Cretaceous-Paleogene rifting on the NW margin of the Australian continent, SE Banda Arc region

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ABSTRACT

The Banda Terrane successions of Timor Island and correlative units in Sumba are widely considered allochthonous with respect to the Australian continental margin successions that form the main part of the Banda arc-continent collision complex. A new interpretation is proposed for the Banda Terrane, which suggests that these units originated on the outermost (northern) edge of the Australian continent. Volcanic successions in the Banda Terrane, which date to the Cretaceous and Paleogene (Aptian/Albian to Eocene), are interpreted as originating in a backarc/marginal basin setting behind a northward-facing arc that rifted away from the NW margin of Australia through this period. The Banda terrane successions are interpreted as representing the southern, continent-attached portion of the marginal basin, and occupied a position on the distal edge of Australia up to the onset of Banda arc-continent collision in the Miocene.

Supporting evidence for an Australian margin origin of the Banda Terrane includes very similar age ranges for zircons dated to the Cretaceous in Sumba and Timor (Banda Terrane) and in sandstones of the Ungar Formation in Tanimbar, the latter forming an element of the Australian margin succession. In Timor there is also previously reported evidence for continental margin rifting during the Late Cretaceous, while contemporaneous Late Cretaceous-Paleogene volcanism is also recognised in the Bird's Head-Misool region of eastern Indonesia, which forms part of the Australian continental margin. In addition, a number of stratigraphic links between the Banda Terrane and the Australian continental margin successions in Timor are summarised in this study.

The effects of the Cretaceous-Paleogene rifting event are also apparent in subsidence curves derived from petroleum exploration wells drilled on the northern 'passive' continental margin of Australia from SW of Timor to the Bird's Head-Misool region of eastern Indonesia. Inferred rift-related subsidence commenced in the Aptian-Albian on the Australian palaeo-margin immediately east of Timor and developed sporadically but in regionally consistent groupings throughout the Late Cretaceous and Paleogene.

Keywords: *Banda Terrane, Timor Island, NW Australia, Cretaceous-Paleogene rifting*

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INTRODUCTION

In a previous paper published in this journal (Charlton, 2012), the present writer reviewed the paleogeographic evolution of the SE Banda Arc region that extends from Timor Island in the west to the Tanimbar and Kei islands in the east (Figure 1). The present paper seeks to continue the evolutionary development of this region through the Cretaceous and Paleogene. Remarkably, although much closer to the present-day in time, the paleogeographic evolution through the Cretaceous and Tertiary is rather less-well constrained than for the earlier period covered by the preceding paper. The difficulty centres primarily around the ongoing controversy regarding the degree to which there is an 'allochthonous', non-Australian component in the present-day Banda arc-continent collision complex. At present, probably the majority opinion amongst geologists actively investigating this area is that there is a substantial body of allochthonous material in the Banda forearc, and particularly in Timor island where stratigraphic elements such as the Mutis metamorphic complex (in Indonesian West Timor, and its direct equivalent the Lolotoi Complex in Timor-Leste) and their cover sequences including the Cretaceous-Paleogene Palelo Group, the Eocene Dartollu Limestone Formation and Paleogene Metan and Barique volcanic successions are considered to derive from a pre-collisional Banda forearc that developed on the southern margin of

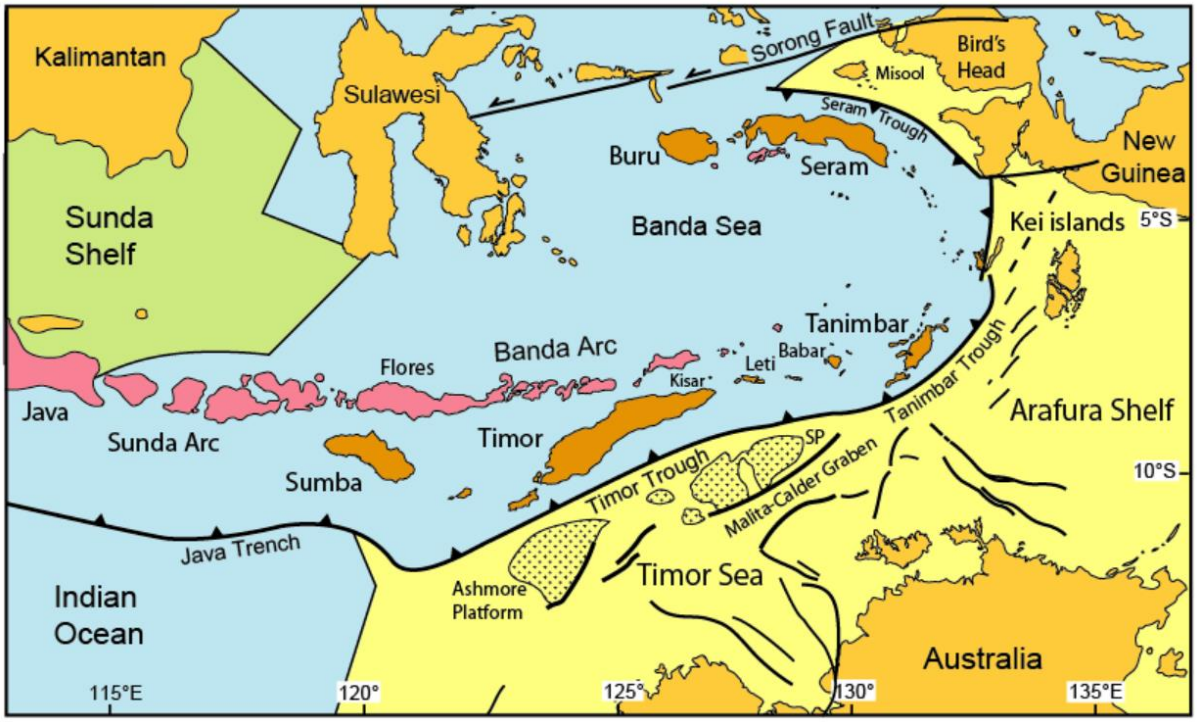


Figure 1: *Location and tectonic setting of the SE Banda Arc region. The Banda-Sunda volcanic arc is shown in pink; the forearc ridge (Sumba, Timor, Tanimbar, western Kei islands, Seram and Buru) in brown. The offshore NW Australian continental shelf (including the offshore areas of the Bird's Head structural block) is shown in yellow; the offshore shelf of the Sundaland continental block in green. Structural highs on the outer Australian margin south of Timor are indicated by the cross symbol (SP: Sahul Platform).*

'Asian' Sundaland. In contrast, the present writer is of the opinion that there is no such substantial allochthon in the Banda collision complex, and that the Mutis/Lolotoi Complex and its cover successions (hereafter referred to as the Banda Terrane, following Harris, 1991, 2006) also originated on the distal north-western margin of the Australian continent. Critical to this interpretation is a suggestion that the various volcanic successions associated with the Banda Terrane did not originate in arc environments as is widely interpreted in the allochthonous model, but rather in oceanic rifting within a marginal basin that developed off the northwest margin of the Australian continent during the Cretaceous and Paleogene.

REGIONAL TECTONIC SETTING

The area under consideration in this study comprises the zone of collision between the north-western continental margin of Australia and island arc systems forming the south-eastern borders of the Asian continent, and particularly the Sundaland structural domain that forms the primary sub-element of the Asian continent in western Indonesia (Figure 1). Arc-continent collision in this region has been ongoing since the Late Miocene, with Keep and Haig (2010) dating the commencement of collision to between 9.8–5.5Ma in Timor. Prior to this, it is widely interpreted that the present Banda Arc formed a direct eastward continuation of the Sunda oceanic subduction system in, and to the south of, present-day Java Island. In the allochthon model the forearc of this pre-collisional subduction zone would have included a microcontinental fragment previously rifted from the Sundaland margin that was obducted onto the Australian margin during collision as the so-called Timor allochthon (or Banda Terrane).

The Banda Arc extends from the islands of Sumba and Flores in the west to the Kei Island group in the east (Figure 1). The inner volcanic arc is a direct lateral continuation of the Sunda volcanic arc to the west, while Sumba forms the westernmost island of the Banda forearc ridge that also includes Timor, a series of smaller islands further east including Kisar, Leti and Babar, and then the larger Tanimbar island group, before the forearc ridge turns northward to the Kei islands and then further northward and then westward again through the islands of Seram and Buru. The islands of the Banda forearc ridge are, for the most part (except for Buru and Sumba islands at either extremity of the arc), considered to form foreland fold and thrust belts composed primarily of distal Australian margin successions stacked beneath the pre-collisional forearc during arc-continent collision. The extent to which there is any remaining pre-collisional forearc in the present-day collision complex is a matter of significant debate in Timor (the Timor allochthon problem) but appears to be minor in other forearc islands to the east and northeast of Timor. In Seram island, for instance, a substantial allochthon was also formerly interpreted by Audley-Charles et al. (1979), but a more recent detailed structural study (Pownall et al., 2013) does not recognise any significant allochthon in that island.

The island of Sumba is perhaps a special case in that it has been widely interpreted as composed entirely of non-Australian tectonostratigraphic elements, and could, therefore, be considered entirely allochthonous with respect to the

Australian margin. It will be argued in the present study, however, that this exceptionalism for Sumba may not be correct, and that this island also consists largely of Australian margin material, although of an atypical character.

To the south of the Banda forearc ridge is the Timor Trough and its north-eastern continuation the Tanimbar Trough, with a further extension to the north and west as the Seram Trough (Figure 1). The Timor Trough is morphologically the direct eastward continuation of the Java Trench which is the subduction trench of the Sunda Arc, and the Timor-Tanimbar-Seram Trough system similarly marks the deformation front of the arc-continent collision complex, with thrusted and folded successions of the collision complex under the inner slopes of the troughs, but little-deformed Australian margin successions under the outer slopes to the south and east of the Timor-Tanimbar Trough. Further south and east is an extensive area of marine continental shelf bordering onto the Australian continent in the south (the Timor Sea), and the marine shelf separating northern Australia from New Guinea island (the Arafura Shelf). The Timor Sea, the western New Guinea margin, and to a lesser extent the Arafura Shelf are areas that have received considerable interest for petroleum exploration, and the second half of this study considers the drilling records for several wells from this area (see Figure 7).

