A record of continental collision and regional sediment flux for the Cretaceous and Palaeogene core of SE Asia: implications for early Cenozoic palaeogeography

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Abstract: Palaeogene sedimentary rocks exposed in West Java were derived from local volcanic sources and central Sundaland, the continental core of SE Asia. Detrital zircons from seven sandstone samples contain U–Pb age populations with ages of 50–80 Ma, 74–145 Ma, 202–298 Ma, 480–653 Ma and 723–1290 Ma. Late Cretaceous and Palaeogene zircons in Middle Eocene forearc sandstones are interpreted as derived from two spatially and temporally discrete volcanic arcs located in Java and Sulawesi respectively. In contrast, all other populations have a Sundaland provenance. Most Permian–Triassic zircons were derived from granites of this age in the SE Asian Tin Belt. Mid-Cretaceous zircons in all Upper Eocene and Lower Oligocene formations were derived from the Schwener Mountains of SW Borneo. The differences in zircon populations reflect changing Sundaland sources with time. In the Middle Eocene, sediment was derived mainly from the Tin Belt. From the Late Eocene onwards a Borneo source became more important. Older zircon ages are from SE Asia basement that once formed part of Gondwana. Zircons also record the timing of microcontinental collision at the Java margin (c. 80 Ma) that halted Cretaceous subduction and probably resulted in the elevation of large parts of continental SE Asia.

Supplementary material: Methods, sample locality list, tables for U–Pb age measurements, point count data and heavy mineral assemblages, sandstone petrographic descriptions and palaeocurrent data are available at www.geolsoc.org.uk/SUP18489.

Little is known of the palaeogeography, palaeodrainage and sediment pathways in continental SE Asia during the Late Cretaceous and Early Palaeogene. In the Early Cretaceous Sundaland, the area of continental crust that extends from Indochina southeastwards including the islands of Sumatra, Borneo and Java, and the shallow seas between them (Fig. 1), was broadly in its present position, and there was subduction at its western, southern and eastern margins. The addition of microcontinental fragments at the SE Sundaland margin (e.g. Smyth et al. 2007; Hall 2009: Hall et al. 2009) during the Early and early Late Cretaceous halted subduction beneath Sundaland (e.g. Hall 2009; Clements et al. 2011). From the Late Cretaceous to c. 45 Ma the margin was inactive (Hall et al. 2008; Hall 2009) and much of the Sundaland region was emergent (Clements et al. 2011). As a consequence of this regional elevation there are almost no sedimentary rocks of Late Cretaceous–Early Palaeogene age in the region. At c. 45 Ma subduction recommenced (Hall 2009) and sediments started to accumulate within the Sundaland interior and at the continental margins. During the Late Eocene and Oligocene, thick sequences of siliciclastic detritus were deposited across the region (e.g. Doust & Noble 2008; Smyth et al. 2008).

Today large rivers transport huge volumes of sediment from the India–Asia collision zone through Indochina into SE Asia (e.g. Mekong, Irrrawaddy, Red; Ludwig & Probst 1998). It has been suggested that thick accumulations of sedimentary material in SE Asian basins, particularly those that surround Borneo, were derived from similar river systems in Asia during the Palaeogene (e.g. Hutchison 1996; Métivier et al. 1999). However, more recently regional tectonic (e.g. Hall 2002; Hall et al. 2008) and provenance studies (van Hattum 2005; van Hattum et al. 2006) have indicated that the impact of India–Asia collision through SE Asia is less important than ‘indentor-style’ models (e.g. Tapponnier et al. 1982; Replumaz & Tapponnier 2003) suggest. The Palaeogene sedimentary fill of circum-Borneo basins (e.g. the Crocker Fan in NE Borneo), appears to have a local (SW Borneo and Malay Peninsula) SE Asia provenance (based on light minerals, heavy minerals and zircon geochronology; van Hattum et al. 2006). However, detrital zircon geochronological studies in East Java indicate that the Sundaland region did not contribute significant volumes of sediment to SE Java during the Palaeogene (Smyth 2005). There have been no studies of regional sediment flux in central and southern Sundaland (between the islands of Borneo, Sumatra and Java).

In this paper we report U–Pb ages of detrital zircons from sedimentary rocks in West Java that record broad-scale sediment pathways and fluxes across southern Sundaland during the Palaeogene. Interpretation is supported by analyses of detrital modes of light minerals, heavy mineral assemblages and palaeocurrent data. Five formations with depositional ages that range from Middle Eocene to Early Oligocene were chosen, as they provide important information regarding the dispersal of sedimentary detritus during the erosion of a Cretaceous to Eocene regional topographic high in Sundaland. This work also provides information about Late Cretaceous and Early Palaeogene volcanic arcs, the timing of microcontinental collision at the Java margin and evidence for the derivation of sediment from SE Asian basement that was once part of eastern Gondwana. This is the first study concerned with U–Pb dating of detrital zircons in West Java, and the first that addresses patterns of sediment dispersal across this southern part of continental SE Asia.
Fig. 1. Major features of the southern part of the Sunda Shelf. Bathymetry is from Sandwell & Smith (1997). The approximate boundary between Sundaland continental crust and Cretaceous melange according to Hamilton (1979) is shown as a black dashed line. Acidic volcanic and plutonic rocks of ages that correspond to age clusters discussed in this paper are shown. Inset (a) shows West Java; grey boxes correspond to Ciletuh Bay (A), the Bayah Dome (B), the Sukabumi area (C) and the area around Padalarang (D). Samples are numbered 1–7: 28A (1), 30A (2), 8A (3), 4B (4), 2C (5), 22D (6), 13B (7). Black triangles are Holocene volcanoes. Inset (b) is a simplified geological map of West Java compiled from GRDC 1:200 000 scale maps (Geological Survey of Indonesia 1977) by Lokier (2000) with location names discussed in this paper.
Geological background

