U-PB DATING OF DETRITAL ZIRCONS FROM WEST JAVA SHOW COMPLEX SUNDALAND PROVENANCE

Benjamin Clements*
Robert Hall*

ABSTRACT

Paleogene sedimentary rocks in southwest Java record detrital contributions from different sources with different ages. The Ciletuh, Ciemas, Bayah, Cijengkol and Cikalong Formations have depositional ages of Middle Eocene to Early Oligocene. Samples from the Ciletuh Formation are deep marine volcanogenic sandstones whereas samples from the other formations are terrestrial and marginal marine quartz-rich sandstones. All contain abundant zircons from which U-Pb ages have been obtained by Laser Ablation ICPMS dating. Zircons yield a wide range of ages that span the Phanerozoic and Proterozoic, with rare Archean grains. Common age clusters include Late Cretaceous-Paleogene (40–80 Ma), Cretaceous (70–130 Ma), Permian-Triassic (190–270 Ma) and Late Neoproterozoic-Cambrian (480–590 Ma), although not all clusters are present in all samples. The zircon age spectra, combined with field observations, palaeocurrent measurements and light mineral analyses, are used to identify possible sediment sources.

The zircon ages are interpreted to indicate a Cretaceous and Early Paleogene volcanic source for the Ciletuh Formation and Sundaland sandstones for all other formations. Cretaceous zircons are present in all younger (Upper Eocene and Oligocene) quartzose sedimentary rocks. The Middle Eocene volcanogenic Ciletuh Formation contains abundant Cretaceous and Paleogene zircons but few zircons of greater age. In contrast, Cretaceous zircons are almost entirely absent from the Middle Eocene Ciemas Formation. Permian–Triassic zircons in the Ciemas Formation and all other quartz-rich sandstones are interpreted to be derived from granites of this age in the Malay Peninsula and the Indonesian Tin Islands. These zircons are interpreted to be derived from Cretaceous granites that are distributed across the Sunda Shelf, and in the Schwaner Mountains of SW Borneo. The differences in zircon populations of the quartz-rich sandstones thus reflect changing Sundaland sources with time. In the Middle Eocene sediment was derived mainly from the Tin Belt but not from Borneo, but from the late Eocene onwards a Borneo source became more important. Cambrian–Late Neoproterozoic zircons are present in all samples but their source is unknown as no rocks of this age are exposed in the region. All quartz-rich sandstones contain significant Proterozoic zircons, but unlike quartz-rich sandstones in East Java there are almost no Archean zircons.

INTRODUCTION

Today Java is dominated by the modern volcanoes of the Sunda Arc (Figure 1) and the majority of young sedimentary sequences onshore are volcanogenic in origin. However, during periods in Java’s history, particularly the Paleogene, the volcanic contribution was much less and non-volcanic siliciclastic detritus dominated. This paper discusses the provenance of some of these Paleogene sedimentary rocks based mainly on the U-Pb ages of detrital zircons. Zircons from five formations with depositional ages that range from Middle Eocene to Early Oligocene are compared and we discuss likely source regions that may have been exposed and actively supplying detritus to West Java during these times. Provenance studies of this type are rare in Southeast Asia; Soenandar and Kamp (1998) reported zircon fission track ages from NW Java Sea basement and the Ciletuh, G. Walat (here the Bayah Formation) and Jatibarang (volcaniclastic facies known from the sub-surface in the NW Java Sea) Formations in West Java. Facies descriptions and sample locations are absent but they conclude that a “strong Late Cretaceous signal” is present in all samples analysed. U-Pb ages of detrital zircons from East Java (see Smyth, 2005) indicate that Sundaland was not contributing significant volumes of sediment to the southern parts of East Java during the Paleogene

* SE Asia Research Group, Royal Holloway University of London
This is the first report of U-Pb ages of detrital zircons from sedimentary rocks in West Java. Four formations record a ‘Sundaland’ provenance and were deposited in terrestrial and marginal marine conditions (Clements and Hall, 2007). The fifth formation was deposited in deep water and most likely represents detritus eroded from a Cretaceous volcanic arc that is no longer preserved on Java.