To the southwest of Timor and Sumba is the NE corner of the Indian Ocean, the oldest portion of which is the Argo Basin (Figure 2). The NE Indian Ocean began to develop through oceanic rifting on the Australian continental margin during the

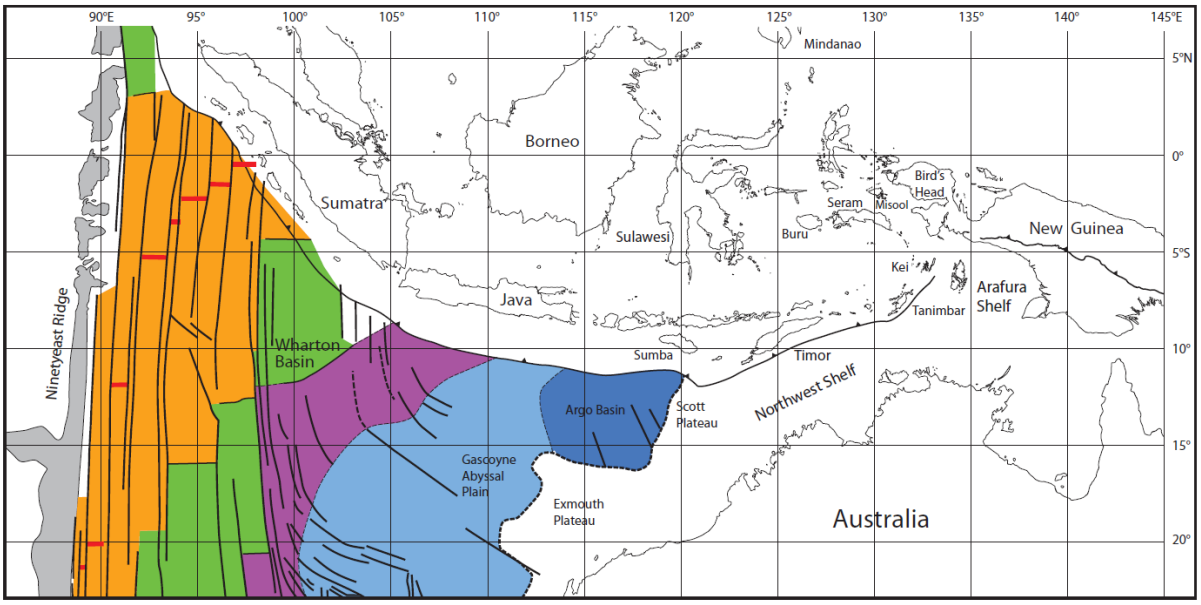


Figure 2: *Simplified spreading map of the northeast Indian Ocean. Oceanic spreading decreases in age from southeast to northwest: dark blue = Argo spreading ~158-130.5Ma (~Oxfordian-Hauterivian); light blue = Gascoyne spreading 130.5-100Ma (~Hauterivian-Albian); purple, green and orange = Wharton spreading subdivided into age bands: purple = 100-83Ma (~Cenomanian-Santonian, Cretaceous magnetic quiet zone); green = 83-66Ma (~Campanian-Maastrichtian); orange = 66-43Ma (Paleocene-mid Eocene). Crustal ages in the Wharton Basin follow Jacob et al. (2014, Figure 2).*

Late Jurassic (Fullerton et al., 1989; Heine and Muller, 2005; Gibbons et al., 2012), and this rifting is clearly connected with Jurassic volcanism on the western margin of Australia to the south of Timor. Latest Jurassic-earliest Cretaceous volcanism was also intercepted in the Banli-1 petroleum exploration well in southern West Timor (Sani et al., 1995). The Indian Ocean continued to develop through the Cretaceous and Paleogene as oceanic spreading propagated to the south and west (Figure 2). The relationship between oceanic spreading in the Indian Ocean and oceanic rifting events interpreted in the present study during the Cretaceous to Paleogene will be considered in a separate paper (Charlton, 2023).

CRETACEOUS – PALEOGENE SUCCESSION IN TIMOR.

Two essentially parallel tectonostratigraphic successions are recognised in the Cretaceous and Paleogene of Timor that can, for brevity, be referred to as the Kolbano and Palelo Associations (Figure 3). The Kolbano Association (also described as the Kolbano Group or Kolbano Megasequence) represents the main stratigraphic succession that accumulated on the distal edge of the northern Australian continental margin. The Kolbano Association consists largely of fine-grained sediments (shales, limestones and radiolarites) deposited in very deep marine environments, primarily outer neritic or deeper, and commonly bathyal and even abyssal. The lowermost part of the Kolbano Association consists of radiolarian shales and cherty radiolarites, commonly reddish in colour, and apparently deposited in ultra-deepwater environments close to or below the carbonate compensation depth (CCD). These rocks are assigned to the Nakfunu Formation in West Timor (Rosidi et al., 1981), and to the Wai Bua Formation in Timor-Leste (Audley-Charles, 1968; and revised stratigraphic nomenclature of Charlton et al., 2020, unpublished). These formations are Early Cretaceous in age, certainly ranging from the late Valanginian to the Aptian (Carter, 1972a, 1972b; Carter, 1973; Clowes, 1997; Munasri, 2019, in Charlton et al., 2020), and may locally range as old as Berriasian in West Timor (Munasri & Sashida, 2018). It seems very likely that the dramatic deepening in sedimentary environments represented by the change from neritic conditions in Timor during the Late Jurassic (*cf*. Charlton, 2012) to abyssal environments during deposition of the Wai Bua/Nakfunu successions is an indication that ocean margin rifting probably continued in the Timor region from the Late Jurassic into the Early Cretaceous.

The predominantly non-carbonate successions of the Wai Bua and Nakfunu Formations pass upwards with apparent gradational transition (in East Timor: Charlton et al., 2020) or perhaps unconformably (in West Timor: Clowes, 1997) into deepwater limestones of the Borolalo Formation in Timor-Leste (Audley-Charles, 1968; Charlton et al., 2020), and the Latan, Menu and Ofu Formations in West Timor (Sawyer et al., 1993; Clowes, 1997). These deepwater limestones, ranging in age from Aptian/Albian (latest Early Cretaceous) to at least the Eocene, have been interpreted as a distal Australian continental margin succession, perhaps deposited on marginal plateaus directly analogous to the Scott and Exmouth Plateaus on the present-day western continental margin of

Australia (Charlton, 1989; Haig, 2012). Deposition in similar deep marine carbonate environments continued into the Miocene, represented by the Aliambata Formation in Timor-Leste (Audley-Charles, 1968; Charlton et al., 2020) and an equivalent succession in West Timor, provisionally described by Charlton & Wall (2004) as the Siu Formation, although this name may be redundant as it now seems clear that the Miocene successions in West and East Timor are sufficiently similar in lithology and age to be described under the single name Aliambata Formation.

The Palelo Association (Palelo Group and stratigraphically related younger units) forms an essentially distinct but parallel Cretaceous and younger lithostratigraphic domain in Timor which, together with the Mutis-Lolotoi metamorphic complexes, comprises the Banda Terrane succession. The Palelo Group is divided into two formations, with the Noni Formation succeeded by the Haulasi Formation (Figure 3). The Noni Formation is composed of radiolarian cherts interbedded with volcanic breccias (van West, 1941; Rosidi et al., 1981; Earle, 1983). As described by van West (1941) from the Miomafo massif in northern West Timor, the lower Palelo (Noni Formation) consists of a basal unit of radiolarian cherts, usually well stratified and dark red brown to dark violet colour, succeeded by more thinly stratified radiolarian cherts,

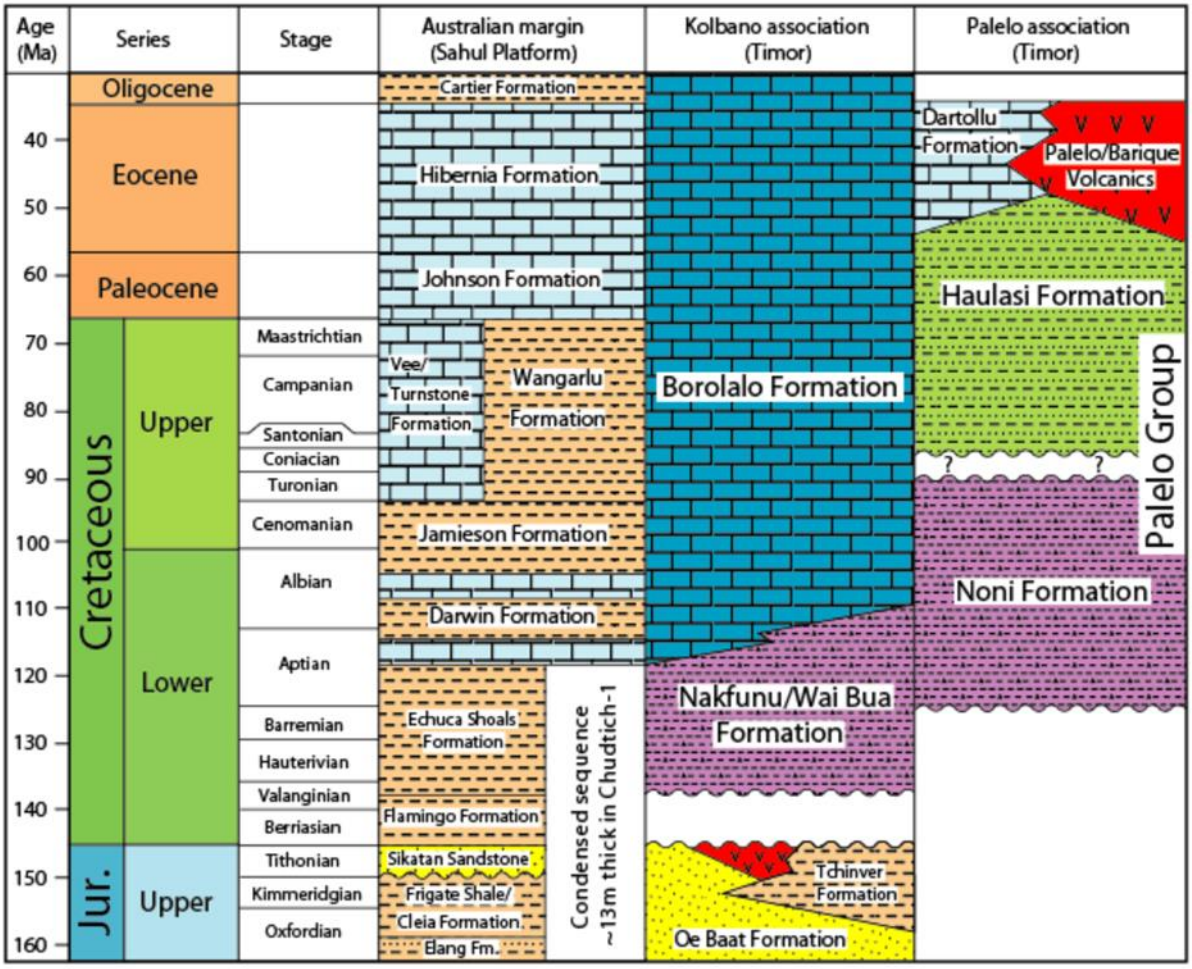


Figure 3: *Cretaceous-Paleogene stratigraphy of the Australian Northwest Shelf (Sahul Platform area) and the Kolbano and Palelo associations of Timor.*

with bedding planes frequently covered by manganese mineralisation. Interbedded volcanic breccias include fragments of slightly schistose albite diabase, establishing a stratigraphic relationship with the crystalline basement. The radiolarian cherts of the lower Palelo are practically devoid of detrital material and were probably deposited in bathyal or abyssal environments. A stratigraphic thickness of 40m was estimated. In West Timor the Noni Formation is dated to the Aptian-Turonian (Audley-Charles et al., 1974; Haile et al., 1979; Munasri & Harsolumakso, 2020).

