Sedimentological characteristics and new detrital zircon SHRIMP U–Pb ages of the Babulu Formation in the Fohorem area, Timor-Leste

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Sedimentological characteristics and zircon provenance dating of the Babulu Formation in the Fohorem area, Timor-Leste, provide new insights into depositional process, detailed sedimentary environment and the distribution of source rocks in the provenance. Detrital zircon sensitive high-resolution ion microprobe (SHRIMP) U–Pb ages range from Neoarchean to Triassic, with the main age pulses being Paleozoic to Triassic. In addition, the maximum deposition ages based on the youngest major age peak (ca 256±238 Ma) of zircon grains indicate that the basal sedimentation of the Babulu Formation occurred after the early Upper Triassic. The formation consists predominantly of mudstone with minor sandstone, limestone and conglomerate that were deposited in a deep marine environment. These deposits are composed of six lithofacies that can be grouped into three facies associations (FAs) based on the constituent lithofacies and bedding features: basin plain deposits (FA I), distal fringe lobe deposits (FA II) and medial to distal lobe deposits (FA III). The predominance of mudstone (FA I) together with intervening thin-bedded sandstones (FA II) suggest that the paleodepositional environment was a low energy setting with slightly basin-ward input of the distal part of the depositional lobes. Discrete and abrupt occurrences of thick-bedded sandstone (FA III) within the FA I mudstone suggests that sandstone originated from a collapse of upslope sediments rather than a progressive progradation of deltaic turbidites. This combined petrological and geochronological study demonstrates that the Babulu Formation in the Fohorem area of the Timor-Leste was initiated as a submarine lobe system in a relatively deep marine environment during the Upper Triassic and represents the extension of the Gondwana Sequence at the Australian margin.

KEYWORDS: Timor-Leste, Fohorem, Babulu Formation, sandstone, lobe system, deep marine environment, SHRIMP zircon U–Pb geochronology.

INTRODUCTION

The island of Timor is located in the southeastern part of the Indonesian archipelago (Figure 1). It is a young accretionary fold-thrust belt formed by the underthrusting of Australian continental margin units beneath the Asian Banda forearc (Harris 2011 and references therein). The Banda arc–continental collisional zone is divided into two main regional litho-tectonic stratigraphic successions representing fragments of continental crust that have Australian and Asian affinities, respectively. An understanding of these successions provides important insight into the stratigraphic relationships and tectonic development of the Banda Arc during arc–continental collisions.

The Gondwana mega-sequence with Australian affinity exposed in a fold-and-thrust belt and mélange complex in Timor Island was previously divided into three principal Triassic lithostratigraphic units, the Niof, Aitutu and Babulu formations, and one predominantly Jurassic unit, the Wai Luli Formation (Charlton et al. 2009). Distinguishing between these stratigraphic elements is fundamental for understanding both the pre-collisional tectonic history of the Gondwana sequence and the tectonic evolution of the Banda Arc. However their detailed sedimentological characteristics, including depositional processes and environments, remain unclear. Recent preliminary geochronological data from individual areas of the Gondwana sequence and Banda forearc units in the Timor region have contributed to the understanding of their origins (Zobell 2007; Standley & Harris 2009), but the systematic stratigraphic elements and their origins are remain unclear.

The Fohorem area, located at the southwestern extreme of Timor-Leste, has a thick succession consisting of the Aitutu and Babulu formations. Because of the adjacent type locality of the Babulu Formation (Babulu...
GEOLOGICAL SETTING

The island of Timor is part of the outer arc of the Banda Arc (Figure 1) and formed due to N- to NE-directed subduction of the northwestern Australian continental margin beneath the southeastern Banda Arc. The island of Timor is part of the outer arc of the Banda Arc (Figure 1) and formed due to N- to NE-directed subduction of the northwestern Australian continental margin beneath the southeastern Banda Arc. The changing sedimentary lithofacies reflect the rapid uplift history of the island from a submarine to a terrestrial environment.

