Detrital zircon U-Pb age and Hf-isotope perspective on sediment provenance and tectonic models in SE Asia

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ABSTRACT

Detrital zircon U-Pb geochronology can make an extremely valuable contribution to provenance studies and paleogeographic reconstructions, but the technique cannot distinguish grains with similar ages derived from different sources. Hafnium isotope analysis of zircon crystals combined with U-Pb dating can help make such distinctions. Five Paleogene formations in West Java have U-Pb age populations of 80–50 Ma (Late Cretaceous–Paleogene), 145–74 Ma (Cretaceous), 298–202 Ma (Permian–Triassic), 653–480 Ma (mid-Neoproterozoic–latest Cambrian), and 1290–723 Ma (late Mesoproterozoic–early Neoproterozoic). Hf-isotopes have been analyzed for 311 zircons from these formations. Differences in zircon U-Pb age and Hf-isotope populations reflect changing sources with time. Late Cretaceous and Paleogene zircons are interpreted as having been derived from two temporally discrete volcanic arcs in Java and West Sulawesi, respectively. The Java arc was active before microcontinent collision, and the W Sulawesi arc developed later, on newly accreted crust at the SE Sundaland margin. The collision age is estimated to be ca. 80 Ma. U-Pb age and \(^{176}\text{Hf}/^{177}\text{Hf}\) characteristics allow a distinction to be made between Cretaceous granitic and volcanic arc sources. Zircons that are older than ca. 80 Ma have a continental Sundaland provenance. Mid-Cretaceous zircons in all upper Eocene and lower Oligocene formations were derived from granites of the Schwaner Mountains of SW Borneo. Permian–Triassic zircons were derived predominantly from granites in the SE Asian Tin Belt. \(^{176}\text{Hf}/^{177}\text{Hf}\) ratios permit distinction between Tin Belt granites in the Main Range and Eastern Provinces, and indicate that only the lower Oligocene

Cijengkol Formation contains significant input from the Main Range Province, suggesting a partial change in drainage pattern. Older zircon ages are more difficult to interpret but probably record contributions from allochthonous basement and sedimentary rocks that were deposited prior to rifting of continental blocks from Gondwana in the early Mesozoic.

INTRODUCTION

Two percent of all global land area is situated in SE Asia, and it is estimated to yield 20%–25% of the sediment supplied to the world’s oceans (e.g., Milliman et al., 1999). This tropical, tectonically active region with its deep Cenozoic basins (up to 15 km in the Malay Basin, Petronas, 1999) and high sediment yield is therefore the ideal natural laboratory for interpreting detrital sedimentary processes. Today, large rivers, such as the Red, Mekong, and Irrawaddy, transport huge volumes of sediment from the India-Asia collision zone through Indochina to the Asian coast (e.g., Ludwig and Probst, 1998; Robinson et al., 2007). Similar sedimentary pathways from the Himalayan orogen have been inferred for sediment transported to Cenozoic basins in SE Asia, particularly those that surrounded Borneo during the Paleogene (e.g., Hutchison, 1996; Métivier et al., 1999). However, recent regional tectonic (e.g., Hall, 2002, 2009a, 2009b; Hall et al., 2009) and provenance (van Hattum, 2005; van Hattum et al., 2006; Hall et al., 2008) studies indicate that the impact of the India-Asia collision across SE Asia was more subtle than that proposed by “indentor-style” models (e.g., Tappin et al., 1982; Replumaz and Tappin, 2003). The Paleogene strata of the circum-Borneo basins (e.g., the Crocker Fan in NE Borneo) have, instead, a local (SW Borneo and Thai-Malay Peninsula) SE Asian provenance (van Hattum et al., 2006; Hall et al., 2008).

Detrital zircon U-Pb geochronology is one of the most rewarding techniques used for provenance and paleogeographic reconstructions (e.g., Kröner and Şengör, 1990; Sircombe and Freeman, 1999; Fedo et al., 2003; Cawood et al., 2003, 2007; Gehrels et al., 2006; van Hattum et al., 2006; Stevens et al., 2010; Hietpas et al., 2011; Leier and Gehrels, 2011). This approach identifies characteristic detrital zircon age clusters and matches them with potential source rock ages. It has been successfully employed for tracing sediment pathways, recording denudation histories, dating volcano-magmatic events, and identifying previously unknown continental crustal fragments in many parts of the world, including SE Asia (e.g., Gehrels et al., 2003; Nemchin and Cawood, 2005; van Hattum et al., 2006, Smyth et al., 2007, 2008; Clements and Hall, 2008; Davis et al., 2010; Magee et al., 2010). However, in geologically complex settings, the ages of zircon populations derived from different source areas may be statistically indistinguishable (e.g., Howard et al., 2009; Davis et al., 2010). In such instances, U-Pb dating of detrital zircon is of limited value, unless supplemented by other lines of evidence. Hf-isotope analyses augment U-Pb data by providing insights into the character and age of each zircon’s parental magma (e.g., Belousova et al., 2006). Similar information can also be obtained from whole-rock studies of the Sm-Nd isotopic system, which behaves similarly to the Lu-Hf isotopic system during most magmatic processes (e.g., Patchett and Tatsumoto, 1980; Blichert-Toft and Albarède, 1997; Blichert-Toft et al., 1999; Vervoort and Blichert-Toft, 1999). However, $^{176}$Hf/$^{177}$Hf ratios are less variable than $^{143}$Nd/$^{144}$Nd ratios in the mantle, giving a more robust background for interpretation of Hf-isotope data (e.g., Vervoort and Blichert-Toft, 1999). The high concentrations of Hf and low Lu/Hf in zircon, and the resistance of most zircon grains to abrasion or alteration during transport, make zircon a highly robust recorder of the Hf-isotope composition of its magmatic host rock. Therefore, combined zircon U-Pb and Hf-isotope studies of zircon have resulted in detailed crustal-evolution models (Bodet and Schärer, 2000; Griffin et al., 2004; Griffin et al., 2006a; Murgulov et al., 2007; Bahlburg et al., 2010; Belousova et al., 2006, 2010; Kuznetsov et al., 2010; Matteini et al., 2010) and sedimentary provenance interpretations (e.g., Veevers et al., 2006; Belousova et al., 2009; Howard et al., 2009; Koglin et al., 2010; Zhou et al., 2011; Fanning et al., 2011).

In this paper we report U-Pb ages and Hf-isotope compositions of detrital zircons from West Java that record broad-scale sediment pathways and fluxes across southern Sundaland (Fig. 1) during the Paleogene. Five formations with middle Eocene to early Oligocene depositional ages record the dispersal of siliciclastic detritus during the waning stages of Cretaceous to Eocene regional uplift and the elevation of Sundaland (the area of continental crust extending SE from Indochina, including Sumatra, Borneo, Java, and the shallow seas between them [Fig. 1]). This study also gives insights into the evolution of Late Cretaceous and early Paleogene volcanic arcs and the timing of microcontinent collision at the Java margin, and demonstrates sediment recycling from the SE Asian basement and perhaps sedimentary rocks that were initially deposited in basins that formed in eastern Gondwana. This is the first study to apply “in situ” detrital zircon U-Pb dating and Hf-isotope analyses to provenance studies in the SE Asian region.

