution**

The samples containing different zircon ages do have a clear geographical pattern. The Archean grains are found only in rocks of the Southern Mountains (Fig. 12B), and the igneous rocks of this area contain no Cretaceous zircons (Fig. 12A). Cretaceous zircons are found only in the north and west of East Java, and these zircons have been identified only in sedimentary and volcanioclastic rocks. This is interpreted to indicate that the Southern Mountains are underlain by material providing Cambrian to Archean zircons but no Cretaceous zircons. To the north and west of the Southern Mountains the underlying rocks do not include Cambrian to Archean material but do include Cretaceous material. Figure 12C shows the distribution of basement rocks interpreted from the zircon ages.

If all the zircon ages are grouped together, five age peaks can be identified (Fig. 13): a Cenozoic peak (5–42 Ma) recording volcanism in the Southern Mountains and Sunda Arcs, a Cretaceous peak (65–135 Ma) consistent with the interpreted age of basement, a Cambrian to Neoproterozoic peak (500–1000 Ma), a Mesoproterozoic to Paleoproterozoic peak (1000–2500 Ma), and an Archean peak (2500–3200 Ma). The Cambrian and older ages were not expected, based on knowledge of the regional geology.

**Source of the Ancient Zircons**

Sundaland, the continental core of SE Asia, is the closest and most obvious source of the very old zircons (Figs. 1 and 13). Rocks that could have provided abundant old zircons include granites of SW Borneo (Hamilton, 1979), the Malay Peninsula (Liew and Page, 1985), the Thai-Malay Tin Belt (Cobbing et al., 1986), and Sumatra (Imtihanah, 2000; McCourt et al., 1996) (Fig. 13). However, in these areas there are no known Archean rocks, nor is there any indication that they are underlain by Archean crust.

Geochemical and isotopic studies suggest a basement no older than Proterozoic in areas of Sundaland, such as the Thai-Malay peninsula, that have been studied (e.g., Liew and Page, 1985). The closest area with extensive granites is the Schwaner Mountains of SW Borneo. Paleogene sedimentary rocks of north Borneo contain debris eroded mainly from the Schwaner granites and the Malay Tin Belt, including detrital zircons (van Hattum et al., 2006). The zircon populations are dominated by Cretaceous zircons with age peaks different from those of East Java; there are abundant Permian–Triassic zircons, rare in East Java; and Precambrian zircons are mainly Paleoproterozoic with very rare Archean grains. The differences in zircon ages rule out a Schwaner or Thai-Malay provenance, and other granite sources in Sundaland are even more distant and paleogeographically unlikely.

The largest and closest area of continental crust of Archean age is Australia, which formed part of Gondwana until the Cretaceous. It has been suggested that small Gondwana continental fragments collided with the east Sundaland margin in Sulawesi during the Cretaceous (e.g., Wakita et al., 1996; van Leeuwen and Muhardjo, 2005), although the source of the fragments was not identified. There is evidence of Late Jurassic–Early Cretaceous rifting of continental fragments from the northwest and west Australian margins (Müller et al., 2000) during continental breakup preceding the separation of India from Gondwana. One of these continental fragments could have collided with the Sundaland margin. Bergman et al. (1996) speculated that there could be old continental crust beneath west Sulawesi, on the basis of lead isotopic compositions of Neogene plutonic rocks, which were suggested to have had an Australian origin. Basement rocks in western Australia are dated as Proterozoic and Archean. Detrital zircons from young sediments of the Perth Basin, derived from the erosion of western Australian basement, have been well studied and dated (Cawood and Nemchin, 2000; Pell et al., 1997; Sircombe and Freeman, 1999). The zircon populations in Perth
Basin sedimentary rocks are remarkably similar in age to those of the Southern Mountains in East Java. Both areas yield zircons with 4200–2500 Ma ages (predominantly 3200–2500 Ma) similar to the Archean Yilgarn and Pilbara Blocks, 2000–1600 Ma and 1300–1000 Ma ages similar to the Paleoproterozoic and Mesoproterozoic Capricorn and Albany-Fraser orogenic belts, and 800–500 Ma ages similar to the Neoproterozoic Pinjara orogenic belt (Fig. 14). A west Australian origin is a geographically simple and plausible explanation for the Precambrian zircons of East Java, but how did they become incorporated in igneous rocks?