GEOLOGY OF THE FOHOREM AREA

The study area is located in the boundary region between the terranes with Australian and Banda affinities and includes the four major tectonostratigraphic units (Figures 2, 3). The terrace with Australian affinity is represented by the Maubisse, Aitutu, Babulu and Makokon formations in ascending order, predominantly occurring in the Fatumean area. The Permian Maubisse Formation (Audley-Charles 1986) is surrounded by the Bobonaro Mélange deposits and is composed of shallow shelf limestone—calcareous shale successions and pillow to massive basalt to trachyandesite. The SHRIMP U–Pb zircon age of the trachyandesite is 270 ± 3 Ma (Appendix I). The Triassic Aitutu and Babulu formations (Audley-
Charles 1968; Bird & Cook 1991; Charlton et al. 2009) are characterised by shallow marine limestone–shale and deep marine siliciclastic successions, respectively. The strata of the formations generally show NE-strike dipping to the NW, with some variability due to folding and thrusting. The strata of the Babulu Formation generally overlie the Aitutu strata, but some Aitutu strata abruptly overlie the Babulu strata as a result of repeated thrusting (Figure 3). The Aitutu Formation is primarily composed of wackestone to packstone with minor amounts of thin-bedded shale and chert nodules, whereas the Babulu Formation is predominantly mudstone with subordinate amounts of sandstone, limestone and conglomerate. The newly defined Makokon Formation, exposed in the small creek of Makokon village, is described as pink to pinkish-grey massive limestone consisting predominantly of foraminiferan pelagite (Figure 3).

The Banda affinity sequence is characterised by Mesozoic to Cenozoic arc–forearc successions consisting of the Fohorem Formation, the Baer Formation (or Dartollu Limestone) and the Cablac Limestone, in ascending order (Figures 2, 3). The first two lithological units are newly classified from the Lolotoi Complex.
Figure 3 Geologic map and cross section of the study area. The Babulu Formation, the main subject of this study, is located on the western part of the map. The strata of the formation above the underlying Aitutu Formation are overlain by the Aitutu strata caused by repeated thrust sheets. Inset maps show the study area and tectonic units. Pmb, Maubisse Formation (basalt); Pml, Maubisse Formation (limestone); TRa, Aitutu Formation; Jb, Babulu Formation; Nm, Makokon Formation; Jf, Fohorem Formation; PEg, Gabbro; Ncl, Cablac Limestone; Nbm, Bobonaro Melange; Nv, Viqueque Formation; QB, Baucau Formation; Qt, fluvial terrace deposit.
Sedimentology and dating of Babulu Formation, Timor-Leste 869

(Audley-Charles 1968) based on lithology (Figure 3). The Fohorem Formation is characterised by effusive to explosive volcanic rocks and minor metapelitic rocks. Most of the volcanic rocks with basaltic to andesitic compositions were subjected to low grade metamorphism (up to greenschist facies) (Standley & Harris 2009) and ductile deformation; SHRIMP U–Pb zircon ages (ca 177–174 Ma; Park et al. 2014) from the andesite were Middle Jurassic. The Baer Formation overlies the Fohorem Formation unconformably and consists of brownish-coloured limestone. The limestone contains abundant nummulites and other foraminifera that indicate a Paleocene to Eocene age. The Cablac Limestone (Audley-Charles 1968; Harris 2006) is surrounded by the Bobonaro Mélange deposits and is composed of peloidal or oolitic packstone to grainstone, commonly including chert nodules and mottled bioturbation structures. The Cablac Limestone is assigned to the initial definition of Audley-Charles’s (1968) Cablac Limestone (Figure 3) because of poor exposure and lack of suitable fossils for age determination in the limestone. The need for further studies of the limestone to resolve controversies surrounding its depositional age and associated affinity, has been identified (Audley-Charles 1968; Harris 2006; Haig et al. 2007, 2008).

The pre-orogenic assemblages are disrupted and mixed during arc–continent collision including the development of the synorogenic Bobonaro Mélange (Figures 2, 3). The Bobonaro Mélange occupies most of the study area, and is composed of unmetamorphosed clay matrix and embedded blocks. The clay matrix is generally reddish to brown to greenish grey in colour, with variations caused by differences in the clay compositions. A pervasive polished and scaly fabric, typically with striation, is commonly developed in the clay. Blocks are unsorted and composed of various lithologies derived from the underlying Maubisse, Aitutu and Babulu formations; blocks range in size from a few centimetres to several tens of metres.