The succeeding Haulasi Formation consists of conglomeratic greywacke, sandstone, tuffaceous shale, and well-bedded grey to greenish marl, with volcanic material common (Rosidi et al., 1981). The upper Palelo series (Haulasi Formation) in the Miomafo massif was described by van West (1941) as consisting of monotonously grey-green greywacke, tuff, marl, and conglomerate. All sedimentary rocks contain volcanic material, and contemporaneous volcanism was interpreted. The sedimentary succession is intruded by occasional dykes of quartz-augite albitites similar to igneous rocks intruding the underlying crystalline schists. Conglomerates are locally dominant, primarily composed of schist fragments, most commonly graphitic mica-schists, and quartz schists. Less abundant but still frequent are epidote-chlorite schist and amphibolite fragments, all closely comparable in composition to the underlying Miomafo crystalline schists. The conglomerates also contain a few fragments of limestone and chert, and many fragments of igneous rocks (mainly augite-andesites) and much more volcanic material, mainly andesitic and dacitic in composition. The upper Palelo series (Haulasi Formation) was estimated to be 350m thick in this area.

At unspecified locations in Timor, Carter et al. (1976) also recorded clasts of Permian fossiliferous limestones in conglomerates of the Haulasi Formation, and Earle (1979) vesicular basalt clasts resembling Permian Maubisse Formation alkaline lavas.

In the Molo massif, Tappenbeck (1940) recorded a planktonic microfauna recovered from marly claystones and greywackes in the upper part of the Palelo series (Haulasi Formation), including *Globotruncana* cf. *canaliculata*, *Globigerina aequilateralis*, *Guembelina* sp., and *Oligostegina laevigata*. *Concavatotruncana canaliculata*, probably the equivalent of Tappenbeck's *Globotruncana canaliculata*, ranges in age from latest Cenomanian-Coniacian (Boudagher-Fadel, 2013), while *Oligostegina laevigata*, which is now considered a calcisphere of uncertain taxonomic affiliation (Elbrächter et al., 2008), occurs in the Turonian of Switzerland (Elbrächter et al., 2008) and SE Turkey (A. ten Dam, undated manuscript online). No definitive faunas pre-dating the Upper Cretaceous were recognised.

The Palelo Group also outcrops extensively in south-central East Timor, on the southern slopes of the Bubususo massif east and west of Samé town (Carter et al., 1976; Standley and Harris, 2009; Charlton et al., 2018). Standley and Harris (2009) reported cherts and tuffs of the Noni Formation in the Sui River north of Samé, but the present writer failed to relocate this unit. In the Caraulun river, 4km west of the Sui River, the Haulasi

Formation unconformably overlies the Lolotoi Complex. It consists of hard, greenish, brown-weathering medium grained sandstones and siltstones/fine sandstones bedded on a decimetre scale, interbedded with coarse conglomerates containing angular to subrounded clasts up to large cobble size (but mostly pebble grade) consisting of schist, greenstone, acicular and occasionally vesicular basalt fragments, and quartz and calcite pebbles. The sandstone-dominated successions grade upward into finer grained and more thinly bedded clastic successions, eventually becoming predominantly black shales with interbedded thin sandstones. The section is estimated to be about 150m thick. Similar successions are exposed in the Sui and Marak rivers further east, and in many other streams in the Samé area. Samples from the Caraulun section yielded Late Cretaceous palaeontological ages based on dinoflagellates (MGPalaeo, unpublished report to Timor Resources, reported in Charlton et al., 2018), and late Albian-late Cenomanian (or younger) and late Coniacian-Maastrichtian ages based on nannofossils (P.T. Rafflesia Baru, 2020, in Charlton et al., 2020).

The Haulasi Formation (upper Palelo Group) is succeeded by the Dartollu Formation, which consists typically of shallow marine limestones rich in larger benthic foraminifera of Eocene age (Audley-Charles, 1968; Haig et al., 2019). Although originally defined and most widely recognised in East Timor, the Dartollu Formation also occurs widely if sporadically in West Timor, as described by Audley-Charles and Carter (1972) under the name Wiluba facies, and as observed by the present writer in joint fieldwork with Adept Titu Eki (Nusa Cendana University, Kupang) in October-November 2022. It appears, although this needs confirmation by further detailed fieldwork, that the essentially non-volcanic Dartollu Formation may be broadly contemporaneous with volcanic successions of the Metan Formation in West Timor, particularly in its type area in the Metan river where Audley-Charles and Carter (1972) described the Wiluba facies (see also earlier mapping of this area by van Voorthuysen, 1940), and similarly in East Timor, in the type area of Audley-Charles's Barique Volcanics, as documented by Haig et al. (2019). Although direct dating of both the Metan (West Timor) and Barique (East Timor) volcanic successions is limited, Costa et al. (2020) have reported a youngest zircon age of 34Ma (late Eocene) from a volcaniclastic sediment attributed to the Barique Formation collected to the north of Samé in Timor-Leste. In addition, a body of gabbro intruding the Lolotoi metamorphic complex near Fohorem in SW Timor-Leste is also likely to be genetically related to the Metan/Barique volcanic successions, with a zircon date of 55Ma (Early Eocene) interpreted as the age of intrusion (KOICA, 2013).

Further shallow marine limestones accumulated during the Oligocene-Early Miocene in the Banda Terrane successions of Timor, described as the Noil Toko Formation in West Timor (Rosidi et al., 1981) and as the Booi Group (or Booi Formation in the Timor GAP stratigraphic nomenclature: Charlton et al., 2020) in East Timor (Haig et al., 2012). The Booi Formation is named after the Booi (or Boi) massif in West Timor where Tappenbeck (1940) described rocks that Haig and colleagues identified as equivalent to the Oligo-Miocene limestones in East Timor. There are some indications that volcanism continued contemporaneously with deposition of the Noil Toko Formation in

West Timor (Kadar, 1978), and the same may be true for East Timor although this has not been established with any certainty.

CRETACEOUS - PALEOGENE VOLCANISM IN THE BANDA FOREARC AND BIRD'S HEAD

Igneous activity is recorded regionally across SE Indonesia and Timor-Leste during the Late Cretaceous and Paleogene.

Timor

As summarised in the previous section, sandstones in the Late Cretaceous-Paleogene Haulasi Formation are primarily volcaniclastic in origin, and the formation in the West Timor area were intruded by younger but undated basic intrusive (shown to the present writer by Adept Titu-Eki). Although only limited igneous rocks have yet been dated radiometrically to the Cretaceous and Paleogene in Timor, several processed samples of Haulasi sandstone have yielded zircons with radiometric ages that fall within this period (see Table 1). These zircons are presumed, for the most part, to derive from erosion of contemporaneous volcanic successions. For Cretaceous-aged samples from Timor (Figure 4), the majority of zircons date to the Santonian-Campanian, with a substantial tail of ages back to the Aptian, no zircons dating to the late Valanginian, Hauterivian or Barremian (gap between 136.7-124.0Ma), and 3 zircon grains dating to the Berriasian-early Valanginian interval – the one grain dated to the Berriasian deriving from the Kolbano Association (sample SZ 37: Zimmermann and Hall, 2019), whereas all the others can be attributed to the Palelo Association.

Note that the lack of Maastrichtian (latest Cretaceous) zircon ages for the Timor samples in Figure 4 is probably because the sample database was derived primarily from sampling specifically of Cretaceous aged sediments (primarily by Zimmermann and Hall, 2019), and the samples analysed were presumably older than Maastrichtian.

As already discussed in the previous section, in addition to Cretaceous igneous rocks, Paleogene volcanics are also recognised in the Banda Terrane successions of Timor, under the names of the Metan Formation in West Timor and the Barique Formation in Timor-Leste.

