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Notes on the Late Cenozoic history of the Kai Islands, Eastern Indonesia

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Abstract

Field and laboratory data on Cenozoic deposits of the islands of Kai Kecil and Kai Besar provide broad age-depth constraints, but are insufficient for a detailed geohistory analysis to determine the timing, rate and magnitude of vertical movements in the eastern segment of the outer Banda Arc. Yet, a tentative reconstruction of the vertical movements of the islands could be made.

On Kai Besar, lower bathyal-upper abyssal Middle-Late Eocene calcilutites and marls, in combination with Upper Oligocene and Lower-Middle Miocene middle bathyal deposits record an Eocene-Miocene passive margin fill. Kai Besar must have emerged sometime during the Late Miocene to Pliocene-Pleistocene, associated with the development of the Banda Arc thrust belt. The absence of elevated coral reefs, which are present on surrounding islands, suggests that the island is presently subsiding.

On Kai Kecil, Late Pleistocene middle bathyal bioclastic turbidites and marls are nowadays situated just above sea level documenting uplift rates up to 500 cm/ka. In contrast to Kai Besar, Kai Kecil has 4–5 elevated reefs, unconformably overlying the Pleistocene core, showing that the island continues to rise.

Introduction

The Indonesian Banda Arc region is considered to be an area of ongoing continent-arc collision (Hamilton, 1979; Bowin et al., 1980; De Smet et al., 1989), where the continents of Australia and Irian Jaya collide with the Banda Arc subduction complex. During landprograms GF1A and GF2A of the Indonesian-Dutch Snellius-II Expedition (1984–1985) successions of Late Cenozoic deposits were recorded and systematically sampled on several outer Banda Arc islands (Fig. 1), in order to reconstruct their Late Miocene to Recent uplift history, in consequence of the collision process. A general overview of the results of this program on the separate islands is given by De Smet et al. (1989). The Kai Islands were investigated to unravel the history of the easternmost segment of the Banda Arc (Fig. 1). From the numerous islands that form the Kai Archipelago, the two largest (Kai Kecil and Kai Besar) were selected for this study. There are only a few publications on the geology of the Kai Islands (Wertheim, 1892; Verbeek, 1908; Brouwer, 1923; Weber, 1938; Heim, 1939; Bursch, 1947; Van Bemmelen, 1949). These papers report geological reconnaissance studies, concerning local observations and regional evaluations, and they provide only scanty information on the geology. Achdan & Turkandi (1982) made a preliminary map of the island group. According to this map,