GEOLOGICAL BACKGROUND

Sundaland (see Figure 1) is the southeast promontory of the Eurasian continental landmass in Southeast Asia. Java lies at its southern margin and West Java straddles the core of Sundaland (Hamilton, 1979). The region has a complex tectonic history and formed by the accretion of continental fragments of Gondwana origin to Eurasia at various stages through the Palaeozoic and Mesozoic (Metcalfe, 1996). The following account summarises basement and felsic plutonic and volcanic rocks exposed in the region. We suggest that some of these rocks have supplied material to West Java during the Paleogene.

Many of what are considered to be 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 Upper Cambrian, Ordovician, Silurian, Devonian, Carboniferous and Permian sedimentary rocks (Metcalfe, 1988). A Proterozoic basement is also indicated by U-Pb zircon inheritance ages from granitoids (Metcalfe, 1988). In Sumatra schists and gneisses that are exposed in the northwest are considered to represent a pre-Carboniferous basement (Barber & Crow, 2006) and an underlying continental basement is inferred from the presence of extrusive ignimbrites and granites of varying ages throughout Sumatra. In Borneo, the oldest rocks exposed are those of the Pinoh Group which are thought to be Carboniferous-Permian or older in age (Amiruddin and Traill 1993; de Keyser and Rustandi 1993; Pieters and Sanyoto 1993).

A Late Triassic orogenic event through what is now Thailand and the Malay Peninsula caused N-S orientated folding and faulting which was accompanied by a major period of granite intrusion. During the Jurassic and Cretaceous the region underwent several phases of uplift and erosion, often accompanied by further episodes of granite magmatism. This was initially associated with subduction preceding collision and later with post-collisional thickening of the continental crust (Hutchison, 1989, 1996). As a result, there are many Permian and Triassic tin-bearing granites as well as minor Cretaceous granites (Bignell and Snelling, 1977; Beckinsale et al., 1979; Liew and Page, 1985; Seong, 1990; Krähenbuhl, 1991; Cobbing et al., 1992) exposed in this region (Figure 1). Some 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. Cretaceous granites are known from the currently submerged Sunda Shelf close to the Schwaner Mountains (Pupilli, 1973), where they are overlain by thin Quaternary sediments (Ben-Avraham and Emery, 1973); hornblende and biotite K-Ar ages of 130–100 Ma (Williams et al., 1988) have been reported from granites of the Schwaner Mountains. Apatite fission track studies indicate rapid exhumation of Schwaner Mountain granites in the Late Cretaceous (Sumartadipura, 1976) and the Schwaner Mountains are known to have been elevated during the Paleogene, providing material to sediments of northern Borneo (van Hattum et al., 2006). In Sumatra granitic bodies represent several distinct periods of plutonic activity; these include the Permian, Jurassic to Early Cretaceous, Mid-Late Cretaceous, Early Eocene and Miocene to Pliocene (McCourt et al., 1996) although these granites are less extensive than those exposed in the Malay Peninsula and Borneo (Figure 1). Granites are also known to exist across the Sunda Shelf, many being penetrated by hydrocarbon exploration wells (Hamilton, 1979).

ANALYTICAL TECHNIQUE

Samples were separated at the Department of Earth Sciences, Royal Holloway University of London using standard crushing, magnetic and heavy liquid separation techniques; zircons were then handpicked. For U-Pb dating of zircon samples were analysed by LA-ICPMS at University College London using a New Wave 213 aperture imaged frequency quintupled laser ablation system (213nm) coupled to an Agilent 750 quadrupole-based ICP–MS. Real time data were processed using the GLITTER software package. Repeated measurements of external zircon standard PLESOVIC (TIMS reference age 337.13±0.37 Ma; Sláma et al., 2008) and NIST 612 silicate glass (Pearce et al., 1997) were used to correct for instrumental mass bias and depth-dependent inter-element fractionation of Pb, Th and U. Data were filtered using standard discordance tests with a 10% cutoff; discordant data that cut Concordia within error are also included. The \(^{206}\text{Pb}/^{238}\text{U}\) ratio was used to determine ages where < 1000 Ma and the
\[ \frac{^{207}\text{Pb}}{^{206}\text{Pb}} \] ratio for older grains. Data were processed using Isoplot (Ludwig, 2003).

**Zircon and provenance bias**

Zircon is an ultra-stable heavy mineral and the most resistant to chemical weathering and diagenesis (Morton and Hallsworth, 1999). First cycle zircons are typically produced by weathering of felsic and intermediate igneous and medium and high grade metamorphic rocks. Multi-cycle zircons are produced by weathering of sedimentary sequences that contain previously deposited zircons (Link et al., 2005). Zircon is present only in trace amounts in mafic rocks. This means that assessing the provenance of sedimentary rocks using zircon only, may not reveal mafic sources or that mafic sources may be under-represented, thus introducing bias. Nonetheless, zircon analysis is a useful tool for stratigraphic correlation, identification of sediment sources and/or understanding transport and depositional histories (Kosler and Sylvester, 2003).