This Cretaceous-Paleogene volcanism, with its broadly calc-alkaline geochemistry (Harris, 2006; Standley and Harris, 2009; Benincasa, 2015), has been widely interpreted as arc volcanism, leading to an interpretation that the Banda Terrane successions occupied a position in a subduction arc on the southern margin of Sundaland during this time period – the Great Indonesian Arc of Harris (2006). A geochemical investigation of these Timor volcanic successions by Standley (2007) aimed at establishing their igneous provenance by reference to various discriminant diagrams based on whole rock and trace element proportions. Standley (2007) concluded: "In summary, discriminant analysis results indicate provenance that is transitional between MORB [mid-ocean ridge basalt] and VAB [volcanic arc basalt],

Table 1. *Samples from the southern Banda Arc (Timor, Sumba, Tanimbar, Babar, Kisar and Leti) yielding zircons of Cretaceous-Paleogene age, as reported in previous publications.*

Author	Sample number	Location	Peak/mean age	Age range	Stage equivalent	Notes
Harris (2006)	70	Caraulun river N of Same town, south-central Timor-Leste	83±1.4Ma	90.9Ma to 80.0Ma (Harris); or 89.2-80.0Ma on 206Pb/238U dating (21 zircons)	Range Coniacian-Campanian; mean age Santonian	Andesite cobble collected from a weakly metamorphosed conglomerate overlying Lolotoi Complex metamorphic rocks. Of 23 zircons dated radiometrically, 21 yielded Cretaceous ages (the other two were Early Jurassic).
Standley & Harris (2009)	8 3 9	Laclubar (Bebe Susu) massif, north-central Timor-Leste	Main peak 87.0±2.7Ma; secondary peak 113.9±8.3Ma	113.8-81.8Ma on 206Pb/238U dating (14 zircons)	Main peak Coniacian; secondary peak Aptian-Albian. Youngest grain Campanian	Metabasic amphibolite.
KOICA (2013)	FP6	Fohorem area of SW Timor-Leste		Youngest zircon age 55Ma	Early Eocene	Gabbro intruding Lolotoi Complex. Interpreted age of intrusion.
Zimmermann (2015), Zimmermann & Hall (2019)	ET 17	N coast of Timor-Leste east of Baucau		139.4-97.3Ma (10 zircons)	Valanginian (2 zircons); Aptian-Cenomanian (8 zircons)	Youngest zircon age is supported by a late Albian-early Cenomanian planktonic foraminiferal age determination (M. BouDagher-Fadel, personal communication to the authors).
Zimmermann (2015), Zimmermann & Hall (2019)	SZ 47	Noil Meto river S of Soe town, south-central West Timor		116.9-75.5Ma (16 zircons)	Aptian-Campanian	See Charlton & Titu Eki (2022, submitted) for further discussion of this sample.
Zimmermann (2015), Zimmermann & Hall (2019)	SZ 37	Margin of Pasi Inlier, Kolbano area, S West Timor		138.7 (1 zircon)	Valanginian	Sample contains Eocene foraminifera (M. BouDagher-Fadel, personal communication to the authors). Kolbano (Australian margin) succession.
Kadarusman et al. (2020)	A160	S of Wini, north-central West Timor		Single zircon grain dated at 93Ma	Turonian	Quartzite
Kadarusman et al. (2020)	A10	Near Atapupu, NE West Timor	Primary peak 71.8±0.83Ma, smaller peaks at 91.0±1.3Ma and 112.5±4.9Ma	117-63Ma	Range Aptian-early Paleocene. Primary peak Campanian, smaller peaks Turonian and Aptian-Albian	Pelitic schist
Kadarusman et al. (2020)	A397	Kunif river, Mutis massif, north-central West Timor	91.1±0.66Ma	Youngest grain 68Ma	Turonian peak age; youngest Maastrichtian	Pelitic schist
Kadarusman et al. (2020)	A445	Kisan river, Mutis massif, north-central West Timor	80Ma peak		Campanian peak	Granulite. Limited analytical data presented.
Kadarusman (2012)	A449	Kisan river, Mutis massif, north-central West Timor	60Ma		Paleocene	Felsic granulite schist. Limited analytical data presented.
Kadarusman et al. (2020)	TM 36	Aileu Complex, near the N coast midway between Dili and Manatuto, Timor-Leste	2 zircons, 73Ma and ~93Ma		Campanian, ~Turonian	Quartzite. Other zircons recovered are considerably older (>200Ma).
Costa et al. (2020)	180503-04	Coinaça tributary of the Caraulun river 4km N of Same, south-central Timor-Leste		Main peak 37Ma, with 80% of 22 concordant age determinations in the range 34-41Ma, and 9% in the range 78-90Ma.	Main peak late Eocene; also Coniacian-Campanian	Non-metamorphosed medium grained volcaniclastic rock. The authors assigned this rock to the Barique Formation, but the present writer's regional mapping placed this outcrop within the Haulasi Formation
Zimmermann (2015), Zimmermann & Hall (2019)	SUM 01	Central Sumba		90.8-81.5Ma (4 zircons)		Siltstone/semi-pelite
Zimmermann (2015), Zimmermann & Hall (2019)	SUM 06	East Sumba		116.7-72.0Ma (60 zircons)		Calcareous sandstone (lithic arenite). Contains *Globotruncana* sp. planktonic foraminifera. Shallow inner neritic environment.
Zimmermann (2015), Zimmermann & Hall (2019)	SUM 10	Central Sumba		115.2-84.7Ma (4 zircons)		Siltstone (lithic arenite)
Zimmermann (2015), Zimmermann & Hall (2019)	SUM 21	West Sumba		100.8-77.80Ma (10 zircons)		Sandstone (lithic arenite)
Zimmermann (2015), Zimmermann & Hall (2019)	SUM 22	West Sumba		92.0-82.8Ma (13 zircons)		Red sandstone (sublithic arenite)
Zimmermann (2015), Zimmermann & Hall (2019)	SUM 24	West Sumba		108.1-80.7 (or 64.1?)Ma (7 zircons)		Siltstone (lithic arenite)
Zimmermann (2015), Zimmermann & Hall (2019)	SUM 30	South-central Sumba		114.0-79.1Ma (15 zircons)		Sandstone (lithic arenite)
Zimmermann (2015), Zimmermann & Hall (2019)	TAN 11	Wotar island, Tanimbar group		124.4-84.6Ma (13 zircons)	latest Barremian-Santonian	Siltstone (sublithic arenite). Ungar Formation - part of the Australian margin succession.
Zimmermann (2015), Zimmermann & Hall (2019)	TAN 28	Teneman island, Tanimbar group		96.8-83.7Ma (3 zircons)	Cenomanian-Santonian	Sandstone. Ungar Formation - part of the Australian margin succession.
Zimmermann (2015), Zimmermann & Hall (2019)	TAN 31	Vatvurat island, Tanimbar group		140.4Ma (1 zircon) and 120.5-89.5Ma (13 zircons)	Berriasian and Aptian-Turonian/Coniacian	Sandstone (subfeldspathic arenite). Ungar Formation - part of the Australian margin succession.
Zimmermann (2015), Zimmermann & Hall (2019)	TAN 45	Laibobar island, Tanimbar group		124.6-104.1Ma (13 zircons)	Aptian-Albian	Sandstone (subfeldspathic arenite). Ungar Formation - part of the Australian margin succession.
Kadarusman (2020)	TLA 62	Laibobar island, Tanimbar group	~70Ma	Youngest age 59Ma	Main peak ~Maastrichtian; youngest late Paleocene	Pelitic schist.
Zimmermann (2015), Zimmermann & Hall (2019)	BAB 25	Babar island, central ridge		125.7Ma & 104.7Ma (2 zircons)	latest Barremian and Albian	Siltstone (grey siltstone/metapelite).
Kadarusman et al. (2020)	KS44	Kisar island		~95Ma (2 zircons) & 66Ma (1 zircon)	~Cenomanian and Maastrichtian	Amphibolite. Only limited information presented.
Kadarusman et al. (2020)	LK29	Leti island		Zircons ranging from 88Ma back to 1985Ma	Coniacian and older	Mica schist. Only limited information presented.
Kadarusman et al. (2020)	LK45	Leti island		85Ma & 37.5Ma (2 zircons)	Santonian and late Eocene	Pelitic schist. Only limited information presented.
Kadarusman et al. (2020)	LK96	Leti island		75-20Ma (29 zircons)	Campanian and younger	Calc silicate rock. Only limited information presented.

which is found most commonly in marginal and back arc basins" – although subsequently Standley and Harris (2009) modified their interpretation to "mixed MORB and volcanic arc affinities for the igneous units". If the former interpretation remains valid, then the Banda Terrane Cretaceous-Paleogene volcanism may have originated not in a volcanic arc, but in a backarc basin. This is a significantly different tectonic environment from a volcanic arc, particularly considering that the backarc basin must have been located behind, but to the south of, the associated arc in order for the Banda Terrane to have been obducted southward onto Timor. However, a marginal basin has two margins: that attached to the associated arc, and that on the continental margin from which the arc detaches. It is the contention of the present study that the Banda Terrane tectonostratigraphic succession represents the trailing continental edge of the marginal basin where a subduction arc migrated northward away from Australia during the Late Cretaceous-Paleogene. The Banda Terrane volcanic successions were thus located on the outermost northern edge of the Australian continental margin prior to arc-continent collision, rather than in a Sunda-Banda (Asian) forearc complex.

Supporting evidence for this interpretation comes from radiometric dating of the Aileu Complex. This metamorphic complex, located in NW Timor-Leste, developed primarily during the Neogene arc-continent collision with a peak of metamorphism at about 5Ma (Berry et al., 2016), although earlier phases of metamorphism extend back to the late Mesozoic (Berry and Grady, 1981). It seems now generally agreed that the bulk of the Aileu Complex protolith consists of Australian continental margin elements (e.g., Boger et al., 2017), and the complex therefore represents part of the pre-collisional Australian continental margin. According to Berry and McDougall (1986), $^{40}Ar/^{39}Ar$ hornblende release patterns for radiogenic metamorphic minerals (hornblende and mica) are consistent with an initial closure to argon loss at ~70Ma (latest Cretaceous). Harris and Long (2000) interpreted this event as related to rifting on the passive continental margin of Australia.

Sumba

Sumba island to the west of Timor also yields a record of Late Cretaceous and Paleogene volcanism similar in age to that in Timor. According to Abdullah et al. (2000), there were three main phases of igneous activity in Sumba, dated at 86-77Ma (~Santonian-Campanian), 71-56Ma (~Maastrichtian-Paleocene) and 42-31Ma (~mid-late Eocene), based on whole rock and mineral $^{40}K/^{40}Ar$ radiometric dating. Zimmermann (2015) collected 7 sandstone/siltstone samples from the Lasipu Formation in Sumba that yielded Cretaceous zircons ranging in age between 117-72Ma (~Aptian-Campanian), with an apparent peak of zircon ages during the Santonian-Campanian, as in Timor (Figure 4).

Abdullah et al. (2000) described Sumba volcanics as displaying the characteristics of a predominantly calc-alkaline and a minor potassic calc-alkaline series, characterised by variable K_2O contents, relatively high Al_2O_3 and low TiO_2 contents, suggesting a typical island arc environment. Standley's 13 analysed samples from Timor, interpreted as marginal basin volcanics, when compared with Abdullah et al.'s 20 analysed samples

from Sumba, show substantial overlap in these parameters, with significant variability in K_2O (Timor 0.02-1.49%; Sumba 0.55-3.65%), relatively high Al_2O_3 (Timor 11.20-21.71% mean 14.85%, Sumba 14.80-19.00% mean 17.60%) and low TiO_2 (Timor 0.11-2.65% mean 1.30%, Sumba 0.47-1.05%, mean 0.79%).