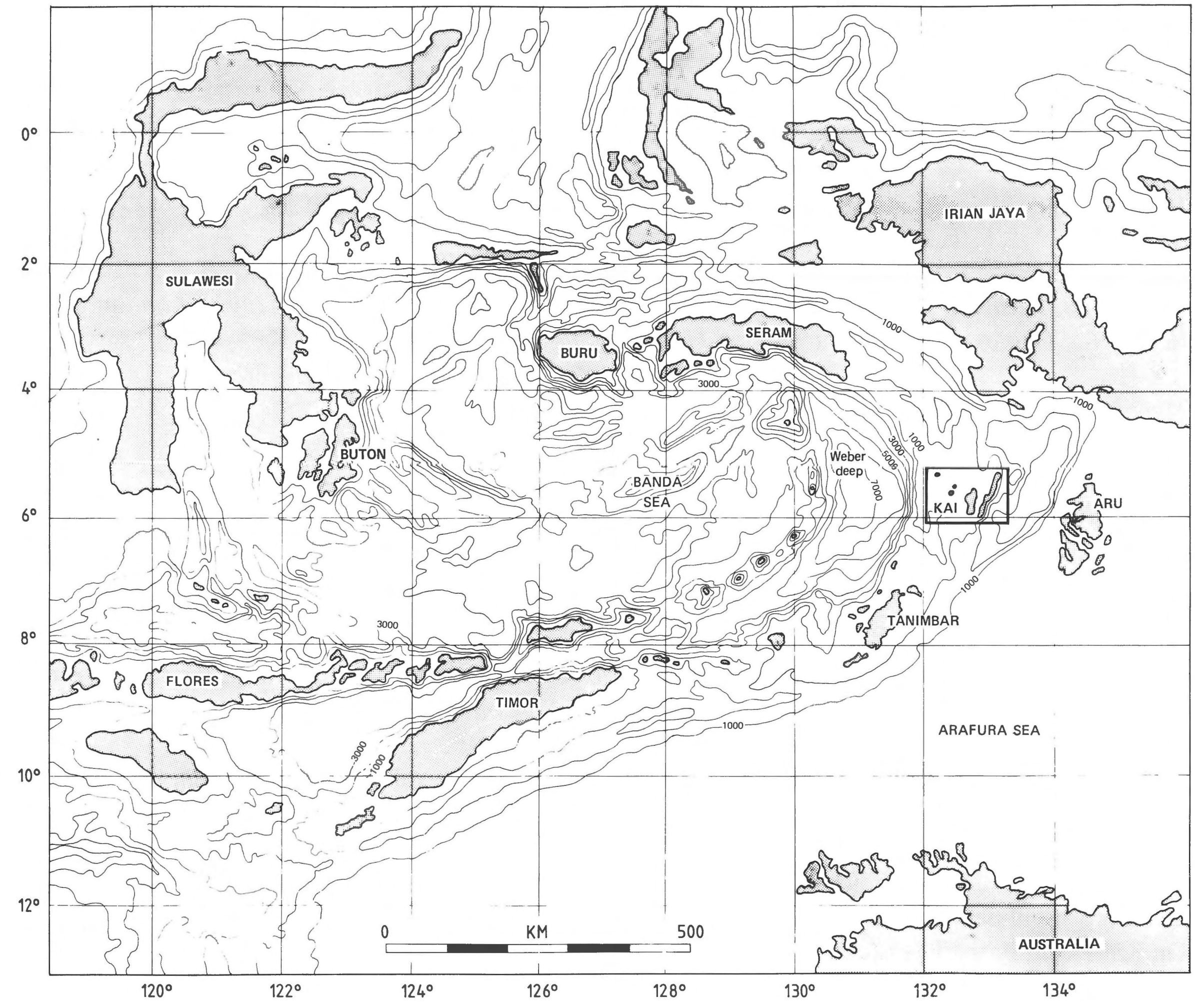

Fig. 1. Map of the eastern Indonesian Banda Island Arc and surrounding areas (with 1000 m waterdepth contours), showing location of the Kai Island group. During the GF1A and GF2A onshore programs of the Snellius-II Expedition also the Neogene of the islands of Buton, Buru, Seram and Timor was investigated.

Plio-Pleistocene rocks are exposed at two places on the island Kai Kecil, which is further built up by coral reefs (Fig. 2). Eocene rocks are reasonably well exposed along the coast of Kai Besar, while there are local outcrops of Oligo-Miocene rocks (Fig. 2). In this paper the results from Kai Besar will be discussed, followed by those from Kai Kecil. We will evaluate the general geological history of this island group in relation to the development of the Banda Arc system.

The material presented in this paper is filed in the Dutch National Museum in Leiden (Rijksmuseum van Natuurlijke Historie) under the first author's name.

Kai Besar

General remarks

Kai Besar is a narrow mountain ridge, reaching up to 800 m above sea level. The island forms a sliver of a large, open anticlinorium with Eocene rocks in the centre. The axis of this anticlinorium is oblique to the axis of the island. Many small open folds on a