**RESULTS OF ANALYSIS**

In total 440 zircon ages are discussed in this paper. Whenever possible at least 60 grains per sample were analysed to ensure 95% confidence levels in defining populations present at 5% (Dodson et al., 1988). Figure 2 is a simplified stratigraphic column showing the approximate depositional ages of the formations discussed; the locations of the four regions, the Bayah Dome, Sukabumi, Ciletuh Bay and Padalarang are shown in Figure 1. Concordia plots for the 7 samples discussed in this paper are provided in Figures 3 and 4. Typically these show analyses for ages < 1000 Ma on the left and analyses for older grains on the right, unless otherwise stated. Custom insets show age clusters in the data. The data is also displayed using density histograms in figures 5, 6 and 7. Figure 5 shows analyses using \[ ^{206}\text{Pb}/^{238}\text{U} \] ratios (< 1000 Ma; age bins are 20 Ma), figure 6 shows \[ ^{206}\text{Pb}/^{238}\text{U} \] ages enlarged from figure 5 that range from 40 Ma to 160 Ma (bins are 5 Ma) and figure 7 shows analyses using \[ ^{207}\text{Pb}/^{206}\text{Pb} \] ratios (> 1000 Ma, age bins are 40 Ma). The results of analyses from each formation are discussed below.

**The Ciletuh Formation**

In West Java there are two formations of Middle Eocene age exposed in the Ciletuh Bay area (Figure 1). These are the Ciletuh and Ciemias Formations (Clements and Hall, 2007) and represent the oldest sequences above basement. The Ciletuh Formation consists of coarse polymict breccias, volcanogenic debrites and turbidites. The breccias contain abundant volcanic clasts (basalt and andesite) as well as laminated volcanioclastic clasts, several types of shallow water limestone clasts and a small number of dacite, granite, and metamorphic clasts. Some basaltic blocks appear to have been extruded contemporaneously with the deposition of the breccia. Grey-green fine to medium grained volcanioclastic sandstones are intercalated with these breccias and become more abundant up section. Many features of the Ciletuh Formation indicate active faulting in deep water, accompanied by basaltic volcanism, and these deposits are interpreted to represent deformation and extension in a deep marine forearc setting (Clements and Hall, 2007). The intercalated volcanioclastic lithofacies of the formation was sampled for zircons and two samples are discussed here: sample JBC2CIL272 (62 grains) and JBC3CIL145 (58 grains). Samples were collected 8 kilometres apart (Figure 1).

From sample JBC2CIL272, 47 analyses (76% of sample) yield ages less than 1000 Ma (Figure 5G) and 15 analyses (24% of sample) yield ages greater than 1000 Ma (Figure 7G). The youngest grain analysed is 57.5±5.8 Ma. One major age cluster (Figure 5G), formed by two smaller clusters (Figure 6G) is present; the first comprises 5 grains (8% of sample) that range from 57.5±5.8 Ma to 70.3±5.7 Ma (2 Paleocene, 3 Late Cretaceous [mean age 65.1 Ma]), the second comprises 14 grains (23% of sample) that range from 87.1±5.9 to 98.2±5.9 Ma (14 Late Cretaceous [mean age 90.5 Ma]). 7 grains (11% of sample) range from 223.6±6.9 Ma to 373.4±9.2 Ma (1 Ordovician, 1 Cambrian and 14 Late Neoproterozoic [mean age 582.8 Ma]). 5 grains range from 789.6±19.6 Ma to 987.2±17.6 Ma but form no significant cluster (Figure 5G). A small cluster (Figure 7G) of 8 grains (13% of sample) ranges from 1040.9±25.4 Ma to 1197±35 Ma (Late Mesoproterozoic [mean age 1130.9 Ma]). 7 grains yield older ages (Figure 7A) but do not form any age clusters. The oldest grain is 2391.8±18.8 Ma (Paleoproterozoic).