Banda forearc islands east of Timor

Zimmermann (2015) and Kadarusman et al. (2020) have also recorded zircons of Late Cretaceous to Paleogene age in several islands of the Banda forearc to the east of Timor. In the Tanimbar Island group Zimmermann (2015) and Zimmermann & Hall (2019) dated samples from the islands of Wotar (sample TAN 11), Teneman (TAN 28), Vatvurat (TAN 31) and Laibobar (TAN 45), all derived from sandstone successions of the Ungar Formation (Charlton et al., 1991). Forty three Cretaceous zircons were separated from these four samples, the majority ranging in age between 124.6-83.7Ma (~Aptian to Santonian or earliest Campanian), similar to the Timor and Sumba Cretaceous zircon ages, although with an earlier, Albian-Cenomanian peak in the age distribution, in comparison to a

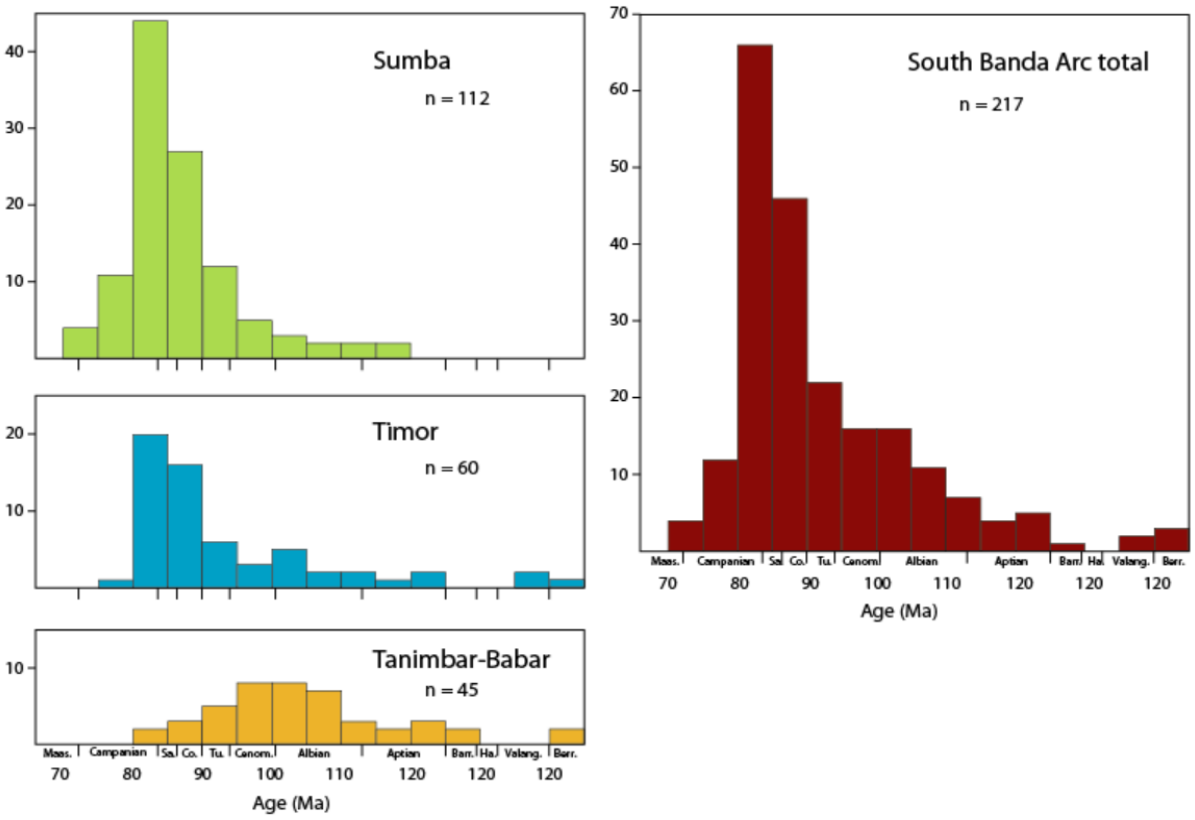


Figure 4: *Cretaceous zircon age distributions from islands of the southern Banda Arc (Sumba, Timor, Babar and the Tanimbar islands). The Sumba graph is cumulative zircon ages from individual grains in Zimmermann and Hall's (2019, Supplementary Data file 4) samples SUM 01, 06, 10, 21, 22, 24 & 30, while the Tanimbar-Babar graph is cumulative for samples TAN 11, 28, 31 & 45, and BAB 25. The Timor graph sums grains from Zimmermann's (2015) samples SZ 37, SZ 47 & ET 17, together with Harris's (2006) sample 70 and Standley and Harris's (2009) sample 8-3-9. For the latter two samples $^{206}Pb/^{238}U$ radiometric ages are plotted, which is Zimmermann's 'preferred' age determinant for Cretaceous samples.*

Santonian-Campanian peak in Timor and Sumba (Figure 4). The small difference in peak zircon ages may reflect an absence of latest Cretaceous sandstones in Tanimbar below an Early Miocene unconformity (cf. Charlton et al., 1991). Kadarusman et al. (2020) also recorded zircons with a peak age of ~70Ma (~Maastrichtian) and a youngest age of 59Ma (~late Paleocene) from a pelitic schist in Laibobar island (Tanimbar group). In Babar Island to the west of Tanimbar, Zimmermann (2015) sampled a siltstone/metapelite (BAB 25) that yielded 2 zircons dated at 125.7Ma (latest Barremian) and 104.7Ma (Albian) (Zimmermann and Hall, 2019). Zimmermann (2015) noted similarity between the lithology of BAB 25 and the Lasipu Formation on Sumba Island. On Leti Island Kadarusman et al. (2020) reported 3 samples containing Cretaceous and younger zircons, including 88Ma (~Coniacian) and unspecified older ages (sample LK29); 85Ma and 37.5Ma (~Santonian and ~late Eocene: sample LK45); and 29 zircons in the range 75-20Ma (~Campanian and younger: sample LK96). On Kisar island Kadarusman et al.'s (2020) sample KS44 contained 3 Cretaceous zircons dated at ~95Ma (2 grains, ~Cenomanian) and 66Ma (~Maastrichtian).

It is particularly significant that although the zircon ages from the eastern Banda forearc islands are essentially similar to those from Timor and Sumba (Figure 4), the Tanimbar samples were collected primarily from the Ungar Formation, which is an element of the Australian continental margin succession, not part of an allochthonous succession. This seems to provide a clear link between the 'suspect' (i.e., possibly allochthonous) successions of Timor and Sumba and the Australian continental margin.

Bird's Head-Misool

Very similar aged volcanism to that documented in the Cretaceous-Paleogene of Timor and Sumba is also found locally in the Australian continental terranes of eastern Indonesia, including the Bird's Head structural block of western New Guinea island and offshore regions to the west including the island of Misool (Figure 1). In the Bird's Head, Fraser et al. (1993) reported that Late Cretaceous sediments of the Jass Polysequence commence with a pronounced volcanic event. Ages reported for volcanic intervals in various petroleum exploration wells include Coniacian-Santonian in the Tarof-2 and Ayot-2 wells, upper Coniacian-Santonian in Agung-1, upper Coniacian-Campanian in Roabiba-1, and Campanian-Maastrichtian in TBE-1X. In TBF-1X (location in Figure 7) a more substantial volcanic interval is dated to the Santonian-Maastrichtian, extending upwards into the Paleocene-lower Eocene. Unfortunately, none of these volcanic successions encountered during drilling have been analysed geochemically, at least not in publicly available datasets. Other indications for Cretaceous-Paleogene igneous activity in the Bird's Head include the Sorong Granite which is dated radiometrically at 71.0±1.5Ma (~Campanian-Maastrichtian: Lunt & Djaafar, 1991), and granite from the base of the Salawati K-1X well which yielded radiometric ages of 79.3±1.1Ma on biotite, and 71.0±1.5Ma on amphibole (~Campanian-Maastrichtian: Amri et al., 1990). In the eastern Bird's Head, a granulite from the Wandamen Gneiss complex yielded a radiometric age of 89.1Ma (~Coniacian) (Robinson et al., 1990), interpreted by the authors as a possible igneous protolith age.

In Misool island the deepwater Waaf Formation, dated to the Cenomanian-early Campanian (Hasibuan & Rusmana, 2007), is described as highly tuffaceous (Pigram et al., 1982). The tuffaceous intervals may be as old as Cenomanian-Turonian (Vogler, 1941), slightly older than the volcanism encountered in the offshore wells. The succeeding Fafanlap Formation (Santonian-Maastrichtian: Hasibuan & Rusmana, 2007) is also highly tuffaceous, with the volcanism continuing through a radical change in marine depositional environment, from bathyal to shallow marine (Pigram et al., 1982). The Late Cretaceous-Paleogene Daram Formation contains sandstones of locally derived volcanic origin (Simbolon et al., 1984).

Relationships between the Kolbano and Palelo Associations in Timor

For the most part the Kolbano and Palelo Associations in Timor form entirely distinct stratigraphic successions (Figure 3). There are, however, several geological observations that tend to blur this clear division:

1. As already mentioned, conglomerates in the Haulasi Formation reportedly include clasts derived from the Permian Maubisse Group, including fragments of Permian fossiliferous limestones (Carter et al., 1976), and vesicular basalts resembling Permian Maubisse alkaline lavas (Earle, 1979). The Maubisse Group (or Formation) has clear palaeontological, stratigraphic and palaeomagnetic affinities to the Australian continental margin (as summarised in Charlton et al., 2002), and the presence of Maubisse material reworked into Haulasi Formation is problematic for the allochthonous model.

2. The Eocene Dartollu Formation, which stratigraphically succeeds the Haulasi Formation, also locally contains reworked fragments of Maubisse Group crinoidal limestones and vesicular lava clasts. The present writer has observed such an outcrop at (9.25363°S, 125.27778°E) in SW Timor-Leste (Figure 5a & b).