Continental SE Asia is a composite region of continental fragments or terranes that are separated by suture zones that represent former oceanic basins. All of these terranes are allochthonous and are interpreted to have been derived directly or indirectly from Gondwana (e.g. Sengor 1979; Metcalfe 1988, 1996) based mainly on comparative studies of the stratigraphy, palaeontology and palaeomagnetism. The continental core of Sundaland comprises the Indochina–East Malaya Block and the Sibumasu Block, which separated from Gondwana in the Devonian and Permian respectively and amalgamated with the South and North China blocks in the Early Carboniferous (Metcalfe 2009) and Early Triassic (Barber & Crow 2009; Metcalfe 2009) respectively. They are separated by remnants of the Permo-Triassic Sukhothai arc (Sone & Metcalfe 2008). Two other blocks, with Gondwana origins, were subsequently added to the core of Sundaland; the SW Borneo Block (Hall 2009; Hall et al. 2009) followed by the East Java–West Sulawesi Block (Smyth et al. 2007; Hall 2009).

Sundaland geology

Many of the oldest rocks exposed in the region are poorly dated. In the Malay Peninsula basement rocks include Proterozoic gneiss, marble, schist and phyllite that are overlain by Late Cambrian to Permain sedimentary rocks (Metcalfe 1988). Proterozoic ages have been suggested by Liew & McCulloch (1985) for Malay Peninsula basement (based on U–Pb zircon inheritance ages (1.5–1.7 Ga) from granitoids). Sevastjanova et al. (2010) demonstrated through zircon U–Pb dating and Hf isotope analyses that basement beneath the Malay Peninsula is chronologically heterogeneous. Sibumasu basement is predominantly Palaeoproterozoic (1.9–2.0 Ga) but includes some Archean components (c. 2.8 Ga) whereas East Malaya basement is also Palaeoproterozoic but with a broader age range (1.7–2.0 Ga) and also has Archean components (2.7 Ga). In Sumatra, schists and gneisises that are exposed in the NW are considered to represent a pre-Carboniferous basement (Barber & Crow 2005) and elsewhere continental basement is inferred from the presence of ignimbrites and granites of varying ages. The oldest rocks exposed above basement are the Carboniferous Tapanuli Group, which consists of tillites, limestones, sandstones and shales. The Permain and Triassic are represented by the Peusangan Group, which comprises sandstones, shales, cherts, limestones and volcanic rocks. In Borneo, the oldest rocks exposed are those of the metamorphic Pinoth group, which have been suggested to be Carboniferous–Permian or older (Pieters & Sanyoto 1993) although they are undated and known only to be intruded by Cretaceous granitoids. These, with rocks that van Bemmelen (1949) called Crystalline Schists, form a continental core in West Borneo that is surrounded by ophiolite, island arc and microcontinental crust accreted during the Mesozoic (Hamilton 1979; Hutchison 1989; Metcalfe 1996; Hall et al. 2008, 2009).

Late Palaeozoic subduction and Triassic collision in Thailand and the Malay Peninsula was accompanied by several episodes of granite intrusion. These were associated with subduction preceding collision, and later with post-collisional thickening of the continental crust (Hutchison 1989, 1996; Sevastjanova et al. 2010). As a result, there are many Permain and Triassic granites (Beckinsale et al. 1979; Liew & Page 1985; Krähenbuhl 1991; Cobbing et al. 1992) in the region (Fig. 1). The majority of these granites form part of the SE Asian tin belt, which extends from Myanmar through the Thai–Malay Peninsula into the Indonesian Tin Islands (Fig. 1). During the Jurassic and Cretaceous the region underwent several phases of uplift and erosion, accompanied locally by further episodes of granite magmatism. Cretaceous granites are known from the currently submerged Sunda Shelf (Hamilton 1979) and the Schwaner Mountains of SW Borneo (e.g. Williams et al. 1988; van Hattum et al. 2006) as well as smaller occurrences in Sumatra (Barber & Crow 2005) and the Central Belt of the Malay Peninsula (Cobbing et al. 1992).

Evidence for subduction and collision in SE Asia prior to 45 Ma

Subduction and magmatism

Throughout most of Sundaland there are abundant plutonic and volcanic rocks of Jurassic and Early Cretaceous age and many of these are commonly interpreted as subduction related. These typically occur inboard from a zone of arc and ophiolitic magmatism. In the earliest complexes (which were accreted to the margin in the early Late Cretaceous; see below), and high-pressure–low-temperature subduction-related metamorphic rocks. This demonstrates that there was subduction beneath the Sundaland–Eurasian margin in the Early and late Early Cretaceous prior to microcontinental collisions. This Jurassic to Early Cretaceous active margin can be traced along the present SW margin of Sumatra, through West Java, across the Java Sea, and into the Meratus Mountains of SE Borneo (Fig. 1). In contrast, there is almost no evidence for subduction-related volcanism during the latter part of the Late Cretaceous and Palaeocene, except in parts of West Sulawesi and Sumba. The paucity in plutonic and volcanic rocks of this age throughout the region is interpreted (along with other lines of evidence; see below) to represent a period without subduction (Hall 2009).