From sample JBC3CIL145, 53 analyses (91% of sample) yield ages less than 1000 Ma (Figure 5F) and 5 analyses (9% of sample) yield ages greater than 1000 Ma (Figure 7F). The youngest grain analysed is 40.3±8.6 Ma (Middle Eocene) and is very similar to the depositional age of the formation (e.g. van Bemmelen, 1949; Schiller et al., 1991; P
Lunt pers. comm. 2006; Clements and Hall, 2007). One major age cluster (Figure 5F) is present; this comprises 24 grains (41% of sample) that range from 40.3±8.6 Ma to 98.8±9.1 Ma (7 Eocene, 8 Paleocene and 9 Late Cretaceous [Figure 6F]); the mean age of these ages is 62.7 Ma. 7 grains (12% of sample) range from 104.9±9.9 Ma to 192.6±9.9 Ma (2 Early Cretaceous and 5 Jurassic) but form no convincing cluster. A small cluster (Figure 5F) of 8 grains (14% of the sample) that ranges from 203.7±9.9 to 286.8±12.4 Ma (4 Triassic and 4 Permian [mean age 246.8 Ma]) and another cluster of 9 grains (16% of sample) that ranges from 319.7±11.7 to 381.4±14.1 Ma (7 Early Carboniferous and 2 Late Devonian [mean age 351.2 Ma]) can be distinguished. 11 grains yield older ages (Figures 5F and 7F) but do not form any age clusters. The oldest grain is 2511.2±14.3 Ma (Archean).

The Ciemas Formation

The Middle Eocene Ciemas Formation comprises quartz-rich sandstones, pebbly sandstones and conglomerates. Pebby material is predominantly vein and/or metamorphic quartz and is usually highly rounded, interpreted to represent the reworking of sedimentary rocks of pre-Cenozoic age. Sandstones are typically texturally immature as indicated by poor sorting and angular grains but compositionally mature, being 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 a narrow shelf edge (Clements and Hall, 2007).

From sample JBC2CIE259, 41 analyses (64% of sample) yield ages less than 1000 Ma (Figure 5E) and 23 analyses (36% of sample) yield ages greater than 1000 Ma (Figure 7E). The youngest grain analysed is 46.1±12.7 Ma (Middle Eocene) and is similar to the depositional age of the formation (e.g. van Bemmelen, 1949; Schiller et al., 1991; P Lunt pers. comm. 2006; Clements and Hall, 2007). No major age cluster is present in the sample. The most significant minor clusters (Figure 5E) comprise 9 grains (14% of sample) that range from 214±14.4 to 264.1±19.9 (5 Triassic and 3 Late Permian [mean age 238 Ma]) and 11 grains (17% of sample) that range from 480.2±34.7 to 614.9±27.6 Ma (1 Ordovician, 4 Cambrian and 6 Late Neoproterozoic [mean age 552.1 Ma]). No other age clusters exist. The majority of analyses are older than these two clusters and considerable variation in ages is observed (Figure 5E and 7E). Analyses yield abundant ages that extend back to 2700.1±28.2 Ma with no major breaks. 4 Archean grains are present in the sample, the oldest is 3629.4±19.8 Ma.

The Bayah Formation

The Late Eocene Bayah Formation comprises dark, pyrite-rich marine mudstones and siltstones in the lower part that grade upwards into quartz-rich sandstones, pebbly sandstones and conglomerates. Pebby material is predominantly vein and/or metamorphic quartz and is usually highly rounded, interpreted again to represent the reworking of pre-Cenozoic fluvial/terrestrial sediments like the Ciemas Formation. Sandstones are typically texturally immature and generally poorly sorted despite being composed predominantly of quartz, much of which is of metamorphic origin. Paleocurrent indicators suggest material was sourced from the north and the formation is interpreted to have been deposited predominately by large braided rivers (Kusuma Brata, 1991; Clements and Hall, 2007) as channel and overbank, deltaic and coastal plain deposits. Two samples were analysed from the upper quartz-rich part of the formation. Sample JBC2BAY187 is from the Bayah Formation exposed in the Bayah Dome and sample JBC2WAL137 is from the Bayah Formation exposed at G. Walat, Sukabumi (Figure 1). The Bayah Formation was deposited during the Late Eocene (P. Lunt, pers. comm., 2006; R.J. Morley, pers. comm., 2006; Clements and Hall, 2007 [Figure 2]).