3. Sidewall Core number 12, from the Betano-2 petroleum exploration well drilled in southern East Timor in 1973, is a Senonian (Late Cretaceous) reddish-brown argillaceous limestone assignable on age and lithology to the Borolalo Formation (Audley-Charles, 1968; Charlton et al., 2020). This limestone contains lenticular concentrations of metamorphic grains, interpreted by micropalaeontologist D.J. Carter (1973) as deriving from the Lolotoi Complex. During the Late Cretaceous the Lolotoi Complex should, according to the allochthon model, have occupied a position in the Asian plate margin, and should not therefore have formed a sedimentary source in the hinterland of the Australian-margin Borolalo Formation.

4. On the northern slopes of Mount Mundo Perdido in SE Timor-Leste, Benincasa (2015) recorded two samples of Eocene red mudstone/shale containing planktonic foraminiferal faunas, and with both originating from bathyal or deeper environments of deposition. One (sample AB236, located at 8.71073°S, 126.34083°E) was assigned to the Kolbano Group; the second (AB234, at 8.71058°S, 126.34053°E) to the Barique Group (or Formation), which is an element of the Palelo Association. Assignment of the second sample to the Barique Group was probably based on the occurrence of relatively fresh volcanic material within the sample, while the first was probably

assigned to the Kolbano Group on the absence of volcanic material. These two similar rock types, outcropping less than 40m from one another, were, according to the interpretations implicit in the allochthonous model, derived from entirely distinct tectonostratigraphic terranes that would have been separated by hundreds or thousands of kilometres during the Eocene.

5. Shallow marine limestones of the Eocene Dartollu Formation and the Oligo-Miocene Noil Toko and Booi Formation (Palelo Association) interdigitate with deeper marine limestones that appear indistinguishable from time-equivalent successions in the Kolbano Group.

6. In the Miomafo massif in West Timor, van West (1941) described bedding planes in Noni Formation cherts as frequently covered by manganese mineralisation. Manganese mineralisation is widely seen in the Australian margin succession of Timor, including in the Triassic Aitutu Formation and the Cretaceous Wai Bua/Nakfunu Formation, with the mineralisation developing during or soon after sedimentary deposition. It is a coincidence that both the supposed Australian and Asian margin successions



Figure 5: *(a) Outcrop of Dartollu Formation consisting of whitish-pink benthic foraminiferal calcarenite/rudite enclosing clasts of porphyritic basalt, interpreted as derived from the Permian Maubisse Formation. (b) From the same locality, a block of Maubisse Formation crinoidal limestone enclosed within the Dartollu Limestone. Near Hasain village, Covalima, Timor-Leste (9.25363°S, 125.27778°E). (c) Outcrop of pillow basalt volcanics and (d) angular basaltic clasts enclosed in pinkish limestone matrix of Kolbano Group type at the same locality. Noil Fatu, northern Kolbano area of West Timor (9.79593°S, 124.49328°).*

should develop similarly rich manganiferous mineralisation.

7. In West Timor Sawyer et al. (1993) noted that some facies mapped within the Palelo Group were similar to Kolbano Sequence samples. These included:

• Lithological similarity between the Noni Formation in the Molo region (central West Timor) and the Nakfunu Formation in the Kolbano area.

• Similarities between Paleocene aged micrites and wackestones assigned to the Haulasi Formation east of Kefamenanu (north-central West Timor) and the Ofu Formation in the Kolbano area.

• Lithologies assigned to the "Ofu Series" by de Waard (1957) east of Nikiniki that include an interbedded micrite and pillow lava on tectonic strike with a similar Cretaceous limestone containing matrix supported andesite(?) boulders.

The locality east of Nikiniki (site of Sawyer's sample RKS-301: 9.79593°S, 124.49328°) was re-visited by the present writer together with Timorese geologists Adept Titu Eki and Permenas Manilapai (Barka), and our observations concur with Sawyer's interpretation that Kolbano Group limestones were stratigraphically associated with volcanic rocks at this locality (Figure 5c & d).

EOCENE FAUNAL PROVINCIALITY

The Dartollu Formation is a succession of shallow marine limestones of Eocene age (Audley-Charles, 1968; Haig et al., 2019) that lie stratigraphically above the Haulasi Formation, and below or contemporaneous with the Barique Volcanics (Figure 3). In a study of Eocene regional biogeography, Lunt (2003) identified two distinct benthic foraminiferal faunas in the Eocene of the Indo-Pacific region that he considered demonstrated faunal provincialism with significant palaeotectonic implications. Of the two faunas, one is typified by the genera *Assilina*, *Pellatispira* and *Biplanispira* ('*APB*') and the other by the genus *Lacazinella*. The *APB* fauna was interpreted as an Eocene equatorial grouping found primarily in Southeast Asia and Pacific islands, while the *Lacazinella* fauna was interpreted as a higher latitude, subtropical grouping found primarily on the northern margin of Australia. The Dartollu Formation in Timor contains an *APB* fauna, suggesting, in Lunt's model, an equatorial palaeolatitude, consistent with an allochthonous origin for this formation.

There are, however, some problems with this model. Firstly, as Lunt (2003) recognised, the division between the *APB* and *Lacazinella* faunas is not perfect. In a foraminiferal limestone from Papua New Guinea, elements of the two faunas co-occur in the same rock unit, and indeed in one case were found within the same thin section. Furthermore, *Assilina*, an element of the *APB* fauna, has been identified in the Sahul Shoals-1 exploration well on the outer Australian continental margin immediately south of Timor (sidewall cores at 3815m depth (3 specimens) and at 4012m (1 specimen): Sahul Shoals-1 well completion report, BOCAL, 1970, identifications by R. Wall). However, Lunt (2003) cautioned that "*Assilina* can be confused for flat forms of *Operculina* … especially by [oil] industry biostratigraphers who are used to examining planktonic foraminifera". A third discrepancy is that on Lunt's regional paleogeographic map (Lunt,

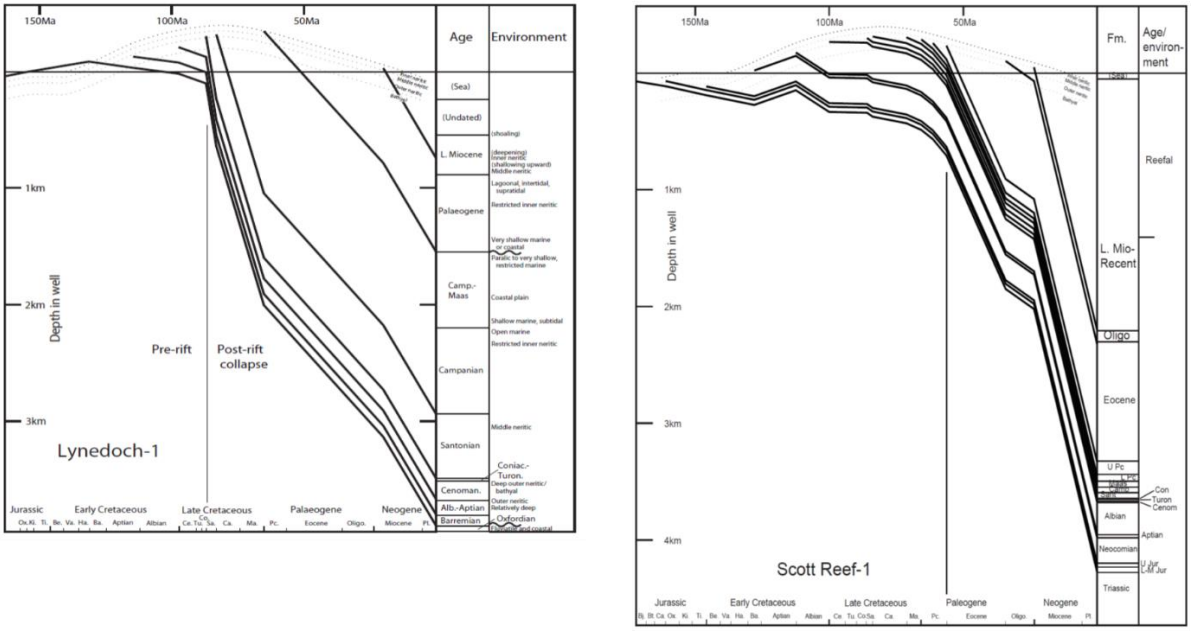


Figure 6: *Subsidence curves for the Lynedoch-1 (Calder Graben south of the Tanimbar islands: Figure 8) and Scott Reef-1 well (SW of Timor) illustrating a dramatic onset of subsidence in the mid-Cretaceous and Paleogene respectively.*

2003, Figure 5) several sites in the western Pacific that contain an *APB* fauna locate at the same subtropical palaeolatitude as do sites with *Lacazinella* faunas on the Australian continental margin.

Two further possible discrepancies between Lunt's provincial interpretation and regional geology concern the occurrence of *APB* faunas within rocks from Banda Arc islands that also show stratigraphic ties to the Australian continental margin. The first example is the Dartollu Limestone in Timor, which, as mentioned above, at one locality contains reworked fragments of the Maubisse Formation that have an undisputed Australian continental margin affinity. The second is a very similar case from Seram island in the northern Banda Arc, where Eocene conglomerates contain *Pellatispira* (*APB* fauna) amongst other benthic foraminifera (and with no mention of *Lacazina*/*Lacazinella*), but also clasts of Triassic limestone and Triassic greywacke-sandstone (Germeraad, 1946, pp.29-30). The Triassic of Seram is considered directly correlatable with the Triassic of Timor and is an Australian-margin stratigraphic succession.

Although Lunt's (2003) interpretation of faunal provinciality in the Eocene is at first sight an attractive proposition, it probably does not delineate palaeotectonic provinces sufficiently strongly to justify palaeo-plate boundaries, and thus probably does not greatly constrain the northern/southern Tethys origin of the Banda Terrane in Timor.