Figure 12. Distribution of samples that contained zircon populations of (A) Cretaceous ages, and (B) Archean ages (Smyth, 2005). (C) Interpreted character of the basement terranes in East Java.
Incorporation of Zircons into East Java Igneous Rocks

Zircons are highly refractory and are well known for surviving repeated episodes of melting (e.g., Hanchar and Hoskin, 2003). Ancient zircons could have been introduced into Paleogene magmas of the Southern Mountains Arc either by subduction of Gondwana-derived sediments or crust, or by passage of magmas through a previously emplaced Gondwana-origin continental fragment at depth beneath the Southern Mountains.

Subduction of Gondwana Sediment

Sediment 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, and there is no evidence of a sediment supply and distribution system like this in the past. The huge Bengal Fan is fed by erosion from the Himalayas, but there is no evidence for a comparable orogenic belt in Australia during Cenozoic times. During the early Cenozoic, Australia lay much farther south of its current position (Hall, 2002), and there is little sedimentary cover today on the Indian-Australian plate south of Java (Masson et al., 1990; Kopp, 2002) in what would have been more proximal parts of such a fan.

It is unlikely that material could have been introduced into the Java Trench by axial transport from the Himalayas via the Bengal Fan, or from the Bird’s Head microcontinent, New Guinea. If sediment was produced by the erosion of the Himalayas, it would require transport via the Bengal Fan to the Java Trench and total transport distances >4000 km. Although mud-rich material is considered to have reached northern Sumatra in the distal parts of the Bengal Fan (Curry et al., 2002), there were topographic barriers at the Investigator Fracture Zone and the Ninety East Ridge, and even then a further 2000 km of along-trench transport. Today there is no material from the Bengal Fan reported in the Java Trench off the shore of East Java (e.g., Masson et al., 1990) and no significant sediment cover on the Indian plate south of Java (Kopp, 2002). It is equally unlikely that sediment from the Himalayan region could have traveled southeastward from Indochina across Sundaland, bypassing numerous basins and associated structural highs (Hall and Morley, 2004) to enter East Java. This would require transport distances >3500 km.

The basement rocks of the Bird’s Head microcontinent were not available for erosion during most of the Cenozoic, and the Bird’s Head was the site of deposition of thick marine carbonates of the New Guinea limestones (Fraser et al., 1993; Pieters et al., 1983). Even had the Bird’s Head been supplying large volumes of sediment, along-trench transport distances >2000 km would have been required for material to enter the subduction zone beneath Java. This is equivalent to material from southern Mexico or northern Washington State entering the Allistos Arc.
(Busby et al., 2006) of Baja California, or for northern Norway or Alabama to have been sources for the Lough Nafooey Arc (Draut and Clift, 2001) of the Irish Caledonides.

**Subduction of a Gondwana Fragment**

Subduction of continental crust is even less likely. Buoyancy forces make subduction of continental crust difficult, and even if these were overcome, the fragment would have been required to supply material to the arc from the middle Eocene to the early Miocene, a period of ~20 m.y. The fragment of crust either remained stationary beneath the Southern Mountains or was 1500 km in length, based on the present subduction rate of 75 mm/year (McCaffrey, 1996), or on Cenozoic plate tectonic reconstructions (Hall, 2002).
Accretion of a Gondwana Fragment

The most likely explanation is that continental crust was already present beneath the Southern Mountains Arc when subduction began in the middle Eocene. We suggest that this was a western Australia–rifted continental fragment that collided with the margin of Sundaland during the Late Cretaceous and may have terminated the Cretaceous phase of subduction. Subduction was renewed in the middle Eocene, and Cenozoic melts were contaminated by interaction with continental crust beneath the Southern Mountains. The distribution of pre-Cenozoic zircons indicates that north of the Southern Mountains there is no continental basement, and the deep crust is arc or ophiolitic, perhaps representing material accreted during Cretaceous subduction or underplated during collision. The continental fragment could have been quite large and may be traceable into Sulawesi. Zircon dating and geochemical evidence (van Leeuwen and Muhardjo, 2005) show that the Malino Metamorphic Complex of NW Sulawesi (Fig. 13) contains zircons with ages up to 3500 Ma.

