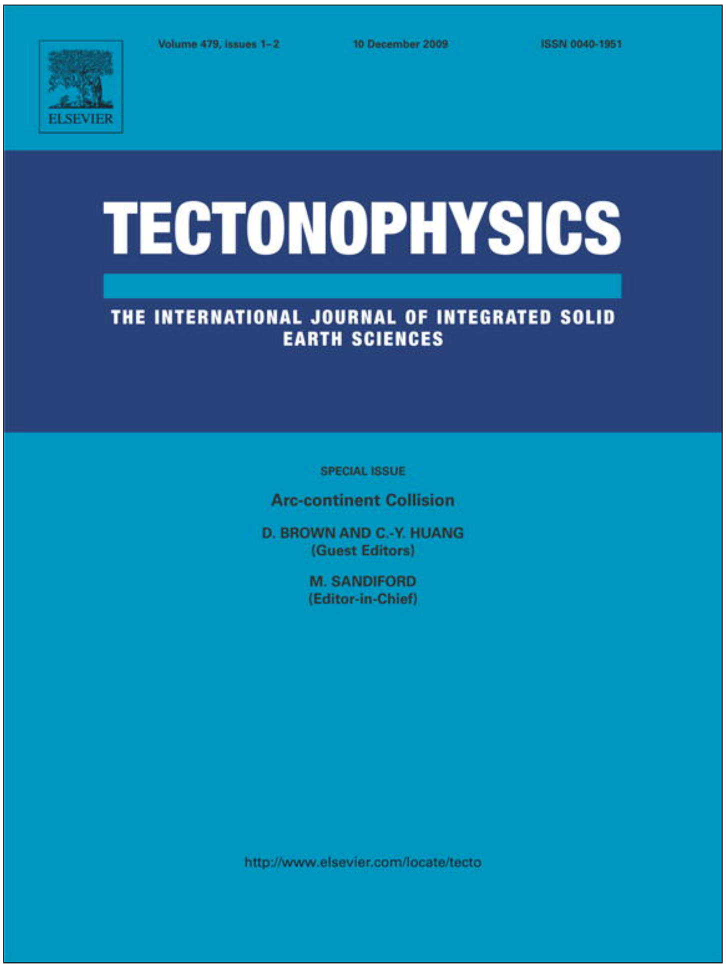
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Surface uplift history of the incipient Banda arc-continent collision: Geology and synorogenic foraminifera of Rote and Savu Islands, Indonesia

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A B S T R A C T

Field mapping and analysis of foraminifera from synorogenic pelagic units of Rote and Savu Islands, Indonesia reveals high rates of surface uplift of the incipient Banda arc-continent collision during the past 1.8 myr. New geological maps of these islands document accretion to the Banda forearc of Triassic through Tertiary sedimentary cover units from the down-going Australian continental margin. Foraminifera-rich synorogenic deposits of the Batu Putih Formation unconformably overlie these accreted units. We use paleodepth versus time estimates from benthic and planktic foraminifera's to measure long-term surface uplift rates for the accretionary wedge. Although strong currents in the region cause some problems with reworking, several distinctive species have been found. Synorogenic deposits in Savu and Rote yield foraminifer's of biozone Neogene (N) 18 to N22 (5.6–1.0 myr) that were deposited at estimated depths of around 3000 m. These deposits are unconfomrably overlain by uplifted coral terraces. The highest coral terraces in Savu are >300 m above sea level and perhaps as old as 0.8 myr. In Rote the highest coral terrace is 200 above sea level and ~0.2 myr old.

These data indicate that collision of the Australian continental margin with the Banda Arc, which initiated much earlier in Timor, has propagated westward towards Rote where it is in the initial stages of accretionary wedge emergence. Collision of the Scott Plateau propagated SE from Sumba (2–3 Ma) to Savu (1.0–0.5 Ma) and then to Rote (0.2 Ma). Average rates of surface uplift of the Batu Putih Formation pelagic deposits during the past 2 myr in Rote and Savu are ~1.5 and 2.3 mm/a, respectively. The rise of these islands is clogging the Indo-Pacific seaway.

1. Introduction

An unresolved question about mountain building processes is whether an equilibrium state is reached where uplift and erosion are balanced in maintaining topographic relief over long periods of time (England and Molnar, 1990). One of the places where this idea can be tested is in the western Banda arc-continent collision where mountains emerge above sea level over the past few million years, and multiple proxies are available to measure uplift rates across a variety of time scales ranging from 10^6 to 10^3 years (Fig. 1). This study focuses on the ascent of pelagic foraminifera-rich chalk deposited on the actively deforming Banda Arc accretionary wedge as it is uplifted by Pliocene to present arc-continent collision. Benthic and planktic foraminifers in these deposits provide depth and age constraints needed to reconstruct uplift histories at temporal scales of 10^5 to 10^6 years. Although there is some erosion of these deposits after reaching the surface, the majority of their ascent is in a submarine environment, which implies little erosional exhumation. Therefore, we interpret the record of vertical movements provided by these deposits as representing mostly surface versus rock uplift.

In this study we analyze the biostratigraphic record of sedimentary rocks throughout Rote and Savu, two of the youngest islands to emerge in the collision zone (Fig. 2). We find evidence for uplift of the islands due to buoyancy and crustal shortening both associated with subduction of the Scott Plateau of the Australian continental margin. Previous work in the region reveals that emergent parts of the transition from subduction to collision are near areas where strain is partitioned away from the deformation front into intra-forearc and backarc plate boundary segments (Silver et al., 1983; Harris, 1991; Synder et al., 1996; Merritts et al., 1998). How much of the uplift is due to crustal versus lithospheric processes remains poorly understood, and this study alone cannot resolve this issue. However, we can use depth versus age relations provided by detailed analysis of foraminifers to address the following questions: 1) Does the age of island emergence vary along orogenic strike, which is predicted by shortening during collision propagation, or do they emerge simultaneously, which is predicted from lithospheric process, such as slab tear? 2) What are the rates of surface uplift? And 3) how do these rates compare with those predicted from known convergence rates or slab tear rates?

1.1. Geological overview

The Banda arc region is an evolving arc-continent collision at the intersection of the large Asian, Australian, and Pacific Plates (Hamilton,

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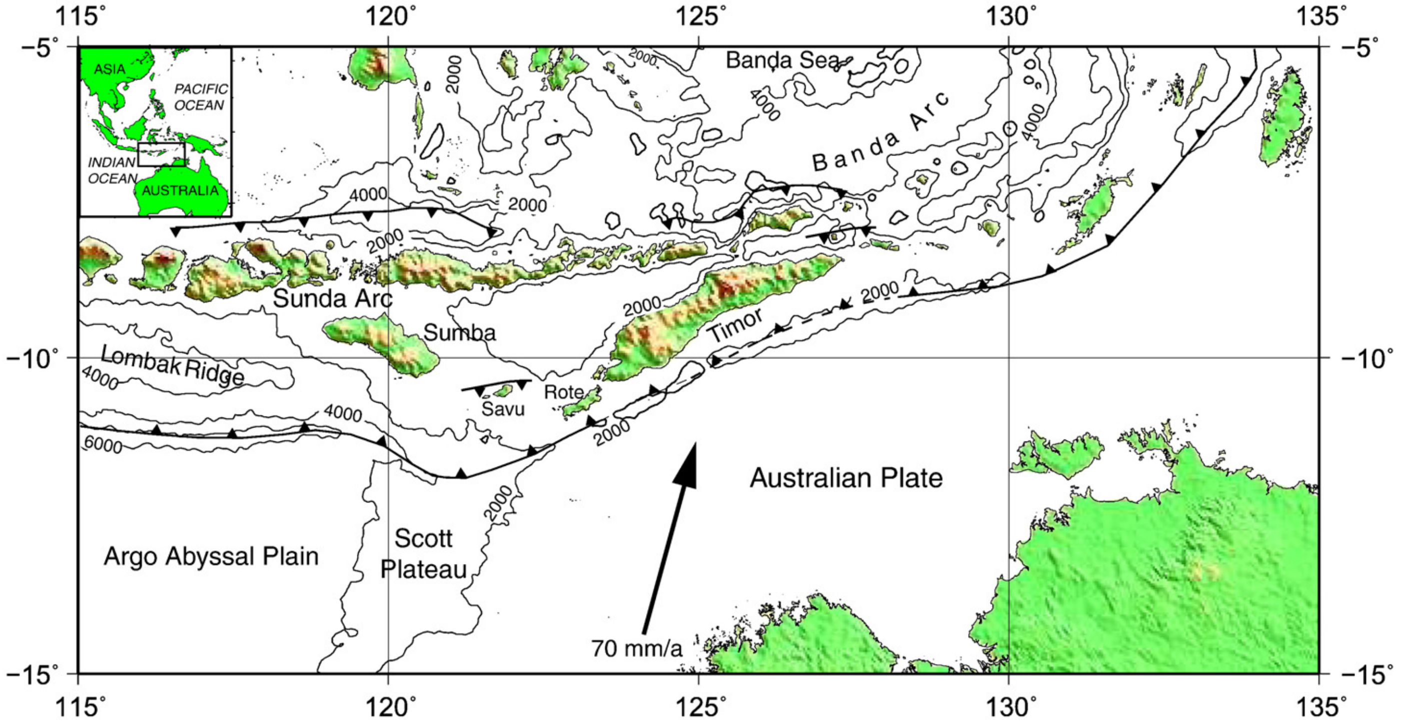


Fig. 1. Digital elevation location map with bathymetry showing the transition from subduction (Lombak Ridge) to collision (Timor). Sumba, Savu and Rote islands represent various stages of incipient collision. Active faults are shown with teeth on the hangingwall. The convergence direction of the Australian plate is 015° at 70 mm/a.

1979). The Sunda and Java Trenches mark the convergent boundary between Southeast Asian and Australian plates, which is the site of subduction of oceanic lithosphere beneath the Sunda arc. The eastern end of the Java Trench encounters the Australian continental margin and transitions from subduction to arc-continent collision (Fig. 2). Because the continental margin is oblique to the trench, the collision propagates

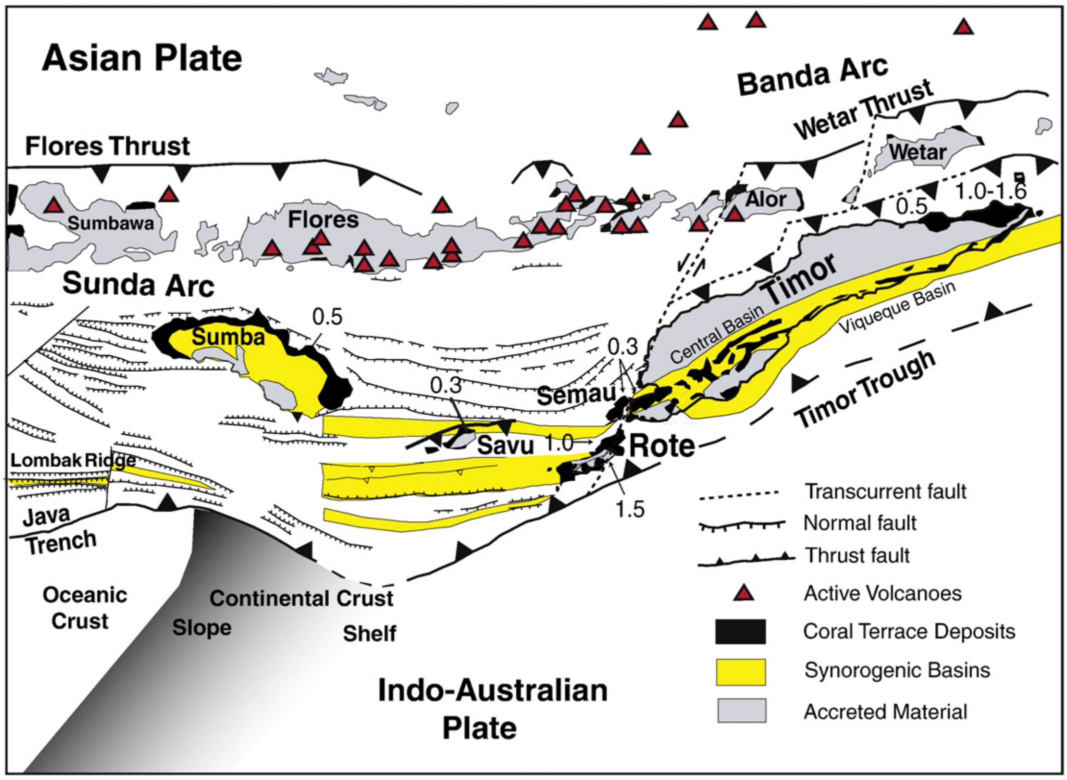


Fig. 2. Tectonic features of the western Banda arc-continent collision. Synorogenic basins of the accretionary wedge are progressively uplifted from west to east. Our samples are from parts of the synorogenic basins exposed on Savu and Rote Islands. These islands occupy a transitional position between wedge widening and wedge narrowing; between wedge uplift without erosion and wedge shortening with erosion. Uplift rates calculated from U-series age determinations of coral terraces are shown. Submarine structure modified from van der Werff (1995).