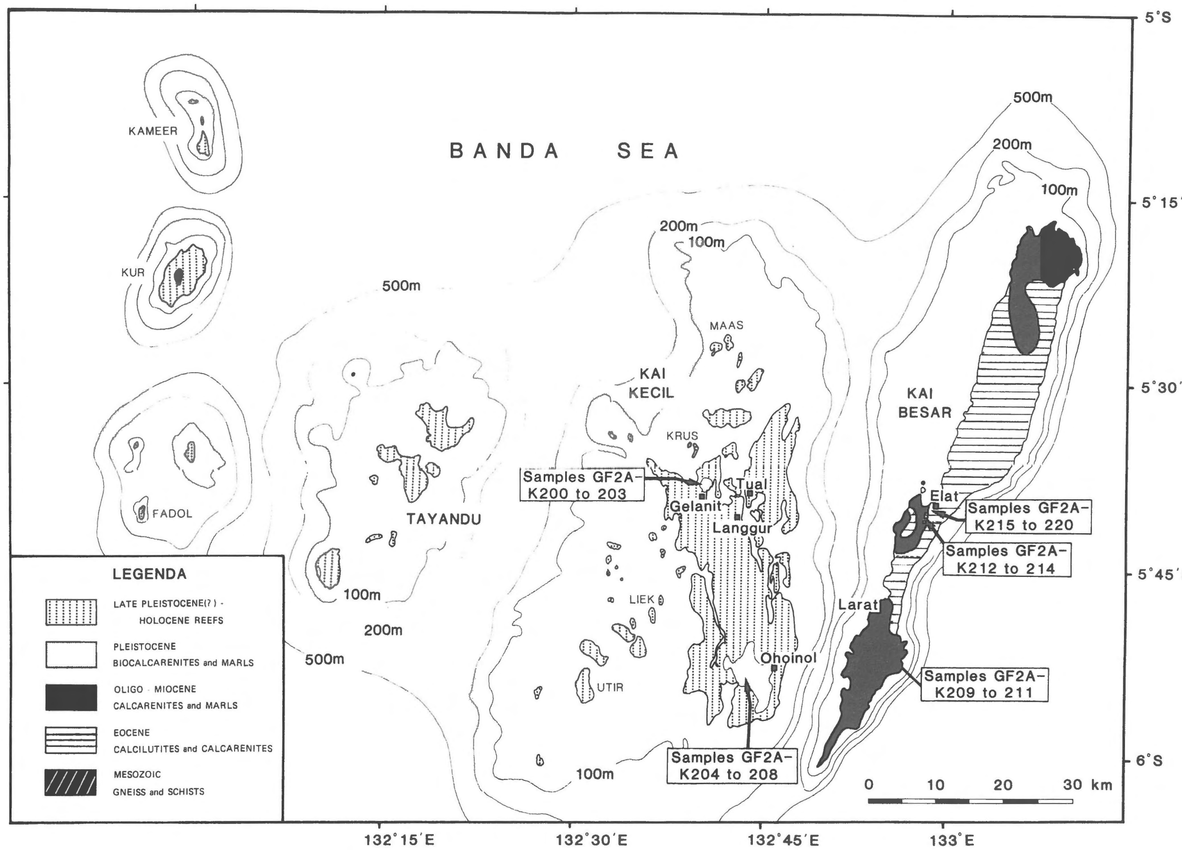

Fig. 2. Geological sketch map of the Kai Island group (with 100 m, 200 m and 500 m waterdepth contours), showing sample locations (simplified after Achdan & Turkandi, 1982).

100 m scale are visible in exposures along the coastline. Overall the island has a coherent structure (Fortuin, 1986). The small exposures of Plio-Pleistocene deposits, indicated on the preliminary map of Achdan & Turkandi (1982), have not been observed during this expedition. Alternatively, outcrops of Eocene and Oligo-Miocene have been studied and sampled (Fig. 2).

Of the Eocene deposits a 40 m thick sequence was studied, south of the village Elat (Fig. 3). These deposits consist of brown, well-bedded (dm-scale), laminated calcilutites and fine-grained, burrowed calcarenites. According to Brouwer (1923) and Van Bemmelen (1949) the thickness of the Eocene deposits may exceed 1000 m in the central parts of the island. We took 6 samples (K215–K220); for locality details see Fig. 2 and Fortuin (1986).

According to Bursch (1947), the Upper Oligocene rocks on Kai Besar are of shallow water origin. However, sediment descriptions indicate intercalations of coarse- and fine-grained sediments, and Bursch's faunal descriptions show a mixture of neritic and middle-lower bathyal benthic faunas. We therefore assume that we are dealing with slope or rise sediments containing large amounts of shallow water material, brought in by gravitites (see also discussion). The stratigraphic thickness of the Oligo-Miocene is unknown. The poorly exposed and badly weathered material consists of yellowish, poorly bedded calcarenites and marls, locally containing silica concretions. According to Brouwer (1923) and Van Bemmelen (1949) the stratigraphic

