ABSTRACT
Quartz-rich sandstones in the Banda Arc Islands are thought to be the equivalent of Mesozoic sandstones on the Australian NW Shelf, where they are important proven and potential reservoirs. Previous studies suggested that rivers draining Australia provided most of the sediment input, and there have been suggestions of a northern provenance for some Timor sediments. We summarise results from a provenance study of Triassic and Jurassic sandstones of the Banda Arc between Timor and Tanimbar, which used several methodologies including conventional light and heavy mineral point-counting, textural classification, and laser ablation (LA-ICP-MS) U-Pb dating of detrital zircons. Some of the new results challenge traditional ideas; some new sources are suggested with implications for palaeogeographic reconstructions and sediment pathways. Most sandstones are quartz-rich and detrital modes suggest a recycled origin and/or continental affinity, consistent with an Australian source. However, many of the sandstones are texturally immature and commonly contain volcanic quartz and volcanic lithic fragments. Heavy mineral assemblages are dominated by rounded ultra-stable minerals, but mixed with angular grains, and indicate an ultimate origin from acid igneous and metamorphic sources. Detrital zircon ages range from Archean to Mesozoic, but variations in age populations indicate differences in source areas along the Banda Arc both spatially and temporally. They suggest that sediment was derived mainly from the Bird’s Head, Western and Central Australia in the Triassic. In the Jurassic new local sources close to Timor need to be considered, combined with recycling of NW Shelf material. In the Tanimbar Islands and Babar, sediment came from both the Australian continent and from the Bird’s Head. Sandstones in Timor show a greater acid igneous signature in the east, whereas the west is more dominated by metamorphic sources. A new palaeogeographic model is proposed to explain the history of some of these islands in relation to the autochthonous Bird’s Head.

INTRODUCTION
Timor, Babar and Tanimbar are situated in eastern Indonesia between Australia, New Guinea and Sulawesi (Figure 1) and are part of the outer Banda Arc islands. They have been elevated as a result of on-going convergence and subduction processes. Many of the exposed rocks (Figure 2) are the equivalents of offshore formations along the NW Shelf of Australia that contain important hydrocarbon reservoirs (e.g. Jurassic Plover Formation).

It has been generally assumed that during the Mesozoic, large rivers drained the Australian continent and large fluvio-deltaic systems filled the major offshore basins of the NW Shelf (Figure 1), and that most sandstones south of Timor contain sediment delivered from those rivers draining northern Australia. Bishop (1999) suggested that marine sandstone reservoirs and deltaic mudstones of the Jurassic Plover Formation were deposited within a fluvial to marginal marine setting. Barber et al. (2003) proposed sediment pathways for the Jurassic Plover Formation (offshore) through the Malita and Calder Graben with deltaic fans from the greater Kimberley area, including pathways along the Goulburn Graben. Further west, Southgate et al. (2011) suggested Australian sources, based on detrital zircon geochronology, with main pathways from Western Australia via the Perth and Canning Basin (Lewis and Sircombe, 2013). However, there were additional suggestions of a northern source for some Timor sandstones (Bird and Cook, 1991). A few provenance studies have been done in the Banda region, but none using heavy minerals and few studies have used detrital zircon geochronology. This paper reports the results of a new provenance study in the region.
GEOLOGICAL BACKGROUND

Structure, basement, sequences of siliciclastic sedimentary rocks and fossil assemblages vary considerably from island to island in the Banda Arc. Rocks include an extensive series of Mesozoic sedimentary, metamorphic and volcanic rocks (Hamilton, 1979). A simplified stratigraphy showing formations investigated is presented in Figure 2. Lithologies are mainly siliciclastic and calcareous sedimentary rocks that were derived from the Australian continental margin and were subsequently uplifted due to Neogene collision of the arc with the north Australian margin.

Timor consists predominantly of Mesozoic sedimentary rocks (Permian to Cretaceous). Wanner (1913) described the folded lithologies and klippen that are exposed all over the island, as complex and difficult to unscramble. The Triassic Niof and Babulu Formations are common in West Timor (Kekneno and Kolbano area) and consist of mudstones, very fine-grained greenish-grey siltstones and grey, well-bedded sandstone beds. Specimens of *Daonella* indicate a Middle Triassic age (de Roever, 1940). The Jurassic Wai Luli Formation in West Timor contains light grey mudstones and finely bedded fine-grained siltstones. The Oe Baat Formation contains fine-grained sandstones with conglomeratic layers.