In Sumatra there are abundant plutonic and volcanic rocks that record subduction through the Jurassic and Early Cretaceous. The majority of these form the Woyla Group (Cameron et al. 1980; Barber 2000) and represent the volcanic products of the intra-oceanic Woyla Arc that was accreted to the Sundaland margin in the early Late Cretaceous. There are also abundant Late Jurassic and Early Cretaceous I-type plutons that formed along the active margin (McCourt et al. 1996) as well as associated volcanic products such as Early Cretaceous andesites that occur in the Omblin Basin (e.g. Koning & Aulia 1985) and other examples from within the Sumatra Fault Zone (e.g. Rosidi et al. 1976). Palaeocene ages are restricted to mainly basaltic rocks in southern Sumatra and minor basaltic dyke swarms in northern Sumatra (Bellon et al. 2004).

In SE Borneo there are andesitic lavas, tuffs and volcanic breccias that were assigned entirely to the Hanuyan Formation by Wakita et al. (1998) or placed within the Alino Group by Sikumbang & Heryanto (1994) and Yuwono et al. (1988) that are interpreted to represent a volcanic arc suite. These lithologies are approximately Late APTian to Cenomanian in age (115–93.5 Ma) (Yuwono et al. 1988; Wakita et al. 1998). Overlying the Alino Group is the Manunggul Group (Sikumbang & Heryanto 1994) or Formation (Yuwono et al. 1988), which comprises volcanicogenic extrusive rocks that are intruded by basaltic to dacitic dykes and gabbroic to granitic stocks with K–Ar ages that range from 87 ± 4 Ma to 72 ± 4 Ma, interpreted by Yuwono et al. (1988) to be subduction-related, based on their chemistry.

In contrast to the rest of the Sundaland region, there are several occurrences of igneous rocks of Late Cretaceous and
Palaeocene age exposed in West Sulawesi. In the northern part of West Sulawesi the Latimojong Formation (Campanian to Maastrichtian), composed predominantly of marine sediments, tuffs and basaltic to dacitic flows, contains a number of U–Pb zircon age populations, the youngest of which is 120–80 Ma (van Leeuwen & Muhardjo 2005). In southern Sulawesi the Balangbaru (Turonian to Maastrichtian turbidite fan; Hasan 1990) and Marada (Campanian to Maastrichtian turbidites; van Leeuwen 1981) Formations contain volcanic lithic fragments and are, in places, associated with volcanic sills. Unconformably overlying the Balangbaru Formation in the Bantimala region of South Sulawesi is the Bua Formation (Sukamoto 1982; Yuwono et al. 1988). This is predominantly volcanic (andesitic) and intrusive rocks with K–Ar ages that range from 65 to 58 Ma (Yuwono et al. 1988). In the Bira region, further east, slightly younger (Eocene) volcanic rocks, called the Langi Volcanics (van Leeuwen 1981; Sukamoto 1982), comprise predominantly andesitic lithologies. Volcaniclastics in the lower parts contain zircons that yield a fission track age of 62 ± 2 Ma (Hall 2009). The Langi Volcanics are intruded by a tonalite–granodiorite with a K–Ar age of 52–50 Ma (Yuwono et al. 1988). Both the Bua Formation and Langi Volcanics have a calc-alkaline character (van Leeuwen 1981) and were interpreted by Elburg et al. (2002) as subduction-related.

The lower part of the Balangbaru Formation has been interpreted as representing part of a post-collisional passive margin sequence by Hasan (1990) and Wakita et al. (1996), whereas the abundance of volcanic detritus in the upper part is interpreted to indicate derivation from a volcanic arc (van Leeuwen 1981). Hasan’s (Hasan 1990) interpretation of a Late Palaeocene to Early Eocene volcanic arc setting for the Bua Formation is supported by geochemistry, and this interpretation implies that the episode of subduction was relatively short-lived and of limited extent, as well as occurring after collision of the East Java–West Sulawesi Block. On the basis of structural and stratigraphic relationships, van Leeuwen (1981) suggested that this short-lived subduction system was westerly dipping.

On Sumba there are lithologies of similar character, and of broadly equivalent age, to those exposed in West Sulawesi (Hall 2009). Late Cretaceous and Palaeocene turbidites that contain volcanic detritus were assigned to the Lasipu Formation by van Leeuwen (1981) and these rocks record two magmatic episodes based on K–Ar dating: (1) Santonian to Campanian (Sukamoto 1982; Yuwono et al. 1988). This is predominantly volcanic (andesitic) and intrusive rocks with K–Ar ages that range from 65 to 58 Ma (Yuwono et al. 1988). In the Bira region, further east, slightly younger (Eocene) volcanic rocks, called the Langi Volcanics (van Leeuwen 1981; Sukamoto 1982), comprise predominantly andesitic lithologies. Volcaniclastics in the lower parts contain zircons that yield a fission track age of 62 ± 2 Ma (Hall 2009). The Langi Volcanics are intruded by a tonalite–granodiorite with a K–Ar age of 52–50 Ma (Yuwono et al. 1988). Both the Bua Formation and Langi Volcanics have a calc-alkaline character (van Leeuwen 1981) and were interpreted by Elburg et al. (2002) as subduction-related.