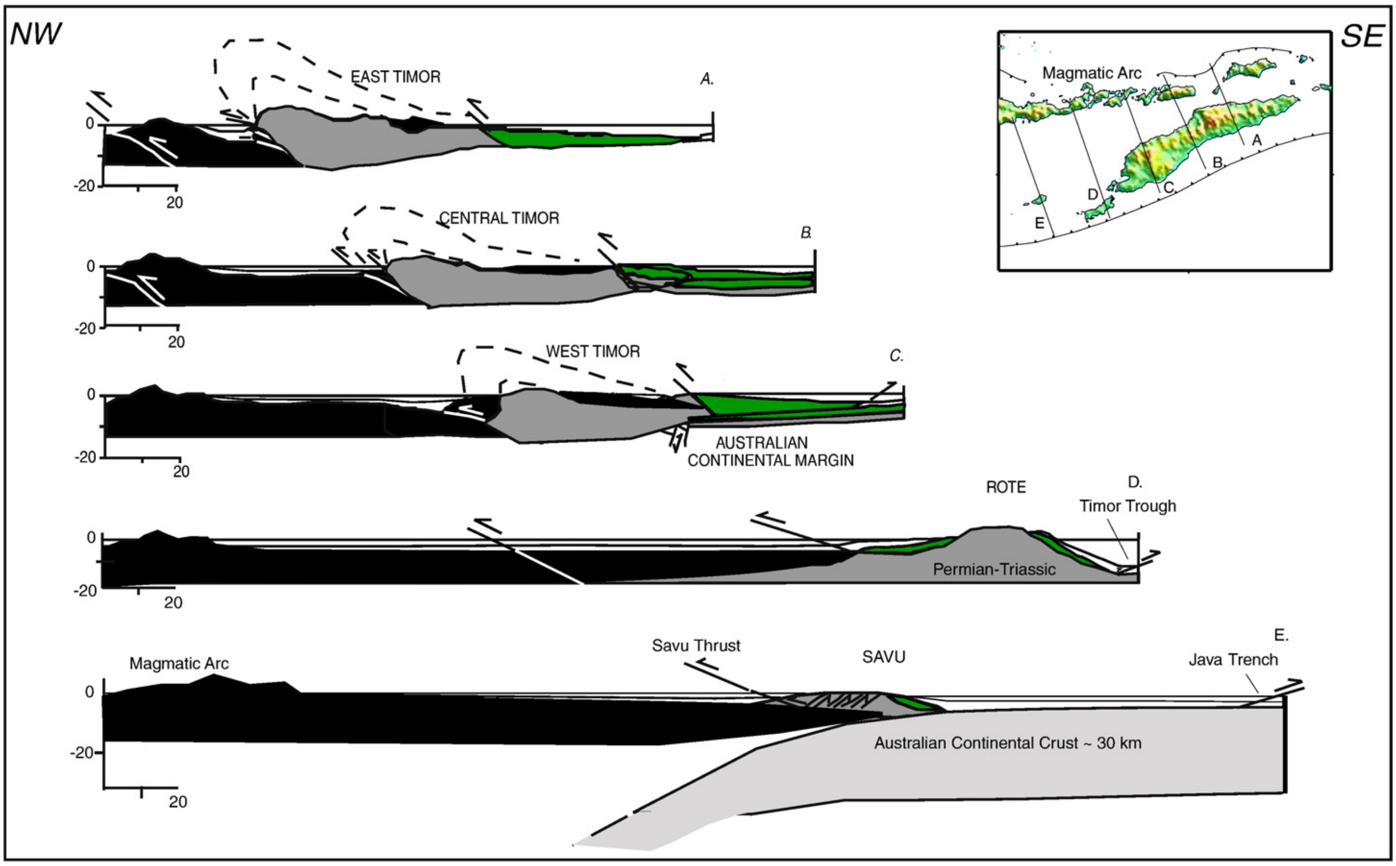


Fig. 3. Serial sections through Timor, Rote, and Savu Islands. The sections suggest a time-space equivalence along orogenic strike at least from Rote (initial phase) to East Timor (advanced stage). Lithotectonic units explanation: Black — forearc basement; Dark grey—Gondwana Sequence sedimentary basement and mélange; Green — Australian passive margin sequence; White — synorogenic deposits. Revised from Harris (1991) and Harris et al. (2000).

from Timor to the west through time at an estimated rate of 110 km/Ma (Harris, 1991). East of Timor the collision zone makes a counterclockwise U-turn curve called the Banda arc.

Subduction zone volcanism initiated in the Banda Arc about 15 Ma ago due to continued subduction of Jurassic to Early Cretaceous oceanic lithosphere (Abbot and Chamalaun, 1981; Hall, 2002). A small accretionary wedge, like the one currently forming the Lombok ridge just west of Sumba, formed in front of the new arc complex, which is the bedrock underlying much of the Latest Miocene to Pliocene synorogenic deposits found in Savu, Rote and southern Timor (Harris et al., 1998). These deposits include deep marine chalk and calcilutite that covered the entire accretionary wedge before it was uplifted due to the underthrusting of the distal Australian continental rise and slope.

Erosion of the emerging accretionary wedge initiated a change in synorogenic sedimentary facies from deep marine chalk to turbidite deposits. These deposits become increasingly more clastic-rich upward until they are overlain by coral terraces and fluvial gravel, which document continued emergence and widening of the islands. Serial section through various parts of the Banda orogen, including Savu and Rote Islands (Fig. 3), document the rise of synorogenic deposits from initial depths of the accretionary ridge and slope 3000–4000 m to at least 1200 m above sea level in Timor. Not shown in the Rote section is a pervasive left-lateral strike-slip component to the deformation that we observed throughout most of the units. Transvergence in Rote is most likely due to parallelism between the NE–SW continental margin and direction of convergence.

Emergence of the Banda arc-continent collision forms two parallel ridges of young islands. The inner ridge is the Miocene-present Banda volcanic arc (Fig. 2). The outer ridge is the uplifted accretionary wedge that transitions into one of the youngest fold and thrust belts of Earth, currently encroaching on the NW Shelf of Australia. However, only the hinterland part of the fold and thrust belt is exposed (Fig. 3). South of these islands the position of the plate boundary, defined to the west by the Java Trench, becomes ambiguous due to transitional geological and geophysical features, including: 1) the transition of the convex southward Java Trench to convex northward Timor Trough (Fig. 1), 2) broad patterns of seismicity (McCaffrey et al., 1985), 3) distribution of strain along multiple plate boundary segments (Silver et al., 1983; Harris, 1991), and 4) systematic changes in the GPS velocity field (Genrich et al., 1996).

New GPS measurements (Nugroho et al., 2009) show that Sumba, Savu and Flores move in the same direction relative to Asia as the subducting Australian plate, but at only one third the velocity (23–32 mm/a). Timor and the arc islands to the north also move in the same direction as Australia, but at two-thirds its rate (47–50 mm/a). Rote occupies a kinematic transition zone between these two different groups of islands and moves at 44 mm/a relative to Asia. The similarity in directions of motion of the Banda arc-forearc with the Australian Plate, and increasing velocities relative to Asia eastward toward the most mature parts of the oblique collision are interpreted as a progressive increase in coupling of the Banda arc-forearc with the Australian plate as the arc-continent collision propagates westward (Nugroho et al., 2009-this issue).

2. Lithologies of savu and rote island

The geology of Rote was first explored by Brouwer (1942), who documented fossiliferous Permian, Triassic, Jurassic, Cretaceous, Eocene, and Miocene sedimentary rocks that correlate with similar units in Timor. Gondwana Sequence units that make up the base of Australian continental margin cover, and rise and slope deposits of the

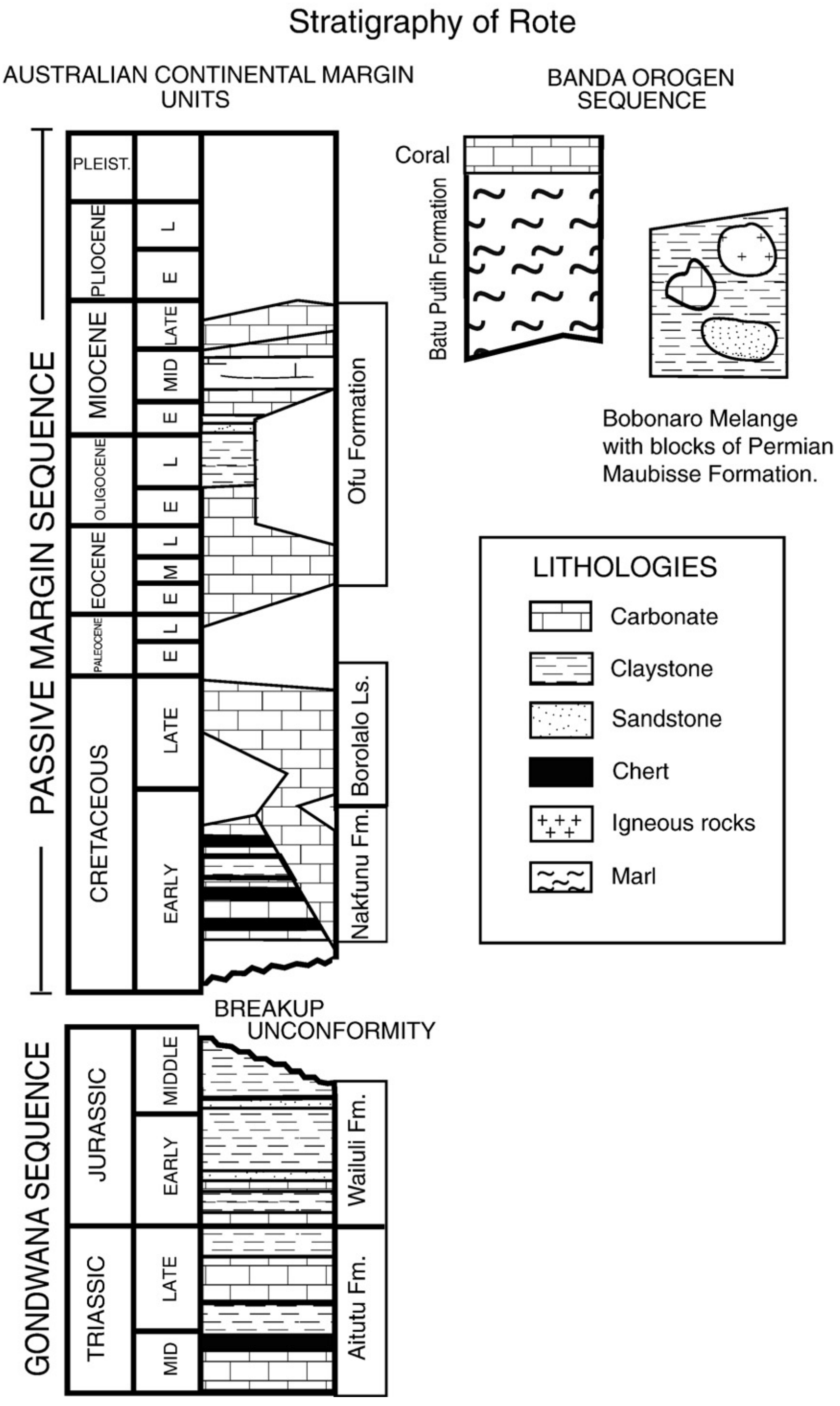


Fig. 4. Lithologic units of Rote Island.