DISCUSSION

The stratigraphic record in East Java provides insights into the nature of the deep crust beneath the arc, the history of Indian-Australian plate subduction, and the contribution of the volcanic arc to basin formation. It also poses some questions about the continuity and location of volcanic activity, which have relevance for other arcs.

Deep Character of the East Java Volcanic Arc

Little is known about the deep crust beneath the young arcs of the Western Pacific and Indonesia. There have been few seismic refraction studies and few xenolith studies, and the deep crust is almost invariably covered by younger volcanic and sedimentary rocks. In East Java the old zircons in the Eocene to Miocene arc products provide evidence of the character of the deep crust. The insight gained was completely unexpected. When this study began, it was thought that the entire region was underlain by Cretaceous arc and ophiolitic fragments, as suggested by Hamilton (1979). The distribution of ages shows that north of the Southern Mountains there is indeed crust of this character, as indicated by the small exposures of basement, but beneath the Southern Mountains themselves there is a fragment of continental crust of Gondwana character and western Australian origin.

The presence of a continental fragment beneath the arc accounts for the unusually acidic character of arc volcanism in the Eocene to early Miocene arc. The acidic products of this arc have been overlooked partly because the resistant “Old Andesites” are topographically so much more obvious, although acidic volcanic and minor intrusive rocks are well exposed in many parts of the Southern Mountains. However, the main reason why the acidic products of the Eocene to early Miocene arc were missed by earlier studies is because they were erupted explosively and dispersed as volcanic ash, the ash was reworked into sediments, and the processes of eruption and tropical weathering combined to remove the unstable volcanic constituents, leaving well-sorted quartz-rich sandstones. These were previously interpreted as having been eroded from a continental Sundaland source, but careful examination of the sandstones reveals abundant evidence of their volcanic origin on the basis of textures, light mineral constituents, quartz character, clay mineralogy, and zircon character and ages (Smyth, 2005).

Age of Subduction

The character of the oldest parts of the East Java stratigraphic successions indicates that Cenozoic volcanic activity began in the middle Eocene (ca. 45 Ma). There is little evidence to support the common assumption (e.g., Hall, 2002; Heine et al., 2004; Metcalfe, 1996; Scotese et al., 1988) that subduction continued from the Mesozoic into the Cenozoic without significant interruption. The stratigraphy of East Java indicates that older subduction probably terminated in the Late Cretaceous with the collision of a continental fragment rifted from western Australia. We suggest that the continental fragment extended from East Java to North Sulawesi. Ophiolites were emplaced from Java to North Borneo during this collision. The oldest sedimentary rocks above the basement in East Java are of uncertain age but are middle Eocene or older and lack volcanic debris. There is little evidence for latest Cretaceous to early Eocene volcanic activity in most of the Sundaland margin between Sumatra and Sulawesi. Subduction resumed in the middle Eocene when Australia began to move northward rapidly after 45 Ma (Hall, 2002; Müller et al., 2000; Schellart et al., 2006), and has continued to the present day.

Formation of the Kendeng Basin

When volcanic activity resumed in the middle Eocene a basin began to form directly north of the arc. Most of the investigations of sedimentary basins on land in East Java and in the East Java Sea (Fig. 1) have been carried out as part of hydrocarbon exploration activity, and little attention has been given to areas close to the modern arc. The Sunda Shelf basins are typically >100 km from the arc and are characterized by many features typical of fault-controlled basins; explanations for their origin have therefore interpreted them as types of backarc basins resulting from subduction rollback, rift and thermal sag, or strike-slip faulting (e.g., Hamilton, 1979; Matthews and Bransden, 1995).