GEOLOGICAL SETTING

The SE Asian region is tectonically complex and bordered by subduction zones that are characterized by intense seismicity and volcanism. The region comprises numerous fragments of continental crust, ophiolitic suture zones that were once oceanic basins, ancient and active volcanic arcs, and young ocean basins.
Figure 1. Major features of the southern part of the Sunda Shelf. Bathymetry is from Sandwell and Smith (1997). Acidic volcanic and plutonic rocks of ages that correspond to age clusters discussed in this chapter are shown. Inset shows West Java; black boxes correspond to the Ciletuh Bay (A), the Bayah Dome (B), the Sukabumi area (C), and the area around Padalarang (D). Black triangles are Holocene volcanoes.
The entire region is allochthonous and has developed predominantly by the addition of continental fragments to the active margins (Hall, 2008). The majority of these continental fragments were derived from Gondwana (e.g., Şengör, 1979; Audley-Charles, 1983; Metcalfe, 1988, 1996), and this SE Asian “core” is referred to as Sundaland. Sundaland includes the Indochina–East Malaya and Sibumasu blocks, which separated from Gondwana in the Paleozoic. Indochina–East Malaya separated from Gondwana in the Devonian and amalgamated with the South and North China blocks, forming the composite Cathaysia block in the Early Carboniferous (Metcalfe, 2009), whereas Sibumasu separated in the Permian and was part of Sundaland by the Early Triassic (Barber and Crow, 2009; Metcalfe, 2009). Two other continental Gondwana-derived blocks—SW Borneo (Banda) (Hall, 2009b; Hall et al., 2009) and E Java–W Sulawesi (Argo) (Smyth et al., 2007; Hall et al., 2009)—were subsequently added to the core of Sundaland in the Mesozoic.

In the Early Cretaceous, Sundaland was broadly in its present position, with subduction at its western, southern, and eastern margins. Subduction beneath Sundaland ceased in the Late Cretaceous after the addition of microcontinental fragments at the Java margin (e.g., Smyth et al., 2007; Hall, 2009b; Hall et al., 2009). From the Late Cretaceous to ca. 45 Ma the margin was inactive (Hall et al., 2009; Hall, 2008) and much of Sundaland was emergent (Hall and Morley, 2004; Clements et al., 2011). As a consequence of this regional elevation, almost no sedimentary rocks of Late Cretaceous–early Paleogene age are preserved in the region. Little is known about the Late Cretaceous and early Paleogene paleogeography and paleodrainage in Sundaland. At ca. 45 Ma subduction recommenced (Hall, 2009b) and sediments started to accumulate within the Sundaland interior and at the continental margins. During the Late Eocene and Oligocene, thick siliciclastic strata were deposited across the region (e.g., Polachan et al., 1991; Doust and Noble, 2008; Smyth et al., 2008).

SUNDALAND GEOLOGY AND POTENTIAL SEDIMENT SOURCES

Most of the Sundaland region is underlain by heterogeneous Precambrian metamorphic basement that is poorly exposed and typically poorly dated. Traditionally it was assumed that in the Malay Peninsula, basement rocks included Precambrian gneisses, marbles, schists, and phyllites overlain by Cambrian to Permian sedimentary rocks (Metcalfe, 1988). However, high-grade schists and granulites exposed, for example, in Indochina (e.g., the Kon-thum massif in central Vietnam, the Doi Inthanon Metamorphic Complex in Thailand, etc.) that were previously assumed to be Archean (e.g., Baum et al., 1970; Hutchison, 1989) are now known to be much younger and yield Paleozoic, Mesozoic, and Cenozoic isotopic ages (e.g., Carter et al., 2001; Nagy et al., 2001; Nam et al., 2001). Hf-isotope data for detrital zircon and baddeleyite (Bodet and Schärer, 2000) and Nd-isotope studies (Lan et al., 2003) from Indochina suggest that the basement is no older than 2.4–2.5 Ga beneath this area. Sevastjanova et al. (2011) demonstrated through U-Pb and Hf-isotope studies of zircon dating that the basement beneath the Malay Peninsula is predominantly Paleoproterozoic (1.9–2 Ga beneath Sibumasu, and 1.7–2 Ga beneath East Malaya), probably with minor Archean components (ca. 2.7–2.8 Ga). U-Pb ages of inherited zircon and Nd model ages (\(T_{DM}^\text{Nd}\)) of granitoids also suggest the presence of Proterozoic basement beneath the Malay Peninsula (Liew and McCulloch, 1985; Cobbing et al., 1992). In Sumatra, schists and gneisses that are exposed in the northwest are considered to represent a pre-Carboniferous basement (Barber and Crow, 2005), and elsewhere, continental basement is inferred from the presence of ignimbrites and granites of varying ages. The oldest sedimentary rocks are Carboniferous and consist of limestones, sandstones, and shales. Granitoids from the islands of Bangka and Belitung yield Proterozoic (1.0–1.8 Ga) \(T_{DM}^\text{Nd}\) (Cobbing et al., 1992). In Borneo, the isotopically undated metamorphic Pinoth Group is suggested to be Carboniferous–Permian or older (Amiruddin and Trail, 1993; de Keyser and Rustandi, 1993; Pieters and Sanyoto, 1993). However, most of the island is composed of ophiolitic, island arc, and microcontinental crust accreted during the Mesozoic (Hamilton, 1979; Hutchison, 1989; Metcalfe, 1996; Hall et al., 2008, 2009).

Late Paleozoic–early Mesozoic subduction of Paleo-Tethys oceanic crust and collision of continental fragments in central Sundaland (Thailand, the Malay Peninsula, and Sumatra) were accompanied by a major period of granitoid intrusion (e.g., Hutchison, 1977; Cobbing et al., 1992; Metcalfe, 2000). This was initially associated with subduction preceding collision, and later with post-collisional thickening of the continental crust (Hutchison, 1989, 1996) and emplacement of granitoids into the suture zone (Barber and Crow, 2009; Sevastjanova et al., 2011). As a result, there are many Permian and Triassic tin-bearing granitoids in the region (Fig. 1) (Bignell and Snelling, 1977; Beckinsale et al., 1979; Liew and Page, 1985; Seong, 1990; Krähenbühl, 1991; Cobbing et al., 1992). Most of these granitoids form part of the SE Asian Tin Belt, which extends from Myanmar through the Thai-Malay Peninsula into the Indonesian Tin Islands (Fig. 1). Minor Jurassic and abundant Lower Cretaceous plutonic and volcanic rocks (exposed in Sumatra, SE Borneo, and Sulawesi) are also commonly interpreted as subduction-related and post-collisional. These typically occur inboard of a zone of arc-related and ophiolitic subduction complexes (accreted to the margin in the early Late Cretaceous), and high-pressure, low-temperature, subduction-related metamorphic rocks. 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 (Cobbing, 2005), the Central Belt of the Malay Peninsula (Cobbing et al., 1992) and Thailand (Cobbing et al., 1992). In contrast to the abundant evidence for Jurassic and Cretaceous subduction in the region, there is little evidence for subduction-related volcanism during the Late Cretaceous and Paleocene, except in parts of West Sulawesi (van Leeuwen, 1981; Hasan, 1990; Elburg et al., 2002) and Sumba (Abdullah et al.,
The paucity of plutonic and volcanic rocks of Late Cretaceous to early Eocene age throughout the region is interpreted to represent a period of subduction quiescence (Hall, 2009b).

### STRATIGRAPHY

The ages of sedimentary fill in many of the basins throughout Sundaland vary only slightly, and they share characteristics that indicate a similar Cenozoic history and tectono-stratigraphic development. In all instances, basins overlie older rocks with a profound unconformity, and Upper Cretaceous and Paleocene strata in the region are almost entirely absent (Clements et al., 2011). Sedimentary rocks above the unconformity are Eocene and younger, and many are terrestrial and were deposited across the region in extensional half-graben basins, and at the Sundaland continental margins. The sedimentary record for the Cretaceous and early Paleogene, however, has largely been lost, although the oldest deposits above the unconformity, deposited throughout much of Sundaland, including West Java, provide a reworked record of the broad-scale sediment fluxes that typified the Late Cretaceous to Paleocene regional elevation of Sundaland.