The island of Babar is a typical mud volcano. Fahrizal (1993) described various units, and separated Mesozoic lithologies into shales and erupted fragments. The Triassic Maru Formation contains well-bedded thinly laminated grey-green fine-grained sandstones with dark weathering colours. Visual and lithological similarities to the Triassic Maru Formation in the Tanimbar Islands suggest a comparable age, depositional environment and origin along the NW Shelf of Australia. Jurassic sandstones are limited to the northern edge of the basin (Suparman et al., 1987) and comprise fine-grained greenish-grey micaceous rocks that are well-bedded and locally contain mud clasts and plant fragments.

The Tanimbar Islands are the most distal part of the former Australian margin, and have been located within northern Gondwana from at least Early Permian times (Charlton, 2012). Charlton et al. (1991) assigned Upper Triassic to Lower Jurassic sandstones to the Maru Formation which consists of well-bedded sandstones with interbedded siltstone. These sandstones were suggested (Charlton et al., 1991) to be petrographically similar to the Triassic Babulu Formation in Timor (Bird and Cook, 1991). The Ungar Formation was divided by Charlton et al. (1991) into three parts: 1) the Upper Jurassic Lower Sandstone Member which contains massive to poorly-bedded, coarse-grained mature quartz sandstones; 2) the Upper Jurassic to Lower Cretaceous Arumit Member which consists of red shale and interbedded red sandstone, mudstone and chert layers that represent a clear marker within the Ungar Formation, and yields radiolarians that have been dated by Jasin (1996); 3) the Lower Cretaceous Upper Sandstone Member, which includes fine to medium-grained arkosic sandstones.

METHODOLOGY

Petrology

Traditional point counting of at least 300 relevant grains of quartz, feldspar and lithic rock fragments (>0.0625mm) was undertaken to acquire light mineral modes used to produce ternary plots for each unit (Dickinson and Suczek, 1979; Dickinson et al., 1983). The fields in the diagrams for QFL (Quartz-Feldspar-Lithics) and QmFLt (Quartz monocrystalline-Feldspar-Lithic total) have been widely interpreted to indicate possible derivation from ‘continental block’, ‘recycled orogen’ or ‘magmatic arc’ settings. Recent studies have highlighted issues with over-simplified interpretation of these plots when applied in tropical settings (Garzanti et al., 2007; Smyth et al., 2008; Sevastjanova et al., 2012; van Hattum et al., 2008). Textural categories from 1 to 4 were assigned to sorting and roundness of grains. Sorting categories are (1) poorly sorted, (2) moderately sorted, (3) well sorted and (4) very well sorted. Rounding categories are (1) angular, (2) sub-angular, (3) sub-rounded and (4) rounded.

Heavy Minerals

Detrital heavy minerals were analysed using standard methods after Mange and Maurer (1992). Samples collected were crushed, decarbonated in 10% acetic acid, sieved and washed (meshes of 0.063mm and 0.250mm) and separated in a funnel using sodium polytungstate (SPT: 3Na₂WO₄·9WO₃·H₂O) or the lithium equivalent lithium polytungstate (LST) which have densities between 2.82–2.95 g/ml at room temperature.

Identification of heavy minerals was performed manually by using the optical polarising microscope (NIKON Eclipse Lv 100) and additional SEM-analyses were performed to confirm selected
minerals. The ribbon count method used was described by Galehouse (1971).

Common ultra-stable heavy minerals were grouped by their most likely protoliths, based on suggested source rock associations (Feo-Codecido, 1956; Mange, 2002; Nichols, 2009).

Zircon, tourmaline, anatase, monazite, topaz and xenotime are considered to indicate acid igneous (granitic) sources. Pyroxene (Ortho–OPX and Clino–CPX), titanite (sphene) and chromium spinel represent basic igneous and ultrabasic (commonly arc-related) sources.

Rutile, garnet, epidote, andalusite, sillimanite, kyanite, chlorite, staurolite and corundum are interpreted to indicate metamorphic sources, mainly of continental character.

Other minerals, such as amphibole, baryte, brookite, zoisite, clinozoisite, sphalerite, prehnite, chloritoid, cassiterite, allanite and vesuvianite are present either in very low percentages or can be assigned to more than one group.