LATE CRETACEOUS-PALEOGENE SUBSIDENCE OF THE NW AUSTRALIAN CONTINENTAL MARGIN

It has long been assumed (including by the present writer: Charlton, 2012) that following Late Jurassic oceanic rifting the northwest Australian continental margin, including the future Timor region, formed

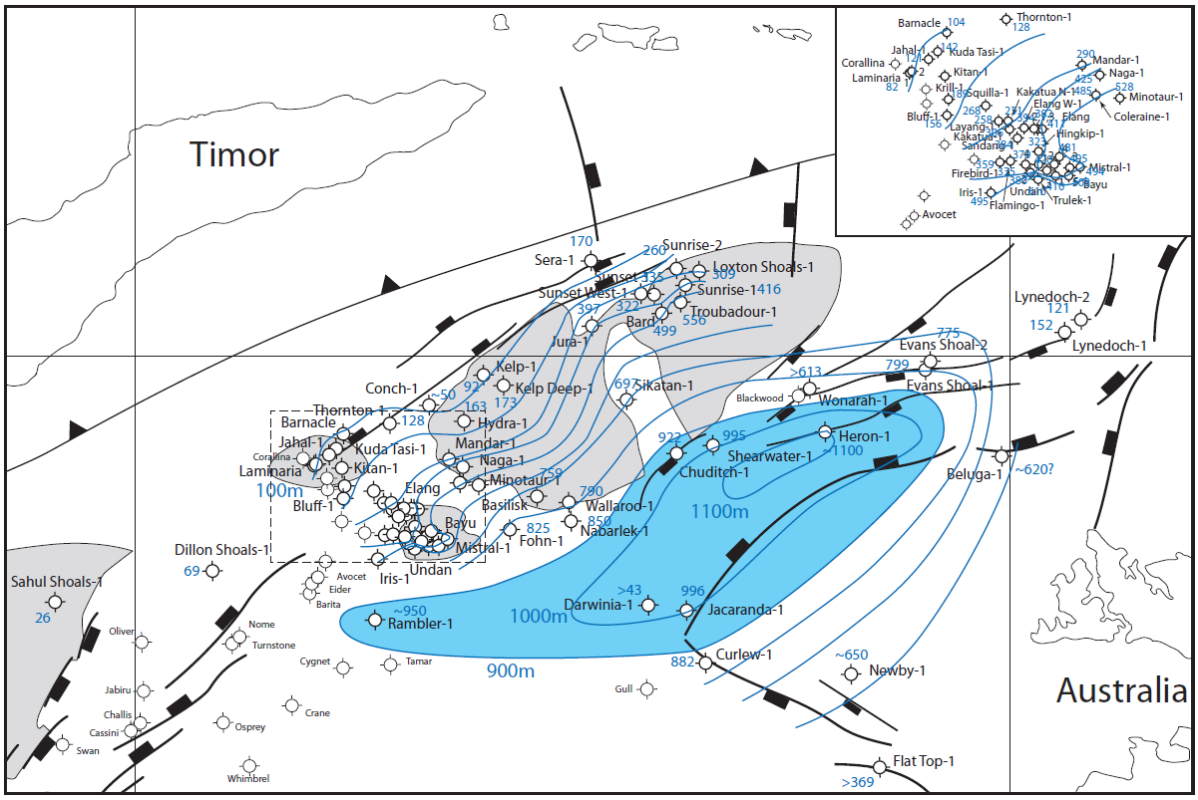


Figure 7: *Isopach thickness of the Jamieson Formation (late Albian-Cenomanian: see Figure 3) on the eastern Northwest Shelf of Australia. During this short interval of deposition (~12m.y.) more than 1100m of predominantly shaly sediments were deposited in neritic environments at the axis of the Malita Graben, contemporaneous with less than 50m of sedimentation over the northern Ashmore Platform. Thicknesses >900m are shaded blue.*

a relatively simple, distal passive continental margin with a northward progression from shelf to slope and continental rise environments (e.g. Audley-Charles, 1986), although perhaps developed on distinct marginal plateaus analogous to the Scott and Exmouth Plateaus of the present-day western Australian margin (Charlton, 1989; Haig, 2012). In most such interpretations a stable and quiescent passive margin tectonic setting is inferred from the Early Cretaceous through to the Miocene, during the accumulation of the Kolbano Association in Timor (Figure 3). However, indications that this apparently long-standing tectonic quiescence may have been overstated include, for instance, the remarkable subsidence recorded in the Scott Reef-1 well to the SW of Timor, where reefal and shallow marine depositional environments have been maintained during the accumulation of more than 3000m of sedimentary section since the Eocene (Figure 6). Similarly, more than 1000m of subsidence is recorded in wells drilled in the Malita Graben to the SE of Timor during deposition of the Jamieson Formation in the late Albian and Cenomanian – a period of only about 12m.y. duration (Figure 7). Neither of these dramatic subsidence phases appear consistent with a structurally quiescent passive margin setting.

In order to assess the pattern of subsidence on the northwest Australian continental margin since the Jurassic, a series of subsidence curves have been constructed for the wells shown in Figure 8, covering an area extending from southwest of Timor, through the former Timor-Leste–Australia Joint Petroleum Development Area (previously also known as the Indonesia-Australia Zone of Co-operation), to the eastern Australian continental margin around the Calder Graben, and then northwards into eastern Indonesia on the western edge of the Arafura Shelf and the Bird's Head structural block. Examples of subsidence curves for the Scott Reef-1 and Lynedoch-1 wells are shown in Figure 6, while generalised subsidence curves for several wells respectively west and east of Timor are shown in Figure 9. Many wells show a characteristic steepening in the subsidence curve during the Late Cretaceous or Paleogene, indicating accelerated subsidence during that time, although the precise onset of accelerated subsidence varies regionally. The earliest onset of rapid subsidence occurred during the early Albian at Evans Shoal-1 but commenced as late as late Palaeocene at Dillon Shoals-1 south of Timor. The timing for the onset of rapid subsidence shows significant regional grouping, however,

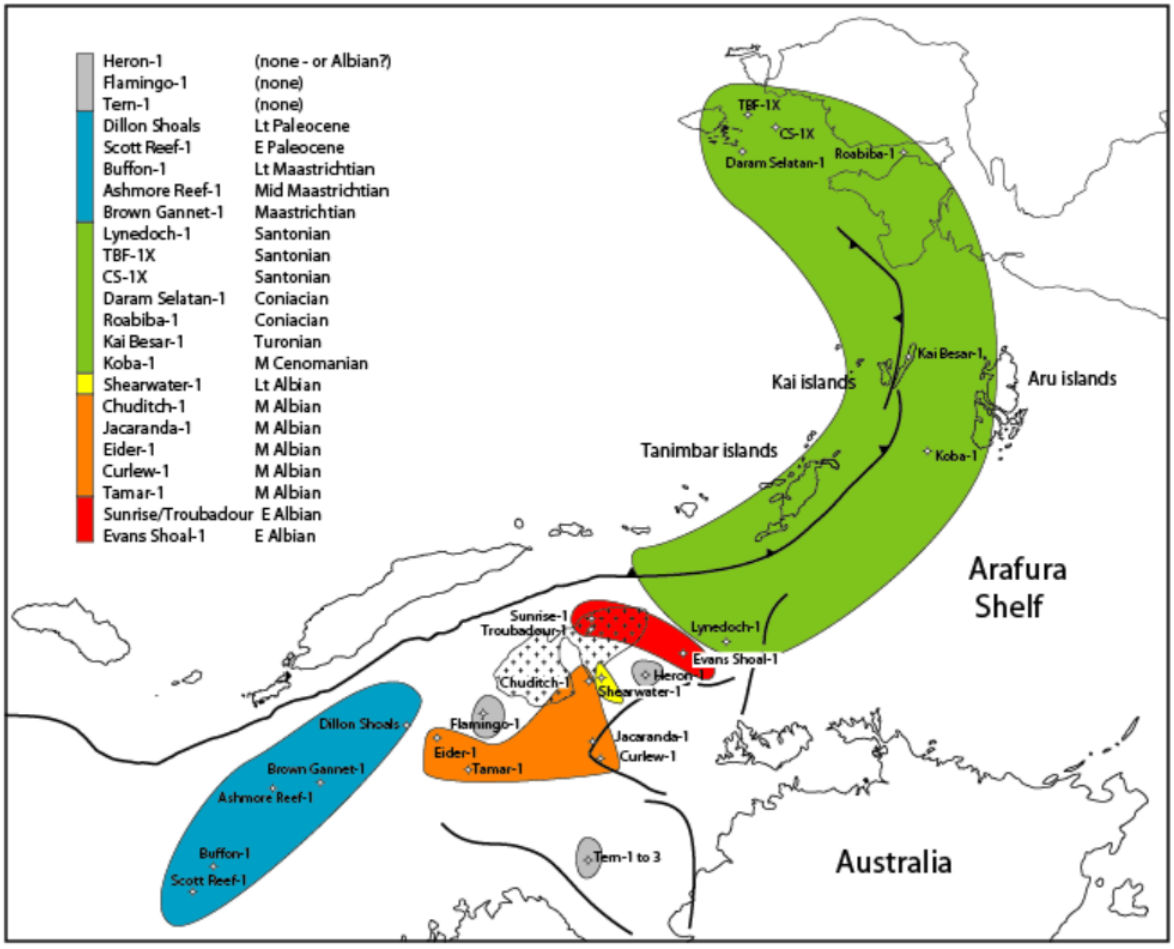


Figure 8: *Timing for the onset of rapid subsidence recorded in wells around the northwest Australian continental margin (northern Australia and eastern Indonesia) from the 'mid' Cretaceous to the Paleogene.*

with distinct subsidence phases indicated on Figure 8.

SYNTHESIS

The distribution of zircon ages dated to the Cretaceous from sandstone and metamorphic rocks collected in the southern Banda forearc (Figure 4) shows a strong degree of congruence between the various island groups. This is particularly remarkable considering that the Tanimbar samples were collected primarily from the Ungar Formation, which is considered part of the Australian continental margin succession (Charlton et al., 1991), while the samples from Sumba and most of the samples from Timor derive from the 'suspect' Banda Terrane successions, widely considered to derive from the Asian continental margin. Instead, the congruence of ages suggests that the Sumba and Banda Terrane (Timor) volcanic successions may be genetically tied to the Australian margin rather than to the Asian margin. The southern Banda forearc volcanism is also precisely contemporaneous with volcanism in the Australian-affinity Bird's Head-Misool structural domain, and this provides a further link to the Australian continental margin. Taken together with the apparently marginal/backarc basin geochemistry of the volcanics (Standley, 2007) and the evidence from the Aileu Complex in Timor for Australian continental margin rifting in the Late Cretaceous (Berry and McDougall, 1986; Harris and Long, 2000), this all suggests an origin for the volcanism in a zone of backarc rifting behind an island arc terrane that broke away northward from the NW continental margin of Australia during the Late Cretaceous and Paleogene.