#### Middle Eocene

In West Java, middle Eocene rocks (van Bemmelen, 1949; Schiller et al., 1991; P. Lunt, 2006, personal commun.; Clements, 2008) are exposed in the Ciletuh Bay area (Fig. 1). These are the Ciletuh and Ciemas Formations (Clements and Hall, 2007) (Fig. 2 and Table 1) and represent the oldest sequences above basement (Fig. 2).

The Ciletuh Formation consists of coarse polymict breccias, volcanogenic debris flow deposits, and turbidites (Clements and Hall, 2011). The breccias contain abundant volcanic clasts (basalt and andesite) as well as laminated volcaniclastic clasts, several types of limestone clasts, and a small number of dacite, granite, and metamorphic clasts. Gray-green fine-to medium-grained volcaniclastic turbidite sandstones are intercalated with the breccias and become increasingly abundant up section (Clements et al., 2011). Sedimentary rocks above the unconformity are Eocene and younger, and many are terrestrial and were deposited across the region in extensional half-graben basins, and at the Sundaland continental margins. The sedimentary record for the Cretaceous and early Paleogene, however, has largely been lost, although the oldest deposits above the unconformity, deposited throughout much of Sundaland, including West Java, provide a reworked record of the broad-scale sediment fluxes that typified the Late Cretaceous to Paleocene regional elevation of Sundaland.

#### Upper Eocene

The upper Eocene (van Bemmelen, 1949; P. Lunt, 2006, personal commun.; R.J. Morley, 2006, personal commun.) Bayah Formation comprises dark marine mudstones and siltstones in the lower part that grade upward into quartz-rich sandstones, pebbly sandstones, and conglomerates with interbedded coals and rare limestone stringers (Fig. 2 and Table 1). Pebble material is predominantly vein and/or metamorphic quartz and is usually highly rounded and interpreted to represent the reworking of pre-Cenozoic sedimentary rocks (Clements and Hall, 2007). Paleocurrent indicators (Clements and Hall, 2011) indicate that material was sourced from the north, and the formation is interpreted to have been deposited predominantly by large braided rivers (Kusumabhrata, 1994; Clements and Hall, 2007) as channel and overbank, deltaic, and coastal plain deposits.

#### Lower Oligocene

The lower Oligocene Cikalong Formation (P. Lunt, 2006, personal commun.; Clements, 2008) comprises quartz-rich sandstones, pebbly sandstones, and conglomerates intercalated with thick sequences of marine carbonaceous siltstones. These are interpreted as turbidites (Clements and Hall, 2007). Rare volcaniclastic (tuffaceous) 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, volcanioclastic sandstones and conglomerates, and shallow water coralline and foraminiferal limestones. Quartz-rich sandstones and conglomerates were deposited in terrestrial to shallow-marine conditions, and paleocurrent indicators suggest that material was sourced from the north.

#### METHODS

Heavy minerals were separated from 63–250 μm grainsize fraction using sodium polytungstate (SPT) solution (density 2.89 g/cm³) and the funnel separation technique described by Mange and Maurer (1992). For U-Pb dating and Hf-isotope analyses, zircons were separated using a Franz magnetic separator (>1.7 μA and 20° tilt angle) and diiodomethane (DIM) liquid
with a density of 3.3 g/cm³, mounted in araldite resin on glass slides and polished. Polished zircon mounts were imaged using a reflected light microscope in order to map positions of mounted zircon grains. Zircon U-Pb LA-ICP-MS (laser-ablation inductively coupled plasma mass spectrometry) dating was performed at University College London with a New Wave 213 aperture imaged frequency quintupled laser ablation system coupled to an Agilent 7500 quadrupole-based ICP-MS. External zircon standard Plesovice (TIMS [thermal ionization mass spectrometry] reference age 337.13 ± 0.37 Ma; Sláma et al., 2008) and the U.S. National Institute of Standards and Technology (NIST) silicate glass 612 (Pearce et al., 1997) were used to correct for instrumental mass bias. The analytical procedure for zircon U-Pb dating is described in Stevens et al. (2010). Whenever possible, at least 60 grains per sample were analyzed in each sample (Dodson et al., 1988; Andersen 2005). Data were processed using GLITTER (Griffin et al., 2008) and Isoplot (Ludwig, 2003, 2008) software. U-Pb ages were filtered using standard discordance tests.
with a 10% cutoff; discordant data that cross concordia within error are also included into probability-density histograms. The $^{208}\text{Pb} / ^{206}\text{Pb}$ ratio was used to calculate ages younger than 1000 Ma, and the $^{207}\text{Pb} / ^{206}\text{Pb}$ ratio for older grains (e.g., Cawood and Nemchin, 2000). Raw data tables are presented in the supplementary data section.¹

Hf-isotope analyses were performed at GEMOC ARC National Key Centre at Macquarie University, Australia. Analyses were performed in May 2008 using a New Wave Research 213 nm laser-ablation microprobe attached to a Nu Plasma multicollector ICP-MS. $^{176}\text{Hf} / ^{177}\text{Hf}$ ratios were measured in the same zircons that were previously dated with the U-Pb technique. The analytical procedure for Hf-isotope analyses is described in detail by Griffin et al. (2000, 2002, 2004; Belousova et al., 2009). Interferences of $^{176}\text{Lu}$ and $^{176}\text{Yb}$ on $^{176}\text{Hf}$ were corrected using measured intensities of interference-free $^{172}\text{Lu}$ and $^{172}\text{Yb}$ (e.g., Griffin et al., 2000, 2002, 2004; Belousova et al., 2009). Analyses with $^{176}\text{Yb} / ^{177}\text{Hf} > 0.2$ or $^{176}\text{Lu} / ^{177}\text{Hf} > 0.005$ were rejected (e.g., Belousova et al., 2010).

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Zircon $^{176}\text{Hf} / ^{177}\text{Hf}$ ratios were used for calculating model ages. Zircon Hf model ages show time when isotopic composition of zircon was identical to that of the zircon’s parental magma,

### TABLE 1. COORDINATES (WGS-84) AND DESCRIPTIONS OF SAMPLES DISCUSSED IN THIS STUDY

<table>
<thead>
<tr>
<th>Sample</th>
<th>Formation</th>
<th>Age</th>
<th>ID</th>
<th>Lithological description and depositional setting</th>
<th>Lat (S)</th>
<th>Long (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2C</td>
<td>Bayah</td>
<td>U. Eocene</td>
<td>JBC2WAL137</td>
<td>Medium- to coarse-grained quartz-rich sandstone—fluvial channel sand</td>
<td>6.9033</td>
<td>106.7971</td>
</tr>
<tr>
<td>4B</td>
<td>Bayah</td>
<td>U. Eocene</td>
<td>JBC2BAY187</td>
<td>Fine- to medium-grained quartz-rich sandstone—upper delta slope sandstone</td>
<td>6.9545</td>
<td>106.2401</td>
</tr>
<tr>
<td>8A</td>
<td>Ciemas</td>
<td>M. Eocene</td>
<td>JBC2CIE259</td>
<td>Medium- to coarse-grained quartz-rich sandstone—shallown-marine tidal sandstone deposited on narrow shelf</td>
<td>7.1866</td>
<td>106.4043</td>
</tr>
<tr>
<td>13B</td>
<td>Cijengkol</td>
<td>L. Oligocene</td>
<td>JBC2CUJ191</td>
<td>Medium-grained quartz-rich sandstone—fluvial channel sand</td>
<td>6.8670</td>
<td>106.1130</td>
</tr>
<tr>
<td>22D</td>
<td>Cikalong</td>
<td>L. Oligocene</td>
<td>JBC2CIK117</td>
<td>Poorly sorted medium-grained pebbly sandstone—submarine “deep” water channel sand</td>
<td>6.8600</td>
<td>107.3726</td>
</tr>
<tr>
<td>28A</td>
<td>Ciletuh</td>
<td>M. Eocene</td>
<td>JBC2CIL272</td>
<td>Fine-grained gray volcanogenic sandstone—submarine turbiditic sand</td>
<td>7.2428</td>
<td>106.3884</td>
</tr>
<tr>
<td>30A</td>
<td>Ciletuh</td>
<td>M. Eocene</td>
<td>JBC3CIL145</td>
<td>Medium-grained gray volcanogenic sandstone—submarine turbiditic sand</td>
<td>7.1852</td>
<td>106.4353</td>
</tr>
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</table>