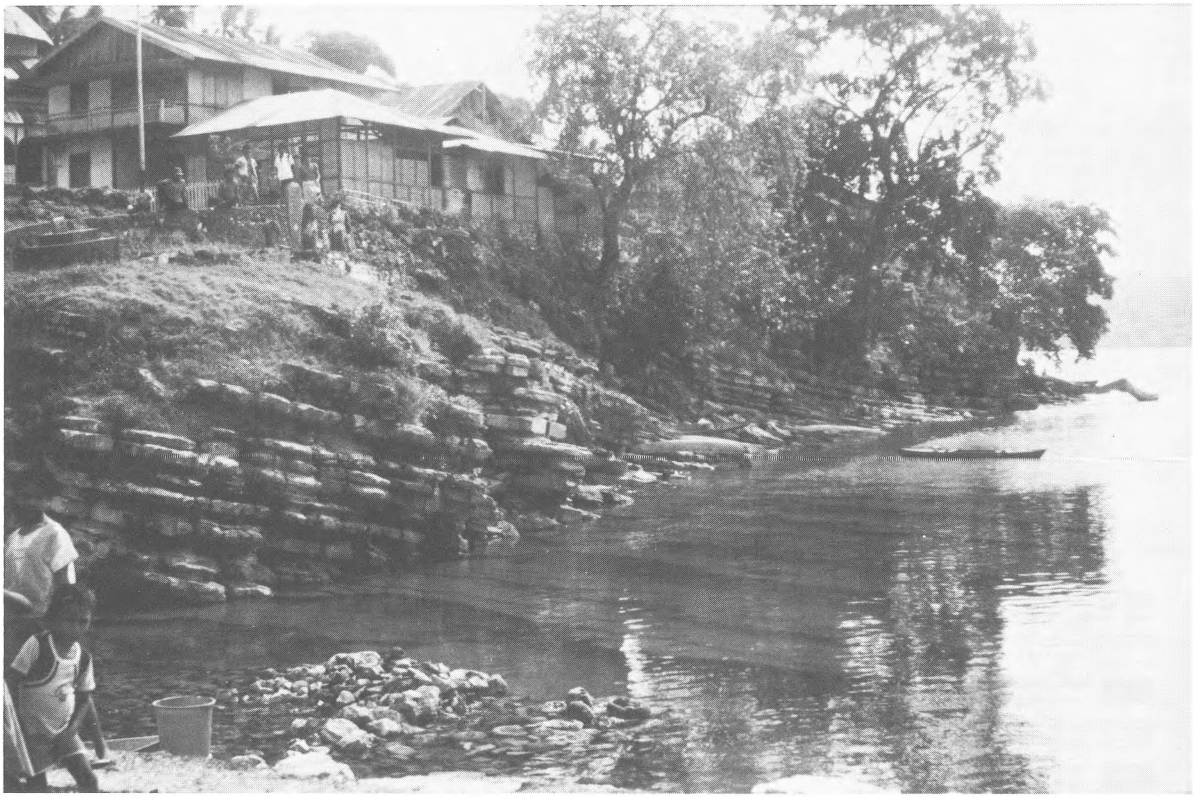

Fig. 3. Photograph of part of the Middle-Late Eocene sequence of calcilutites and marls, south of the village Elat on Kai Besar (see Fig. 2).

thickness of the Oligo-Miocene sequence may reach 750 m in the south of the island. We collected 6 spot samples (K209–214); for locality details see Fig. 2 and Fortuin (1986). Although the extant coral reefs around the island are very large, the island shows no elevated reefs, except for a small one near the village of Larat that emerged only a few metres above sea level, and which according to Achdan & Turkandi (1982) is Oligocene in age.

Age

The samples K215–K220 in the sequence of Eocene sediments studied here are all badly preserved and age-diagnostic planktic foraminiferal species have not been observed. The samples, however, do contain nannofossils, which were analyzed by Perch-Nielsen (pers. comm.). Characteristic are *Pemma* sp., *Coronocyclus prionion* (Deflandre and Fert), *Sphenolithus radians* Delflandre, and *Hayella situliformis* Gartner, indicating a Middle-Late Eocene age. Lacking are the typical Eocene disc-shaped discoasters. However, these are known to be absent in nearshore areas or in areas with abnormal salinities. The latter seems to be the case here, suggested by the presence in variable quantities of *Braarudosphaera bigelowii* (Gran and Braarud) and *Micrantholithus* sp.

Several spot samples were taken in the Oligo-Miocene rocks. Only sample K214 contains microfauna, but because of the bad preservation we were not able to recognize diagnostic planktic foraminiferal species. Nannofossils have been encountered within the samples, but again zonal markers were not observed. *Cyclicargolithus floridanus* (Roth and Hay), *Calcidiscus leptoporus* (Murray and Blackman) and *Calcidiscus macintyrei* (Bukry and Bramlette) are abundant, pointing to an Early-Middle Miocene age (Perch-Nielsen, 1985).

Paleobathymetry

Benthic foraminifera are poorly preserved in the Middle-Late Eocene samples. Yet, some species could be distinguished, such as *Cibicidoides* sp. cf. *C. tuxpamensis* (Nuttall), *Cibicidoides* sp. cf. *C. ungerianus* (d'Orbigny), *Nuttalides truempyi* (Nuttall), *Pullenia* sp. cf. *P. eocenica* Cushman and Siegfus, *Globocassidulina subglobosa* (Brady), *Hanzawaia* sp. cf. *H. cushmani* (Nuttall) and *Laticarinina* sp., indicating deposition at lower bathyal-upper abyssal depths (1000–3000 m (average 2000 m); Tjalsma & Lohmann, 1983; Van Morkhoven et al., 1986; Van Marle, 1988).

The Early-Middle Miocene sample K214 contains poorly preserved benthic foraminifera. Some species could be recognized, such as *Planulina wuellerstorfi* (Schwager), *Bolivina spathulata* (Williamson), *Bolivinita quadrilatera* (Schwager), *Globocassidulina subglobosa* (Brady) and *Uvigerina proboscidea* Schwager. These predominantly middle bathyal forms (500–1500 m (average 1000 m); Van Marle, 1988) are mixed with shallow water forms, such as *Amphistegina* sp., *Cibicides pseudoungerianus* (Cushman), *Cibicides dutemplei* (d'Orbigny) and *Reussella simplex* (Cushman). Sample K214 represents apparently slope deposits, containing large amounts of displaced material, brought in by gravitites.

Results

Our field and laboratory data were insufficient for a detailed reconstruction of the vertical movements of Kai Besar. Nevertheless, we can conclude that during Middle-Late Eocene times sediments were deposited at lower bathyal to upper abyssal depths, and during Early-Middle Miocene times at middle bathyal depths.