passive margin sequence are also found (Fig. 4). Both of these mostly sedimentary sequences have been scrapped off of the Australian continental lower plate as it subducted beneath the Banda Forearc. Unconformably overlying the accretionary wedge is the Banda Orogen Sequence, which consists of mélange and synorogenic deposits. Detailed mapping of Rote (Fig. 5) and Savu (Harris et al., 2009) reveal the following units:

1) The Triassic Aitutu Formation (Audley-Charles, 1968) is a white to pink, *Halobia*-rich limestone with interbedded carbonate mudstones and some chert nodules. This formation is exposed along the north coast of Rote near Baa (Fig. 5), but is not found in Savu (Harris et al., 2009).
2) The Late Triassic Babulu Formation (Gianni, 1971) consists mostly of interbedded sandstone and shale. Most of the section consists of thinly bedded limestone with chert nodules, shale, siltstone and thick sandstone beds. A marker bed in the middle part of the section consists of a 10 cm thick packstone containing *Halobia*. The limestone section of the Babulu Formation is sandwiched between two massive to bedded sandstone units. The Babulu Formation is exposed extensively in south-central Savu, but is not recognized in Rote.
3) The Jurassic Wai Luli Formation (Audley-Charles, 1968) is a homogenous dark grey and red colored mudstone and shale with interbedded organic-rich limestone, calcilutite, siltstone, and characteristic ironstone concretions. The basal units in Savu consist of pink calcilutite overlain by a series of pillow basalt (Harris et al.,

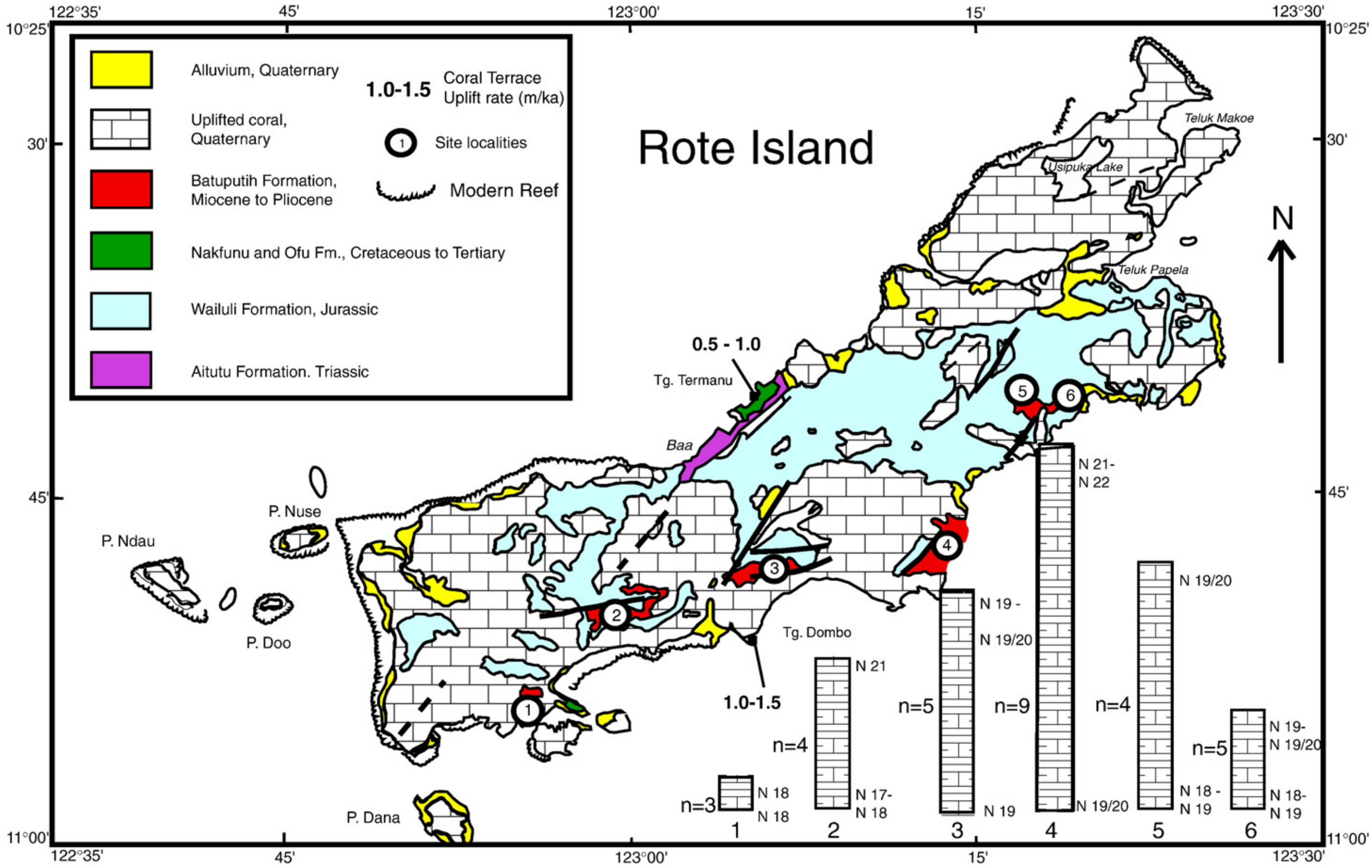


Fig. 5. Geologic map of Rote Island. Circled numbers are site locations of foraminifer's analysis. Columns are measured sections of Batu Putih Formation and ages at each site. The thickest section (4) is 237 m. Major differences between this map and an earlier version published by Rosidi et al. (1979) are: 1) most areas previously mapped as mélange are identified as Wai Luli Formation, and 2) areas previously mapped as Noele Marl are Batu Putih Formation.

2009). The Wai Luli Formation is exposed mostly in the core of both Savu and Rote Islands. It is highly strained by flexural flow-type deformation, and locally grades into block-in-clay mélange. Within the mélange are blocks of Gondwana Sequence-sandstones, Permian crinoid-rich limestone, and metamorphic and igneous rocks. The contact between the Wai Luli and underlying Triassic rocks is well exposed along the south coast of Savu (Harris et al., 2009) and at Termanu point in Rote (Fig. 5).

4) Cretaceous to Tertiary deposits consist of a Fe/Mn-rich shale and mudstone interlayered with radiolarian chert locally interbedded with calcilutite (Nakfunu Formation), which are overlain by thick calcilutite layers interbedded with mudstone (Borolalo Limestone and Ofu Formations). These pelagic successions mostly represent rise and slope deposits of the Australian continental margin sequence (Haig and McCartain, 2007) and Scott Plateau. Only small outcrops of isoclinally folded Nakfunu Formation are found in Savu (Harris et al., 2009). In Rote, excellent sections are exposed on both the north and south coasts (Fig. 6).

Biostratigraphic analysis of the well-exposed chert, calcilutite and mudstone section of Nakfunu Formation at Termanu Point (Fig. 6) yields a uniform assemblage of calcareous nannoplankton diagnostic of the Berriasian to Valanginian (144–132 Ma), which includes *Cyclagelosphaera deflandrei*, *Watznaueria brittanica* and *W. communis.* We found the same nannoplankton in samples we collected from near the type locality of the Nakfunu Formation in the Oetuke River section of West Timor. Late Cretaceous (Campanian to Maastrichtian) nannoplankton are found in the Borolalo Limestone, which overlies the Nakfunu Formation.

Thick sections (>200 m) of folded Ofu Formation are exposed at Batu Hun, which is a large (~1 km^2) sea stack to the east of Termanu Point (Figs. 5 and 6b).

5) The Neogene Viqueque Group of Timor (Kenyon, 1974), or the Banda Orogen Sequence as we refer to it here, is a synorogenic deposit that consists of four Formations. The basal unit is the Batu Putih Formation (Audley-Charles, 1968), which consists of massive, foraminifera-rich chalk deposits with some calcilutite and vitric tuff horizons. The depositional environment is consistent with a deep, low energy, open sea that received minimal terrigenous input.

The depositional contact between the Batu Putih Formation and underlying accretionary wedge is unconformable. In Rote, the Batu Putih Formation is found in discontinuous patches along the southern coast (Fig. 5). Thicknesses vary from 37–50 m in the west to 237 m in the eastern part of the island. In Savu, the Batu Putih Formation is found mostly in the eastern part of the island where sections >100 m thick are exposed and 240 m thick were penetrated by the Savu #1 well (Harris et al., 2009). Kenyon (1974) reports ages for the Batu Putih Formation in East and Central Timor from Neogene foraminifera zones N18–N19 (5.6–4.2 Ma), and in western-most Timor ranges up to zone N20 (4.2–3.4 Ma). All foraminiferal zones and ages are according to Blow (1969), Berggren and Miller (1989) and the 2004 Global Time Scale (Gradstein et al., 2004). However, locally an older (Zone N15–N17) calcilutite and mudstone unit is found in both West and East Timor that underlies the Batu Putih Formation, which Kenyon (1974) named the Tanah Ratu Limestone.