Apatite is a very common mineral and abundant in all samples of this study (up to 50%). Since it can be found in different groups (acid igneous, granite pegmatite, contact metamorphic and basic igneous), it is treated separately.

Further varietal studies of zircon (colourless: euhedral, subhedral, subrounded, rounded, anhedral, elongate, zoned; purple: rounded, idiomorphic; brown, matrix-attached) and tourmaline (brown: rounded, idiomorph; blue: rounded, idiomorphic; green: all shapes) were performed during counting.

**Zircon geochronology**

Geochronology using detrital zircons is a powerful method to assess provenance and correlate sedimentary units with identical provenance (e.g. Goldstein et al., 1997; Cawood et al., 1999; Cawood et al., 2003; Fedo et al., 2003; Gehrels et al., 2006; Sevastjanova et al., 2011; Schoene, 2014). The maximum depositional age (MDA) of sedimentary rocks can be determined (Dickinson and Gehrels, 2009) and it is a valuable tool to improve tectonic models and palaeogeographic reconstructions (Murphy et al., 2004).

Selected samples were imaged with scanning electron microscope cathodoluminescence (SEM-CL) at University College London. U-Pb ages were acquired by the author at University College London using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS). U and Pb isotopes were analysed, using the following parameters: spot sizes of the ablation pits: 20-35μm; pulse repetition: 8-10Hz; dwell time: 25s; warm-up: 10-15s; wash-out: 18s. The ablated material was carried in helium gas into the plasma. A quadrupole mass spectrometer (Agilent Technologies 7700 Series ICP-MS) was used. Standards that were used were the Plešovice zircon (337.13±0.37 Ma) by Sláma et al. (2008) and a reference glass NIST SRM 612 (Pearce et al., 1997). In summary, 2540 concordant grains were analysed from 24 samples (17 Triassic and 7 Jurassic). An average of 108 grains per sample (42 to 173) was achieved.

The numerical ages assigned here to periods, epochs and stages are based on Gradstein et al. (2012).

**RESULTS**

**Textures and petrography**

Figure 3 shows the results of point counting and textural analysis of sandstones from the various islands. In general samples are dominated by quartz with varying concentrations of feldspar and lithic fragments. Sorting and rounding vary between the islands.

**Triassic**

In West Timor, grains are angular to sub-angular and poorly sorted to very well sorted. Samples plot in the recycled orogen / dissected magmatic arc field on the QFL diagram and within the dissected magmatic arc / transitional-recycled orogen on the QmFLt diagram (Figure 3A). Textures plot in an immature to mature field with negligible recycling.

In East Timor compositionally immature sandstones (sub-angular to subrounded/ moderately to well-sorted grains) are characteristic of the Babulu Formation. The moderately immature lithic arenites plot in the recycled orogen (QFL)/ mixed magmatic arc (QmFLt), displayed in Figure 3A.

The Maru Formation in Babar commonly contains material indicating a mixed source. Polycrystalline quartz is common as well as lithic (volcanic) fragments and un-weathered feldspar grains. Sandstones are generally moderately immature, lithic-dominated arenites with textures suggesting relatively few cycles of reworking. However, the compositions of the samples plot in a recycled
orogen field of the QFL diagram (Figure 3A) and range from lithic recycled, transitional recycled to quartzose recycled in the QmFLt diagram. Volcanic quartz is also abundant in all samples and is likely to be derived from a contemporaneous acid igneous source.

Triassic quartz-dominated sandstones are significant rocks in Taninbar. Textures vary between angular to rounded and poorly to very-well sorted. Lithic fragments and feldspar grains are common in the Maru Formation on Taninbar. Sandstones are generally immature lithic to feldspathic arenites. The QFL diagram shows modal compositions that indicate a recycled orogen source, the QmFLt diagram shows a dissected/mixed magmatic arc and quartzose recycled character (Figure 3A). Volcanic quartz is abundant and likely to have been derived from a contemporaneous acid igneous source.

Jurassic

The one Jurassic sample from West Timor is a moderately immature (sub-angular grains and poorly to moderately sorted) lithic to feldspathic arenite which plots on the QFL diagram within the area of recycled orogen source (Figure 3B). The QmFLt diagram shows mixed magmatic arc affiliation.