The Early-Middle Miocene deposites are the youngest sediments found on the island, showing that the island raised above sea level during an uplift phase after the Middle Miocene. Accepting Brouwer's (1923) and Van Bemmelen's (1949) thickness of 1750 m for the pre-Miocene section, placing the Miocene at 1000 m waterdepth, finding the Middle-Late Eocene today at 800 m above sea level and assuming uplift started 10 Ma ago related to the evolution of the Banda Arc subduction system (De Smet et al., 1989), the average rate of uplift amounts to 36 cm/ka. This is a bare minimum, since uplift may as well have started later and certainly may have ceased before present time. In fact, the lack of elevated coral reefs, while surrounding islands all show extensive elevated reefs, suggests that the island presently is subsiding.

Kai Kecil

General remarks

The geology of Kai Kecil strongly contrasts that of Kai Besar. Kai Kecil and the region to the west including the Tayandu Islands, Kur and Fadol, consist of coral reefs which unconformably overlie deformed pre-Mesozoic to Tertiary rocks (Weber, 1925; Achdan & Turkandi, 1982), that at least partially were brought up by mud volcanic processes (Weber, 1923; Heim, 1942). Active mud volcanism is known to occur in tectonically unstable regions, and is a common phenomenon in eastern Indonesia (Williams et al., 1984; Barber et al., 1986). Kai Kecil is formed by 4 to 5 reef terraces, which still retain their original horizontal position. Their maximum elevation is no more than a few tens of metres above sea level. Only at two places the Tertiary nucleus crops out: in the north near the village Gelanit and in the south near Ohoinol (Fig. 2). Both exposures are only a few square metres.

Because of the limited exposure, the stratigraphic interval covered does not exceed a few metres. The sediment, consisting of yellowish, well-bedded (dm-scale), bioclastic calcarenites and marls, is fairly weathered. We collected 10 samples (K200–208B); for locality details see Fig. 2 and Fortuin (1986).

Age

Qualitative analyses have been carried out on the planktic foraminiferal and the nannofossil content of the collected samples, of which only K200, K201, K207, K208A and K208B are fossiliferous. Biostratigraphic correlations and age indications presented here follow the chronostratigraphic correlation schemes of Berggren et al. (1985).

Characteristic planktic foraminiferal species are

Globorotalia truncatulinoides (d'Orbigny), *G. pachytheca* Blow, *G. crassaformis* (Galloway and Wissler), and left-coiling *G. menardii* (Parker, Jones and Brady). These indicate deposition during plankton chronozones N22–N23 of Blow (1969).

Characteristic nannofossils are *Pseudoemiliani lacunosa* (Kamptner) and *Gephyrocapsa oceanica* Kamptner, while rarely some badly preserved specimens of *Discoaster brouweri* Tan have been found. This indicates deposition during nannofossil chronozone NN19 of Martini (1971), assuming the discoasters to have been reworked (Perch-Nielsen, pers. comm.). According to the zonation scheme of Okada & Bukry (1980) the ranges of *P. lacunosa* and *G. oceanica* overlap within subzone CN14a.

Concluding, we can say that both the planktic foraminifera and the nannofossils indicate that the sediments have been deposited during the Pleistocene, most probably within nannofossil subzone CN14a, which correlates with the age-interval of 900 to 450 ka B.P. (on average 675 ka B.P.).

Paleobathymetry

The benthic foraminiferal content of all samples has been analyzed qualitatively and quantitatively. Only samples K200, K201, K207, K208A and K208B contain a well preserved benthic microfauna, the other samples are barren. Counting results of these samples are published in Van Marle (1989b). Characteristic benthic foraminiferal species are *Uvigerina proboscidea* Schwager, *Bolivina robusta* Brady, *Trifarina bradyi* Cushman, *Globocassidulina subglobosa* (Brady) and *Uvigerina peregrina* Cushman var. *dirupta* Todd.

This Pleistocene fauna resembles Recent benthic foraminiferal faunas from eastern Indonesia reported by Van Marle (1988) and especially quantitative correlation between the two will supply accurate paleobathymetric information (Van Marle, 1989b). The counting results of every fossil sample containing microfauna were therefore compared with the counting results of every Recent sample and linear correlation coefficients were calculated according to the standard method (Davis, 1973). Results of this correlation, shown in Table 1, suggest deposition at depths between 400 and 1100 m.

Another statistical method to determine paleodepth is the Z-score method, described by Van Marle (1989a). According to this method, highly positive Z-score values (higher than 1.96) for a taxon in a standardized Recent data-set mark the optimal position (depth-range) of this taxon. In the Recent material of van Marle (1988), 64 taxa show highly positive Z-score ranges. Van Marle (1989a) defined five depth zones (related to watermasses) in terms of assemblages of these taxa, having their maximum positive Z-score value within the zone in question. Plotted against depth, the cumulative percentages of these taxa accurately show the relative importance of the designated five depth zones.