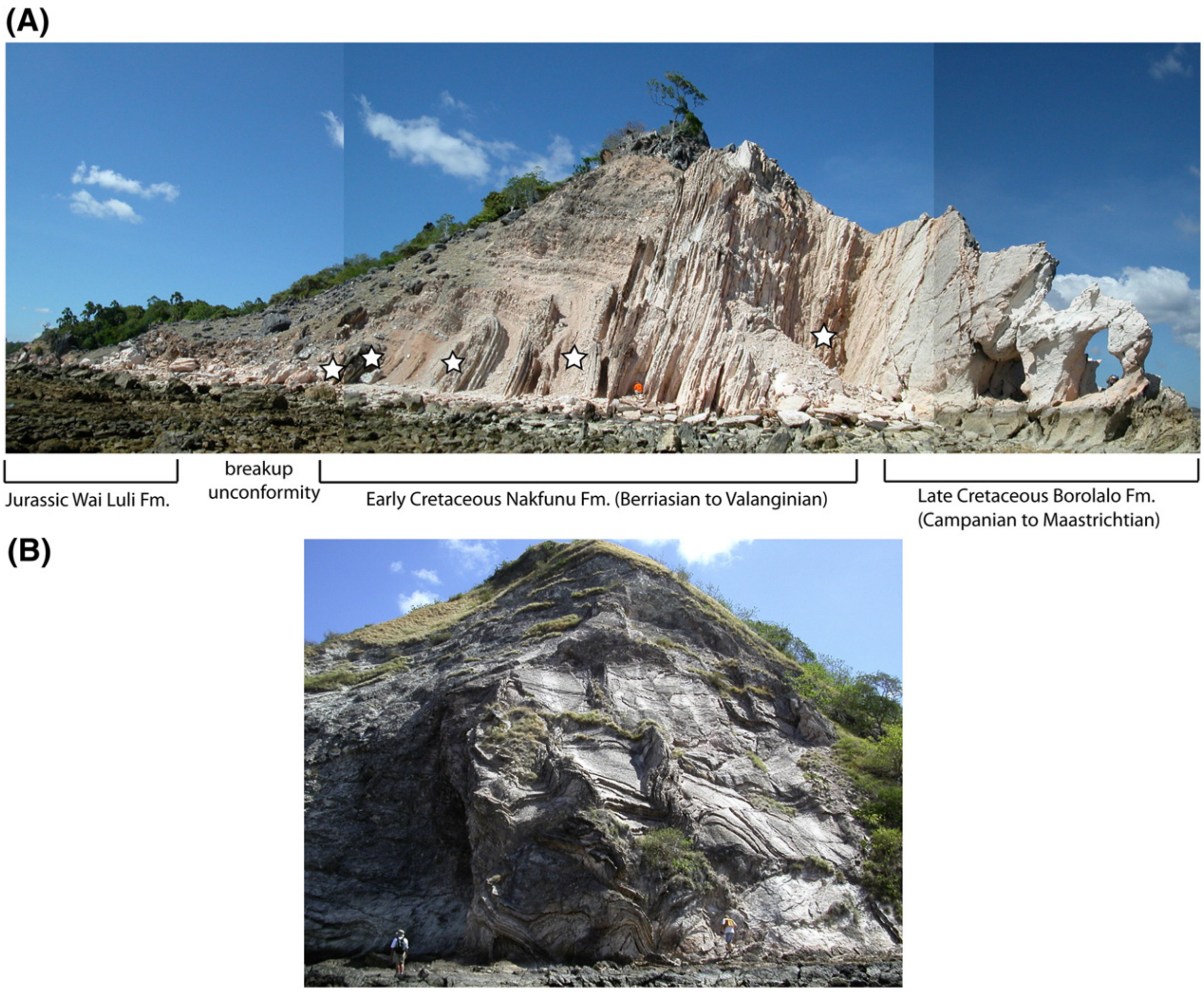


Fig. 6. Photographs of accreted Australian passive margin sequence units at Termanu Point in Rote. A) Looking east at pink calcilutite, mudstone and chert layers. Carbonate increases upsection to Borolalo Limestone (arch). Fault-propagation fold is south-vergent with a slightly overturned forelimb. Stars indicate calcareous nannoplankton sample locations discussed in text. Person in red for scale B) Photo looking south at Tertiary micritic limestone of the Ofu Formation, which overlies Late Cretaceous Borolalo Limestone. Note steep fold hinge lines of secondary folds, which are consistent with components of oblique slip.

Maximum thickness estimates of the Batu Putih Formation are provided by seismic images acquired offshore the north coast of Savu. These data show a continuous succession of high amplitude reflections up to 1000 m thick over acoustic basement (Harris et al., 2009). Observations from the Savu #1 well that ties into one line and onshore mapping indicate that the basal calcilutite of this thick section is N18 while the top of the succession is as young as Holocene. These age and thickness constraints yield a sedimentation rate around 178 m/Ma (Harris et al., 2009). The 240 m thick section drilled and dated in the Savu #1 well yields sedimentation rates of 171 m/Ma. Two unconformities identified in the well indicate this is a minimum rate (Apthorpe, 1975). These rates are slightly higher than modern sedimentation rates measured in the Timor Trough of 140 m/Ma (Ganssen et al., 1987).

Overlying the Batu Putih Formation in Timor is the Noele Marl Formation, which consists of calcilutite and marl interbedded with turbiditic sandstone, and tuffaceous material. These deposits become more clastic-rich and coarsen upwards. The Noele marl Formation ranges in age from N20–N22 (4.2–0.7 Ma). Its absence in Rote, Savu and Sumba (Fig. 7) indicates that these islands are at different stages of collisional evolution than Timor. During the time of Neole Marl Formation deposition in Timor, Batu Putih Formation chalk was deposited on the accretionary wedge (Savu and Rote) and in the forearc basin (Sumba), which have emerged much later than Timor.

The other two Neogene units are the Quaternary Baucau coral limestone Formation, which covers most of Rote and much of Savu, and the Ainaro gravel Formation, which is locally interbedded with the coral (Audley-Charles, 1968). These deposits document continued emergence (coral) and uplift and erosion (gravels) of the islands during the Quaternary (Fig. 7). The coral forms multiple uplifted terraces with U-series age determinations that yield ages of Holocene to 130 ka on the lowest terraces (Merritts et al., 1998; Harris et al., 2009).

3. Uplift history

Initial estimates of the uplift history of the outer arc islands of the Banda arc-continent collision are based on micropaleontology studies of synorogenic deposits in Timor by Audley-Charles (1986). The onset of uplift of Timor at around 3–5 Ma, from a deep submarine accretionary ridge to a mountainous fold and thrust belt now reaching nearly 3 km high, is estimated at 3 mm/a. After 3 Ma, uplift is interpreted to have slowed to around 1.5 mm/a, which is corroborated by recent studies of uplifted coral terraces on the north coast (Cox et al., 2006).

A more detailed study of foraminifera in the Batu Putih and Noele marl Formations during the past 3 myr was conducted by De Smet et al. (1990). They used foraminifers to determine chronostratigraphy and paleobathymetry from two sites in the Central Basin of Timor (Fig. 2), which were uplifted in two relatively short episodes. At about 3.0 Ma, pelagic calcilutite was deposited on the accretionary wedge at

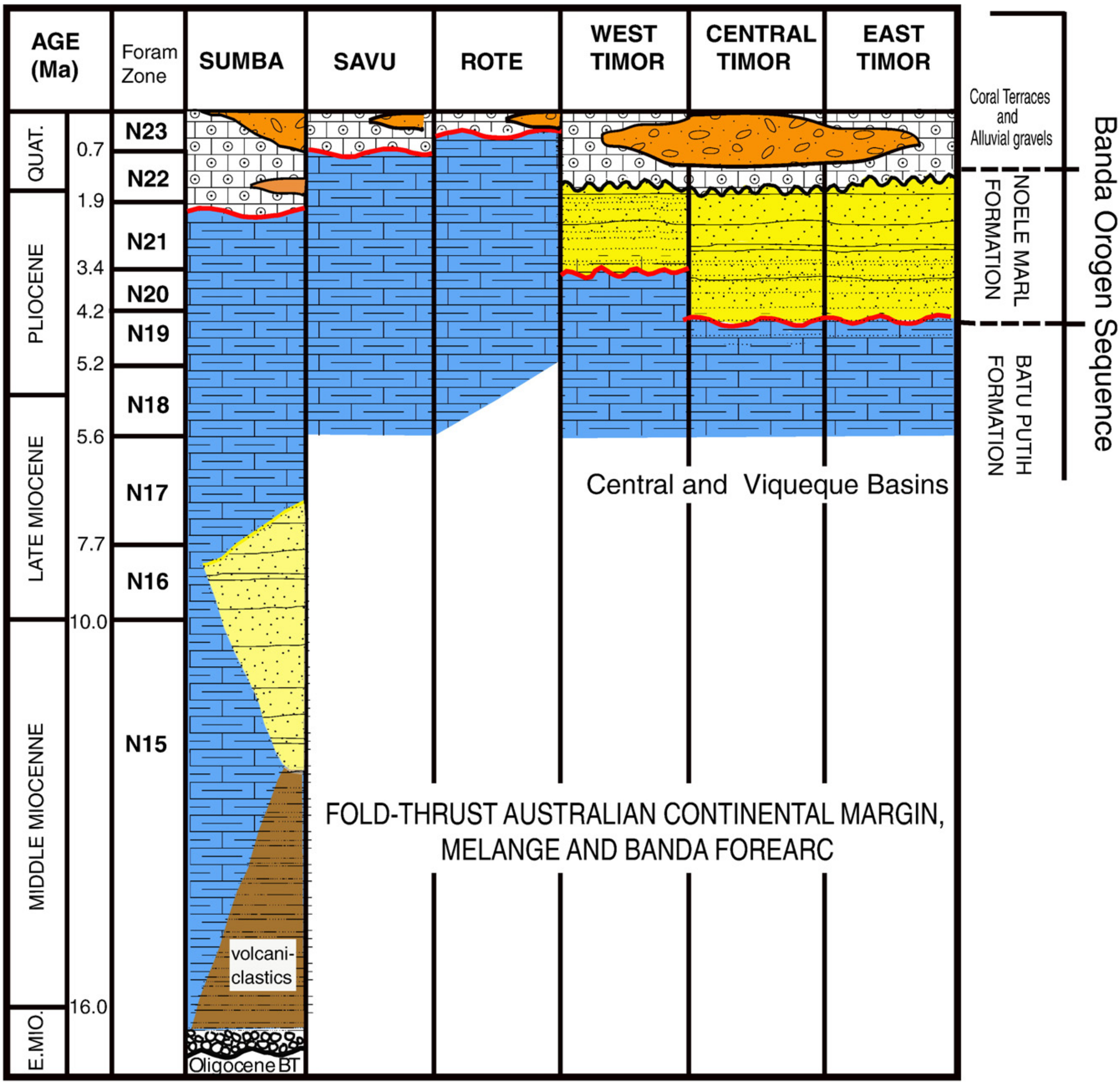


Fig. 7. Spatial and temporal distribution of Banda Orogen Sequence synorogenic units from East Timor to Sumba. Changes in lithofacies and depth of deposition through time indicate the arc-continent collision propagated westward along the Australian passive margin from East and Central Timor to Rote, and along the eastern edge of the Scott Plateau from Sumba to Rote. The Noele Marl Formation is most likely being deposited in offshore basins of Rote and Savu.

a water depth of about 1500 m. A short period of rapid uplift at 2–3 mm/a is reported at ~2.0 Ma, which was followed by deposition of 1.5 km of distal turbidites. This event was followed by a long relatively quiet period during which hemipelagic marls and turbidites accumulated at upper-middle bathyal depths (~1000 m). A second period of rapid uplift started at ~0.2 myr ago and resulted in emergence of large parts of the Central Basin at rates of 5 to 10 mm/a (De Smet et al., 1990). Similar studies of uplift rates of the Viqueque Basin in East Timor between 5.6 and 1.9 Ma estimate rates of 0.5–0.3 mm/a (Haig and McCartain, 2007).

Fortuin and De Smet (1991) also investigated rates and magnitudes of late Cenozoic vertical movements in the outer Banda arc islands of Buton, Buru, Seram, Kai, Tanimbar and Sumba. Synorogenic deposits with a high time-stratigraphic resolution show pulses of uplift with durations between 0.1 and 1 myr, and rates exceeding 5 mm/a. Analyses of foraminifers in Sumba (Fortuin et al., 1997) yield surface uplift rates of 0.73 mm/a.