The synorogenic sedimentary rocks are composed of Cenozoic limestone successions consisting of the Viqueque and Baucau formations. The Pliocene Viqueque Formation (Audley-Charles 1968) occurs as an irregular blocks, unconformably above the Bobonaro Mélange deposits. It consists mostly of white, massive marlstone and claystone with minor conglomerate and limestone interbeds. The lower Pleistocene to Holocene Baucau Formation is a sequence of terraced reef limestone (Audley-Charles 1968) and consists of white, hard and mostly recrystallised coral reef limestone. All the coral specimens collected from the formation have been identified as scleractinians. All the above lithologic units are partially covered by the Holocene alluvium and colluvium deposits.

**FACIES ASSOCIATIONS**

The Babulu Formation in the study area is predominantly composed of mudstones with subordinate amounts of sandstone, limestone and conglomerate (Figure 4). These lithologies differ markedly from the typical Babulu Formation elsewhere in Timor, which is described as consisting predominantly of sandy deposits (Charlton et al. 2009). The deposit crops out mostly along the riversides of Mota (river) Maubui and Mota Halibo in the study area (Figure 3). To interpret the depositional processes and environments of the formation, detailed columnar logs were measured at different scales, particularly where well-exposed thick sandstones were encased within the mudstones (Figure 4). Based on lithology, grain size, primary sedimentary structures and bedding features, six lithofacies were defined (Table 1). These facies were grouped into three facies associations (FAs), representing basin plain deposits (FA I), distal fringe lobe deposits (FA II) and medial to distal lobe deposits (FA III) (Figure 5).

**Facies association 1: Basin plain deposits**

This association comprises the majority of the Babulu Formation, and is composed of homogeneous mudstones (Mh) with subordinate amounts of limestone and thin sandstone layers (Figures 5, 6a). The mudstones are laminar- to thin-bedded, massive to stratified in appearance and purple or dark grey to blackish in colour. Each layer is laterally persistent with distinct lower and upper boundaries. The mudstones may contain numerous shale, sandstone and limestone blocks up to 3 m in diameter (Figures 5, 6b, c) and highly distorted internal stratification (Figure 6b) in the different stratigraphic levels. Orthoconic nautiloids are also found in the mudstone (Figure 6a). The limestone occurs as beds or nodules within the mudstone. Under the microscope, this limestone consists of diverse fossil allochems, including fragments or bodies of miliolid foraminifera, crinoids, echinoids, calcareous chaetetid sponges, sphinctozoans, calcimicrobes, bivalves, gastropods, ostracods, brachiopods and unidentifiable skeletons as well as non-skeletal allochems such as oncoids, peloids and quartz (Figure 7). The intercalated sandstone layers (a few centimetres thick) within the mudstones, consist of moderate- to well-sorted, fine- to medium-grained sand and have distinct lower and upper boundaries and lenticular or wedge-shaped geometries.

The thinly bedded mudstones with good lateral continuity are indicative of suspension settling of fine-grained, dilute turbidity currents on the outer lobe, or in a basin plain in a predominantly low-energy setting (Hodgson 2009; Prélat et al. 2010; Prélat & Hodgson 2013). The intercalated limestone within the mudstone is indicative of intermittent input of carbonate materials by resedimentation processes such as turbidity flows or debris flows (Playton et al. 2010). Miliolid foraminifera are an important indicator fossil for shallow marine environments throughout the Mesozoic (Flügel 2004), and their presence in the sediments suggests that these carbonate materials were sourced from a shallow carbonate platform. The large blocks with distortion of their internal stratification and the blocks in the mudstones are interpreted as deposits from a debris fall caused by the gravitational collapse of semi-consolidated upslope deposits. The intercalated sandstone layers indicate intermittent input of low concentration sand-laden turbidity flows caused by the occasional progradation of thin lobes into the basin plain.
Figure 4 Columnar log of the Babulu Formation at the Fatumea section, representing an overview of the formation. The formation is mostly composed of shale/mudstones with minor amounts of limestone and sandstone. See inset map for the location of the columnar log.
Detailed columnar logs of the Babulu Formation, particularly where well-exposed thick sandstones are encased within the mudstones. Thick-bedded sandstones commonly contain abundant mud chip streaks. See inset map of Figure 4 for logging locations and Table 1 for brief descriptions of lithofacies.