When we apply this method to the counting results of the fossil samples from Kai Kecil, the cumulative percentages of the same assemblages of taxa show the values they ought in Depth zone III (400–1000 m) conform the Recent situation (Van Marle, 1989a), indicating that deposition took place within this depth interval (Fig. 4). A paleodepth of around 1000 m seems most likely, because the cumulative percentages of the deeper depth zones (IV and V) are relatively high. This is caused by the presence of species such as *Cassidulina carinata* Silvestri, *Planulina wuellerstorfi* (Schwager), *Oridorsalis umbonatus* (Reuss), *Pullenia bulloides* (d'Orbigny) and *Bulimina aculeata* d'Orbigny.

Supplementary paleobathymetric information can be obtained by analyzing the P/B ratio. To reconstruct paleodepth, the model of Van Marle et al. (1987) for eastern Indonesia has been applied. Results are shown in Table 2, and correspond with the paleobathymetric interpretations based on the correlation method and the Z-score method, described above, confirming a most likely paleodepth of around 1000 m.

Results

Our data are insufficient for a detailed reconstruction of the vertical movements of Kai Kecil. We can, however, conclude that sometime between 900–450 ka B.P. (subzone CN14a of Okada & Bukry, 1980) open marine conditions prevailed, and sediments were deposited at a paleodepth of around 1000 m. These deposits are nowadays found just above sea level, and the total uplift therefore was approximately 1000 m. Using the age of the top of subzone CN14a we can conclude that the average rate of uplift was 220 cm/ka, though it probably has been higher (up to 500 cm/ka) as the younger section was eroded (or remained unsampled). An early Holocene age of the overlying reefs would set a maximum rate of 500 cm/ka.

Achdan & Turkandi (1982) interpreted the outcrops of Pleistocene basement as anticlinal nuclei. The overlying Late Pleistocene(?)-Holocene reefs have an undisturbed subhorizontal position, indicating that the youngest uplift movements occurred without much deformation.

Table 1. Linear correlation coefficients calculated between Pleistocene samples from Kai Kecil and Recent samples from the eastern Banda region of Van Marle (1988). The Recent samples are arranged according to depth. A cut-off value of 40 is maintained for the correlation coefficients, because trial and error experimentation proved only values higher than 40 to be reliable. The bulk of the correlations can be found between 400 and 1100 m.

Recent samples		Samples Kai Kecil				
	Waterdepth	K200	K201	K207	K208A	K208B
G5-4-72B	60 m					
G5-4-71B	78 m					
G5-4-70B	90 m					
G5-4-73B	92 m					
G5-6-161B	100 m					
G5-4-74B	141 m					
G5-6-160B	150 m					
G5-2-67B	150 m					
G5-6-159B	210 m					
G5-4-75B	244 m					
G5-6-158B	317 m					
G5-4-76B	342 m					
G5-2-66B	486 m	62	62	83	81	67
G5-4-77B	495 m		56	45		
G5-6-156B	545 m				50	40
G5-2-64B	684 m		44	49	45	51
G5-6-155B	711 m			44	62	57
G5-4-78B	714 m	41	65	61	49	51
G5-4-80B	904 m		45	52	43	42
G5-6-154B	914 m			41	44	42
G5-2-63B	919 m	47	51	67	66	61
G5-4-81B	1080 m		47	49	55	58
G5-6-153B	1088 m	41	43	48	52	52
G5-2-62B	1097 m				47	45
G5-4-82B	1288 m					
G5-6-152B	1290 m					
G5-2-61B	1402 m					
G5-6-151B	1509 m					
G5-2-60B	1564 m					
G5-4-83B	1654 m			47	46	50
G5-4-84B	1760 m	58	61	72	62	61
G5-2-58B	1816 m					
G5-6-150B	1840 m				48	
G5-6-148B	1954 m				50	41
G5-2-54B	2119 m					