Uplifted coral terraces with U-series age determinations throughout the Banda orogen yield uplift rates over the past of 10^3 to 10^5 years of 0.3 to 1.5 mm/a. Merritts et al. (1998) calculated coral uplift rates on Rote of 1–1.5 mm/a, and on the nearby island of Semau of 0.2–0.3 mm/a. Jouannic et al. (1988) measured coral terrace uplift rates near Kupang, West Timor of 0.3 mm/a. Coral terraces on the north coast of Savu, which are associated with the north-directed Savu thrust system, yield uplift rates at least 0.3 mm/a (Harris et al., 2009). Eastern Sumba has coral uplift rates of 0.5 mm/a (Pirazzoli et al., 1991). Along the north coast of East Timor coral terrace uplift rates vary from <0.3 to 1.5 mm/a (Cox et al., 2006).

Geochronological studies of metamorphic rocks along the north coast of central East Timor (Berry and McDougall, 1986) and detrital apatite fission track ages from throughout Timor (Harris et al., 2000) indicate exhumation rates of 2.1–3.0 mm/a.

In summary, long-term uplift rates as high as 10 mm/a are estimated for some parts of Timor using foraminifera to determine chronostratigraphy and paleobathymetry. In Rote and Savu, uplift rate data is only available from age determinations over the past 130 ka of coral terraces, which show maximum rates of 1.5 mm/a. The highest rates are near the south-directed deformation front of Rote. Lower rates (0.3 mm/a) are found associated with north-directed thrusting at the rear of the accretionary wedge in Savu and along orogenic strike in westernmost Timor. This study provides age versus depth estimates from detailed analysis of foraminifera in Rote and Savu where uplift rates of coral terraces and GPS measurements exist to help understand the relations between uplift at a range of time scales and known plate convergence rates.

4. Foraminiferal analysis

4.1. Methods

We mapped, measured, and sampled each occurrence of the Batu Putih Formation on both Rote (Fig. 5) and Savu (Harris et al., 2009). This includes three sites in Savu (Harris et al., 2009) and six sites in Rote (Fig. 5). At each site samples were collected at the base and at 1–3 m intervals to the top of the exposure. The homogenous nature of the chalk with little to no bedding planes or lithologic variation, and the paucity of outcrops provide challenges for correlation of internal units from one site to the next. Sixty samples were collected throughout the massive successions of chalk on Rote and Savu. Of these, 30 samples from Rote and 10 from Savu yield identifiable foraminifera (Table 1), which are assigned age and depth estimates according to Postuma (1971), Bolli and Saunders (1985), Berggren et al. (1995), Adisaputra (1989), van Marle (1989a,b), Cifelli (1990), Richardson (1990), Chaisson and Leckie (1993), Kennett and Srinivasan (1983) and Berggren and Miller (1989).

Table 1
Sample location.

Sample	Latitude	Longitude	Elevation (m)
RT-002	10.5326	122.5624	37
RT-003	10.5339	122.5642	12
RT-004	10.5344	122.5644	10
RT-TX04	10.4853	123.11	130
RT-W03	10.507	122.5925	10
RT-027	10.5	122.5926	75
RT-029	10.5056	122.5829	65
RT-024	10.5048	122.592	27
RT-X06	10.4837	123.525	177
RT-X05	10.4852	123.511	225
RT-X03	10.4845	123.522	20
RT-X02	10.49	123.439	150
RT-X01	10.4844	123.46 55	
RT-V08	10.474	123.1325	225
RT-V09	10.472	123.1329	20
RT-Y08	10.4722	123.1332	198
RT-V05A	10.471	123.1331	142
RT-V05C	10.471	123.1331	137
RT-Y01	10.4739	123.1359	12
RT-U10	10.4222	123.1725	200
RT-U11	10.4139	123.1738	190
RT-U08	10.413	123.1742	170
RT-U12	10.4213	123.1727	50
RT-U02	10.4141	123.1814	125
RT-040C	10.414	123.1818	80
RT-040B	10.414	123.1818	75
RT-040A	10.414	123.1818	60
RT-U03	10.4147	123.182	45
SV-62 1	0.5222	121.9665	17
SV-60 1	0.5282	121.9801	61
SV-67 1	0.5034	121.9055	146
SV-64 1	0.4981	121.9031	78
SV-71b	10.4579	121.8865	
SV-71a	10.4579	121.8865	81
SV-72a	10.4493	121.885	23
SV-72c	10.4493	121.885	

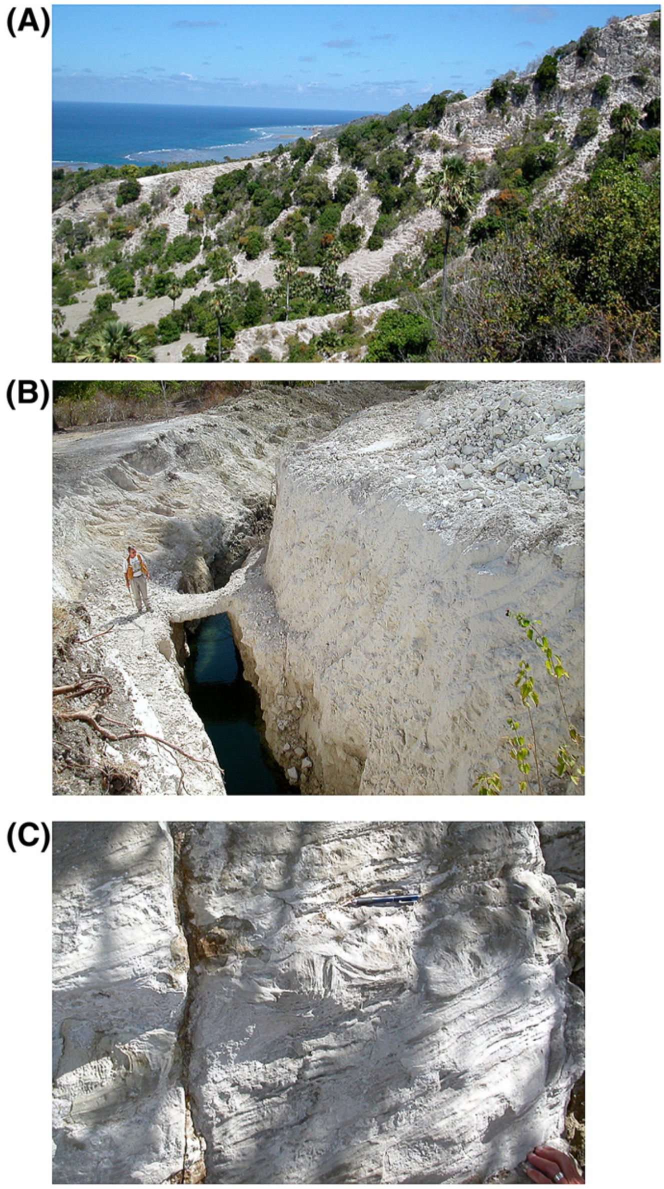


Fig. 8. Photographs of Batu Putih Formation chalk in Rote. A) Looking SW from Site 4 (Fig. 5) at thickest deposit of chalk. Notice modern fringing reef in distance. Exposed on shore are uplifted Holocene coral overlying chalk deposits. At around 180 m elevation these chalk successions are overlain an uplifted, 125 ka coral reef. B) Fresh outcrop of massive chalk from near Tebole Village (Site 4). C) Detail of rare bedded interval within chalk that shows slump structures near Oeseli Village of Site 2 (10° 53′ 49.2″, 122° 55′ 40.4″).

Another method used to estimate paleobathymetry is the planktic (P) to benthic (B) foraminifera ratio (van Marle et al., 1987). This analysis utilizes the greater abundance of benthic foraminifers in shallow water versus planktic foraminifers, which live passively (floating) and are found ubiquitously. The P/B ratio of foraminifera in every sample is found by examining 300 random individuals and using the formula (van Marle et al., 1987):

$$P/P + B \times 100\%$$

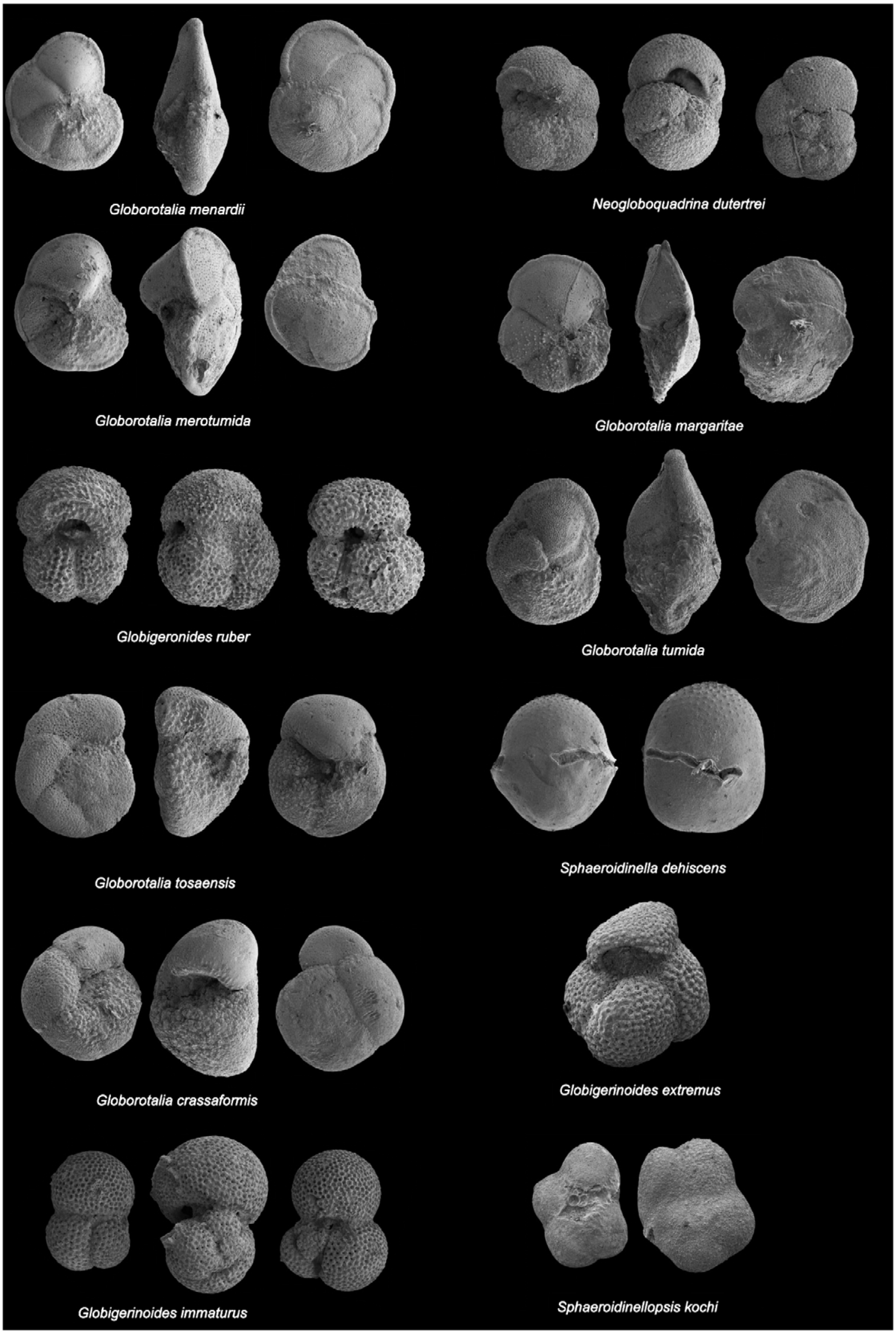


Fig. 9. SEM images of characteristic Late Neogene planktic foraminifera from Rote and Savu Islands. Magnifications vary: *Globorotalia menardii* view 160×,*Globorotalia merotumida* view 340×,*Globigeronides rubber* view 230×,*Globorotalia tosaensis* view 250×, *Globorotalia crassaformis* view 180×, *Globigerinoides immaturus* view 150×, *Neogloboquadrina dutertrei* view 180×, *Globorotalia margaritae* view 250×, *Globorotalia tumida* view 180×, *Shaeroidinella dehiscens* view 180×, *Globigerinoides extremus* view 200×, *Sphaeroidinellopsis kochi* view 150×.