Table 1 Brief description and interpretation of lithofacies of the Babulu Formation.

| Facies                        | Description                                                                 | Interpretation                                      |
|-------------------------------|------------------------------------------------------------------------------|-----------------------------------------------------|
| Disorganised conglomerate     | About 0.4 m thick; disorganised and poorly sorted; matrix- to clast-supported pebble-sized mud chips with muddy sand matrix; parallel to subparallel alignment of elongated mud chips; sharp and non-erosive lower boundary | Cohesive debris flow                                 |
| Massive to crudely stratified sandstone | Thin- to very thick-bedded; moderately to well sorted fine to medium sandstone with mud chip streaks and sparsely outsized mud blocks; parallel to subparallel alignment of elongated mud chips; sharp or scoured lower contact; pass upward into either ripple cross-laminated or stratified sandstones | Rapid fallout deposition with weak traction from highly concentrated, quasi-steady turbulent flow |
| Stratified sandstone          | Thin- to thick-bedded; low-angle inclined to planar-stratified, moderately to well sorted fine to medium sandstone; sharp to flat lower contact; pass upward into either massive or ripple-cross laminated sandstones | Tractive deposition from low-concentration, quasi-steady turbulent flow |
| Ripple-cross laminated sandstone | Thin- to medium-bedded; well sorted fine to medium sandstone; asymmetric, non-parallel | Deposition from dilute turbulent flow               |
| Homogeneous mudstone          | Less than 0.2 m thick; massive to laminated and fines upward slightly; dark gray to blackish in colour; each lamina laterally continuous; sparsely including sandstone blocks and calcareous nodules | Suspension settling of fine-grained turbulent flow   |
| Limestone                     | Occurred as beds, nodules or boulders within mudstones; consisting of skeletal wackstone to grainstone, and boundstone, including diverse fossil allochems | Resedimented shallow marine carbonate               |

Figure 5 Detailed columnar logs of the Babulu Formation, particularly where well-exposed thick sandstones are encased within the mudstones. Thick-bedded sandstones commonly contain abundant mud chip streaks. See inset map of Figure 4 for logging locations and Table 1 for brief descriptions of lithofacies.
Facies association II: Distal fringe lobe deposits

This association within the FA I mudstones (Mh) is characterised by the alternation of sandstone and mudstone (Figures 5, 8). The 0.5 m-thick sandstone units are composed of massive sandstones (Sm), low angle to planar stratified sandstones (Ss) and ripple cross-laminated sandstones (Sr). These sandstones consist of moderate to well-sorted fine- to medium-grained sand of a light grey to greenish grey colour. Each sandstone bed is laterally persistent over several tens of metres with sharp and flat bases and tops. Some of these beds have wedge-shaped or lenticular and channelised geometries.

The thinly bedded and laterally persistent massive to stratified sandstone, alternating with mudstones with sharp and flat bases, is interpreted as sand-laden turbidity flows on the distal fringe of lobes (Prélart & Hodgson 2013). The ripple cross-laminated sandstone is interpreted as traction movement with fallout processes during waning turbidity flows (Mulder & Alexander 2001; Mulder et al. 2003). Some channelised sandstone beds are interpreted as a filling of minor channels or scours influenced turbidity flows.

Facies association III: Medial to distal lobe deposits

This association is the most interesting feature of the formation and is characterised by the frequent and abrupt presence of thick- to very-thick-bedded sandstones (up to 10 m thick) within the FA I mudstones (Figures 5, 9a). It is composed of massive sandstones (Sm), low angle to planar stratified sandstones (Ss), minor ripple cross-laminated sandstones (Sr), homogeneous mudstones (Mh) and disorganised conglomerates (Cm). Each sandstone bed is several tens of centimetres to up to 3 m thick, and some are amalgamated into several to tens of metres thick units with sharp and non-erosional lower surfaces that are laterally persistent over several tens of metres with sheet to tabular geometries. The massive sandstones (Sm) commonly include either one or more discontinuous (≥5 m long) stringers or thin streaks of mud chips and blocks (Figures 5, 9b). The elongated mud chips are generally aligned parallel to the bedding plane or may be imbricated. The sandstones (Sm) are concave-upward, with erosional to flat lower surfaces and relatively flat or slightly undulatory.
The stratified and ripple cross-laminated sandstones (Ss, Sr; Figure 9c) commonly occur above and below the massive sandstones with either sharp or gradational contacts (Figure 5). Some stratified sandstones are also overlain by ripple cross-laminated sandstones and vice versa. The disorganised conglomerate (Cm) is present only in the Fatumea I section and is composed of clast- to matrix-supported, pebble-sized intraformational mud chips set in a muddy sand matrix (Figure 9d). It is about 0.4 m thick and laterally persistent (>5 m in lateral extent) with non-erosive lower surfaces.