From sample JBC2BAY187, 54 analyses (92% of sample) yield ages less than 1000 Ma (Figure 5D) and 5 analyses (8% of sample) yield ages greater than 1000 Ma (Figure 7D). The youngest grain analysed is 31.4±12.7 Ma (Early Oligocene). Despite being apparently younger than the depositional age of the Bayah Formation (Upper Eocene) this analysis is well within error of the 33.9±0.1 Ma top Eocene boundary. 3 other analyses (33.2±12.1 Ma to 35.7±12.4 Ma) closely define the depositional age of the formation. One major age cluster (Figure 5D) is present, this comprises 21 grains (36% of sample) that range from 60.5±12.2 Ma to 112.4±12.5 Ma (1 Paleocene, 13 Late Cretaceous and 7 Early Cretaceous [mean age 97.8 Ma]). Two smaller clusters exist; these comprise 14 grains (24% of sample) that range from 188.9±14 Ma to 259.3±22.6 Ma (2 Early Jurassic, 10 Triassic and 2 Late Permian [mean age 223.8 Ma]) and 7 grains (12% of sample) that range from 500.2±21.7 Ma to 594±23.9 Ma (4 Cambrian and 3 Late
Neoproterozoic [mean age 542.7 Ma]. 7 grains yield older ages, the oldest is 2216.9±52.9 Ma (Paleoproterozoic).

From sample JBC2WAL137, 54 analyses (76% of sample) yield ages less than 1000 Ma (Figure 5C) and 16 analyses (24% of sample) yield ages greater than 1000 Ma (Figure 7C). The youngest grain analysed is 80.8±4 Ma (Late Cretaceous). One major age cluster (Figure 5C) is present, this comprises 22 grains (31% of sample) that range from 80.8±4 Ma to 146.3±4.4 Ma (5 Late Cretaceous, 15 Early Cretaceous and 2 Late Jurassic [Figure 6C]); the mean of these ages is 119 Ma. Four smaller clusters exist; these comprise 7 grains (10% of sample) that range from 216.4±5.2 Ma to 268.7±6 Ma (5 Triassic and 2 Permian [mean age 238 Ma]), 6 grains (8% of sample) that range from 520.7±9.8 Ma to 566.5±10.4 Ma (3 Cambrian and 3 Late Neoproterozoic [mean age 542.7 Ma]), 7 grains (10% of sample) that range from 1149.9±24.7 Ma to 1205.4±29.2 Ma (Mesoproterozoic [mean age 1171.2 Ma]) and 6 grains (8% of sample) that range from 1757±22.3 Ma to 1894.4±21.9 Ma (Paleoproterozoic [mean age 1821.2 Ma]). The oldest grain yields an age of 2466.3±19.4 Ma (Early Paleoproterozoic).

The Cikalong Formation

The (predominantly) Early Oligocene Cikalong Formation comprises quartz-rich sandstones, pebbly sandstones and conglomerates intercalated with thick sequences of marine carbonaceous siltstones. Pebbles are highly rounded and thin channels, load casts, normal grading and fluid escape structures suggest rapid deposition (Clements and Hall, 2007). Euhedral plagioclase and apatite grains indicate a minor volcanic component. The Cikalong Formation is exposed at a number of localities that extend from the southwest of Sukabumi east-northeast toward Padalarang (Figure 1). Sample JBC2CIK117 is a quartz-rich sandstone.

From sample JBC2CIK117, 55 analyses (80% of sample) yield ages less than 1000 Ma (Figure 5B) and 14 analyses (20% of sample) yield ages greater than 1000 Ma (Figure 7B). The youngest grain analysed is 49.1±4.3 Ma (Early Eocene). Two major (but poorly defined) age clusters (Figure 5A) are present, these comprise 23 grains (41% of sample) that range from 49.1±4.3 Ma to 179.9±6.4 Ma (3 Eocene, 5 Late Cretaceous, 8 Early Cretaceous and 7 Late and Middle Jurassic [see Figure 7A]) and 21 grains (38% of sample) that range from 203.8±5.9 Ma to 298.9±8.4 Ma (15 Triassic and 6 Permian); the mean averages of these ages are 116.8 Ma and 235 Ma respectively. 13 grains yield variable Early Paleozoic and Neoproterozoic ages, the oldest grain yields an age of 2590.8±19.8 Ma (Archean).