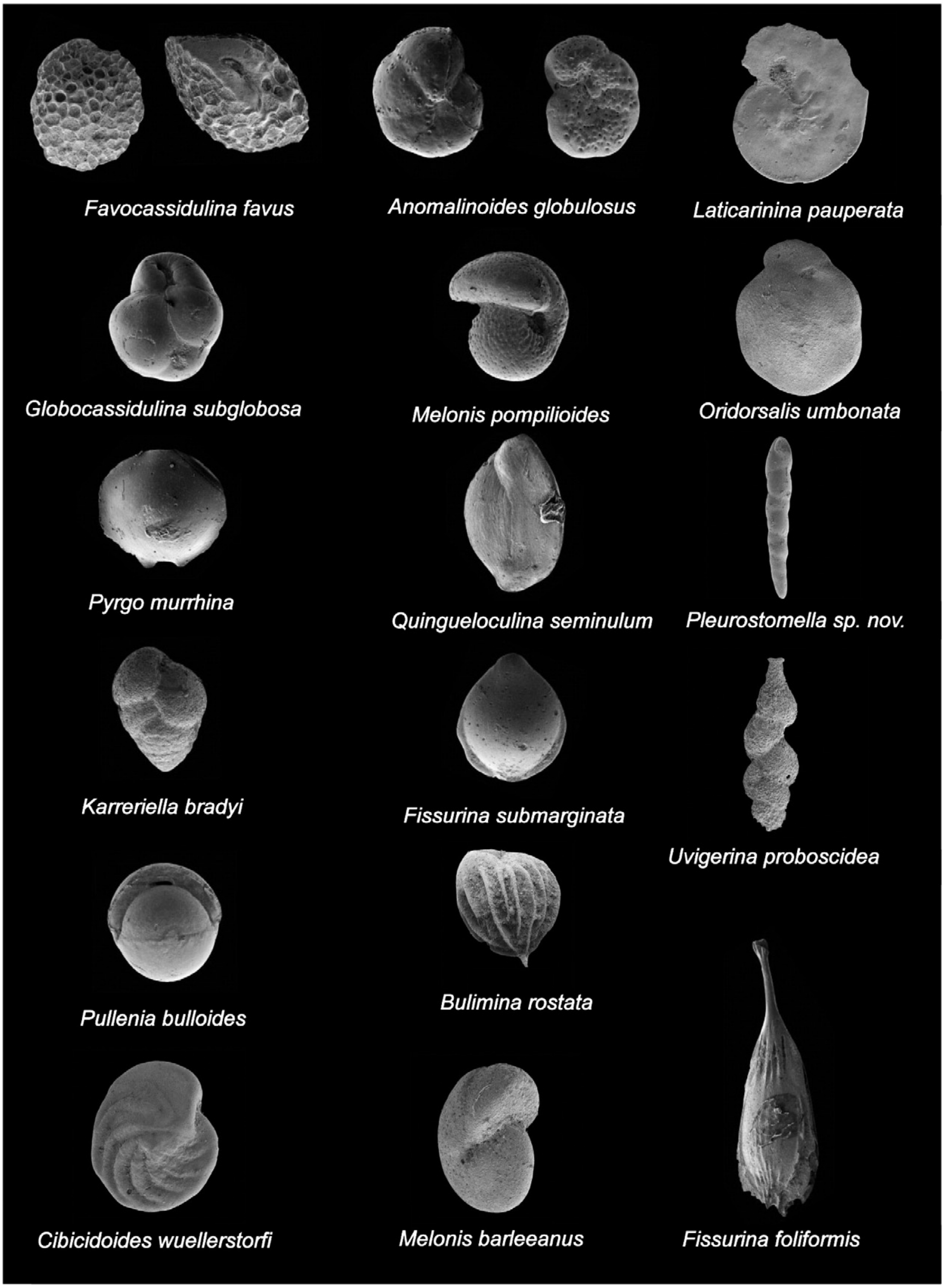


Fig. 10. SEM images of characteristic deep-sea benthic foraminifera from Rote and Savu Islands. Magnifications vary: *Favocassidulina favus* view 100×, *Globocassidulina subglobosa* view 150×, *Pyrgo murrhina* view 200×, *Karreriella bradyi* view 200×, *Pullenia bulloides* view 200×, *Cibicidoides wuellerstorfi* view 100×, *Anomalinoides globulosus* view 200×, *Melonis pompilioides* view 100×, *Quingueloculina seminulum* view 100×, *Fissurina submarginata* view 200×, *Bulimina rostata* view 250×, *Melonis barleeanus* view 200×, *Laticarinina pauperata* view 90×, *Oridorsalis umbonata* view 90×, *Pleurostomella sp. nov.* view 130×, *Uvigerina proboscidea* view 130×, *Fissurina foliformis* view 100×.

To obtain the depth (D), the formula is transformed to:

$$D = e^{(0.061 \cdot P\ +\ 1.25)}$$

The P/B ratio for most samples in rote and savu is 90–99% planktic foraminifers, which is consistent with water depths >2500 m (van Marle et al., 1987).

Additional details about each site, all of the species found in each sample and relative abundance of species are provided in Roosmawati (2005).

4.2. Occurrence

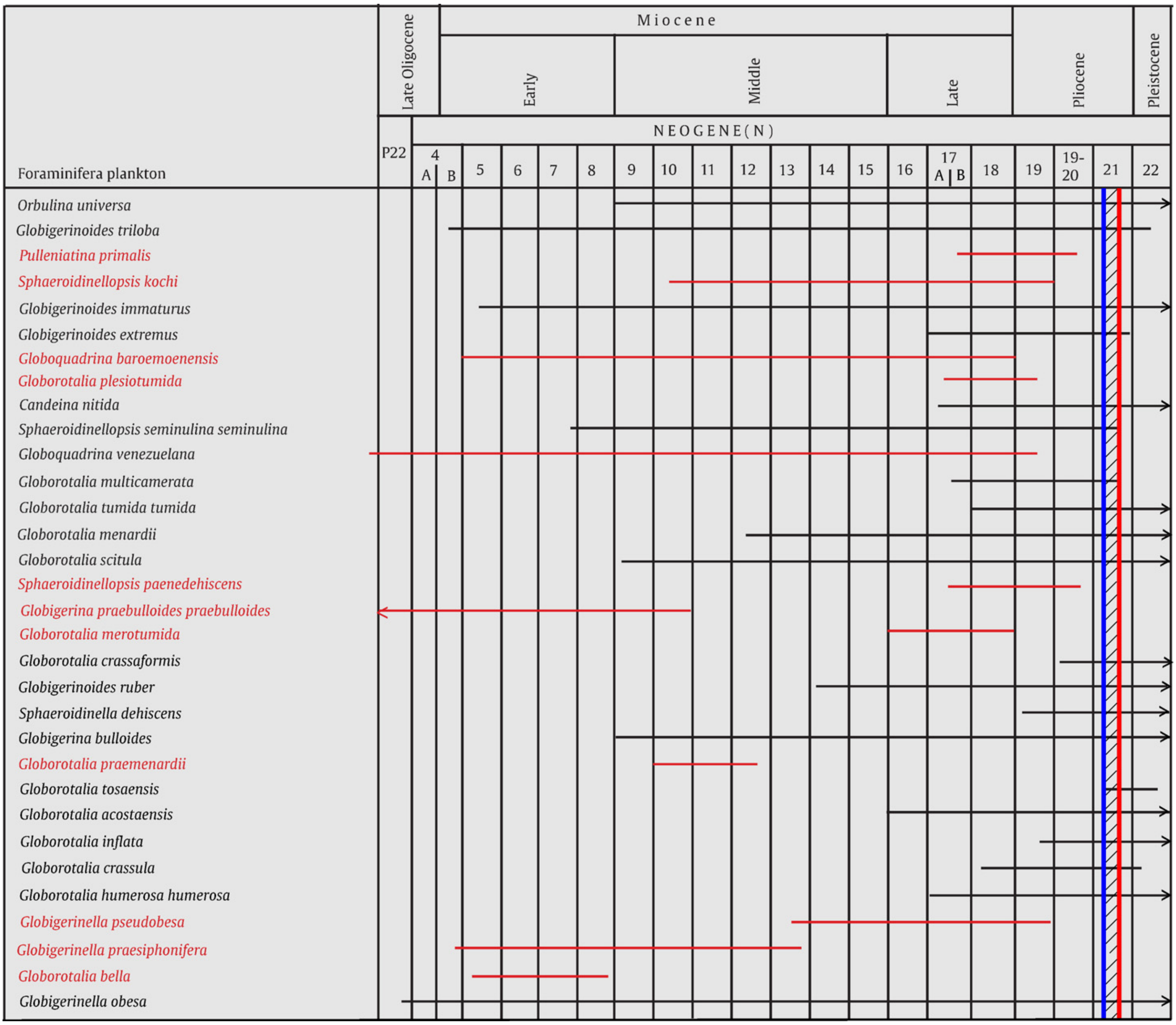
The best-exposed sections of the Batu Putih Formation are found near the south coast of Rote and northern and eastern Savu (Fig. 8). They consist of cliff-forming massive chalk outcrops around 50 m high. The base of the Batu Putih Formation is locally exposed and commonly overlies scaly clay mélange. The top of the unit is mostly eroded away, but is sometimes found beneath an armor of Pleistocene coral and gravel terrace deposits of the same age (Fig. 4).

Planktic and benthic foraminifera are present in most samples of chalk and calcilutite we collected from the Batu Putih Formation, and generally show good to excellent preservation (Figs. 9 and 10). Some partially dissolved foraminifera are also found indicating deposition depths near the lysocline, which is >3000 m in the region (Mohtadi et al., 2007).

4.3. Reworked fossils

In almost every sample there are abundant planktic foraminifers older than the last appearance of oldest species and benthic foraminifers shallower than estimated depth ranges. These species

Table 2
Planktonic foraminifera sample analysis from Site 4, SE Rote.



Red are reworked.

are interpreted as reworked from submarine erosion of older and shallower units. Strong currents through this rapidly closing oceanic gateway between the Pacific and Indian Oceans are well documented by the common occurrence of contourites along the sea floor (i.e. Reed et al., 1987). The presence of *Globorotalia archeomenardii*, *Globorotalia fohsi fohsi*, *Globorotalia praemenardii*, and *Globigerinoides primordius*, with short age ranges must represent reworked species.

Another test of reworking is the relative abundance of various species ((van Marle et al., 1987). In most cases, suspect species only account for <5% of the individuals in random counts. The source of reworked species is unknown, but similar foraminifers are documented from the Sunda Shelf and Sumba (Effendi and Apandi, 1985).