Subduction complexes

Cretaceous subduction complexes that include ophiolitic and arc-type rocks are exposed along the west coast of Sumatra, in Java and in SE Borneo, and are products of subduction beneath Sundaland that continued until the early Late Cretaceous. In Sumatra, the Woyla Group includes ophiolitic rocks, pelagic and volcaniclastic sedimentary rocks, and basaltic–andesitic volcanic rocks, interpreted as a Late Jurassic–Early Cretaceous intra-oceanic arc (Barber & Crow 2005). In Java, similar subduction-related lithologies comprise pillow basalts, cherts, limestones, schists and metasedimentary rocks, interpreted as arc and ophiolitic fragments (e.g. Parkinson et al. 1998; Wakita 2000). High-pressure and ultrahigh-pressure (UHP) metamorphic rocks at Karangsambang, East Java, such as jadeite–quartz-glaucophane bearing rocks and eclogites, are diagnostic of subduction metamorphism (Miyazaki et al. 1998). Radiolarian biostratigraphy (Wakita et al. 1994) and K–Ar dates on muscovite from quartz–mica schist (124–110 Ma; Miyazaki et al. 1998; Parkinson et al. 1998) yield Cretaceous ages for subduction-related rocks. In the Meratus Mountains, SE Borneo, ultramafic rocks, basalt, chert, siliceous shale, mélange and schist are interpreted to represent accreted arc and oceanic-type crust (Parkinson et al. 1998; Wakita et al. 1998). Radiolarian biostratigraphy yields ages that range from Middle Jurassic to Late Cretaceous (Wakita et al. 1998).

Collision of the East Java–West Sulawesi block (Hall 2009) was probably responsible for termination of subduction beneath Sundaland (Smyth et al. 2007; Hall 2009). The collision must have been later than the youngest radiolarian ages (Wakita et al. 1994; Wakita et al. 1998) associated with pillow basalts in Java and Borneo (early Late Cretaceous), and the microcontinent must have been in place before initiation of the present phase of subduction at c. 45 Ma (Hall 2002, 2009). The timing of collision between the Woyla Arc and Sumatra is estimated at 98–92 Ma (M. J. Crow, pers. comm.) based on overthrust Aptian–Albian fringing reef carbonates and associated metamorphism of rocks of mid-Cretaceous age (Barber & Crow 2009). Plate reconstructions (Hall et al. 2009), based on the evidence summarized above, interpret the microcontinent to have arrived between 92 and 80 Ma.

Summary of the Sundaland Cretaceous active margin

There are abundant granitic and acid igneous rocks older than 80 Ma exposed throughout the Sundaland region, the majority of which are located inboard of the Early Cretaceous subduction zone that extended along the West Sumatra margin, through West Java and into the Meratus Mountains in SE Borneo, and are interpreted as the consequence of subduction of Tethyan oceanic lithosphere (e.g. Hall 2009). In contrast, there is almost no evidence for subduction-related volcanism during most of the Late Cretaceous and Palaeocene, except in West Sulawesi and Sumba, where there is evidence for a short-lived (westerly dipping?) Late Palaeocene to Early Eocene subduction system. This paucity of volcanic rocks is interpreted to indicate the termination of subduction in the early Late Cretaceous and a period without subduction during the remainder of the late Cretaceous (e.g. Hall 2009). Tectonic reconstructions (Hall et al. 2009) predict WNW–ESE convergence between 63 and 50 Ma in the region of present-day Sumba and West Sulawesi consistent with a short-lived subduction system in the Palaeocene.

Consequences of continental collision in the Late Cretaceous

In addition to the paucity of volcanic rocks younger than c. 80 Ma the termination of subduction in the Late Cretaceous around much of Sundaland is supported by radiolarian ages from cherts associated with basalts from within the zone of accreted rocks that lie outboard of the Early Cretaceous subduction zone (e.g. Parkinson et al. 1998; Wakita et al. 1998). Except in West Sulawesi and Sumba there was no subduction beneath the Sundaland region from about 80 Ma until 45 Ma. The paucity of sedimentary rocks of Late Cretaceous to Palaeocene age indicates regional uplift (Hall & Morley 2004; Hall et al. 2009) during this time and has been interpreted by Clements et al. (2011) as a response to changing dynamic topography, driven initially by subduction, and later by collision and subsequent slab breakoff. Clements et al. (2011) suggested that during Jurassic
and Early Cretaceous subduction there was a dynamic topographic low centred on Sundaland. When subduction ceased in the Late Cretaceous the dynamic topography was reversed and the entire region became emergent although without great elevation (as a consequence of a long-wavelength uplift) and detritus, eroded from exposed Sundaland, was transported to the continental margins. This was deposited off the shelf, presumably later to be subducted when subduction resumed beneath Sundaland at 45 Ma. The sedimentary record for this time interval has therefore been lost, but the oldest sediments deposited above the unconformity, of Middle Eocene age, provide a reworked record of the broad-scale sediment fluxes that typified the Late Cretaceous to Palaeocene regional elevation of Sundaland.

Stratigraphy

Middle Eocene

In West Java Middle Eocene rocks (van Bemmelen 1949; Schiller et al. 1991; Clements 2008; P. Lunt, pers. comm.) are exposed in the Ciletuh Bay area (Fig. 1). These are the Ciletuh and Ciemas Formations (Clements & Hall 2007) and represent the oldest sequences above the basement (Fig. 2).

The Ciletuh Formation consists of coarse polymict breccias, volcanogenic debrites and turbidites (Fig. 3e). The breccias contain abundant volcanic clasts (basalt and andesite) as well as laminated volcanioclastic clasts, several types of limestone clasts and a small number of dacite, granite, and metamorphic clasts. Grey–green fine- to medium-grained volcanioclastic turbidite sandstones are intercalated with the breccias and become increasingly abundant up-section (Clements et al. 2009). Many features, such as the variable and highly angular nature of breccia clasts, and contemporaneous basaltic volcanic rocks (see discussion by Hall et al. 2007; Clements et al. 2009), of the Ciletuh Formation indicate active faulting in deep water and these deposits are interpreted to represent deformation and extension in a deep marine forearc setting (Hall et al. 2007; Clements et al. 2009).