DISCUSSION

Density histograms for all samples analysed are illustrated in Figures 5, 6 and 7; these show the number of analyses plotted against age. Age clusters common to several samples are highlighted and colours are used to indicate different interpreted sources. We suggest that zircon ages for the Ciletuh
Formation reflect input from a Cretaceous and Early Paleogene local volcanic source whereas zircon ages from all other formations reflect sediment derived predominantly from Sundaland.

**Local volcanic arc source**

Three samples from the Ciletuh area have been analysed. Sample JBC2CIE259 is from the Ciemas Formation and contains only two Cretaceous grains, this sample is discussed below. The two samples from the Ciletuh Formation (JBC2CIL272 and JBC3CIL145) are dominated by Late Cretaceous and Early Paleogene ages (Figures 5 G, F and 6 G, F). A distinction between a Mid-Late Cretaceous cluster and a latest Cretaceous-Paleogene cluster can be made in sample JBC2CIL272 (Figure 6G).

We interpret these ages to indicate a local volcanic source, probably a volcanic arc that was eroded and re-deposited during the Middle Eocene. It has been suggested that there was a passive margin to the south of Java between the Late Cretaceous and Middle Eocene (Carlile and Mitchell 1994; Parkinson et al. 1998; Clements and Hall, 2007) after collision of a continental fragment of Gondwana origin, termed the E Java-W Sulawesi block (Hall, 2008), terminated subduction during the Late Cretaceous (Smyth et al., 2007). We suggest that the Mid-Late Cretaceous ages from sample JBC2CIL272 represents detritus from a mature calc-alkaline arc that existed prior to this collision. The Late Cretaceous and Paleogene ages from both Ciletuh samples are interpreted to represent post collisional volcanism. Many features of the Ciletuh Formation breccias indicate active faulting in deep water, accompanied by basaltic volcanism. This deformation and extension is suggested to have occurred in a deep marine forearc setting, possibly relating to the onset of subduction (Clements and Hall, 2007).

Subtle differences in older zircon ages also exist between the two Ciletuh samples and this is interpreted to represent slight heterogeneities in the source material. In JBC2CIL272 there are minor clusters of Permian and Triassic (4 analyses), Late Neoproterozoic and Cambrian (16 analyses) and Late Mesoproterozoic (8 analyses) age. In JBC3CIL145 there are minor clusters of Permian and Triassic (8 analyses) and Early Carboniferous and Late Devonian (8 analyses) age. Both samples contain grains that yield Proterozoic ages. Permo-Triassic and Late Proterozoic-Cambrian ages are also present in most non-volcanic siliciclastic samples (see Figure 5). We interpret (see below) these ages to typify a Sundaland signature and suggest that, despite being dominated by a local volcanic arc component, minor contributions from Sundaland are seen in both Middle Eocene Ciletuh samples. This is consistent with the position of the arc at the Sundaland margin, but separated from the continent by a marine gap.

**Sundaland source**

Zircon ages from the Middle Eocene Ciemas Formation are markedly different from those of the Ciletuh Formation. Only one Paleogene and two Cretaceous ages are present (Figures 5 and 6). This suggests that neither the Late Cretaceous volcanic arc nor any Cretaceous Sundaland sources were actively supplying material to onshore West Java during the Middle Eocene. This is in agreement with field observations that the Ciemas and Ciletuh Formations were deposited in very different settings and that their present proximity is not depositional, but most likely due to thrusting (Hall et al., 2007).

We also suggest that the absence of Cretaceous analyses from the Ciemas Formation (marginal marine quartz-rich sandstone) is further supported by the interpretation that the Early Paleogene to Late Cretaceous zircons in the Middle Eocene Ciletuh Formation samples (deposited to the south of Java in deep water) are not a Sundaland signal and far more likely representative of a local volcanic arc source.

The most prominent age clusters in the Middle Eocene Ciemas Formation are Permian-Triassic and Late Neoproterozoic-Cambrian (Figure 5E). These age clusters are present in most other non-volcanogenic siliciclastic samples and likely sources are discussed below. The Ciemas Formation contains significantly more Pre Cambrian grains (49 [77% of sample]) than any other sample (Figure 5E and 7E). These analyses form no distinct clusters and thus are difficult to interpret; nevertheless they indicate a source or number of sources with varying ages that were supplying detritus to West Java during the Middle Eocene, many of which are not present in other samples.