¹GSA Data Repository Item 2012130—Tables DR1–DR8: Zircon Hf and U-Pb data—is available at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.
which is considered to be the time when new continental crust was generated (e.g., Arndt and Goldstein, 1987; Griffin et al., 2002; Hawkesworth et al., 2010; Belousova et al., 2010; Dhuime et al., 2011). There are three main approaches for calculating Hf model ages: (1) TDM is calculated based on measured $^{176}$Hf/$^{177}$Hf (et al., 2011). There are three main approaches for calculating Hf ratios and present day chondritic (CHUR) and depleted mantle (DM) values. This approach does not consider the crystallization (U-Pb) age of zircon, and because of this yields only a minimum estimate for the age of the source material of the zircon’s parental magma. (2) $T_{DM}^c$ assumes that zircon parental magma was produced from an average continental crust that originally separated from the depleted mantle (Belousova et al., 2006). $T_{DM}^c$ provides a more realistic estimate of source age of analyzed zircons, because detrital zircons are mostly derived from crustal rocks. (3) $T_{NC}$ assumes that most continental crust is generated along the destructive plate margins and argues that composition of the new continental crust is isotopically enriched relative to the depleted mantle (e.g., Dhuime et al., 2011). Therefore, $T_{NC}$ is calculated using isotopic signatures of island arcs that are argued to be more representative of the newly generated continental crust (e.g., Dhuime et al., 2011). Differences between model ages that are calculated using different approaches may exceed 300 m.y. (e.g., Dhuime et al., 2011).

Model ages also do not always correspond to “real” continental crust formation events (e.g., Arndt and Goldstein, 1987; Kemp et al., 2006). Zircons preserve Hf-isotope signatures from all significant sources that contributed to parental melts of these minerals. Model ages of zircons that are produced from mixed sources (e.g., melting of heterogeneous basement or mixed crust and mantle-derived source) will only show a geologically meaningless average age of all sources from which these zircons were produced. Therefore, zircon Hf model ages can be used with confidence for determining ages of crust formation when only supported by other lines of evidence—e.g., matching U-Pb zircon age populations.

In the present study, crustal model age data are treated as semiquantitative owing to uncertainties in calculating and interpreting these ages. In order to avoid over-interpretation, crustal model ages are reported in Ga, and analytical errors are not given.

In order to produce a data set that is comparable to previously published Hf-isotope studies in Australia (e.g., Griffin et al., 2002, 2004, 2006a; Belousova et al., 2009, 2010) and in Sunda- land (e.g., Sevastjanova et al., 2011), we have used an approach identical to these studies. Initial Hf-isotope ratios ($^{176}$Hf/$^{177}$Hf) were calculated for each zircon using the $^{176}$Lu decay constant (1.865 × 10$^{-11}$) (Scherer et al., 2001), measured $^{176}$Hf/$^{177}$Hf ratios, and LA-ICP-MS U-Pb ages determined from the same zircon grain. The $^{176}$Lu decay constant (1.865 × 10$^{-11}$) of Scherer et al. (2001) was used because it gives the best fit for terrestrial rocks (Amelin and Davis, 2005; Albarède et al., 2006). The chondritic (CHUR) ratios of $^{176}$Hf/$^{177}$Hf = 0.0332 and $^{176}$Lu/$^{177}$Hf = 0.282772 (Blichert-Toft and Albarède, 1997), depleted mantle (DM) ratios of $^{176}$Hf/$^{177}$Hf = 0.283251 (Nowell et al., 1998), and LA-ICP-MS U-Pb ages determined from the same zircon grain.

### RESULTS

In this section we present results of 594 U-Pb analyses of zircon from the five formations shown in Figure 2; 320 of these grains were analyzed for Hf-isotope compositions. Results are summarized in Table 3. Two samples are from the middle Eocene volcaniclastic Ciletuh Formation, which was deposited.

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**TABLE 2. PRECISION AND ACCURACY FOR REFERENCE STANDARD ZIRCONS (91500, MUD TANK, AND TEMORA 2) USED IN THIS STUDY**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Technique</th>
<th>$n$</th>
<th>$^{176}$Hf/$^{177}$Hf ±2σ</th>
<th>$^{176}$Lu/$^{177}$Hf ±2σ</th>
<th>$^{176}$Yb/$^{177}$Hf ±2σ</th>
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<td><strong>91500</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wiedenbeck et al. (1995)</td>
<td>S-TIMS</td>
<td>6</td>
<td>0.282284 ± 60</td>
<td>0.000288 ± 3</td>
<td></td>
</tr>
<tr>
<td>Goolaefts et al. (2004)</td>
<td>MC-ICP-MS (solution)</td>
<td>59</td>
<td>0.282302 ± 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Griffin et al. (2006b)</td>
<td>LA-MC-ICP-MS</td>
<td>632</td>
<td>0.282307 ± 58</td>
<td>0.000317 ± 54</td>
<td>0.0115 ± 50</td>
</tr>
<tr>
<td>This study</td>
<td>LA-MC-ICP-MS</td>
<td>4</td>
<td>0.282337 ± 26</td>
<td>0.000321 ± 1</td>
<td>0.0128 ± 2</td>
</tr>
<tr>
<td><strong>Mud Tank</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Woodhead and Hergt (2005)</td>
<td>MC-ICP-MS (solution)</td>
<td>5</td>
<td>0.282507 ± 6</td>
<td>0.000042</td>
<td></td>
</tr>
<tr>
<td>Griffin et al. (2007)</td>
<td>LA-MC-ICP-MS</td>
<td>2190</td>
<td>0.282523 ± 43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>This study</td>
<td>LA-MC-ICP-MS</td>
<td>56</td>
<td>0.282525 ± 17</td>
<td>0.000023 ± 1</td>
<td>0.0011 ± 1</td>
</tr>
<tr>
<td><strong>Temora 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Woodhead and Hergt (2005)</td>
<td>MC-ICP-MS (solution)</td>
<td>3</td>
<td>0.282568 ± 8</td>
<td>0.00109</td>
<td></td>
</tr>
<tr>
<td>Woodhead and Hergt (2005)</td>
<td>LA-MC-ICP-MS</td>
<td>92</td>
<td>0.282680 ± 22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>This study</td>
<td>LA-MC-ICP-MS</td>
<td>3</td>
<td>0.282689 ± 18</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note: S-TIMS—solution thermal ionization mass spectrometry; MC-ICP-MS—multicollector inductively coupled plasma mass spectroscopy; LA—laser ablation.*
in a forearc setting. All other samples are quartz-rich sandstones deposited in terrestrial and marginal-marine settings. Detrital zircon age populations range from 3629 Ma to 31 Ma in the sample set. In this study we define nine populations on the basis of age “clusters” on probability-age distributions from all samples analyzed (Figs. 4 and 5). Initial $^{176}$Hf/$^{177}$Hf ($e_{Hf}^{TDM}$) range from 0.280847 to 0.283210, giving $e_{Hf}$ values from $-40.0$ to $+18.5$ and crustal model ages ($T_{DM}^{c}$) from 0.1 to 4.0 Ga. The oldest zircon analyzed for Hf-isotope composition has a U-Pb age of ca 2.7 Ga, $e_{Hf}^{TDM} = -6.0$, and $T_{DM}^{c}$ 3.6 Ga.

