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Paleomagnetism of rocks from Sumba: tectonic implications since the late Cretaceous

HANS WENSINK

Paleomagnetic Laboratory Fort Hoofddijk, Utrecht State University, Budapestlaan 17, 3584 CD Utrecht, The Netherlands

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Abstract—The island of Sumba (Southeast Indonesia) is a continental fragment that is situated in the transition zone from the Sunda Arc to the Banda Arc, between the active volcanic inner arc to the north and the locally less well developed outer arc to the south. On Sumba, rock samples for paleomagnetic research have been collected from three formations: (a) the late Cretaceous Lasipu Formation; (b) the Paleocene Massu Formation; (c) the early Miocene Jawila Formation. The sediments of the Lasipu Formation revealed a mean ChRM direction with Declination (D) = 226.8°, Inclination (I) = 33.5°, $a_{95} = 7.6°$ with a paleolatitude of 18.3°; the volcanics of the Massu Formation gave a mean ChRM direction with $D = 275.6°$, $I = 14.6°$, $a_{95} = 9.4°$ with a paleolatitude of 7.4°; the volcanics of the Jawila Formation presented a mean ChRM with $D = 357.1°$, $I = -19.3°$ with a paleolatitude of 9.9°. These paleomagnetic data have been interpreted in terms of an original position of the Sumba fragment in the northern hemisphere in late Cretaceous time. Between the late Cretaceous and Paleocene, Sumba performed a counterclockwise (CCW) rotation of 50° and a drift of 11° to the south; between the Paleocene and early Miocene the fragment moved a CCW rotation of 85° and a drift of 17° to the south. Since the early Miocene, Sumba has occupied its present position. The significance of this interpretation for the tectonic evolution of Southeast Asia is discussed.

INTRODUCTION

THE ISLAND of Sumba is located to the south of the continuous volcanic arc of the Sunda–Banda System (Fig. 1). On the volcanic arc islands of Sumbawa and Flores to the north of Sumba there is active volcanism. However, the row of volcanoes on East Sumbawa, to the northwest of Sumba's north coast, is positioned slightly further north. This could be due to the present uplift and tilt of Sumba (Chamalaun *et al.* 1981). South of Sumba the deformation front along the Java Trench continues eastwards to the active tectonic front in the Timor Trough. The transition from subduction of oceanic crust of the Indian Ocean to subduction of continental crust of Australia takes place to the south of East Sumba; here, the Sunda Arc becomes the Banda Arc. In the transition zone the deformation front shows a bulge towards the south, the Savu Bulge. The outer-arc high, well developed in the Sunda Arc, has disappeared near Sumba. The outer-arc high to the southeast of Sumba emerges on the islands of Savu and Roti, and further to the east on Timor. Its structure is very complicated with