Both Late Eocene Samples (Bayah Formation [JBC2BAY187 and JBC2WAL137]) and both Early Oligocene samples (Cikalong [JBC2CIK117] and Cijengkol [JBC2CIJ191] Formations) have very similar zircon age signatures to each other (Figure 5 and 6). The most prominent age cluster is mid Cretaceous for sample JBC2BAY187, Early Cretaceous for sample JBC2WAL137, Early Cretaceous for sample JBC2CIK117 and Late Jurassic and Cretaceous for sample JBC2CIJ191.
We suggest that these zircon ages correspond well with known isotopic ages of Cretaceous granites distributed across the Sunda Shelf, and in the Schwaner Mountains of SW Borneo (Williams et al., 1988; van Hattum et al., 2006). Note that these ages are older than the Early Paleogene and Late Cretaceous age clusters in the Ciletuh Formation samples interpreted as volcanic.

Other similar age clusters are common to the Bayah, Cikalong and Cijengkol Formations; these are Permian-Triassic and Late Neoproterozoic-Cambrian (Figure 5). Mean ages for these two age clusters in all samples are Early-Middle Triassic and latest Neoproterozoic respectively. We suggest that the Permo-Triassic ages, for the Bayah, Cikalong and Cijengkol Formations and the Middle Eocene Ciemas Formation, correspond well with known isotopic ages of Permian and Triassic granites distributed throughout the Malay Peninsula and Indonesian Tin Islands (Bignell and Snelling, 1977; Beckinsale et al., 1979; Liew and Page, 1985; Seong, 1990; Krähenbühl, 1991; Cobbing et al., 1992).

The Late Neoproterozoic-Cambrian ages do not match any rocks in the region. Proterozoic gneiss, marble, schist and phyllite are known from the Malay Peninsula (Metcalfe, 1988) and the Pinoh Group, exposed in SW Borneo, is known to be older than Permian-Carboniferous (Amiruddin and Trail 1993; de Keyser and Rustandi 1993; Pieters and Sanyoto 1993) as are schists and gneisses that are exposed in the northwest of Sumatra (Barber & Crow, 2006). A similar 500 Ma to 650 Ma age signal is attributed to ‘Pan-Gondwanaland’ post-collisional extension (Veevers, 2007) as well as to Ross-Delamerian orogenic cycles in eastern Antarctica and eastern Australia (e.g. Goode et al., 2004; Glen, 2005). Much of the basement of Southeast Asia is of Gondwana origin (e.g. Metcalfe, 1996) and may record these signals too, so zircons of these ages in sedimentary rocks in West Java could represent such basement lithologies that ultimately originated from Gondwana.

CONCLUSIONS

Detrital zircons from seven samples from five formations contain abundant zircons from which U-Pb ages have been obtained by Laser Ablation ICPMS dating. Depositional ages range from Middle Eocene to Early Oligocene and a number of sources have been identified. The Ciletuh Formation was sourced predominantly from a Late Cretaceous-Paleogene volcanic arc. Mid Cretaceous ages record pre-collisional volcanism (E Java-W Sulawesi block [Hall, 2008]) and latest Cretaceous-Paleogene ages record post-collisional volcanism. A minor Sundaland contribution is recorded in the Ciletuh samples.

The Ciemas, Bayah, Cijengkol and Cikalong Formations have a complex Sundaland provenance. During the Middle Eocene there was no Cretaceous source supplying material to onshore West Java, either from the Cretaceous volcanic arc that was sourcing the Ciletuh Formation or Sundaland. Siliciclastic material was derived mainly from granitic rocks of the Malay Peninsula and Indonesian Tin Islands. During the Late Eocene a Cretaceous Sundaland source, probably the Schwaner Mountains of SW Borneo, became important in supplying detritus to West Java. The Malay Peninsula and Indonesian Tin Islands likely remained an important source during these times as indicated by the presence of Late Permian and Triassic grains. The Early Oligocene Cijengkol Formation contains more Permian and Triassic grains than Cretaceous grains, perhaps indicating the waning importance of the Schwaner Mountains as a source. Cambrian and Late Neoproterozoic zircon ages are present in most samples. It is not possible at present to identify a specific source/sources that correspond to these ages, because no rocks of this age are known from the region. Basement rocks in the Malay Peninsula, northwest Sumatra and/or southwest Borneo may have contributed material.