The extremely thick-bedded sandstones are interpreted as resulting from the deposition by turbidity flows as evidenced by basal erosive surfaces and moderate to good sorting indicating flow turbulence, and parallel and/or ripple laminated top divisions showing layer-by-layer deposition (Hodgson 2009). Therefore, these sandstones, together with the internal variation of depositional structures and repeated mud chip layers, are interpreted as a gradual aggradation of a highly concentrated, sustained quasi-steady turbidity flow (Kneller & Branney 1995; Mulder & Alexander 2001; Mulder et al. 2003; Petter & Steel 2006; Plink-Björklund et al. 2001). Good preservation of the mud chips and blocks within the massive sandstones indicate an origin in the upper parts of the turbidity currents (e.g. Postma et al. 1988) that have not disaggregated sufficiently in the body of the flow to increase the clay content and suppress turbulence. Lack of significant internal erosion surfaces in

Figure 7 Photomicrographs of limestone in the mudstone. The limestone is composed of diverse fossil allochems: (a) miliolid benthic foraminifera (MF), (b) brachiopod (Br) and echinoid (E) fragments, (c) crinoid fragments (Cr), and (d) chaetetid sclerosponge fragment (Cr) and calcimicrobes.

Figure 8 Deposit features of FA II. Thin- to medium-bedded, massive sandstone (Sm) encased within the mudstone show a good lateral continuity with sharp and flat bases and tops.
the thick sandstones, which were formed by erosive bypass of sediments in feeder channels of a lobe system, suggests that these are deposits from the relatively medial to distal part of the lobe (Hodgson 2009; Macdonald et al. 2011). The unidirectional ripple cross-lamination at the top of the massive to stratified sandstones is interpreted as traction movement with fallout processes during waning turbidity flows (Mulder & Alexander 2001; Mulder et al. 2003). The disorganised conglomerates are interpreted as debris flows (Johnson 1984).

**U–Pb Geochronology**

Handpicked zircon grains were mounted in an epoxy disk with the FC-1 zircon standard (1099 Ma; Paces & Miller 1993). The surface was ground using abrasive paper and polished with a diamond suspension to expose the grain interiors. The mount was then photographed at 50× magnification in reflected and transmitted light to reveal internal structures within the zircons. For further investigation of zonation microstructures, cathodoluminescence (CL) and backscattered electron images were also obtained using a scanning electron microscope (JEOL 6610LV). After whole-image analysis, the mount was ultrasonically cleaned in petroleum ether and ethyl alcohol, rinsed in Millipore water and then dried in an oven at 60°C. It was then evaporatively coated with high purity Au prior to SHRIMP analysis. U–Pb ages were measured using a SHRIMP-IIe MC installed at the Korea Basic Science Institute (KBSI) in Ochang. Analytical procedures for the SHRIMP dating largely followed those of Williams (1998) and Williams et al. (2009). U–Pb isotopes of zircon were collected using a primary oxygen ion (O2−) beam of 3.0 to 4.0 nA intensity at 10 KeV with a diameter of approximately 25 μm. Secondary ions, accelerated to 10 KeV, were analysed by cycling of the magnet through five scans. The mass resolution at 1% of the 238U16O peak height was greater than 4500, and the total Pb sensitivity was within the range of 14 to 19 counts/s/ppm Pb/16O 2−. Prior to each analysis, the surface of the analysis site was pre-cleaned by rastering the primary beam for 3 minutes to reduce surface common-Pb. The measured 206Pb/238U ratio was calibrated using the FC1 zircon. Concentrations of U and Th were calculated with reference to standard SL13 (Sri Lankan gem zircon, U = 238 ppm). Ages were calculated and concordia diagrams produced using the Squid 2.50 and
Isoplot 3.71 programmes of Ludwig (2008, 2009). The reproducibility of reference materials for samples ranges from 0.19–0.21%. A ratio of 137.818 was used for natural abundance of $^{238}\text{U} / ^{235}\text{U}$ (Hiess et al. 2012). The age data in the probability density diagrams are shown using $^{207}\text{Pb} / ^{206}\text{Pb}$ ages for zircons older than 1.0 Ga, and $^{206}\text{Pb} / ^{238}\text{U}$ ages for younger zircons. The $^{207}\text{Pb} / ^{206}\text{Pb}$ age is more reliable for the older zircon having large amounts of radiogenic Pb, whereas $^{206}\text{Pb} / ^{238}\text{U}$ age is ideal for younger zircon due to low radiogenic Pb content and uncertainty of common Pb correction (Anderson 2007). Ages with less than 15% discordance were used to avoid analytical bias owing to Pb loss or common Pb contamination.