The Ciemas Formation comprises quartz-rich sandstones, pebbly sandstones and conglomerates (Fig. 3b and c). Pebbles are predominantly vein and/or metamorphic quartz and are usually highly rounded; they are interpreted to represent the multiple reworking of sedimentary rocks of pre-Cenozoic age. Sandstones are typically texturally immature (indicated by poor sorting and angular grains) but compositionally mature (composed predominantly of quartz, much of which is of metamorphic origin). Many features indicate rapid deposition and the formation is interpreted
to have been deposited in relatively shallow water on the shelf edge (Clements & Hall 2007; Clements 2008).

**Summary of Middle Eocene formations**

The Ciletuh and Ciemas Formations were deposited contemporaneously in the Middle Eocene and are now exposed close to each other. The two formations are texturally and compositionally very different. Modal compositions (Fig. 4) show that only a minor Sundaland contribution is present in the forearc sandstones of the Ciletuh Formation, and there is no volcanically derived detritus in the Ciemas Formation. The two formations are interpreted to have been deposited far from each other and their present proximity is due to Miocene thrusting (Clements et al. 2009).

**Upper Eocene**

The Upper Eocene (van Bemmelen 1949; P. Lunt, pers. comm.; R. J. Morley, pers. comm.) Bayah Formation comprises dark marine mudstones and siltstones in the lower part that grade upwards into quartz-rich sandstones (Fig. 3f), pebbly sandstones and conglomerates with interbedded coals (Fig. 3a) and rare limestone stringers. Pebby material is predominantly vein and/or metamorphic quartz and is usually highly rounded and interpreted to represent the reworking of pre-Cenozoic sedimentary rocks. Palaeocurrent indicators indicate that material was sourced from the north and the formation is interpreted to have been deposited predominantly by large braided rivers (Kusumahbrata 1994; Clements & Hall 2007) as channel and overbank, deltaic and coastal plain deposits (Fig. 3a, c and f).

**Lower Oligocene**

The Lower Oligocene Cikalong Formation (Clements 2008; P. Lunt, pers. comm.) comprises quartz-rich sandstones, pebbly sandstones and conglomerates intercalated with thick sequences of marine carbonaceous siltstones. These are interpreted as turbidites (Clements & Hall 2007). Rare volcaniclastic (tuffac-
eous) sandstone beds indicate a contribution from a distal volcanic source.

The Oligocene Cijengkol Formation (Clements 2008) is exposed in the Bayah Dome (Fig. 1) and comprises quartz-rich sandstones and conglomerates, volcaniclastic sandstones and conglomerates and shallow water coralline and foraminiferal limestones. Quartz-rich sandstones and conglomerates were deposited in terrestrial to shallow marine conditions and palaeo-current indicators suggest that material was sourced from the north.

Heavy minerals; non-volcanic samples

With few exceptions, heavy mineral assemblages are similar for each of the four quartz-rich formations analysed and are dominated by zircon with significant amounts of rutile, tourmaline, anatase and minor apatite and monazite. Minor amounts of other heavy minerals, including cassiterite, garnet, amphibole, spinel, chlorite, andalusite and cordierite are also present (Fig. 5). Various zircon types, including euhedral, subhedral, rounded and zoned, are common in all samples. Zircons are mostly colourless, but purple and brown grains are not uncommon. Rounded zircon grains (mostly colourless and some purple) have strongly pitted and frosted surfaces, suggesting sedimentary reworking. This is consistent with the wide range of zircon ages in all samples (see below). Euhedral zircon, angular brown tourmaline, monazite and cassiterite also indicate granitic sources. Zircon, tourmaline, rutile, apatite, monazite and cassiterite are minerals that are associated with acid igneous and metamorphic source rocks. Anatase indicates a contact metamorphic and/or granitic source or hydrothermal activity. A contact metamorphic contribution is also supported by rare garnet that is locally anisotropic suggesting a variety of grossular (Mange & Maurer 1992) as well as vesuvianite (derived from impure limestones) although both minerals may be associated with contaminated volcanic rocks such as those reported from the Somma–Vesuvius volcanic products, Italy (e.g. Lima et al. 2007). Rutile, although present in acid igneous rocks (Feo-codecido 1956), is more common in medium- to high-grade metamorphosed basic and intermediate igneous or sedimentary rocks (e.g. Zack et al. 2004). A high-temperature metamorphosed sedimentary source is supported by the presence of rare sillimanite in two of the samples. Chromian spinel (most abundant in the Ciomas Formation) indicates a minor ophiolitic contribution. The presence of cassiterite (between 1 and 3% from all samples) is interpreted to indicate a contribution from the tin belt granites (Fig. 1). Tin in the tin belt occurs in the form of cassiterite (SnO₂) and is commonly found in offshore placer deposits (e.g. Hosking 1977).

Apatite is typically associated with acid igneous rocks (plutonic and volcanic). In this study apatite is abundant only in Cikalong Formation samples (between 7 and 20% of the assemblage) and is present as both elongate–euhedral–weakly pleochroic–clouded and rounded–pitted–clear crystal forms (Fig. 5), indicating volcanic and plutonic–sedimentary sources respectively. The apatite in predominantly siliciclastic sandstones could be from the collapse of ash clouds that originated from active margin volcanoes. However, lack of apatite in other formations suggests that this process is unlikely to have contributed the majority of apatite to the Cikalong Formation. Instead, volcanogenic sandstones that have been mapped (Clements 2008) in close proximity to Cikalong Formation quartz-rich...
sandstones are the probable source of the majority of volcanically derived apatite. Non-volcanic (plutonic) apatite is likely to have originated from granitic rocks.