ACKNOWLEDGMENTS

This work has been funded by the SE Asia Research Group. We thank Dr Andrew Carter from UCL for all his assistance with the analytical work, Agus Harsolumakso, Benyamin Sapiie and other ITB geologists and Djadjang Sukarna and the Pusat Survei Geologi (former GRDC) for their cooperation, help and support. Ivan Yulianto and Edy Slameto provided invaluable field support. We are grateful to Peter Lunt for considerable help with planning, practical assistance and discussions.
regarding the geology of West Java and to Marcelle BouDagher-Fadel, Bob Morley, Bernhard Seubert, and Moyra Wilson who have all assisted us in different ways.

REFERENCES


Sumartadipura, A.S., 1976, Geologic map of the Tewah quadrangle, central Kalimantan, Bandung, Indonesia, Geological Research and Development Centre, scale 1:250,000.


Figure 1 – Major features of the southern part of the Sunda Shelf between Java, Borneo, Sumatra and the Malay Peninsula. Bathymetry is from Sandwell and Smith (1997). The approximate boundary between Cretaceous continental crust and Cretaceous melange (after Hamilton, 1979) is shown in red. The extent of acid volcanic and plutonic rocks of ages that correspond to age clusters from zircons discussed in this paper are shown (adapted from Tate, 2001; Barber and Crow, 2005). Inset 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: JBC2CIL272 (1), JBC3CIL145 (2), JBC2CIE259 (3), JBC2BAY187 (4), JBC2WAL137 (5), JBC2CIK117 (6), JBC2CIL191 (7). Red triangles are volcanoes.
Figure 2 – Simplified stratigraphic column of the sedimentary sequences discussed in this paper. Regions are shown in Figure 1.
Figure 3 – Concordia plots for the Ciletuh (samples JBC2CIL272 and JBC3CIL145) and Ciemas (sample JBC2CIA259) Formations. Analyses are shown using $^{206}\text{Pb}/^{238}\text{U}$ ratios for ages < 1000 Ma on the left and analyses using $^{207}\text{Pb}/^{206}\text{Pb}$ ratios for ages < 1000 Ma on the right.
Figure 4 – Concordia plots for the Bayah (samples JBC2BAY187 [Bayah Dome], JBC2WAL137 [G. Walat, Sukabumi]), Cikalong (JBC2CIK117) and Cijengkol (JBC2CIJ191) Formations. Analyses are shown using $^{206}$Pb/$^{238}$U ratios for ages < 1000 Ma on the left and analyses using $^{207}$Pb/$^{206}$Pb ratios for ages < 1000 Ma on the right.
Figure 5 – Density histograms for all grains from all formations with calculated ages <1000 Ma. Analyses calculated using \(^{206}\)Pb/\(^{238}\)U ratios. Bins are 20 Ma. Highlighted zones correspond to age clusters; green represents a local volcanic source (VA), red represents a Schwane Mountains source (Cretaceous and Paleogene [K-P]), orange represents a Tin Belt source (Permian-Triassic [P-T]) and blue represents an unknown Late Neoproterozoic-Cambrian (NP-C) source. Two facies types exist, these are shown in black; 1 = Quartz-rich sandstones, 2 = volcanogenic.
Figure 6 – Density histograms for analyses that yield ages between 40 Ma and 160 Ma from all formations. Analyses calculated using $^{206}\text{Pb}/^{238}\text{U}$ ratios. Bins are 5 Ma. Highlighted zones correspond to age clusters. Green represents a local volcanic source for the Ciletuh Formation (note the distinction between pre and post-collisional volcanism) and red represents a Cretaceous ?Schwaner source. Two facies types exist, these are shown in black; 1 = Quartz-rich sandstones, 2 = volcanogenic.
Figure 7 – Density histograms for all grains from all formations with calculated ages >1000 Ma. Analyses calculated using $^{207}$Pb/$^{206}$Pb ratios. Bins are 40 Ma. Highlighted zones from left to right are: 1040-1240 Ma, 1720-1900 Ma, 2300-2420 Ma and 2450-2600 Ma. Two facies types exist, these are shown in black; 1 = Quartz-rich sandstones, 2 = volcanogenic.
Figure 8 – Schematic Palaeogeographic 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 with only minor contribution from Sundaland. During the Late Eocene both the Schwaner Mountains and the Tin-Belt granites are interpreted to have been supplying material to West Java. The possible waning of the Schwaner Mountains as a source may have occurred during the Early Oligocene; sediments however continued to be sourced from Sundaland. Java and Borneo have been rotated in accordance with tectonic reconstructions of the region (Hall, 2002).