**Neoarchean to Paleoproterozoic**

One small population spans from Archean to Paleoproterozoic. Population A has an age range of ca. 2590–1717 Ma (32 grains; 7.5% of the sample set). Population A forms no distinct clusters and represents a broadly dispersed age group; 11 grains from Population A are from the Ciemas Formation. Most of the formations have very few of these grains. $e_{Hf}$ values in population A range from $-18.6$ to $+7.6$, and $T_{DM}^{c}$ values vary from 2.4 to 4.0 Ga. Most zircons in population A plot close to CHUR (11 of 28 analyzed zircons have $e_{Hf}$ values between $-1.8$ and $+1.5$, and $T_{DM}^{c}$ values of 2.4–3.0 Ga) (Fig. 6).

**Mesoproterozoic to Early Neoproterozoic**

Population B has an age range of 1290–723 Ma (76 grains; 15.1% of the sample set) and is represented in all samples (Fig. 4). Population B zircons have a wide range of $e_{Hf}$ values from $-29.5$ to $+18.5$, and $T_{DM}^{c}$ values of 0.5–3.6 Ga.

**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 represented in all samples. Most of the zircons have ages between 607 and 480 Ma (49 grains; 11.6% of the sample set). Hf isotope data suggest two sub-populations. C1 is common in the upper Eocene–lower Oligocene samples and has “crustal” $e_{Hf}$ values ($-28.9$ to $-3.6$), and $T_{DM}^{c}$ of 1.7–3.3 Ga. One zircon gives an extremely low $e_{Hf}$ value of ca. $-40.0$, and $T_{DM}^{c}$ of 4.0 Ga. C2 is common in the middle Eocene samples and has a wide range of $e_{Hf}$ values between $-27.0$ to $+5.6$, and $T_{DM}^{c}$ values of 1.2–3.2 Ga.

**Carboniferous and Devonian**

Population D has an age range of 422–305 Ma (17 grains; 4% of the sample set) and is represented in all samples. Most of the zircons have ages between 379 and 305 Ma (15 grains; 3.5% of the sample set). Grains of this population are rare in several samples. Hf-isotope signatures reveal three sub-populations. D1 zircons (2 of 12 zircons analyzed from this population) yield “crustal” $e_{Hf}$ values ($-10.2$ to $-9.8$) and $T_{DM}^{c}$ = ca 2.0 Ga. D2, the most abundant sub-population ($n = 7$), yields $e_{Hf}$ values

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**Figure 3.** Weighted-average plots (Ludwig, 2008) for $^{176}$Hf/$^{177}$Hf values in each of Mud Tank, 91500, and Temora 2 zircon standards analyses. MSWD—mean square of weighted deviates.
TABLE 3. DETRITAL ZIRCON U-Pb AGE POPULATIONS AND THEIR εHf AND T<sub>DM_c</sub> IN ANALYZED SAMPLES

<table>
<thead>
<tr>
<th>Population</th>
<th>Cluster</th>
<th>Age range, Ma</th>
<th>No. grains</th>
<th>% of data set</th>
<th>Middle Eocene</th>
<th>Upper Eocene</th>
<th>Lower Oligocene</th>
<th>εHf</th>
<th>T&lt;sub&gt;DM_c&lt;/sub&gt;, Ga</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Neoarchean – Paleoproterozoic</td>
<td>2590–1717</td>
<td>32</td>
<td>7.5</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>−18.6 to +7.6 (+1.8 to +1.5)</td>
</tr>
<tr>
<td>B</td>
<td>Mesoproterozoic – Early Neoproterozoic</td>
<td>1290–723</td>
<td>76</td>
<td>15.1</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>−29.5 to +18.5 (−28.9 to −36)</td>
</tr>
<tr>
<td>C</td>
<td>Mid-Neoproterozoic – Cambrian</td>
<td>653–480 (607–480)</td>
<td>56 (49)</td>
<td>13.2 (11.6)</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>−40.0 to −3.6 (−29.8 to −36)</td>
</tr>
<tr>
<td>D</td>
<td>Carboniferous – Devonian</td>
<td>422–305 (379–305)</td>
<td>17 (15)</td>
<td>4.0 (3.5)</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>−10.2 to −10.0 (−6.1 to −12.6)</td>
</tr>
<tr>
<td>E*</td>
<td>Permian – Triassic</td>
<td>298–252</td>
<td>23</td>
<td>5</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>−12.3 to −4.9 (−8.1 to −12.3)</td>
</tr>
<tr>
<td>F</td>
<td>Jurassic</td>
<td>199–145</td>
<td>20</td>
<td>4.7</td>
<td>+</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>−3.9 to +15.1 (−7.8 to +15.1)</td>
</tr>
<tr>
<td>G</td>
<td>Early to mid Late Cretaceous</td>
<td>154–74</td>
<td>70</td>
<td>16</td>
<td>+++</td>
<td>–</td>
<td>+++</td>
<td>+++</td>
<td>−21.7 to +15.3 (−1.1 to +15.3)</td>
</tr>
<tr>
<td>H</td>
<td>Latest Cretaceous to Paleocene</td>
<td>110–87 82–50</td>
<td>15 (22)</td>
<td>3.5 (5.2)</td>
<td>+++</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>−8.2 to +2.7 (11.8 to +13.8)</td>
</tr>
<tr>
<td>I</td>
<td>Eocene – Oligocene</td>
<td>40–31</td>
<td>9</td>
<td>2.1</td>
<td>+</td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>−4.6 to +16.6 (–4.6 to +16.6)</td>
</tr>
</tbody>
</table>

Note: Numbers in parentheses show intervals that include the majority of zircon grains within the given population.
*Three zircons have distinctly different U-Pb ages (257–263 Ma) and εHf (−14.6, −13.8, and +16.5).
T<sub>DM_c</sub> (crustal model age) = 2.2 Ga and 0.2 Ga.
Figure 4. Probability density plots for detrital zircon ages presented in this study. Plots are an accumulation of individual Gaussian curves of each age measurement normalized to one, and measurement densities. Vertical bands represent age ranges for different sources; shades of gray enhance clarity. P-K—Paleocene–Cretaceous, P-T—Permian–Triassic.
Figure 5. Probability density plots for detrital zircon ages 0–350 Ma. See explanation of Figure 4. VA—volcanic arc; PCV—post-collisional volcanics.
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 represented in all samples, although there are notably fewer zircons from this population in the middle Eocene Ciletuh Formation samples.

Hf-isotope data show that population E can be split into three sub-populations that are similar to those identified in the Malay Peninsula (Sevastjanova et al., 2011). Sub-cluster E1 has a wide range of $\varepsilon_{Hf}$ values ($-11.4$ to $+10.0$), and $T_{DM}^C$ values ($0.7–2.0$ Ga). Sub-cluster E2A includes “crustal” zircons with $\varepsilon_{Hf}$ values of $+5.0$ to $+12.6$, and $T_{DM}^C$ of $0.5–1.0$ Ga.

Latest Cretaceous to Paleocene

Population H has an age range of 110–50 Ma (37 grains; 9% of the sample set). It contains two prominent sub-clusters, H1 between 110 and 87 Ma (15 grains; 3.5% of the sample set) and H2 between 82 and 50 Ma (22 grains; 5.2% of the sample set). Population H is represented only in middle Eocene volcanic forearc sandstones of the Ciletuh Formation. The two sub-clusters of population H have very different Hf-isotope values. H1 has “crustal” to chondritic $\varepsilon_{Hf}$ values ($-8.2$ to $+2.7$), and $T_{DM}^C$ of $1.0–1.7$ Ga. H2 has $\varepsilon_{Hf}$ values ($+11.8$ to $+13.8$), plotting close to the depleted-mantle evolution, and $T_{DM}^C$ of $0.3–0.4$ Ga.