Samples from the Jurassic Sandstone Unit in Babar have high abundances of volcanic quartz combined with lithic fragments and feldspar. Sandstones have an immature recycled character with sub-angular grains and moderate to very well sorted textures. Samples fall in the recycled orogen to transitional recycled orogen / mixed magmatic arc fields. Minor local reworking of older (Triassic) material is possible for the Jurassic Sandstone Unit in Babar (Figure 3B).

In Taninbar there is a relative high concentration of rounded monocrystalline quartz in the Jurassic Lower Sandstone Member of the Ungar Formation. Lithic fragments and feldspar are considerably less abundant than in the Triassic Maru Formation. Sandstones generally are relatively mature with angular to rounded grains and range from poorly sorted to very well-sorted. The QFL diagram indicates a recycled orogen / quartzose source, and the QmFLt diagram a dissected to mixed magmatic arc provenance (Figure 3B).

Heavy minerals and their protoliths

Triassic

The Niof Formation in West Timor shows a strong metamorphic signal (46%), based on the relative abundance of andalusite and chlorite (Figure 4A). The Babulu Formation in the Kolbano area contains, on average, 37% metamorphic, 16% acid igneous and 16% basic igneous grains. The metamorphic signal is indicated by garnet and chlorite. There is a mixture of rounded zircon and tourmaline as well as idiomorphic grains. 20% of zircon grains are attached to a matrix. It is striking that matrix-attached zircon grains are dominant in the Kekneno area, whereas in the Kolbano area a mix of rounded and idiomorphic zircons predominates.

In the East Timor sandstones, heavy minerals include a mixture of grains with metamorphic and acid igneous character (Figure 4A). Zircon varieties include idiomorphic, matrix-attached and rounded. Tourmalines are dominated by idiomorphic grains. Metamorphic minerals are predominantly garnet and rutilite (ET 11 and ET 16), and garnet, andalusite and epidote (ET 09).

Babar sandstones consist on average of 49% acid igneous/sedimentary (zircon, tourmaline), 17% metamorphic (rutilite, garnet, minor Al-silicates) and 7% basic igneous/ultramafic (pyroxene and Cr-spinel) grains (Figure 4A). Zircon shapes are dominantly idiomorphic (50%) with 40% rounded grains and 10% matrix-attached. Tourmaline morphologies are dominated by idiomorphic grains (69%) accompanied by 31% rounded.

Taninbar sandstones consist on average of 49% acid igneous/sedimentary, 21% metamorphic (garnet, rutilite and minor andalusite) and 9% basic to intermediate igneous grains (Figure 4A). Morphologies of zircons are dominantly idiomorphic. Tourmalines are 80% idiomorphic and 20% rounded. In general, samples are compositionally and texturally very similar to Triassic samples from Babar.

Jurassic

Grains in West Timor sandstones are 43% metamorphic origin (indicative minerals are garnet, andalusite and chlorite), suggesting a medium grade contact and regional metamorphic source (Figure 4B). The acid igneous minerals contribute on average 21% and the basic igneous 2%. Morphologies are clearly dominated by idiomorphic zircon (~67%) and tourmaline (~67%) grains. A contemporaneous igneous source is interpreted for the Jurassic in West Timor, mixed with metamorphic input.

BAB 34 and BAB 35 show different abundances of heavy minerals in Babar. BAB 34 appears similar to
other Jurassic samples in West Timor and Tanimbar, dominated by 69% acid igneous/sedimentary and 26% metamorphic grains (Figure 4B). Morphologies of zircons and tourmaline are dominated by rounded grains. BAB 35 in comparison consists of 20% acid igneous/sedimentary, 9% metamorphic and 40% basic/intermediate igneous grains. Morphologies of zircons are dominated by idiomorphic grains (53% idiomorphic, 31% rounded, 16% matrix-attached). Tourmalines are 74% idiomorphic and 26% rounded.

Tanimbar samples consist, on average, of 77% acid igneous/sedimentary, 11% metamorphic and 2% basic igneous to intermediate grains (Figure 4B). Morphologies of zircon are dominated by rounded grains. Tourmalines are 88% rounded and 12% idiomorphic. The predominance of rounded zircon and tourmaline is characteristic of the Lower Sandstone Member of the Ungar Formation. In contrast to the Triassic Maru Formation, metamorphic and contemporaneous igneous grains are less abundant. The Arumit Member sandstones consist of 25% acid igneous/sedimentary, 19% metamorphic (garnet, epidote, sillimanite) and 2% basic igneous to intermediate grains. The heavy minerals are dominated by apatite (41%). Morphologies of zircon are idiomorphic (47%), rounded (29%) and matrix-attached (24%). Tourmalines are 85% idiomorphic and 12% rounded.