The zircon grains (50–300 $\mu$m in diameter) from three sandstones (BA21, BA6 and BA12) occurred as subhedral to euhedral crystals showing oscillatory and sector zoning in CL images (Figure 10a–c). Many grains had rounded to sub-rounded terminations, indicating abrasion during sedimentary transport and reworking. The analysed zircon grains had a range of U contents and Th/U ratios as follows: (1) 52–1134 ppm and 0.21–1.30 for the Belulic Leten 1 measured section sample BA21; (2) 33–1013 ppm and 0.03–2.56 for the Belulic Leten sample BA6; and (3) 81–1150 ppm and 0.20–1.74 for the Fatumea measured section sample BA12 (Appendix II). The combined $^{206}\text{Pb} / ^{238}\text{U}$ and $^{207}\text{Pb} / ^{206}\text{Pb}$ apparent ages and age clusters of the grains ranged from Neoarchean to Triassic/Early Jurassic, depending on the area (Figure 10a–c; Appendix II): (1) 2492, ca 1845–1720, 1565–1533, 1126, 920, ca 352–254 and 204 Ma for Belulic Leten 1 measured section sample BA21; (2) 2721, 2196, ca 1875–1440, 1035, 820, ca 597–577, 497, ca 409–457, ca 378–332, ca 290–238 and 193 Ma for Belulic Leten sample BA6; and (3) ca 1842–1726, ca 1570–1429, 931, 601, 568 and 290 Ma for the Fatumea measured section sample BA12.

In three sandstone samples (BA21, BA6 and BA12), the estimated deposition ages are inferred from the major
Figure 11 Concordia and probability density plots of SHRIMP U–Pb isotopic analyses of detrital zircon from the sampled sandstones in the Babulu Formation and Bobonaro Mélange.
pulses around the Paleozoic to Triassic ranging from 597 Ma to 236 Ma and a youngest age of ca 203–193 Ma (Figure 10a–c) because of the possibility that the very few Jurassic ages are the result of radiogenic Pb loss from older grains. The age results for the detrital zircons suggest that deposition of the Babulu Formation was initiated after the Upper Triassic (238 Ma).

In contrast, sandstone (B13) from the Babulu Formation in the Bobonaro Mélange in the western part of the Fatumean area contains zircon grains (50–400 μm in diameter) with a euhedral to subhedral crystal shape (Figure 10d) and are oscillatory and sector-zoned under CL. The grains showed low to moderate U contents (18–656 ppm) and a wide range of Th/U ratios (0.02–2.18) (Appendix II). Estimated ages were concentrated between 400 and 236 Ma, but ages of 62 SHRIMP spot analyses ranged from 2804 to 236 Ma. This suggests a detrital origin of zircons from this rock and

Figure 12 Histograms for the age results of the present SHRIMP U–Pb and compiled LA-MC-ICP-MS U–Pb zircon age dating.
sedimentation after the early Upper Triassic (Figure 11d). The provenance of the B13 sandstone from the Bobonaro Mélange is likely similar to the provenances of the BA6 samples from the Babulu Formation because the probability density diagrams of the three specimens are similar, with the exception of the upper limit ages (Figure 11).