It is important to note that the Cikalong Formation was deposited in relatively deep water (several hundred metres) whereas all other quartz-rich sandstones were deposited in a terrestrial or shallow marine setting (Clements & Hall 2007; Clements 2008). Apatite is considered unstable under conditions of acidic weathering and more stable during burial diagenesis (Morton 1986), indicating that apatite could have been removed by chemical dissolution from formations that were deposited in a terrestrial setting (and subject to acidic weathering for longer periods). However, the presence of andalusite, which is considered relatively unstable in deep burial conditions (e.g. Morton & Hallsworth 1999), in some of the samples is a good indicator that these rocks were not subjected to significant diagenetic dissolution.

In all samples analysed for heavy minerals (all quartz-rich formations) it is predominantly the ultra-stable heavy minerals that are present (Fig. 5). This is interpreted as partly due to the significant contribution of material from granitic rocks that commonly contain heavy minerals such as zircon, apatite, tourmaline, but also reflecting about 50 Ma of sediment reworking in Sundaland, with probable multi-cycle terrestrial reworking of clastic detritus, and removal of less stable heavy mineral varieties. This polycyclic history for some of the clasts in the sandstone samples is supported by the highly rounded detrital zircon varieties (of all ages) in all samples.

**Palaeocurrent data**

Palaeocurrent data were collected as part of an extensive field programme in West Java during several field seasons. All data are unidirectional and include cross-bedding, current ripples, and flute and groove casts. The majority of palaeocurrent indicators are from quartz-rich sandstones. These data indicate that clastic material was derived from the north and this is consistent with a continental Sundaland provenance. Forearc sandstones of the Ciletuh Formation also have a northerly provenance but contain little continental debris, suggesting derivation from a forearc high.

**Detrital zircon geochronology**

A total of 594 zircon U–Pb analyses were obtained from seven samples and five formations. Two samples are from the Middle Eocene volcanoclastic Ciletuh Formation, which was deposited in a forearc setting. All other samples are quartz-rich sandstones deposited in terrestrial and marine settings. These are the Ciemas (Middle Eocene), Bayah (Upper Eocene), Cikalong and Cijengkol (Lower Oligocene) Formations. At least 60 grains per sample were analysed to ensure 95% confidence levels in defining populations present at 5% (Dodson et al. 1988; Anderson 2005).

Detrital zircon ages, from all samples, range from 3629 to 31 Ma. In this study we define nine populations on the basis of age ‘clusters’ on probability–age distributions from all samples analysed (Fig. 6).

**Archaean to Palaeoproterozoic**

Population A spans the Archaean to Palaeoproterozoic with an age range of 2590–1717 Ma (32 grains; 7.5% of the sample set). Population A has no distinct clusters and represents a broad dispersed age group; 11 of the 32 grains from Population A are from the Ciemas Formation.

**Mesoproterozoic to Early Neoproterozoic**

Population B spans the Mesoproterozoic to Early Neoproterozoic with an age range of 1290–723 Ma (76 grains; 15.1% of the sample set). Population B is present in all samples (Fig. 8).

**Mid-Neoproterozoic to Cambrian**

Population C has an age range of 653–480 Ma (56 grains; 13.2% of the sample set). It forms one prominent age cluster and is present in all samples. The majority of grains have ages between 607 and 480 Ma (49 grains; 11.6% of the sample set).

**Carboniferous and Devonian**

Population D has an age range of 422–305 Ma (17 grains; 4% of the sample set). It forms one broadly dispersed age group and is present in all samples. The majority of grains have ages between 379 and 305 Ma (15 grains; 3.5% of the sample set).

**Permian to Triassic**

Population E has an age range of 298–202 Ma (73 grains; 17.3% of the sample set). It contains two prominent sub-clusters, one between 298 and 252 Ma (23 grains; 5.4% of the sample set) and one between 246 and 202 Ma (50 grains; 11.8% of the sample set). Population E is present in all samples although there are notably few grains from this population in the Middle Eocene Ciletuh Formation samples.

**Jurassic**

Population F has an age range of 199–145 Ma (20 grains; 4.7% of the sample set). It forms one small broadly dispersed age group and is present in all Late Eocene and Early Oligocene samples. Zircons of this age are most abundant in Lower Oligocene formations, particularly the Cijengkol Formation (Sample 13B). Two grains from this population are also present in one Middle Eocene Ciletuh Formation sample (Sample 30A).

**Early to mid-Late Cretaceous**

Population G has an age range of 145–74 Ma (70 grains; 16.5% of the sample set). It forms one prominent age group that is represented in all Late Eocene and Early Oligocene samples.

**Late Cretaceous to Palaeocene**

Population H has an age range of 110–50 Ma (38 grains; 9% of the sample set). There are two prominent sub-clusters, one between 110 and 87 Ma (15 grains; 3.5% of the sample set) and one between 82 and 50 Ma (22 grains; 5.2% of the sample set). Population H is present only in Middle Eocene volcanoclastic forearc sandstones of the Ciletuh Formation.

**Eocene to Oligocene**

Population I has an age range of 40–31 Ma (nine grains; 2.1% of the sample set). Detrital zircon grains from Population I are present in Samples 30A (Middle Eocene Ciletuh Formation), 4B (Upper Eocene Bayah Formation) and 22D (Lower Oligocene
Cikalong Formation). Ages of these grains are all similar to depositional ages (within error) of these formations and were probably sourced from the Palaeogene volcanic arc.