**Zircon Geochronology**

**Triassic**

Histograms of detrital zircon ages from Triassic formations in the Banda Arc are notably similar (Figure 5A), with comparable proportions of Precambrian to Phanerozoic grains. Results show a mixture of different age populations. In West Timor the Niof and Babulu Formations are grouped together. The youngest zircon age (208.1±2.3 Ma; SZ 41) constrains the maximum depositional age (MDA) to Late Triassic (Rhaetian). Other samples also indicate Late Triassic ages: 230.5±4.2 (Carnian), 237.2±4.1 (Ladinian-Carnian), 208.1±2.3 (Rhaetian), 217.1±2.5 (Norian), 209.5±4.4 (Norian). Most abundant age populations (Figure 5A) are Permo-Triassic (29.1%), Cambrian to Carboniferous (28.3%) and Paleoproterozoic (20.5%). The main peaks are at 250, 320, 1200, 1600 and 1800 Ma.

In East Timor the youngest zircon age from samples ET 11 (MDA: 230.5±3.4 Ma) and ET 16 (MDA: 227.7±2.8 Ma) constrain the maximum depositional age of the Babulu Formation to Late Triassic (Carnian-Norian). Age spectra are composed of 57.3% Phanerozoic, 39.3% Proterozoic and 3.4% Archean ages. Most abundant populations are Permo-Triassic (29.5%), Cambrian to Carboniferous (27.4%) and Paleoproterozoic (23.6%). The main peaks are at 230, 330, 550, 1200 and 1600 Ma.

Grouped Triassic samples in Babar have a youngest zircon age (209.5±3Ma; BAB 05) which indicate a maximum depositional age of Late Triassic (Norian/Rhaetian) for the Maru Formation. Samples contain 55.9% Phanerozoic, 42.6% Proterozoic and 1.5% Archean ages. Principal populations are Cambrian to Carboniferous (30.7%), Paleoproterozoic (28.9%) and Permo-Triassic (25.3%). The main peaks are at 230, 270, 320, 370, 1600 and 1800 Ma.

Triassic samples in Tanimbar belong to the Maru Formation. The youngest zircon age (202.2±2.4 Ma; TAN 24) within this group indicates a maximum depositional age of Late Triassic (Rhaetian). Samples include 62.6% Phanerozoic, 36.2% Proterozoic and 1.3% Archean ages. Most abundant age populations are Permo-Triassic (31.3%), Cambrian to Carboniferous (31%) and Paleoproterozoic (25.2%). The main peaks are at 230, 290, 360, 1600 and 1800 Ma.

**Jurassic**

Histograms for Jurassic formations on different islands in the Banda Arc differ significantly from each other (Figure 6). The different relative proportions of Precambrian and Phanerozoic ages (Phanerozoic domination in West Timor) and (Precambrian domination in Tanimbar) indicate different sources.

In West Timor one Jurassic sample (SZ 44) has a youngest zircon age of 148.2±2.1 Ma (MDA) that indicates Latest Jurassic (Tithonian) or younger deposition. It is striking that the clear predominance of Phanerozoic zircon grains (99.2%) consists of 85.9% Jurassic ages. The second most abundant age group is Permian-Triassic (13.3%). The main peaks are at 160 to 180 Ma. Only one Proterozoic grain was found (0.8%). Archean grains are missing.

The Jurassic Sandstone Unit in Babar has a youngest zircon age of 193.4±3 Ma, constraining the maximum depositional age to Early Jurassic (Sinemurian). Age populations are similar to Triassic samples from Babar and also Tanimbar. Most abundant age populations are Paleoproterozoic (30.5%), Cambrian to Carboniferous (29%) and Permian-Triassic (19.3%).
In Tanimbar the Lower Sandstone Member of the Ungar Formation was undated but suggested to be Jurassic (Charlton et al., 1991). Parynomorph analyses, provided by an unpublished company report (2000) indicated Late Jurassic ages for rocks on the islands close to sampling locations of this study. TAN 18 and TAN 20 were sampled just below the well-dated Arumit Member which contains Upper Jurassic- Lower Cretaceous cherts (Jasin, 1996). The youngest zircon age (318.1±4 Ma; TAN 30) within this member indicates a maximum depositional age of Carboniferous (Bashkirian), which is rather unexpected considering the Jurassic depositional age. Most abundant age populations are Paleoproterozoic (41.2%), Mesoproterozoic (34.4%) and Neoproterozoic (14.3%). The main peaks are at 350, 900, 1200, 1600, 1800 and 2500 Ma.