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 represented in all upper Eocene and lower Oligocene samples, but it is most abundant in the lower Oligocene Cijengkol Formation. Two grains from this population are also present in the Ciletuh Formation (Sample 30A). $\varepsilon_{Hf}$ values range from $-3.9$ to $+15.1$, and $T_{DM}^C$ values from $0.2$ to $1.4$ Ga. Most population F zircons (nine of 14 zircons analyzed) have $\varepsilon_{Hf}$ values of $+7.8$ to $+15.1$, suggesting a mantle source.

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 upper Eocene and lower Oligocene samples. It is present only in quartzose siliciclastic formations and is distinguished from Population H on the basis of field relations (discussed below). Population G is not present in the middle Eocene Cienmas Formation. Most population G zircons (30 of 32 analyzed) have chondritic to mantle-like $\varepsilon_{Hf}$ ($-1.1$ to $+15.3$), and $T_{DM}^C$ of $0.2–1.2$. Only two zircons yield “crustal” $\varepsilon_{Hf}$ of $-21.7$ and $-12.5$. These zircons have $T_{DM}^C$ of $1.6$ and $1.3$ Ga, respectively.

DISCUSSION

All Sundaland basement blocks are interpreted to have been rifted from the Eastern Gondwana margin (e.g., Metcalfe, 1996, 2009), and thus similarities are expected for major Precambrian zircon ages that represent regional tectono-magmatic events characteristic of Gondwana. For example, the 607–480 Ma signal present in SE Asia samples is also observed, to varying degrees, in igneous and detrital rocks from South America, Africa, Antarctica, Australia, East Asia, and Europe, and is commonly interpreted to represent processes related to the amalgamation of Gondwana (e.g., Cawood and Buchan, 2007; Condie et al., 2009). For younger zircons, however, the different Phanerozoic histories of Sundaland basement terranes are likely to have produced provenance indicators specific to certain areas. Previous provenance studies in SE Asia (e.g., van Hattum, 2005; van Hattum et al., 2006; Clements, 2008; Hall et al., 2008) identified two important Sundaland source areas for Cenozoic sediments, the SE Asian Tin Belt and the Schwener Mountains of SW Borneo.

Geochronological data presented here suggest a complex provenance with several source terranes of different ages that contributed sedimentary detritus to West Java during the Paleogene.
Figure 6. Plots of detrital zircon U-Pb ages vs. their $\varepsilon_{Hf}$ ratios in the middle Eocene, late Eocene, and early Oligocene siliciclastic rocks of West Java. DM—depleted mantle.
A northerly derivation (from Sundaland) for all quartz-rich sandstones is supported by detrital modes, heavy mineral assemblages, and paleocurrent data (Clements and Hall, 2011). In contrast, the Ciletuh Formation is primarily volcanogenic and was deposited in a deep-marine forearc setting (Clements et al., 2009). Based on these observations and the detrital zircon U-Pb age and Hf-isotope data (discussed below), we suggest that the Ciletuh Formation contains detritus from temporally and spatially discrete Cretaceous and early Paleogene local volcanic arcs (situated in the area of present-day Java and West Sulawesi, respectively), whereas all other formations contain siliciclastic material derived from Sundaland.

“Local” Volcanic Sources (Middle Eocene Ciletuh Formation)

The Middle Eocene Ciletuh and Ciemas Formations were deposited contemporaneously, although in disparate regions, and are juxtaposed in the Ciletuh Bay area (Fig. 1). Three samples from this area have been analyzed. Sample 8A is from the Ciemas Formation and contains only two Cretaceous zircons; this sample is discussed in the following section.

The two samples from the Ciletuh Formation are dominated by mid–Late Cretaceous and early Paleogene grains (Figs. 5 and 7). We observe a clear distinction between a mid–Late Cretaceous cluster and a latest Cretaceous–Paleogene cluster (Fig. 5), particularly when comparing εHf values (Fig. 7). Analyzed mid–Late Cretaceous zircons (100–80 Ma) have εHf values that are close to CHUR, and latest Cretaceous–Paleogene (80–50 Ma) zircons have much higher εHf values, plotting close to depleted mantle (Fig. 7). We interpret the events represented by these two discrete clusters as local and having resulted from subduction-related volcanism. These volcanic rocks were then eroded and redeposited during the middle Eocene.

There is no evidence for subduction beneath the Sundaland margin by the Late Cretaceous and middle Eocene (e.g., Hall, 2009b), and this has led to the suggestion that the margin was inactive (e.g., Hall, 2009b). The termination of subduction was likely due to microcontinent collision at the Sundaland margin, which now lies beneath parts of East Java and West Sulawesi (e.g., Hall et al., 2009; Granath et al., 2011). We interpret the mid–Late Cretaceous ages from sample 28A to represent detritus from a mature calc-alkaline arc that existed prior to early Late Cretaceous collision. The latest Cretaceous and Paleogene ages from both Ciletuh samples (28A and 30A) most likely represent a contribution from volcanic rocks exposed in West Sulawesi and Sumba that have a calc-alkaline character (e.g., van Leeuwen, 1981) and are interpreted by Elburg et al. (2002) as subduction related. West Sulawesi and Sumba were part of the E Java–W Sulawesi block (Fig. 8) and therefore already had amalgamated to Sundaland by the time subduction recommenced outboard of this block (Fig. 8). We interpret the time gap between these two volcanic periods (1–2 m.y.) to mark the age of collision (ca. 80 Ma), acknowledging that it was probably diachronous along the length of the Cretaceous Sunda margin. Crustal Hf-isotope signatures (εHf = −8.2 to +2.7) for the mid–Late Cretaceous zircons (population H1) support the interpretation that the arc, prior to collision, was built on old Sundaland continental crust at an “Andean-type” margin. The high εHf values (+11.8 to +13.8) for latest Cretaceous–Paleogene zircons (population H2) indicate derivation from a mantle source (e.g., Belousova et al., 2006) and are comparable to those reported for the modern volcanic rocks of the Sunda Arc (Woodhead et al., 2001).

Older sources contributed to both Ciletuh samples. Sample 28A has Permian and Triassic, late Neoproterozoic, and late Mesoproterozoic age clusters. Sample 30A contains Permian and Triassic, Early Carboniferous, and Late Devonian zircons. Both samples have Proterozoic zircons. Permian–Triassic and late Proterozoic U-Pb zircon ages also characterize most non-volcanic siliciclastic samples (Figs. 4 and 5). These ages are interpreted to typify a Sundaland basement signature, and it is suggested that despite being dominated by a local volcanic arc component, minor contributions from Sundaland are recognizable in both middle Eocene Ciletuh samples. This is consistent with the position of the arc at the Sundaland margin, perhaps dissected by drainage systems that transported Sundaland-derived detritus into the forearc. However, the formation was dominated by the deposition of volcanogenic material in relatively deep water (Hall et al., 2007; Clements et al., 2009).

Sundaland Source

Middle Eocene Sedimentary Rocks

Zircon ages from the middle Eocene Ciemas Formation are notably different from those of the Ciletuh Formation. Only one Paleogene and two Cretaceous zircons are present. This suggests that neither the pre-collisional (mid–Late Cretaceous) Java arc nor the W Sulawesi–Sumba (latest Cretaceous–Paleogene) arc, nor any Cretaceous Sundaland sources contributed material to onshore West Java during the middle Eocene. This is consistent with the interpretation of Clements et al. (2009) that the Ciemas and Ciletuh Formations were deposited in very different settings and that their present proximity is not depositional but is due to thrusting. The absence of Cretaceous and Paleogene ages from the Ciemas Formation (marginal-marine quartz-rich sandstone) supports our interpretation that Late Cretaceous and early Paleogene zircons in middle Eocene Ciletuh Formation samples (deposited to the south of Java in deep water) were not derived from Sundaland and are instead erosional products of “local” volcanic arcs.