4.4. Age determinations

The age of the Batu Putih Formation in Rote and Savu is bracketed by using the first appearance of the youngest foraminifera species and the last appearance of older species (Table 2). The oldest units have a well-preserved dissolution resistant assemblage of *Globorotalia tumida tumida* and *Globorotalia merotumida*, which indicate a latest Miocene-earliest Pliocene age, Zone N17/18 (5.6 Ma). In East Rote, the lowest part of the section is early Pliocene, Zone N19/20 (5.2–3.4 Ma), based on the first appearance of *Globorotalia crassaformis* and the last appearance of *Sphaeroidinellopsis kochi*. A late Pliocene age for the top of the section in Tebole is constrained by the first appearance of *Globorotalia tosaensis* and the last appearance of *Sphaeroidinellopsis seminulina seminulina*, *Globorotalia multicamerata*, and *Neogloboqudrina dutertei*, which define Zone N21 (3.4–1.9 Ma).

These same species of foraminifera are also found in the Batu Putih Formation of eastern Savu (Harris et al., 2009) and near the base of the Savu #1 well (Apthorpe, 1975). Age determinations of foraminifera in units drilled by the well indicate a disconformity at 63–70 m depth with Zone N22/23 (Pleistocene) calcilutite intermixed with coral debris directly overlying Zone N19 (4.2–5.2 Ma) age calcilutite. These youngest sections are not found onshore.

The maximum age of the Batu Putih Formation implies that the part of the accretionary wedge these sediments overlie formed by at least 5.6 Ma. Older and more deformed Batu Putih Formation-like units underlie Zone N18 deposits near the village of Viqueque in East Timor (Haig and McCartain, 2007). However, the age of these deposits is not known. In Sumba, Batu Putih Formation equivalent chalk deposits are around the same age (Zone N11) as the eastern Sunda volcanic arc (~15 Ma, Abbot and Chamalaun, 1981). The much younger age of the basal Batu Putih Formation in Savu, Rote and most of Timor is consistent with the location of these islands at the southern of edge of the Sunda/Banda forearc, and provides a minimum age for the formation of accretionary wedge there.

4.5. Depth estimates

Depth of deposition estimates for the Batu Putih Formation is based on taxonomic classification criteria of van Morkhoven et al. (1986), van Marle (1989a,b) and Jones (1994), and the depth of the lysocline in Savu Sea region. Depth range determinations are based on benthic foraminifer species that have the deepest upper depth limit. Most foraminifers in the oldest sections of Savu are severely dissolved, which indicates depths below the lysocline. The lowest fauna diversity with mostly only dissolution resistant species are found in the basal sections of sites 4, 5 and 6 in Rote, which may also indicate the affects of dissolution in the lysocline. Similar conditions are found along orogenic strike to the west on Lombak accretionary ridge, which is around 4 km deep (Fig. 1).

Large depth ranges for most deep-water benthic species cause poor resolution for calculating uplift rates. Notwithstanding these difficulties, we find multiple benthic species with abyssal zone upper depth limits (2000–3000 m). These and other deep marine species include: *Oridorsalis umbonata*, *Cibicidoides wuellerstorfi*, *Pullenia bulloides*, *Globocassidulina subglobosa*, *Melonis pompiliolides*, *Laticarinina pauperata*, *Uvigerina proboscidea*, *Pleuroslomella subnodasa*, *Osangulatiella Umbonifera*, *Favocassidulina favus, Bulimina rostrata*, *Oolina truncata, Cibicidoides globulosus, Pleurostomella sp.nov.* and *Amphicoryna scalaris*.

The Batu Putih Formation in Rote has abyssal zone benthic foraminifera in even the youngest sections (Zone N22) near the top of the highest ridge on the island (section 4, Fig. 5). These deposits unconformably underlie uplifted coral terraces of 120–130 ka (Merritts et al., 1998).

Batu Putih Formation samples in Savu of Zone N18 to N21 age (5.6–1.9 Ma) all yield abyssal zone benthic foraminifera (Harris et al., 2009). The uppermost part of the Pliocene section is different and shows little to no dissolution and increased faunal diversity. This change may indicate some shallowing, perhaps due to accretionary growth during the Pliocene. However, along with *Globorotalia truncatulinoides*, which marks the base of Zone N22 (1.8 Ma), there are characteristic deep-water species, such as *Pullenia bulloides, Oridorsalis umbonatus* and *Palnulina wuellerstorfi* indicating abyssal depths. Immediately overlying these deposits are late Zone N22 to N23 (1.0 to <0.7 Ma) neritic species (0–200 m depth) intermingled with coral. These deposits are overlain by a 121,593 ± 736 year old uplifted coral terrace on the northern most tip of Savu (Harris et al., 2009).

5. Uplift rates

We use a geohistory technique analysis (van Hinte, 1978) to estimate long-term uplift rates for Savu and Rote Islands (Fig. 11). This approach uses estimated benthic foraminifer upper depth limits and present elevation divided by the planktic foraminifer age. The results show little to no uplift during Zone N18 to early N22 on both islands followed by an abrupt pulse of Pleistocene uplift.

In Savu, Zone N22 calcilutite deposited at abyssal depths is overlain by Zone N22/23 neritic species deposited at depths of less than 200 m (Fig. 11). These age and depth relations demonstrate how Savu rose 2000 m in 1 Ma (2 mm/a) and emerged near the surface by ~0.7 Ma. Uplifted and warped coral terraces overlying these deposits are found up to elevations of 388 m on the northern slope of Savu. Minimum uplift rates of 0.3 mm/a are estimated for the past 121 ka from U-series age determinations of one of the lowest terraces (Harris et al., 2009). However, the young ages of foraminifera-rich chalk underlying the highest terraces requires slightly higher uplift rates of at least 0.8 mm/a, which increases the fit between coral terraces and sea level high stands (Harris et al., 2009). Before Zone N22 uplift rates were much slower as the accretionary wedge was uplifted mostly by addition of new material to the accretionary wedge. The average uplift rate of the Batu Putih Formation over the past 5.2 myr is 0.7 mm/a.

In Rote, the youngest foraminifera in the Batu Putih Formation are *Neogloboquadrina duetertrei* (Zone N21) in sample RT-TX04 and *Globeratalia tosaensis* (Zone N22) in sample RT-V08 (Table 1). Both of these samples are from the tops of sites 2 and 4, respectively. Benthic foraminifer species in these samples have upper depth limits of 2500 m, which include *Osangulariella umbonifera* and *Pleurostomella sp. nov.* These deposits are locally overlain by warped, 120–130 ka coral terraces as high as 170–180 m above sea level (Merritts et al., 1998). Minimum uplift rates based on the oldest possible age of these species are of 0.9 mm/a. Maximum rates using the youngest possible age are 2.7 mm/a. The average uplift rate is 1.4 mm/a, which is very similar to rates of uplift over the past 125 ka determined by U-series age analysis of uplifted coral terraces (Merritts et al., 1998). Rote emerged at sea level around 0.5 myr after Savu. Slowing of uplift around the time of emergence may be associated with northward propagation of the Savu Thrust system (Harris et al., 2009). The

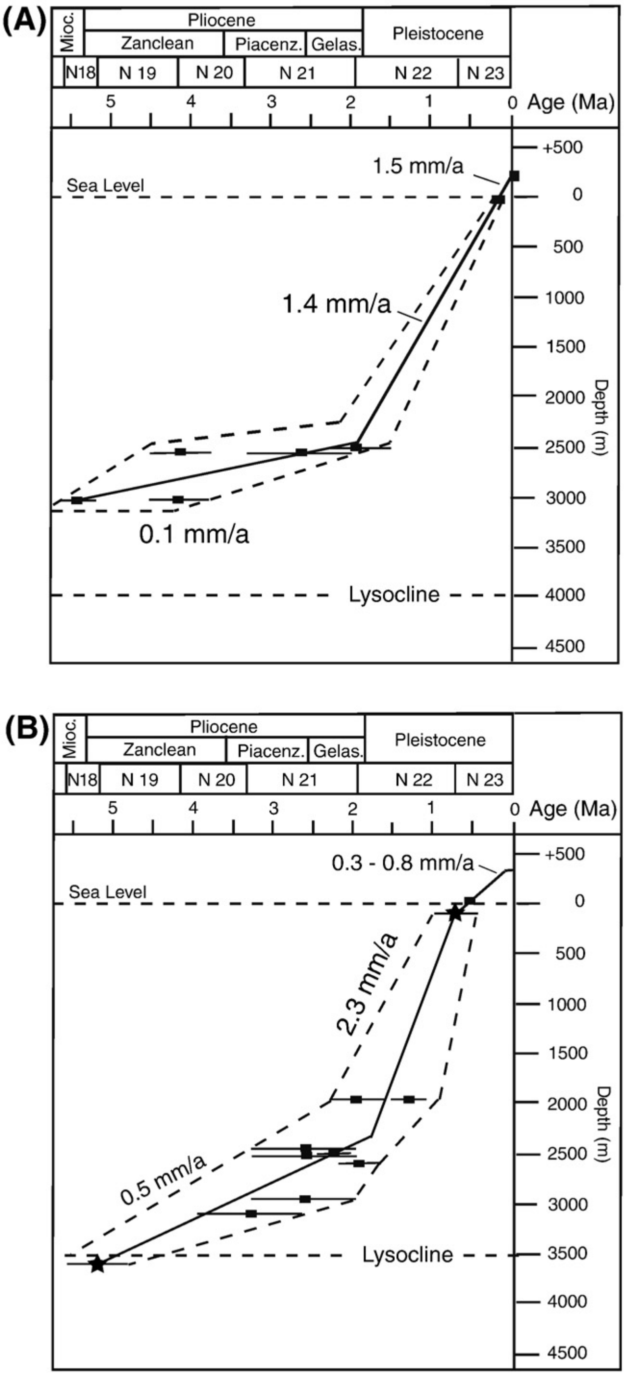


Fig. 11. Geohistory technique analysis diagram of surface uplift rate ranges of Rote (A) and Savu (B). Minimum uplift rates represent the oldest possible upper depth limit of foraminifers at each site. Age range is shown as line through filled square, which is the upper depth limit. Maximum uplift rates represent the youngest possible age of upper depth limits. Parts of curve above sea level are constrained by U-Series ages of analysis of uplifted coral terraces (Merritts et al., 1998; Harris et al., 2009). The mean uplift rate is the solid line. Star is data from the Savu #1 well (Apthorpe, 1975).

average uplift rate of the Batu Putih Formation in Rote over the past 5.6 myr is 0.6 mm/a.

6. Discussion

Geohistory technique analysis of the Batu Putih Formation throughout the outer Banda Arc reveals that it is time transgressive due to collision propagation (Fig. 7). The oldest deposits of Batu Putih Formation-like chalk facies (Miocene Waikabubak Formation) are found in Sumba. These deposits unconformably overlie Cretaceous to Oligocene Sunda forearc basement (Banda Terrane), versus overlying accreted Australian continental margin units as in the rest of the outer Banda Arc islands to the east (Fig. 2). Therefore, synorogenic chalk deposits of Sumba provide the most complete record of the pre-collisional history of the Banda forearc. Geohistory technique analysis of these deposits by Fortuin et al. (1997) indicates a phase of intra-arc rifting at the end of the Oligocene that formed a basin below the CCD (>4500 m). The equivalent of the Batu Putih Formation in Sumba began to accumulate at sedimentation at rates of 36–150 m/Ma at around 7 Ma. The youngest deep-water chalk deposits found in Sumba are 3.8 Ma, which are unconformably overlain by 2.2 Ma reef limestone interbedded with fluvial gravels (Fortuin et al., 1997). During the ~1.6 myr missing interval the chalk deposits were uplifted from ~3000 m depth to the surface at minimum uplift rates of around 1.9 mm/a.