**DISCUSSION**

The samples analysed are mainly of quartz-rich sedimentary rocks. Light minerals show a similar composition in different islands that, according to conventional plots, indicate derivation from a recycled orogen in a continental block setting, with a minor magmatic arc influence. Monocrystalline quartz and lithic volcanic fragments (felsic phenocrysts) are common and indicate an acid volcanic source. Potassium feldspar suggests an acid igneous source. Some polycrystalline quartz and plagioclase may indicate metamorphic or arc-related sources. High volcanic quartz proportions are common, and were not previously reported. Compositionally, sandstones are mainly mature, but textures are mainly immature. Textures suggest a mixture of contemporaneous volcanic and polycyclic recycled input. We therefore interpret differences in compositional and textural maturity to reflect the mixing of contemporaneous and recycled material.

Heavy minerals from the Banda Arc Islands are dominantly ultra-stable minerals zircon and tourmaline, accompanied by apatite, garnet, with subordinate andalusite, chlorite and minor pyroxene. Variations between the islands and individual formations indicate changes in provenance, and possibly different sediment pathways, from the Triassic to the Jurassic.

The few studies with detrital zircon age data at the extreme western and eastern ends of the Banda Arc correlated specific zircon age populations to volcanic, metamorphic, sedimentary and meta-sedimentary sources, and interpreted tectonic events. Provenance and geochronology studies by Southgate et al. (2011), and Lewis and Sircombe (2013) using NW Shelf well samples, and Gunawan et al. (2012) in the Bird’s Head (Figure 5B) are a useful guide to some likely sources of siliciclastic sediments in the Banda Arc. Figure 7 shows a map of greater Australia and SE Asia, highlighting the islands investigated and possible main regions (i.e. granitoid bodies, cratons and fragments) that could have supplied material to the Banda region in the Triassic and Jurassic.

Permian to Triassic age peaks (Figure 5A) in samples of this study are c. 260-240 Ma (West Timor and East Timor) and c. 300-260 Ma (Babar and Tanimbar). Permian to Triassic acid igneous rocks in the Bird’s Head area were identified by Gunawan et al. (2012) as an important source for the Triassic Tipuma Formation. In particular the Netoni Intrusive Complex, the Wariki Granodiorite and the Anggi Granite (Pieters et al., 1983; Pieters et al., 1989; Amri et al., 1990; Robinson et al., 1990) as well as contemporaneous volcanic rocks which need to be considered. In the NW Shelf, Lewis and Sircombe (2013) pointed out that Triassic grains of Norian age in the Mungaroo Formation were unexpected, but their euhedral morphologies suggest short transport distances. Further from the NW Shelf, Permian to Triassic zircons in Sundaland were probably derived from the Tin Belt granitoids in the Thai–Malay Peninsula to Sumatra (Hall and Sevastjanova, 2012). Spencer et al. (2015) suggested similar age peaks (Aileu Complex and Babulu Formations in East Timor) of 230–400 Ma were associated with zircons derived from Tibet and Malaysia. However, Sundaland or Tibet seem very improbable sources for the NW Shelf and Banda sandstones since they are, and were in the Triassic, so distant from the Banda region, as illustrated by tectonic reconstructions (Sevastjanova et al., 2015).

The only Jurassic zircons found in this study are from West Timor samples and have ages of c. 180-160 Ma (Figure 6). Jurassic igneous activity has not previously been recorded in the Banda region. Hall and Sevastjanova (2012) reported that Jurassic zircons are uncommon in most parts of Indonesia. Middle Jurassic zircons have been reported from the Mekongga Formation in SE Sulawesi and a 195 Ma zircon age was reported from the Bobong Formation in the Banggai-Sula Islands (Ferdian, 2012). Park et al. (2014) identified Jurassic zircons from the Lolotoi Complex in East Timor in rocks described as andesites. However, photographs and zircon ages from one of their samples (FV27) suggest it to be volcaniclastic sandstone. Jurassic volcanic activity is suggested here to have provided a new source in the Timor sector of the NW Shelf with an age range of
200-150 Ma, associated with the break-up of Gondwana and the subsequent fragmentation and drift of Australian continental blocks.