**DISCUSSION**

**Geochronological implications of the Babulu sedimentary rocks in the Fohorem area**

Recent studies based on ID-TIMS and SHRIMP U–Pb detrital zircon dating have implications for the provenance and tectonic history of the pre-collisional sedimentary rocks in East Timor and the Savu Island in Indonesia (Zobell 2007; Standley & Harris 2009; this study). Detrital zircon from sandstones from the Babulu Formation in East Timor and Savu Islands in Indonesia and northwestern and western Australia have SHRIMP (from this study) and previous ID-TIMS U–Pb (Zobell 2007; Hall & Sevastjanova 2012) ages between Paleoproterozoic and Paleozoic (Figure 12). In this study, detrital zircon SHRIMP U–Pb ages from four sandstones in the Babulu Formation included in the Gondwana Sequence units ranged from the Neoarchean or Paleoproterozoic (ca 1911 Ma) to Upper Triassic (ca 238 Ma), depending on the locality (Figures 11, 12). Predominant age pluses between the Paleozoic and Late Triassic were identified in these samples. Previously reported U–Pb ages of detrital grains from the Babulu Formation sandstone of the Savu and East Timor (Zobell 2007), using laser ablation (LA)-inductively coupled plasma mass spectrometry (ICP-MS), have produced age ranges from ca 2543 Ma to ca 256 Ma, with major peaks at ca 1878–1857 Ma and ca 329–256 Ma (Figure 12). The combined zircon geochronological data indicate that zircon source regions of the Babulu sandstones should be from the peripheral Australian continent (Figure 12). Although sedimentation of the Babulu Formation was likely initiated after ca 256 Ma in some regions (Figure 12; Zobell 2007), the young major detrital zircon age groups of ca 256–238 Ma from most sandstones of the Babulu Formation in the Fohorem Quadrangle, reflect prolonged sedimentation after the early Upper Triassic (Figure 12).

**Paleoenvironments of the Babulu sedimentary rocks in the Fohorem area**

The Babulu Formation in Timor was previously interpreted as ranging from a non-marine (based on the absence of marine fauna) (Barkham 1993) to an outer fan marine environment where water depths exceeded over 200 m (based on the trace fossil assemblage) (Bird & Cook 1991). The detailed depositional processes, however, still remain to be studied. The predominant occurrence of laminated to thin-bedded mudstone successions, and the lack of hummocky cross-stratification and wave ripples in the intercalated sandstones, indicate that the deposition of the Babulu Formation in the study area was not influenced by storm waves (Pickering et al. 1986). The mudstones (FA I) containing large clasts further indicate that they were deposited near or beyond a high gradient depositional surface, with a slope likely produced by a progradation or aggradation of fan-delta systems (Nemec & Steel 1988; Hwang et al. 1995; Kim et al. 1995; Sohn et al. 1997; Sohn 1999, 2000; Hwang & Chough 2000). The above interpretations suggest that the Babulu Formation was deposited in a relatively deep marine environment that is commonly developed in a submarine lobe system (Prèlat et al. 2010; Macdonald et al. 2011; Prèlat & Hodgson 2013) (Figure 13).

Submarine lobes show complicated vertical variation in lobe successions such as thickening- and/or thinning-upward successions resulting from forward and/or backward stacking of depositional lobes together with the migration of lobe systems (Macdonald et al. 2011; Prèlat & Hodgson 2013; So et al. 2013). The predominant occurrence of the basin plain mudstones (FA I), together with the distal lobe sandstones (FA II), suggests that the paleodepositional environment of the study area was very calm and low-energy setting with slightly basinward input of the distal part of the depositional lobes. The bimodal sedimentary materials from siliciclastic to carbonate materials are indicative of differently sourced submarine lobes from silicic to carbonate shelf...
environments (Charlton et al. 2009). The discrete and abrupt occurrence of thick-bedded sandstones (FA III) within the mudstones (FA I), in particular, shows a lack of systematic vertical variation of the depositional lobe. The non-cyclic architecture of the deposits indicates that the origin of the relatively large submarine lobes is closely related to the collapse of upslope sediments rather than a progressive basinward progradation of distributable depositional lobes in association with deltaic turbidite (e.g. Bird & Cook 1991; Charlton et al. 2009) (Figure 13). These abrupt and intermittent collapses of the basin-fill sediments are interpreted to be the result of new or renewed fault activity during basin evolution (Charlton et al. 2009). The repeated occurrence of thin mud chip layers in the thick-bedded sandstones suggests that the depositional lobe was composed of multiply pulsed turbidity flows, resulted from a retrogressive slope failure of upslope sediments (Mastbergen & van Den Berg 2003; van Den Berg et al. 2002).

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SUPPLEMENTAL PAPERS

Appendix I Concordia plot of SHRIMP U–Pb isotopic analysis of zircon from early Permian trachyandesite in the Maubisse Formation.

Appendix II SHRIMP U–Pb data of detrital zircons from sedimentary rocks of the Babulu Formation in the Fohorem area.

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