Discussion and conclusions

Most West Java Palaeogene sandstones are quartz-rich and were deposited in a variety of settings from terrestrial through marginal marine to fully marine but close to the shelf. Middle Eocene sandstones have been separated into two formations, the Ciemas and Ciletuh Formations (Clements et al. 2009), with very different characteristics, which have been juxtaposed by Miocene thrusting. The Ciemas Formation broadly resembles the Late Eocene to Early Oligocene quartz-rich sandstones of West Java, which are compositionally mature. Compositional detrital modes, heavy mineral assemblages and palaeocurrent data for all these sandstones support a northerly Sundaland continental derivation. In contrast, the Ciletuh Formation sandstones contain little quartz, have a volcanic arc provenance, are texturally and compositionally immature, and represent a deep water environment. They were deposited in an active continental margin setting far south of the emergent Sundaland landmass but zircon...
Middle Eocene Sundaland margin volcanic sources (Ciletuh Formation)

The Middle Eocene Ciletuh Formation is exposed in the Ciletuh Bay area (Fig. 1). The two samples from the Ciletuh Formation are dominated by Cretaceous and Early Palaeogene grains (Fig. 6). Sample 28A has Palaeocene and Cretaceous populations (Population J), with the Cretaceous population dominant. It also contains significant Palaeozoic and Proterozoic zircons (Populations B, C, D, E and G). We interpret this sample to contain material eroded from the Sundaland continent, the pre-collisional Cretaceous arc (Parkinson et al. 1998; Smyth et al. 2007; Hall 2009; Hall et al. 2009) and a Palaeocene arc. In contrast, Sample 30A contains few grains that suggest a Sundaland continental source but is dominated by Palaeocene and Eocene grains (Population J), suggesting that most material came from the Palaeocene arc. The Palaeocene to Eocene grains in both samples are tentatively correlated with the Bua Formation and Langi Volcanics of West Sulawesi and perhaps the Lasipu Formation of Sumba. They are interpreted to represent a contribution from an arc that formed as a consequence of a short-lived phase of subduction in the present-day area of West Sulawesi and Sumba (Fig. 7). There may have been a contribution from the syndepositional active arc (Clements & Hall 2007; Smyth et al. 2007, 2008; Clements 2008), but if so it was small, as most zircons predate initiation of the Eocene to Early Miocene arc. The sharp break in zircon ages at c. 80 Ma (Fig. 6b) suggests cessation of magmatic activity, and subduction, which we interpret to have followed collision of the East Java–West Sulawesi block with Sundaland (Fig. 7).

The pre-Cretaceous zircons are similar in age to zircons present in all the quartzose sandstones discussed below. In Sample 28A there are minor Permian–Triassic (Population G), Late Neoproterozoic (Population C) and Late Mesoproterozoic (Population B) age clusters. In Sample 30A there are fewer older zircons with Permian–Triassic (Population G), Early Carboniferous and Late Devonian (Population D) age clusters, and a very small number of Proterozoic grains. Permian–Triassic and Late Proterozoic ages are also present in most non-volcanic siliciclastic samples (Fig. 6). These ages are typical of a Sundaland basement signature and it is suggested that, despite being dominated by volcanic arc material, contributions from Sundaland are present in both Middle Eocene Ciletuh samples. The Palaeocene and Cretaceous were built on Sundaland continental crust, so the association of Palaeocene–Cretaceous and older zircons is not surprising. It is consistent with the positions of the arcs at the Sundaland margin, with drainage systems that transported Sundaland-derived detritus into relatively deep water in the Middle Eocene forearc (Fig. 8) (Hall et al. 2007; Clements et al. 2009).

Middle Eocene Sundaland detritus (Ciemas Formation)

Zircon ages from the Middle Eocene Ciemas Formation are markedly different from those of the Ciletuh Formation. Only one Eocene and two Cretaceous zircons are present and the most prominent age clusters are Permian–Triassic (Population G) and Late Neoproterozoic (Population C) (Fig. 6). These age clusters are present in all other quartz-rich sandstone samples described in this paper and likely sources are discussed below. The Ciemas Formation sample contains significantly more Precambrian grains (46 (71% of sample)) than any other sample. The contrast with the Ciletuh Formation is not unexpected, as field observations indicate that the Ciemas and Ciletuh Formations were deposited in very different settings (Fig. 8). The very small number of Eocene and Cretaceous zircons in the Ciemas Formation sandstone indicates that almost all detritus from the active and older Cretaceous arcs was deposited in the forearc, whereas Sundaland material was deposited on West Java in depocentres close to the Middle Eocene coast and did not reach the forearc.

The Ciemas Formation zircon ages display no distinct clusters and thus are difficult to interpret. Some of the Ciemas Formation ages are not present in other samples, notably a small number of Archaean and some early Mesoproterozoic grains. Sundaland is composed of continental basement blocks of different ages...
separated by suture zones that have been intruded by numerous granitoids, which could account for the ages of Ciemas Formation zircons (e.g. van Hattum et al. 2006; Smyth et al. 2007; Sevastjanova et al. 2010). The wide spread of ages without distinct age clusters probably reflects several episodes of recycling from multiple sources before deposition as the Ciemas Formation.

**Late Eocene and Early Oligocene Sundaland detritus (Bayah, Cikalong and Cijengkol Formations)**

Late Eocene samples (Bayah Formation) and Early Oligocene samples (Cikalong and Cijengkol Formations) have very similar zircon age profiles. There are a number of Eocene grains (Population K) suggesting a contribution from the active Eocene volcanic arc of East and West Java (Smyth et al. 2007, 2008; Clements 2008) most probably from air-fall deposits. The most prominent age clusters are mid-Cretaceous (Population I) for Samples 4B, 2C and 22D, and Late Jurassic and Cretaceous (Populations H and I) for Sample 13B. Most of these ages are older than the Late Cretaceous and Early Palaeogene clusters in the Ciletuh Formation samples that are interpreted as derived from the West Sulawesi–Sumba volcanic arc, and therefore represent a different source. The Cretaceous ages are typical of those expected from the pre-collisional Sunda arc that extended from Sumatra through Java into SE Borneo. Zircon ages correspond well to known isotopic ages of Cretaceous granites from the Sunda Shelf (Williams et al. 1988), and the Schwaner Mountains of SW Borneo (van Hattum et al. 2006). A Jurassic population (Population H) is well defined in the Cijengkol Formation (Sample 13b) and was probably derived from Jurassic igneous rocks known from Sumatra (McCourt et al. 1996) (Fig. 9).