**Triassic**

Clear trends from east to west are prominent. Sandstones contain higher proportions of quartz in the eastern islands of Babar and Tanimbar, and increasing feldspar and lithic contents towards West Timor. Volcanic quartz also increases towards the east. Heavy minerals show a greater recycled sedimentary to contemporaneous acid igneous (granitoid) input in the east (Babar and Tanimbar) and a greater metamorphic component in the west (West Timor and East Timor).

Zircon histograms from different islands are very similar (Figure 5A). These indicate that the main Triassic source was most likely the Bird’s Head region (Figure 5B), which provided contemporaneous acid igneous material. Polycyclic sedimentary recycled material is suggested to have been derived from Northern/Central Australia. Western Australia is thought to have supplied material of metamorphic origin to Timor.

Samples from the Banda Arc Islands and the Bird’s Head contain more Phanerozoic than Precambrian zircons (Figure 5A). In contrast, sandstones of the NW Shelf of Australia (Rankin Plateau and Exmouth Plateau; Figure 5B) are dominated by Precambrian zircon populations. Archean, Mesoproterozoic and Neoproterozoic grains dominate within the Mungaroo and Brigadier Formations (Figure 5B), that were suggested to have been sourced from Western Australia via the Proto-Perth Basin (Southgate et al., 2011; Lewis and Sircombe, 2013). There is an increase in Permian-Triassic material and a decrease in Neoproterozoic and Mesoproterozoic zircons from west to east. Paleoproterozoic zircons are not abundant in Precambrian populations of the NW Shelf, but are a significant component in the Bird’s Head and the Banda Arc Islands from Tanimbar to Timor, and a strong 1.8 Ga peak is characteristic of the eastern Banda Arc (Tanimbar and Babar) and Bird’s Head area. In Timor the Paleoproterozoic population peak is broader and includes a strong 1.5 to 1.6 Ga population. Further west, the NW Shelf samples include a moderate number of 1.5 to 1.6 Ga zircons and stronger 1.2 Ga peak. Therefore, Neoproterozoic and Mesoproterozoic zircons are suggested to be sourced from Western Australian cratons, whereas Paleoproterozoic populations were probably sourced from Central Australia and possibly New Guinea.

Timor appears to include zircons sourced from both west and east, whereas the eastern island resemble the Bird’s Head and the NW Shelf has a distinctive western Australian character, which includes a significant number of Archean grains. A simplified palaeogeographic reconstruction with possible fluvio-deltaic systems, depositional environments and distribution of terranes along the greater Banda Arc is displayed in Figure 8.

**Jurassic**

Siliciclastic Jurassic formations in West Timor, Babar and Tanimbar are significantly different from one another with some unexpected and striking provenance features. Sandstone petrography and heavy mineral assemblages indicate relatively compositionally and texturally mature quartz-rich sediments, with zircon morphologies suggesting derivation from mixed sources with a polycyclic reworked character for Babar and Tanimbar and a contemporaneous source for West Timor zircons.

Zircon populations have many similarities to those of the Triassic sandstones. However, there are significant differences between the islands indicating regional differences in provenance. A single West Timor sandstone contains a dominant Jurassic peak with a smaller number of Permian and Triassic zircons (Figure 6) which indicates a contemporaneous volcanic source in the Jurassic. Volcanic activity associated with rifting of the southern Banda Block (later SW Borneo), situated to the north of Timor, is proposed (Figure 9). Average Jurassic ages of ~172 Ma are similar to those from the Lolotoi Complex in East Timor reported by Park et al. (2014). Jurassic zircons are also found in granites of the southern Schwaner Mountains of Borneo (van Hattum et al., 2013; Davies et al., 2014), and in granites of the Inner Banda Block (later NW Sulawesi) reported by Hennig et al. (2015) supporting the palaeo-geographic reconstruction shown in Figure 9.