Variation in the age of the Batu Putih Formation may reveal ages and rates of collision initiation and propagation of the Banda Arc. East of Sumba, the maximum age of the Batu Putih Formation is uniformly Zone N18 (<5.6 Ma), and documents that the accretionary wedge there formed 7–9 Ma after initiation of arc volcanism in the outer Banda Arc. However, the minimum age of the Batu Putih Formation is not uniform (Fig. 7), and reveals when the accretionary wedge was uplifted at various stages of collision. In East Timor, the Batu Putih Formation is overlain by Zone N19/20 Noele Marl clastic deposits, which indicates that the northern part of Timor was emergent by this time (Audley-Charles, 1986). In Sumba (Fortuin et al., 1997) and the Central Basin of West Timor (De Smet et al., 1990) the upper sections of the Batu Putih Formation are Zone N20. In Savu the top of the Batu Putih Formation is N22/23 and in Rote late N23.

The top of the Batu Putih Formation provides a maximum age of island emergence (Fig. 7). Decreasing ages from East Timor to Rote indicate a westward propagation of island emergence at a rate of around 104–156 km/Ma (Fig. 12). These rates are consistent with collision propagation rate estimates of 110 km/Ma based on known rates of convergence between the ENE–WSW orientation of the Australian continental margin and the E–W Banda Arc (Harris, 1991). However, the ENE–WSW edge of the Australian continental margin changes its orientation to NW–SE near Rote (Fig. 1) to form the Scott Plateau (Harris, 1991; Keep et al., 2002; Longley et al., 2002).

The NW–SE edge of the Scott Plateau collided first with the Java Trench south of Sumba, then collision propagated SE to Savu and eventually to Rote (Fig. 12). Data presented here are consistent with this prediction and document younger ages at the top of Batu Putih from Sumba to Savu to Rote.

A reconstruction of the collision using depth and age constraints from this study (Fig. 12) shows that abyssal environments at a depth of more than 3000 m prevailed throughout the southern part of the Banda forearc during middle Miocene. The first signs of any change to this environment are the deposition of turbidite successions in synorogenic basins of East Timor during the Early Pliocene and West Timor during the mid-Pliocene (Audley-Charles, 1986). The lack of this change in depositional environment in Rote and Savu (Fig. 7) indicates that they are the first parts of the accretionary wedge west of Timor to emerge. The erosion of these young islands is likely shedding clastic sediment that is accumulating in slope basins offshore. In many ways the current conditions of Savu and Rote are like a reflection of what happened in Timor during the Pliocene.

The topographic relief and elevations of Savu and Rote are very similar with most landmass near sea level and covered with warped and uplifted coral reef deposits. Uplifted coral terraces document that Sumba and Rote are tilted north while Savu is tilted south. This observation implies that shortening is mostly along north dipping thrust faults in Rote versus the south dipping Savu thrust in Savu. In Sumba tilting may be associated with north-dipping thrust faults or

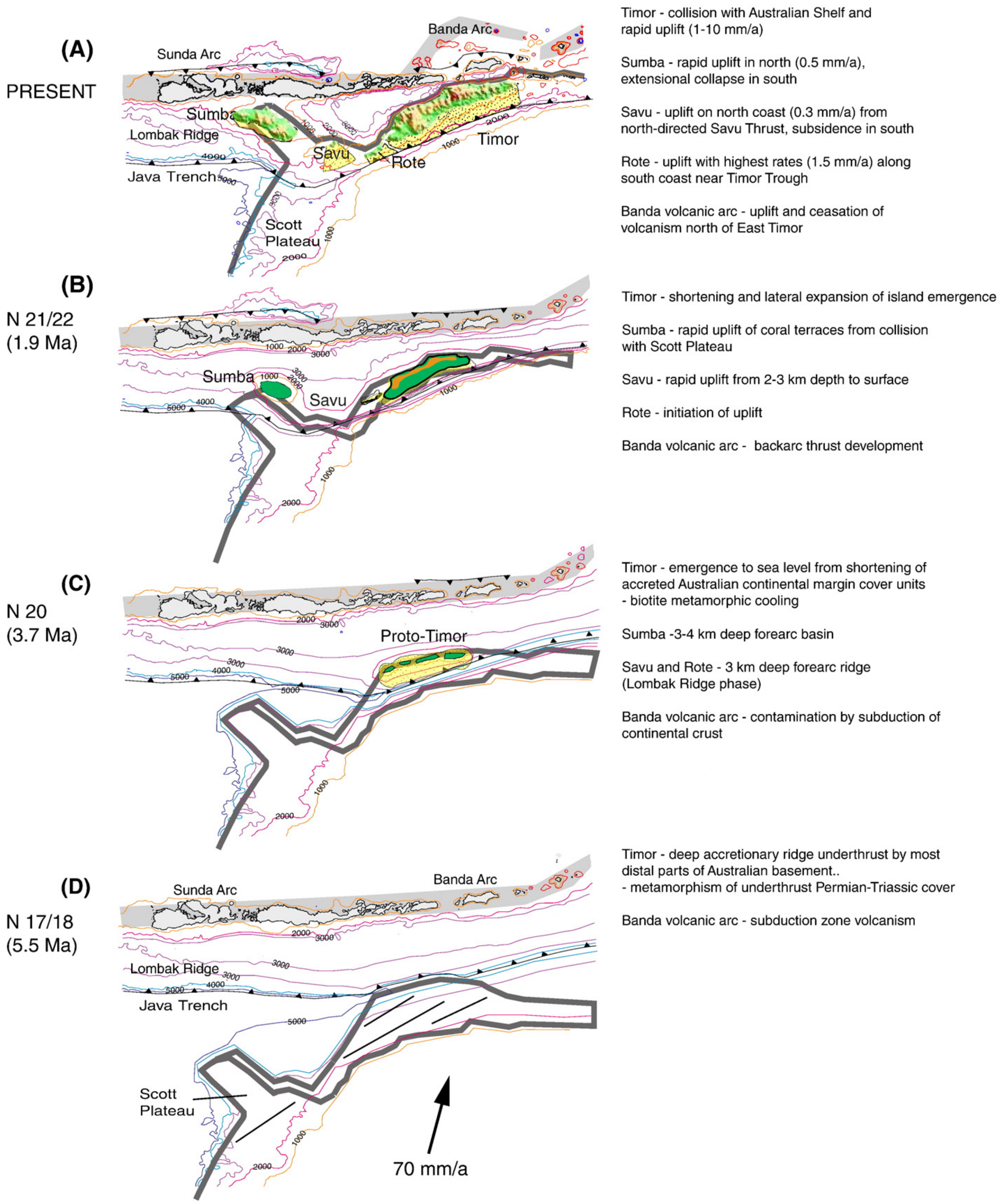


Fig. 12. Palinspastic map of the Banda arc-continent collision using measured velocity (70 mm/a) and direction (015°) of convergence. Shortening of the Australian continental margin is shown by decrease in space between the two lines that represent its width. Green represents land near sea level, brown — mountains, yellow — turbidite deposition and light grey — active volcanism. Bathymetry in 'B' to 'D' is speculative except where constrained by analysis of foraminifera. NE–SW lines in 'D' are approximate axes of rift basins, which is near perpendicular to the NE transform faulted edge of the Scott Plateau. Collision of Australian passive margin initiates in the Timor region and propagates westward toward Rote. Collision of the Scott Plateau initiates in Sumba and propagates SE to Savu and Rote.

extensional collapse. It is evident that accelerated uplift (2 mm/a) above the underthrust the edge of the Scott Plateau is in northern Savu (Harris et al., 2009). Southward tilting of coral terraces in Savu is associated with active accretion of forearc basin rocks to the north-directed front of the Savu thrust system. Passing of the Scott Plateau beneath Rote caused an unconformity at the top of the Batu Putih Formation that is now overlain by coral terraces. We interpret NW tilting of coral terraces in Rote as an indicator of south-directed thrusting and active accretion of Australian continental margin rocks (Fig. 6) to the front of the accretionary wedge, which is only 20 km to the SE.

Near sea-level elevations for Rote and Savu may indicate that they have nearly reached a dynamic equilibrium between surface processes and rock uplift. Pleistocene coral terraces found up to 600 m in both Sumba (Pirazzoli et al., 1991) and East Timor (Chappell and Veeh, 1978; Cox et al., 2006) indicate that surface uplift outpaces erosion in these regions. In the interior of central Timor coral terraces are found up to 1200 m elevation (Rosidi et al., 1979), with several mountainous regions reaching >2000 m elevation. Many of these high regions consist of poorly consolidated rock types, which indicate a major component of dynamic landscape development. These areas are adjacent to the most mature parts of the collision, which is characterized by nearly complete closure of the forearc basin and impingement of the accretionary wedge between the volcanic arc and underthrust thick continental crust of the Australian shelf (Fig. 12A). This event is documented by foraminifer studies of Noele Marl Formation turbidites found in the Central Basin of West Timor that reveal uplift rates as high as 5–10 mm/a over the past 0.2 Ma (De Smet et al., 1990).

The rise of the Banda accretionary wedge plays a significant role in closure of westward circulating surface waters through the Indo-Pacific Seaway (Linthout et al., 1997). A biogeographic barrier between the two oceans is first detected in Early Pliocene Zone N19 (Srinivasan and Sinha, 1998). Restricted flow through the seaway piles up warm water in the equatorial Pacific region, which may have cooled global climate over the past 5 myr (Gasperi and Kennett (1993).

7. Conclusion

The results of detailed examination of planktic and benthic foraminifers in synorogenic chalk deposits (Batu Putih Formation) of Rote and Savu, and from previous work throughout Timor, generally indicate the uplift history of Banda accretionary ridge from its inception at >5.6 Ma to its emergence from 4.2 to 0.5 Ma. Accreted Australian continental margin rocks are found on both islands that correlate directly with those accreted to form the island Timor.

Variation in the age of emergence of both islands documents the history of oblique arc-continent collision propagation along the irregular shaped continental edge of NW Australia. The age of the top of the Batu Putih Formation indicates a change in depositional environment associated with uplift of parts of the accretionary wedge to the surface. In Timor, Zone N19 to N20 turbidite deposits from emerging parts of the island to the north overlie Batu Putih Formation chalk. In Savu and Rote, Pleistocene uplifted coral terraces unconformably overlie chalk deposits. We infer that the offshore portions of the islands of Rote and Savu are currently at the same stage now as Timor was during the Early to mid-Pliocene.

These data indicate that the Banda arc-continent collision is propagating WSW from Timor to Rote at a rate of 104–156 km/Ma, but at the same time also propagates SE from Sumba to Savu to Rote along the NE edge of the Scott Plateau protrusion. The passing of the continental edge beneath the accretionary wedge is associated with short intervals (<1 myr) of rapid uplift at rates of 1.4 to 2.3 mm/a. Independent measurements of surface uplift using coral terraces overlying the emergent chalk deposits in Savu and Rote yield rates of >0.3 to 1.5 mm/a, respectively. We explain differences in rates of early and late Pleistocene uplift in Savu as a result of the south to north underthrusting of the Scott Plateau edge. Similar rates of Batu Putih Formation and coral terrace emergence in Rote we ascribe to ongoing accretion along the deformation front, which is only 20 km to the south.

In terms of equilibrium states of mountain building, changes in depth of Savu and Rote between 5.6 and 1.8 Ma are small, with only the possibility of submarine erosion. However, during the Pleistocene both islands experience a phase of rapid uplift, which starts first in Savu at ~1.8 Ma and in Rote at ~1.0 Ma. Savu may be in the process of returning to its pre-collision equilibrium state. However, Rote maintains fairly high uplift rates (1.5 mm/a) along its south coast possibly due to its proximity to the deformation front.

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