Other age populations are common to the samples from the Bayah, Cikalong and Cijengkol Formations; these are Permian–Triassic (Population G), Late Neoproterozoic (Population C) and latest Meso- to earliest Neoproterozoic (Population B). The Permian–Triassic ages for the Bayah, Cikalong and Cijengkol Formations, and the Middle Eocene Ciemas Formation, correspond well to known isotopic ages of Permian and Triassic granites distributed throughout the Malay Peninsula and Indonesian Tin Islands.

The Proterozoic zircon ages do not match any exposed sources in the Sundaland region or basement sources interpreted from the few studies published up to now (van Hattum et al. 2006; Smyth et al. 2007; Sevastjanova et al. 2010). A 500–650 Ma age signal has been attributed to ‘Pan-Gondwana’ assembly and post-collisional extension (e.g. Veevers 2003, 2007) as well as to Ross–Delamerian orogenic cycles in eastern Antarctica and eastern Australia (e.g. Goodge et al. 2004; Gibson et al. 2011). Other Precambrian age clusters similar to those of the West Java sandstones are commonly reported from detrital samples in Western Australia (Sircombe & Freeman 1999, Cawood & Nemchin 2000; Veevers et al. 2005, and references therein) and have been interpreted (e.g. Sircombe & Freeman 1999) to represent provinces such as the Leeuwin block (480–850 Ma) and Albany–Fraser orogen (1000–1300 Ma). Therefore, we consider that these Proterozoic ages in West Java sandstones record ages of basement that was once part of Gondwana but that now forms the basement to Sundaland. This is consistent with proposals for a NW Australian origin for basement blocks in SW Borneo and East Java–West Sulawesi (Hall 2009; Hall et al. 2009).

There are also sedimentary sources that may have contributed zircons. There are thick, laterally extensive sedimentary sequences of Jurassic and Early Cretaceous age exposed over large areas of Indochina and the Malay Peninsula referred to as the Khorat Group and lateral equivalents (Racey 2009). It is unclear how far south these, and equivalent sequences, extended prior to regional uplift in the Late Cretaceous and development of the SE Asia Regional Unconformity (Clements et al. 2011), but it is probable that some of these rocks were extended well south into Sundaland, and were reworked into Cenozoic sediments.

There are also possible pre-Cenozoic sedimentary sources for zircons in the region (e.g. beneath East Java) where zircons of
varying ages (many of which are Archaean, Proterozoic and Palaeozoic) were transported to the high levels in the crust by magmatic processes and are now found in Palaeogene igneous rocks as xenocrysts and in reworked volcanic ash deposits of the Eocene to Early Miocene volcanic arc (Smyth et al. 2007). These igneous rocks are clearly sampling an older source and the large variation in zircon ages within these rocks probably indicates a sedimentary cover deposited above a Proterozoic basement, rather than Archaean basement, of a Gondwana fragment (Smyth et al. 2007; Hall 2009).

This suggestion is supported by recent discoveries of deep sedimentary basins, or keels, in the NE Java Sea (e.g. Granath et al. 2011), which illustrate that there is significant potential for important sedimentary sources within what has traditionally been referred to as pre-Cenozoic ‘basement’ in the Sundaland region. Imaging of these basins has been possible only through the acquisition of new, long offset, long record crustal-scale seismic data by ION-GXT. Granath et al. (2011) reported a sedimentary section up to 8.5 km thick preserved within a fault-bounded basin beneath the Cenozoic sedimentary section in the NE Java Sea and interpreted these sequences as Mesozoic to possibly Precambrian in age. This interpretation implies that these basins developed on continental crust prior to the break-up of Gondwana and therefore are filled with sedimentary rocks that record an Australian–Indian or Gondwana affinity, rather than a long SE Asian record. It is probable that similar sedimentary sequences are present in other parts of Sundaland (e.g. between West Java and SW Borneo), which could have been eroded during the Early Palaeogene and contributed polycyclic sedimentary detritus, such as detrital zircon, to the Palaeogene sequences discussed in this paper. It is also reasonable to expect some degree of tectonic inversion and exhumation of these deep basins during collision and amalgamation to Eurasia (e.g. East Java–West Sulawesi at c. 80 Ma; discussed above), and during resumption of subduction at about 45 Ma.

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Fig. 9. Schematic palaeogeographical maps of the Sunda Shelf region for the Middle and Late Eocene and Early Oligocene. During the Middle Eocene there is no contribution from the Schwaner Mountains to West Java. The Ciletuh Formation was deposited in deep water, to the south, and sourced mainly from a local volcanic arc source, and the eroded products of the Cretaceous and Palaeocene arcs, with only minor contribution from Sundaland. During the Late Eocene both the Schwaner Mountains and the tin belt granitoids are interpreted to have been supplying material to West Java. During the Early Oligocene there was a possible waning of the Schwaner Mountains source; sediments, however, continued to be sourced from Sundaland. Sediment flux for northern Borneo is from van Hattum et al. (2006). Increasing water depth is indicated by darker contour fills. Java and Borneo are rotated in accordance with tectonic reconstructions (Hall 2002).
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