The most prominent age clusters in the middle Eocene Ciemas Formation are Permian–Triassic and late Neoproterozoic (Fig. 4). These age clusters are present in all other samples described in this chapter, and their likely sources are discussed below. The Ciemas Formation contains significantly more Precambrian grains (46 grains [71% of sample]) than any other interval (Fig. 4). These analyses form no distinct clusters and
are difficult to interpret; nevertheless they indicate a source or number of sources with various ages that were supplying detritus to West Java during the middle Eocene. Some of the Ciemas Formation zircon ages are not represented in other samples, suggesting contribution from other source rocks. Such a wide spread of ages may indicate that some of the Ciemas Formation detritus reflects several episodes of recycling.

Upper Eocene and Lower Oligocene Sedimentary Rocks

Upper Eocene samples (Bayah Formation) and lower Oligocene samples (Cikalong and Cijengkol Formations) have similar zircon age spectra. The most prominent age clusters are mid-Cretaceous in samples 4B, 2C, and 22D, and Late Jurassic and Cretaceous in sample 13B. Cretaceous zircon ages (population G) correspond well with known ages of Cretaceous granites.
Detrital zircon U-Pb age and Hf-isotope perspective on sediment provenance and tectonic models in SE Asia

Distributed across the Sunda Shelf (Williams et al., 1988) and in the Schwaner Mountains of SW Borneo (van Hattum et al., 2006). These zircon ages (population G) are older (145–74 Ma) than the Late Cretaceous and early Paleogene clusters in the Ciletuh Formation samples (population H1) that are interpreted as volcanic in origin and have distinctively different \( \varepsilon_{Hf} \) ratios. Predominantly high mantle-type \( \varepsilon_{Hf} \) (–1.1 to +15.3) for population G are consistent with derivation from I-type granitoids, such as those that are common in the Schwaner Mountains (Williams et al., 1988).

Permian–Triassic, late Neoproterozoic, and latest Mesoproterozoic to earliest Neoproterozoic age clusters are also common to the Bayah, Cikalong, and Cijengkol Formations. Permian–Triassic ages for the Bayah, Cikalong, and Cijengkol Formations, and the middle Eocene Ciencias Formation, correspond well with known isotopic ages of Permian and Triassic granitoids distributed throughout the Malay Peninsula and Indonesian Tin Islands.

**Tin Belt as a Sediment Source**

Permian–Triassic Tin Belt granitoids are widely exposed throughout the Thai-Malay Peninsula and are of comparable age to Permian–Triassic zircons reported in this study. We therefore interpret these granitoids as the main source for the W Java Permian and Triassic zircons. In the Malay Peninsula, Permian–Triassic zircons were sourced from three major magmatic suites: (1) the Permian crust–derived Eastern Province granitoids (\( \varepsilon_{Hf} \) from –13.3 to +9.2), (2) the Early–Middle Triassic Eastern Province granitoids with a mixed mantle- and crust-derived source.
and granitoids are exposed in the Eastern Province, and zircon ages of the Malay Peninsula appear to have been the major source of sediment for the W Java samples. Both Permian and Triassic granitoids are exposed in the Eastern Province, and zircon ages and εHf values from our samples broadly match those from the Malay Peninsula. Permian and Triassic zircons from the Ciomas Formation are similar to the Malay Peninsula zircons but are on the edge of the defined confidence ellipses. Two Late Permian zircons fall well outside the εHf confidence ellipses from the Malay Peninsula data set, and we suggest that these grains have a different provenance from all other Tin Belt–sourced zircons; possible alternative sources for these are discussed below. Sample 13B from the lower Oligocene Cijengkol Formation contains a cluster of early Late Triassic zircons with lower εHf values than those typical of the other W Java samples (Fig. 9). Most of these fall within the confidence ellipse defined for Main Range Province granitoids in the Malay Peninsula, and we therefore infer that a Main Range Province source contributed significantly to the Cijengkol Formation only.

Sample 13B (Cijengkol Formation) is the westernmost sample in this study, and the only sample to contain a significant number of Jurassic zircons. This may indicate a (partly?) different sediment transport route and source for the formation (Fig. 10). Jurassic granitoids are reported from Central Sumatra (Cobbing, 2005), and there are very few reliable ages for Jurassic granitoids elsewhere in southern and central Sundaland. We therefore suggest that the presence of Jurassic zircons and εHf values typical of Main Range Province granitoids record a more westerly sediment transport route for the Cijengkol Formation, possibly through central and southern Sumatra, into West Java (Fig. 10).

**SW Borneo As a Sediment Source**

The Schwaner Mountains (Fig. 1) are the major source of detrital zircon in Paleogene sandstones in the region. These mountains comprise predominantly Late Cretaceous granitoids (e.g., Williams et al., 1988). Hf-isotopes have not been studied in zircons from this area. However, the Schwaner granitoids are predominantly I-type, and S-type plutons are rare (Williams et al., 1988). Hence, zircons sourced from the Schwaner Mountains are expected to have positive εHf values. CL images (van Hattum, 2005) reveal that older zircon cores are rare. This is consistent with a predominantly mantle-like source for the Schwaner granitoids from this study. No firm evidence exists for a contribution from SW Borneo to West Java during the middle Eocene.

**Sources “Outside” Sundaland**

A similar 500–650 Ma age signal to that identified in our samples is attributed to “Pan-Gondwana” assembly and post-collisional extension (e.g., Cawood and Buchan, 2007; Vevers, 2003, 2007) as well as to Ross-Delamerian orogenic cycles in eastern Antarctica and eastern Australia (e.g., Goode et al., 2004; Glen, 2005). Similar Precambrian-age clusters are commonly reported from detrital samples in Western Australia (Sircombe and Freeman, 1999; Cawood and Nemchin, 2000; Vevers et al., 2005, and references therein) and are often interpreted (e.g., Sircombe and Freeman, 1999) to represent provinces such as the Leeuwin block (480–850 Ma) and the Albany-Fraser orogen (1000–1300 Ma). These Proterozoic ages in W Java sandstones are therefore interpreted as recording signals from basement that was once part of Gondwana but that now forms the basement to Sundaland. Paleozoic to Early Cambrian zircons have a wide range of εHf values. The age and spread of 176Hf/177Hf values from these zircons closely resemble those of zircons reported from modern rivers draining the Stanley sheet in the NE part of the Eastern Goldfields area of the Yilgarn Craton, West Australia (Griffin et al., 2004). Based on trace element composition, Griffin et al. (2004) interpreted these grains as having been derived from mafic rocks, carbonatites, and granitoid rocks. It is tempting to make correlations with sediments of the Yilgarn Craton and Western Australia, as Sundaland crust was part of Gondwana prior to breakup. However, similar-age zircons of alkaline affinity are abundant in many Pan-Gondwana orogens (Vevers et al., 2006), indicating that these rocks, and the overlying sediments, probably have a complex history of erosion and redeposition.

Thick, laterally extensive sedimentary sequences of Jurassic and Early Cretaceous age exposed over large areas of Indochina and the Malay Peninsula are 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 eroded and transported elsewhere in Sundaland. Other sources of pre-Cenozoic sedimentary rocks in the region include, for example, SE Java, where zircons of varying ages (many are Archean and Proterozoic) have been incorporated into Cenozoic volcanic rocks as xenocrysts and transported to the shallow crust by volcanic processes (Smyth et al., 2007). These volcanic rocks are clearly sampling an older source, and the large variation in ages within these rocks was interpreted by Hall et al. (2009) to indicate a sedimentary source rather than crystalline basement.