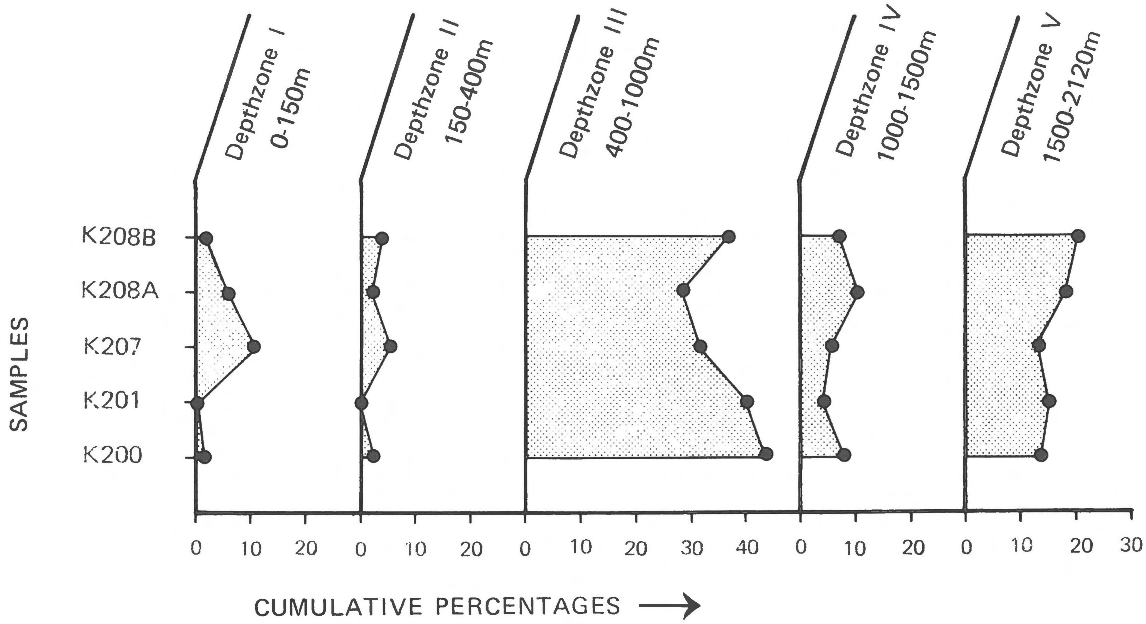

Fig. 4. Cumulative percentages of assemblages of taxa contributing to five designated depth zones (Van Marle, 1989a), plotted per sample of Kai Kecil. The percentages of depth zone III (400–1000 m) are on average higher than 30%, suggesting that deposition took place within this depth interval. For further discussions see text.

Discussion

If the interpretation of a shallow water environment for the Upper Oligocene rocks by Bursch (1947) and Achdan & Turkandi (1982) is correct, the position of Kai Besar was near sea level and part of the island may have emerged during a Late Eocene-Early Oligocene uplift period. The island must have subsided again during the Late Oligocene-Early Miocene, because the Early-Middle Miocene sediments were deposited on the continental slope. However, we have no direct explanation for the Late Eocene-Early Oligocene uplift and Late Oligocene subsidence.The timing is too early to be related to the development of the Banda Arc system, which is supposed to have started in the Miocene and culminated in the Pliocene-Pleistocene (De Smet et al., 1989). The Eocene rocks of Kai Besar were deposited at lower bathyal to upper abyssal depths. We assume that they formed part of the Australian continental rise (De Smet, 1989). During Late Eocene-Early Oligocene times the Australian continent was still far removed from the Southeast Asian Plate (Hamilton, 1979), and had not much influence on the tectonics in this part of the Southeast Asian region. Nevertheless, an Oligocene uplift is documented from several islands of the outer Banda Arc (Pigram et al., 1982; Fortuin et al., 1988), which might be related to overall changes in the regional plate tectonic configurations.

Table 2. Paleodepth estimates for the samples from Kai Kecil, based on the P/B ratios (expressed as the plankton percentage of the total foraminiferal fauna), calculated by applying the model of Van Marle et al. (1987) for eastern Indonesia

Sample	Plankton percentage (%)	Estimated depth (m)
K200	92.5	985
K201	90.0	850
K207	95.0	1150
K208A	96.0	1220
K208B	96.0	1220

In our (deeper water) re-interpretation of Bursch's Oligocene there is no need for an Eocene