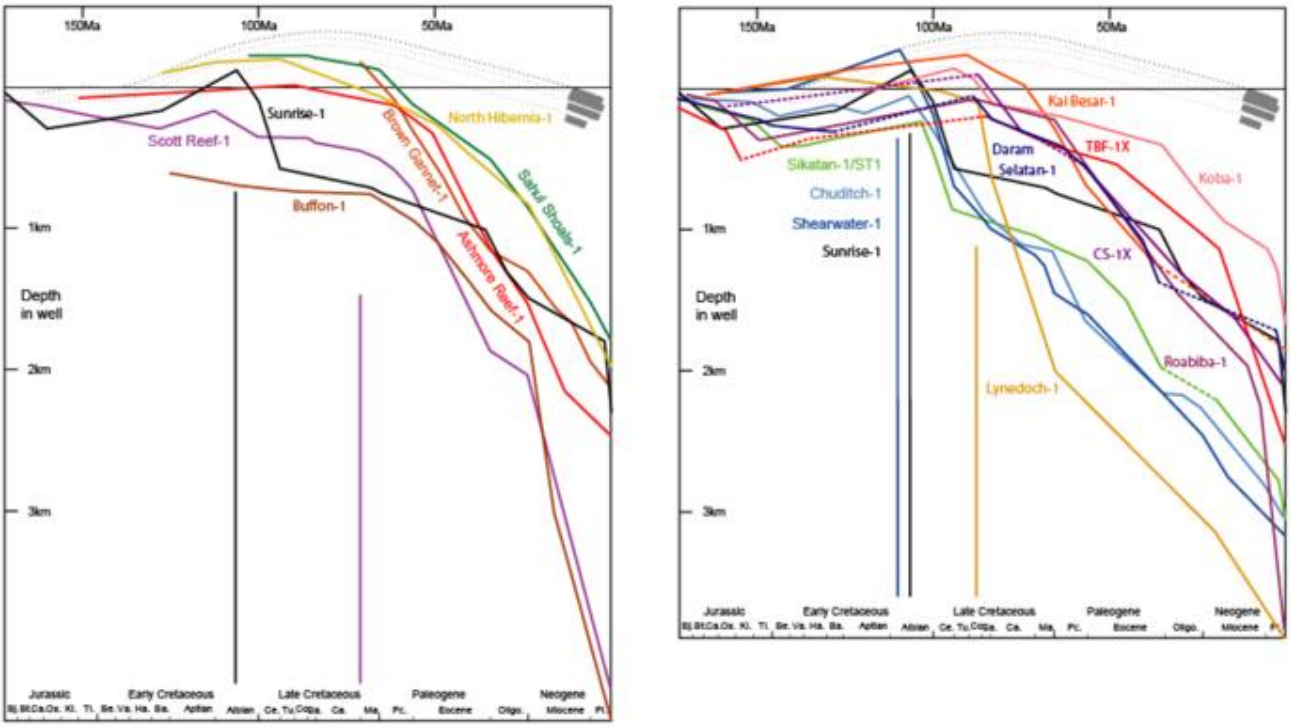


Figure 9: *Representative subsidence curves for the NW Australian margin east and west of Timor (the Sunrise-1 subsidence curve is shown on both graphs for comparison).*

The effects of this rifting event are also apparent in the subsidence curves of petroleum exploration wells drilled on the outer Australian 'passive' continental margin to the south and east of the Timor-Tanimbar-Seram Troughs (Figures 6-9). Figure 4 suggests that the main volcanic phase commenced during the Aptian and may have increased in intensity through the Santonian-Campanian peak of zircon ages in Figure 4, and into the Paleogene based on continuing volcanism in Timor (Metan and Barique volcanics) and Sumba (Abdullah et al., 2000). Figures 8 & 9 suggest that strong subsidence commenced on the Australian margin immediately east of Timor during the Early Albian, with younger initiations of subsidence at various times at different locations throughout the Late Cretaceous and Paleogene. Continental margin subsidence was particularly strong in the area of the Sahul Platform and Malita-Calder Graben within a few million years either side of the Early-Late Cretaceous boundary, during deposition to the Jamieson Formation (Figure 7). In wells such as Chuditch-1 on the Sahul Platform the entire Late Jurassic and Early Cretaceous succession below the Darwin Formation is highly condensed, in this well only totalling about 13m thickness for a sedimentary succession deposited through an interval of about 40 million years (Figure 3). The Darwin Formation itself, Aptian-Albian in age and immediately preceding the Jamieson Formation, is a strikingly different lithological interval from the underlying condensed neritic section, being

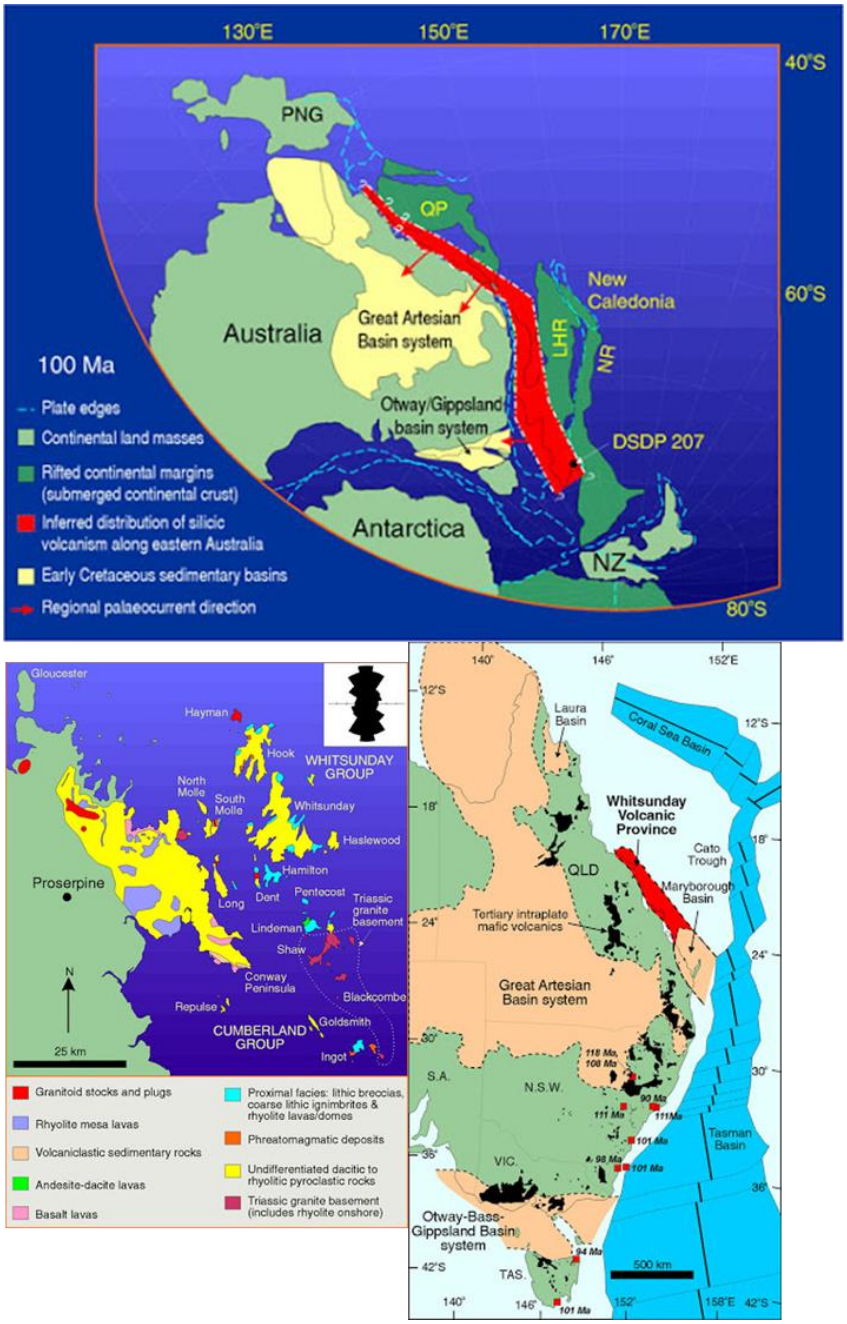


Figure 10: *Continental margin rifting in eastern Australia during the Cretaceous (Bryan, 2005).*

characterised by planktonic foraminiferal limestones and radiolarites that indicate moderately deep marine environments, apparently suggesting significant oceanisation of the outer continental margin of Australia at that time.

Igneous activity in the Bird's Head-Misool region initiated shortly after the commencement of rifting on the NW Australian margin, dating from the Coniacian-Santonian and continuing into the Paleogene (Fraser et al., 1993).

In summary, it appears that there was a previously unrecognised phase of continental margin rifting on the northwest continental margin of Australia (Timor to western New Guinea) that commenced in the late Early Cretaceous (from the Aptian/Albian) and continued through to the Paleogene (until the late Eocene). The geochemistry of volcanic rocks erupted during this rifting phase may suggest that an island arc terrane rifted northward away from Australia, leaving an extensive marginal basin volcanic succession on its southern trailing edge, which is now represented in the southern Banda forearc by, for instance, the Banda Terrane volcanic successions in Timor, and the contemporaneous volcanics associated with the Lasipu Formation in Sumba.

A more detailed account of the rifting history of the SE Banda Arc region, integrated with the known spreading history of the northern Indian Ocean (Figure 2), will be presented in a separate paper (Charlton, 2023). In the meantime, it may be worth highlighting a very similar phase of backarc rifting that developed broadly contemporaneously on the eastern margin of Australia. As illustrated in Figure 10, a major succession of Cretaceous calc-alkaline volcanism is also found in the Whitsunday volcanic province of eastern Australia (Ewart et al., 1992; Bryan et al., 2000). These arc-like volcanics were erupted during the early stages of a continental rifting phase that led eventually to the opening of the Coral Sea off the eastern margin of Australia. Magmatism in the Whitsunday volcanic province is dated between about 130-95Ma (Early Cretaceous, ~Barremian-Albian), with a main phase of igneous activity in the range 120-105Ma (Aptian-Albian: Ewart et al. 1992; Bryan et al., 1997).

The final stages of this eastern Australian volcanism coincide with the initiation of volcanism on the north-western margin of Australia, and it seems quite possible that the two rifting phases were genetically related.

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