The Kendeng Basin is not a typical backarc basin. Backarc basins (Taylor and Karner, 1983) may form by trench rollback, causing generation of oceanic crust (Dewey, 1980; Karig, 1971), rifting of continental crust (Kobayashi, 1985), gravitational collapse in the wake of arc-continent collision (Clift et al., 2003), or by the trapping of old oceanic crust behind an arc (Scholl et al., 1986). Retroarc basins (Dickinson, 1974) form as compressive foreland basins behind a volcanic arc. Busby and Ingersoll (1995) defined backarc basins as oceanic basins behind intraoceanic magmatic arcs, and continental basins behind continental
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Marginal arcs that lack foreland fold and thrust belts. Marsaglia (1995) identified similar categories of backarc basins with the addition of boundary basins resulting from extension along plate boundaries with translational components. Busby and Ingersoll (1995) claim that the Sunda Shelf basins of Indonesia are non-extensional backarc basins formed in a neutral strain regime, although the basis for this assertion is not clear, because there is abundant evidence for rifting of many of these basins (e.g., Cole and Crittenden, 1997; Hall and Morley, 2004).

There is no evidence for either newly formed oceanic crust under the Kendeng Basin or for strike-slip faulting. The basin is much closer to the arc than other backarc basins and most of the “backarc basins” of the Sunda Shelf. The late Cenozoic deformation in the region led to ~10–30 km of contraction at the outer edge of the basin, so throughout the early Cenozoic this basin was very close to the arc. There was extension in the Sunda Shelf from the Eocene, but nowhere was oceanic crust formed. The Kendeng Basin is an asymmetrical depression, the deepest part of the basin lies directly behind the arc, and the Eocene to lower Miocene volcanic and sedimentary sequence thins toward the edge of the Sunda Shelf (Waltham et al., this volume). The basin fill was derived mainly from the Southern Mountains Arc on the south side of the basin. The basin began to form at the same time as arc activity began, and its subsidence history is closely linked to activity in the volcanic arc. There are no seismic lines crossing the basin, and it is not well exposed at the surface, so we cannot assess the role of faulting in the basin development, but it does not have the typical synrift-postrift stratigraphy of many other Sunda Shelf basins. There is no evidence of compressional loading having contributed to basin formation. Thrusting in East Java occurred in the late Neogene long after the Kendeng Basin had formed. The close relationship between volcanic activity and basin subsidence suggests that the two are linked, and we suggest that the load of the volcanic arc was the major cause of basin subsidence. The contribution of volcanic arc loading to basin formation in Indonesia is discussed in greater detail by Waltham et al. (this volume).

Movement of the Volcanic Arc

Activity in the Southern Mountains Arc terminated during the early Miocene (ca. 20 Ma). After a period with little magmatism, a new episode of arc volcanism began in East Java at ca. 12–10 Ma in a new location. The Miocene to Holocene arc is parallel to the Southern Mountains Arc but ~50 km north of it. A significant reduction in volcanic activity in the middle Miocene is a well-known feature of the Sunda Arc from Java eastward, although subduction was continuous during this period (Hall, 2002). Vigorous volcanic activity resumed at the end of the middle Miocene in the Sunda and Banda Arcs at ca. 10 Ma (Hall, 2002; Macpherson and Hall, 2002).

Macpherson and Hall (1999, 2002) suggest that the decline in volcanic activity resulted from northward advance of the subduction hinge. Hinge advance prevented replenishment of the mantle wedge by fertile mantle, and consequently subduction-induced melting was inhibited as the wedge became depleted. The cause of hinge advance was the result of the collision of Australia with eastern Indonesia, and the counterclockwise rotation of the Borneo-Java region this collision induced (Hall, 2002). Arc volcanism resumed when hinge advance ceased and the mantle wedge was replenished by fertile mantle (Macpherson and Hall, 2002).