Recent discoveries of deep, pre-Cenozoic sedimentary basins, or keels, in the NE Java Sea (e.g., Granath et al., 2011) reveal huge volumes of sedimentary rocks that could have contributed detritus to Cenozoic sequences during episodes of uplift, for example, in the Late Cretaceous. Granath et al. (2011) used newly acquired long-offset, long-record seismic data to identify 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; they interpreted these sequences as Mesozoic to possibly Precambrian in age. This interpretation implies that
Figure 9. A comparison of the Hf-isotope compositions of Permian-Triassic zircons from modern rivers in the Malay Peninsula (Sevastjanova et al., 2011), representing the Tin Belt source, and Paleogene sandstones in West Java. Fields are defined as 95% confidence ellipses. DM—depleted mantle.
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these basins developed on continental crust prior to the breakup of Gondwana and therefore are filled with sedimentary rocks that record an early Australian–Greater Indian history before they were incorporated in SE Asia. Similar sedimentary sequences may be partly preserved in other parts of Sundaland, for example, between W Java and SW Borneo. These sequences could have been eroded during the early Paleogene and contributed polycyclic sedimentary detritus to the Paleogene sequences discussed in this paper. For example, several differences between the Ciemas Formation (sample 8A) and all other samples discussed in this study may indicate a contribution from a different source. As previously highlighted, Hf-isotope compositions of the two Permian zircons in the Ciemas Formation fall well outside the 95% confidence ellipses defined from the Malay Peninsula (Sevastjanova et al., 2011). These are unlikely to have been sourced from the Malay Peninsula and therefore indicate a different Permian source in the region. There are also many more Paleozoic zircons in the Ciemas Formation sample, and although these cannot be linked to any particular source, they must represent a complex history that is at least partly different from that of all other samples.

These interpretations are tentative and are based on few analyses; more data are required in order to understand the contribution to Paleogene SE Asia sediments from alternative Permian–Triassic and older sources. Geochronological studies similar to the one presented here, which combine U-Pb and Hf-isotope techniques, will be hugely beneficial in helping to determine
paleosediment-routing systems and improve future tectonic models, particularly in SE Asia where active tectonism, arc volcanism, and a tropical climate have partly obscured the finer details of a rich and complex tectonic history.

Summary and Conclusions

U-Pb ages of detrital zircon suggest four major sediment sources for the Paleogene sandstones in West Java. These are (1) a latest Cretaceous–Paleogene volcanic arc in West Sulawesi–Sumba, (2) a Cretaceous volcanic arc in Java-Sumatra, (3) a Cretaceous granitic suite in the Schwaner Mountains in SW Borneo, and (4) granitoids of the Thai-Malay Tin Belt. Hf-isotope data reveal source regions and histories that could not have been identified by U-Pb analyses alone.

Relatively few zircons were derived from the Eocene–Oligocene Sunda arc, indicating that a geographical divide existed between the arc and onshore Java at this time. This is consistent with paleogeographic interpretations (Clements and Hall, 2007) that show the arc submerging and farther south than its present position.

Two Cretaceous populations of zircons in the Ciletuh Formation are based on U-Pb age and Hf-isotope compositions, which we interpret as representing two different volcanic arc systems. The first was active in the Cretaceous and developed in Java-Sumatra as a consequence of Tethyan subduction beneath Sundaland, which ended at ca. 80 Ma. The second was active in the latest Cretaceous and Paleogene (ca. 80 Ma) and developed as a consequence of subduction beneath West Sulawesi and Sumba that probably ceased in the early Eocene. Hf-isotope compositions indicate that the Java-Sumatra arc was built on Sundaland continental crust at an “Andean-type” margin. The W Sulawesi–Sumba arc was characterized by higher εHf (mantle-like ratios) comparable to those of the present-day Sunda Arc. The break between zircon U-Pb ages (ca. 80 Ma), and therefore between these two volcanic episodes, is interpreted here as representing the docking of the E Java–W Sulawesi microcontinent to Sundaland. This collision had a significant impact on the region and resulted in the cessation of subduction beneath much of Sundaland (except West Sulawesi) and was followed by a period of regional uplift and erosion (Clements et al., 2011) until subduction resumed again at ca. 45 Ma.

A SW Borneo source (the Schwaner Mountains) is characterized by mid-Cretaceous ages and is interpreted as the main source of Cretaceous zircons other than the slightly younger volcanic ages typical of the Ciletuh Formation. Overlap in U-Pb zircon ages from SW Borneo and the Java-Sumatra volcanic arc can blur the distinction between these two sources. However, distinctively different Hf-isotope signatures for these grains allow differentiation between the two Cretaceous zircon populations. Cretaceous zircons from upper Eocene and lower Oligocene formations are characterized by high εHf values that are consistent with provenance from the I-type granitoids, such as those typical of the Schwaner Mountains. Conversely, Cretaceous zircons from the middle Eocene Ciletuh Formation have much lower εHf values and are interpreted here to be from a volcanic arc. The absence of mid–Late Cretaceous zircons in the Ciemas Formation suggests that SW Borneo was not supplying detritus to West Java in the middle Eocene.

Granitoids of the Thai-Malay Peninsula are interpreted to be the major source of Permian and Triassic zircons in the W Java sandstones. Sevastjanova et al. (2011) determined the Hf-isotope compositions typical of the Malay Peninsula Main Range and Eastern Province granitoids, and this has been used to assess the contribution from this area. The upper Eocene Eocene Bayah Formation and lower Oligocene Cikalong Formation contain Permian and Triassic zircons that were derived from the Eastern Province. The Cijengkol Formation appears to have a mixed Eastern and Main Range Province provenance and is the only sample to contain a significant Jurassic cluster. Jurassic granitoids are known from Sumatra, and therefore a paleo-drainage system through present-day central and southern Sumatra is inferred for the Cijengkol Formation.

A few Permian–Triassic zircons have εHf values that fall outside the 95% confidence field defined for a Tin Belt source, suggesting a minor contribution from an alternative Permian–Triassic source that is, at present, uncertain. Cambrian and Precambrian zircons are present in all samples and probably represent a contribution from crystalline basement as well as reworked (pre–early Mesozoic) sedimentary sources.

The results presented here illustrate the immense potential of Hf-isotope analysis of dated zircons to improve and expand the interpretation of detrital zircon studies. The Hf-isotope data provide a tool to distinguish between source rocks of similar age but different geological histories. They also give insights into the genesis of the source rocks involved, which is invaluable in the reconstruction of tectonic settings. Thus in the present study the Hf-isotope data have allowed us to identify the presence of ancient crust beneath the Java-Sumatra arc and to recognize an Andean-style margin. This is a finding with both tectonic and economic-geology significance. The addition of such high-precision in situ Hf-isotope data to a set of dated zircons is, by comparison with the U-Pb analysis itself, both rapid and inexpensive. It should become a standard tool in future detrital zircon studies.

REFERENCES CITED

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tion 246, p. 23–96.

Goode, J.W., Williams, I.S., and Myrow, P., 2004, Provenance of Neo-protro-
zoic and lower Paleozoic siliciclastic rocks of the central Ross orogen, Antartica: Detrital record of rift-, passive-, and active-margin sedimenta-


Granath, J.W., Christ, J.M., Emmet, P.A., and Dinkelman, M.G., 2011, Pre-
tion 355, p. 53–74.


Griffin, W.L., Belousova, E.A., Walters, S.G., and O'Reilly, S.Y., 2006a, Archean and Proterozoic crustal evolution in the eastern succession of the Mt Isa district, Australia: U-Pb and Hf-isotope studies of detrit-


Hall, R., 2008, Continental growth at the Greater Himalayan margin of Southeast Asia, in Spencer, J.E., and Titeley, S.R., eds., Ores and Orogenesis: Circum-Pacific Tectonics, Geologic Evolution, and Ore Deposits: Arizona Geologi-
sical Society Digest, v. 22, p. 245–258.


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