In contrast, sandstones from Tanimbar contain no Jurassic or Permian-Triassic zircons, but abundant Neoproterozoic, Mesoproterozoic and Paleoproterozoic populations. The absence of Jurassic zircons, suggests a position further from the site of active rifting. Samples contain material of mixed provenance from Australia with minimal influence from the Bird’s Head region. The youngest grain is 318.1±3.9 Ma and therefore much older than the depositional age. The most important zircon populations indicate Northern/Central Australia (75.6%) and Western Australia (21.1%) were the
main sources. The Bird’s Head signal (~3.3%) is surprisingly low with no Permian-Triassic zircon populations. The predominance of Proterozoic and Archean ages show striking similarities to Triassic Brigadier and Mungaroo Formations on the NW Shelf of Australia (Figure 5B).

Babar samples contain material indicating a mixed provenance from Australia and the Bird’s Head region and are suggested to be partly reworked from older Triassic material. Major zircon populations indicate sources in Northern/Central Australia (45.2%), the Bird’s Head (41.3%) and Western Australia (12.7%). Contemporaneous sedimentation of the Plover sandstones (Figure 2) within northern Australia took place along the Malita-Calder Graben. The Babar sandstones could be possible distal equivalents.

CONCLUSIONS

Most sandstones are compositionally mature but textures indicate an immature character for many of them. Intermediate-acid igneous and metamorphic ultimate sources are common. The rounding of many zircons suggests multiple episodes of sedimentary recycling. Variations along the north-western Australian margin show that the eastern area (Tanimbar and Babar) is dominated by acid igneous and the western area (Timor) by metamorphic sources.

The Bird’s Head and Sula Spur region are suggested to be previously unrecognized sediment sources from the Triassic onwards. A Western Australian contribution to sandstones in the western islands and a predominantly Central/Northern Australian signal in the eastern islands is suggested. A local and important Jurassic source, associated with rift-related volcanic activity north of Timor is suggested to be associated with separation of the Banda Block from the Australian margin.

As might be expected, considering the distance over which the Mesozoic sandstones of the NW Shelf and Banda Arc were deposited, their provenance is not simple. Light minerals, heavy minerals and detrital zircon dating studies on the Banda Arc islands show that there is a considerable amount still to be learned and that similar studies using offshore material would be of significant benefit to hydrocarbon exploration.

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Figure 1 - Map of the Banda Arc Islands and northern Australia showing the islands investigated and main sedimentary offshore basins with selected sub-basins along the NW Shelf.

Figure 2 - Simplified Triassic and Jurassic stratigraphy for Timor, Babar, Tanimbar and selected formations from offshore Australia (Fm=Formation).
**Figure 3** - Overview of point counting analysis of sandstones from the various islands for the Triassic (A) and the Jurassic (B). Ternary plots after Dickinson (1987) indicate possible provenance affiliation (Q – Quartz, F – Feldspar, L – Lithic fragments, Qm – Monocrystalline quartz, Lt – Total lithic fragments). Simplified comparisons between sorting and rounding were used to estimate maturity.
Figure 4 - Overview of heavy mineral percentages, grouped protoliths and varietal morphology of sandstones from the various islands for the Triassic (A) and the Jurassic (B).
Figure 5 - Histograms showing zircon ages for grouped Triassic formations in the Banda Arc (A) in the Bird’s Head area and offshore Australia (B) with possible source regions. Bin width for the Phanerozoic on the left (0-500 Ma) is 10 Ma, and for the Precambrian on the right (500-4000 Ma) is 50 Ma.
Figure 6 - Histograms showing zircon ages for grouped Jurassic formations in the Banda Arc. Bin width for the Phanerozoic on the left (0-500 Ma) is 10 Ma, and for the Precambrian on the right (500-4000 Ma) is 50 Ma.
Figure 7 - Simplified overview of locations of most relevant potential source areas for the outer Banda Arc Islands based on Southgate et al. (2011), Gunawan et al. (2012) and Lewis and Sircombe (2013).
Figure 8 - Triassic palaeogeographic reconstruction with tectonic elements and major sediment directions showing suggested sources and pathways. The provenance features suggest three principal source areas – Western Australia, Northern/Central Australia and Bird’s Head/Sula Spur.
Figure 9 - Simplified palaeogeographic map with tectonic elements and major sediment directions for the Late Jurassic. Suggested sources and possible pathways are indicated. The provenance features suggest three principal source areas – Western Australia, Northern/Central Australia and Bird’s Head/Sula Spur.