Why the volcanic arc moved to its new position 50 km north of the Southern Mountains Arc is uncertain. There is evidence of thrusting and contraction in Java in the late Neogene, but its timing is not precisely known; this is part of our current research. It is possible that contraction was linked to large-scale arc dynamics, such as coupling of the subduction and overriding slab. There is evidence of an old consolidated accreted material in the Java forearc that acts as a backstop to the active accretionary prism (Kopp et al., 2001). This suggests two phases of arc migration, and these may be linked to the two phases of arc volcanism on land in East Java. It is also possible that when the subduction hinge advanced and the mantle wedge was not being replenished, one result was a rigid, stronger overriding lithospheric plate that later failed when hinge advance ceased and weaker, warmer mantle replenished the wedge. Another control could have been the nature of the crust beneath the arc. The zircon ages indicate that there was a change in basement type north of the Southern Mountains and that the boundary between continental and ophiolitic crust at depth may have been a preexisting structural weakness that influenced the position at which melts could rise when arc activity resumed.

Other possibilities for explaining arc migration include subduction erosion and a change in dip of the subducting slab. Subduction erosion seems unlikely, as the width of the arc-trench gap today is >300 km, and because marine data support active accretion at that time (e.g., Kopp et al., 2001). A change in subduction angle cannot be ruled out, but it is notable that today the slab dip has increased to a very high angle after the slab descended to 100 km, as seen in seismicity data (England et al., 2004). A lower, not a higher, angle would be expected if the arc had moved north owing to the change in dip of the slab.

The jump in position of the volcanic arc is a feature of other Indonesian arcs (e.g., Halmahera Arc; Nichols and Hall, 1991) and reflects the changing stresses at the plate boundary over time. We prefer an explanation that links the change in position of the arc to plate reorganization in the region. However, it is difficult to test different hypotheses. Comparison of arc development to the east and west of East Java, from Bali eastward, and toward West Java and Sumatra, might provide insights, but unfortunately even less is known of arc history in these regions than in East Java. This East Java study shows that our understanding of arc tectonics is still incomplete and that studies of arc stratigraphy are essential if our knowledge of arc dynamics is to be improved.

Conclusions

The case study of early Cenozoic arc volcanism in East Java shows the importance of examining arc stratigraphy. Insights
have been gained into the eruptive history, formation of a deep basin behind the arc, and the character of the deep crust.

The early Cenozoic stratigraphy of East Java provides a record of a cycle of arc activity from initiation in the middle Eocene (ca. 42 Ma) to termination in the early Miocene (ca. 20 Ma). The Kendeng Basin, directly behind the Southern Mountains Arc, contains >6 km of volcanioclastic and sedimentary rocks. The basin is not a typical backarc basin, and its subsidence history is linked to volcanic activity within the Southern Mountains Arc.

The final stage of volcanic activity in the Southern Mountains Arc is marked by the Semilir Eruption (ca. 20 Ma), which distributed ash over a wide area and may be comparable to the Pleistocene eruption of Toba in Sumatra. Following this phase of major eruptions, there was a lull in volcanic activity during the middle Miocene, followed by resumption in arc activity to the north of the Southern Mountains Arc, along the axis of the modern Sunda Arc during the late Miocene. The mechanisms that resulted in the decline in volcanism, and northward movement in arc axis, are not yet understood and show that our understanding of arcs is still incomplete.

The stratigraphic record of volcanic arcs can provide insights into the character of the deep crust. The entire East Java region was previously thought to be underlain by Cretaceous arc and ophiolitic fragments, but Archean to Cambrian zircons within acidic products of the Southern Mountains Arc point to the occurrence of a continental crust of Gondwanan character and western Australian origin beneath the old arc. This continental fragment is thought to have collided with Sundaland during the Cretaceous and is interpreted to have terminated the Cretaceous phase of subduction. The extent of this fragment is not known but may be traceable into Sulawesi. The use of inherited zircons to determine the character of the deep crust may be applicable in other arcs.

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REFERENCES CITED


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