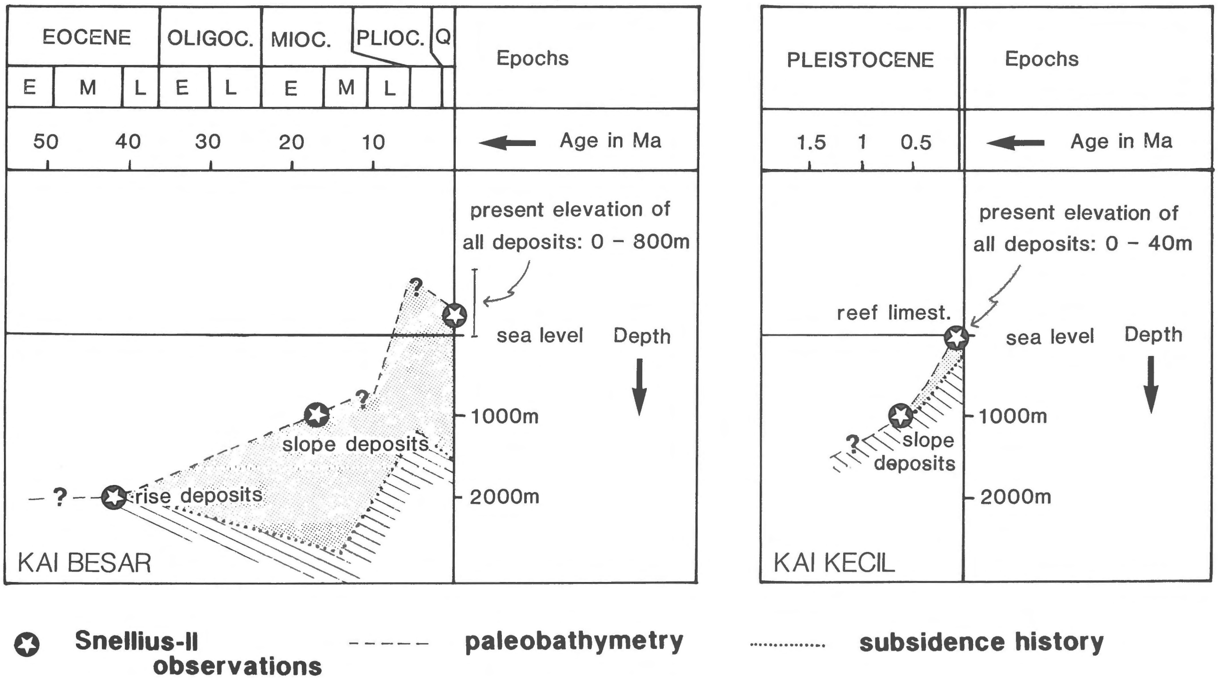

Fig. 5. Schematic geohistory diagrams (Van Hinte, 1978) based on the average data reported in the text, showing vertical movements of Kai Besar and Kai Kecil respectively. Note the differences in horizontal time-scale of the two diagrams. Based on the absence of elevated reef terraces, a Late Pleistocene to Recent subsidence of about 100 m is assumed for Kai Besar. The rate of the Late Pleistocene uplift of Kai Kecil is in the order of 220–500 cm/ka.

uplift and subsequent subsidence and we are simply looking at an Eocene-Miocene passive margin fill (De Smet, 1989) that was uplifted in the Late Miocene-Pliocene, as a result of which Kai Besar emerged (Fig. 5). This period of uplift can be related to the collision of the Banda Arc with the Australian continent. Many islands in the arc show a history of spasmodic vertical movements since the Late Miocene, and especially in the Pliocene-Pleistocene, as is documented by Snellius-II data (De Smet et al., 1989). On Timor for example rates of uplift are up to 1000 cm/ka, while on Buton and Seram they are up to 250 cm/ka.

On Kai Kecil, Late Pleistocene sediments were deposited at middle bathyal depths and uplifted since then (Fig. 5). According to regional tectonic studies, the Kai Islands lie in a major sinistral transpressional regime at the boundary between the NNE-moving Australian Plate and the Banda Sea Plate (Bowin et al., 1980; De Smet, 1989). Convergence is taking place in the area of the Kai Islands, resulting in the development of a thrust belt, as is well documented by Schlueter & Fritsch (1985) in the area north of Tanimbar. We now understand that the tectonic unit containing Kai Besar is being thrust under Kai Kecil, causing the current subsidence of the former and uplift of the latter island, as was described above.

Conclusions

On Kai Besar, lower bathyal-upper abyssal Middle-Late Eocene calcilutites and marls, in combination with Upper Oligocene and Lower-Middle Miocene middle bathyal deposits record an Eocene-Miocene passive margin fill. Uplift, associated with the development of the Banda Arc thrust belt, started at the earliest in the Late Miocene and was at its maximum in the Pliocene-Pleistocene. During this period Kai Besar emerged and locally was brought to about 800 m above sea level. The original elevation of the island may have been higher, since the absence of elevated coral reefs suggests that Kai Besar presently is subsiding.

On Kai Kecil, Late Pleistocene (900–450 ka B.P.) bioclastic calcarenites and marls were deposited at a depth of approximately 1000 m, as is shown by the quantitative comparison of the fossil benthic foraminiferal faunas with Recent eastern Indonesian faunas. The deposits were uplifted during the Late Pleistocene faster than 220 cm/ka and are nowadays found just above sea level. This fast uplift can be explained by the thrusting of Kai Besar under Kai Kecil, caused by the collision of the Banda Arc with the Australian continent.

Field and laboratory data from the Kai Islands provide only broad age-depth constraints and are insufficient for a detailed geohistory analysis. Further onshore investigations on the Kai Islands may provide additional data on the history of vertical movements. However, limited occurrences of Miocene-Pliocene deposits and the poor rate of exposure hamper reconstruction of a detailed stratigraphic record. To properly define the history of the easternmost segment of the outer Banda Arc, a comparison of our findings and offshore data is therefore essential.

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