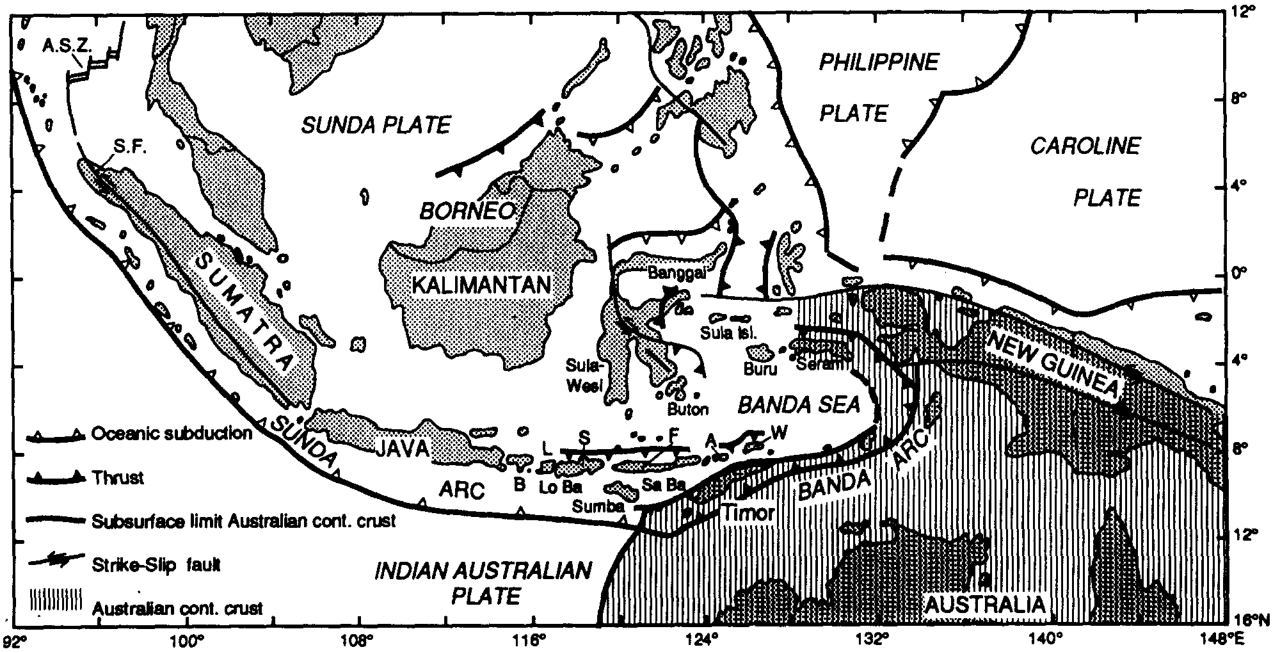

Fig. 1. Structural map of Indonesia with the position of Sumba, south of the Sunda–Banda volcanic arc and north of the deformation front. A.S.Z. is Andaman spreading zone; S.F. is Semangko fault; B is Bali; L is Lombok; S is Sumbawa; F is Flores; A is Alor; W is Wetar; Lo Ba is Lombok Basin; Sa Ba is Savu Basin.

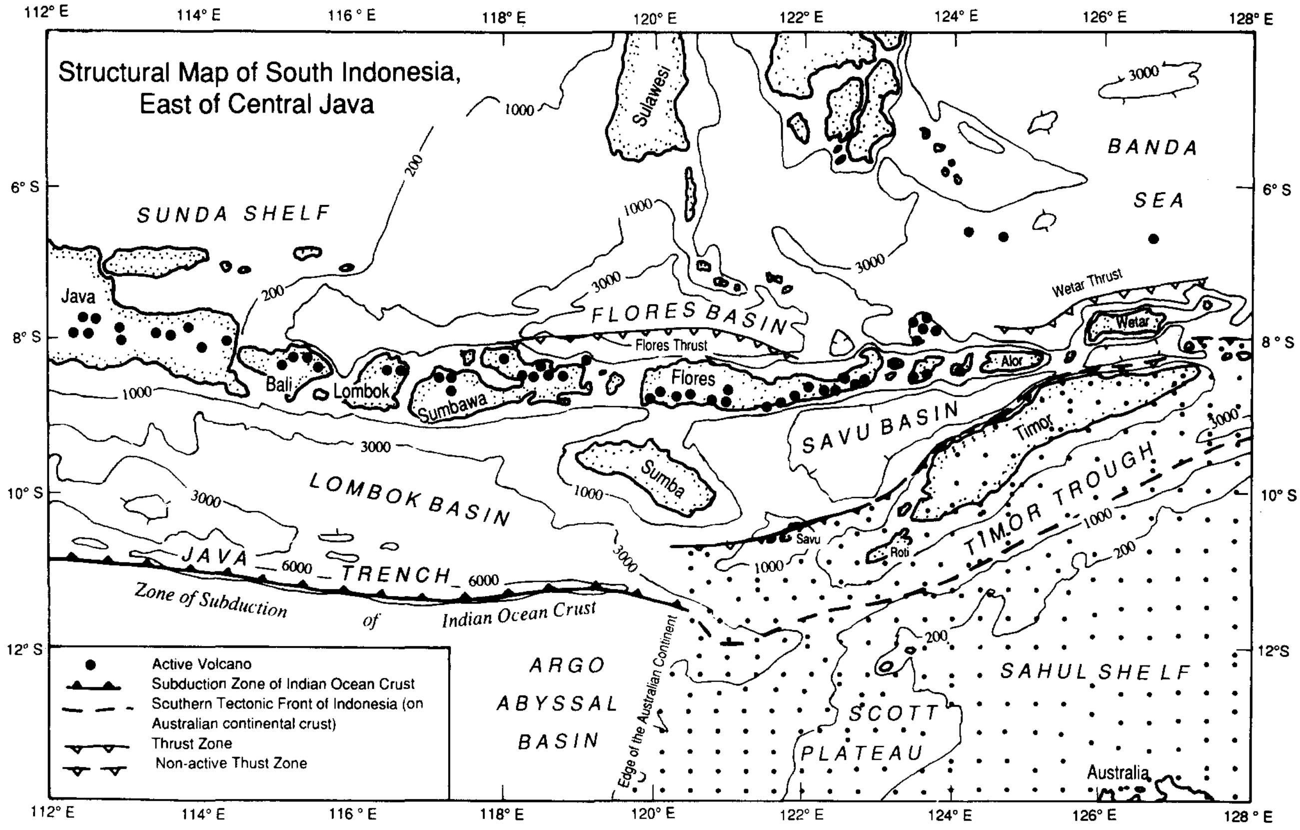

Fig. 2. Map of South Central Indonesia with the position of Sumba at the eastern end of the Sunda Arc. Dotted area is Australian continental shelf.

imbricated rise and slope sediments of the Australian margin, with rifted blocks and, locally, thrusted allochthonous units.

Sumba lies obliquely between two fore-arc basins, the Lombok Basin to the west and the triangular Savu Basin to the east (Katili 1975, Hamilton 1979). The island does not fit in the Sunda–Banda Arc System and forms an alien continental fragment (Fig. 2). Both the distribution and depth of earthquakes and the position of active volcanoes indicate that at present subduction of oceanic crust continues beneath the crustal fragment of Sumba.

The geology of Sumba is well known (van Bemmelen 1949, Laufer and Kraeff 1957, Hamilton 1979, Chamalaun *et al.* 1981, Burollet and Sallé 1982, von der Borch *et al.* 1983). The oldest rocks are sediments of late Cretaceous age (Table 1). These deposits, of the Lasipu Formation, consist of siliciclastic mudstones, tuffaceous sandstones, diamichites and turbidites; slumps occur rather frequently. The dark, silty mudstones contain a microfauna of Coniacian to early Campanian age (Burollet and Sallé 1982). The formation is at least 200 m thick. In some areas the Lasipu sediments comprise part

Table 1. Comparison of stratigraphical successions of Sumba and Timor, mainly after Audley-Charles (1985)

Age	Sumba	Formation	Timor (Lolotoi–Palelo–Allochth.)	Formation
Quaternary	Reef Limestones		Reef Limestones	
Pliocene	Reef & Lagoon. Pelagic Chalks;		Molasse	
	Limestone Volcanoclastic	Sumba Fm	Scaly Clay	Bobonaro Fm
Miocene	W Turbidites E		Tuff (N17)	
		Palamar Fm	(Hiatus)	
	Lagoonal and Reef Limestone		Reefal	Cablac Fm
	Basalt Lavas and Agglom.	Jawila Fm	Limestones	
			(Hiatus)	
Oligocene	Shallow Marine Limestone	Paumbapa Fm	Neritic	Wiluba Fm
Eocene	and Sandstones		Limestones	
Paleocene	Basalt & Andesite Lavas	Massu Fm	Basalts & Rhyolites	Metan Fm
	Agglomerates, Intrusives		Lavas & Agglomerates	
Late Cretaceous	Granodiorites & Volcanics	Tanadaro Fm	??	
	Siliciclastic Mudstones, Tuff.		Pelagic Limestones,	
	Sandst., Diamicitites, Turbidites	Lasipu Fm	Radiolarian Chert,	Noni Fm
	Submarine Fans		Turbidites, Diamicitites	
Mesozoic–Paleozoic	—		Sedimentary and	Lolotoi
			Metamorphic Rocks	Complex

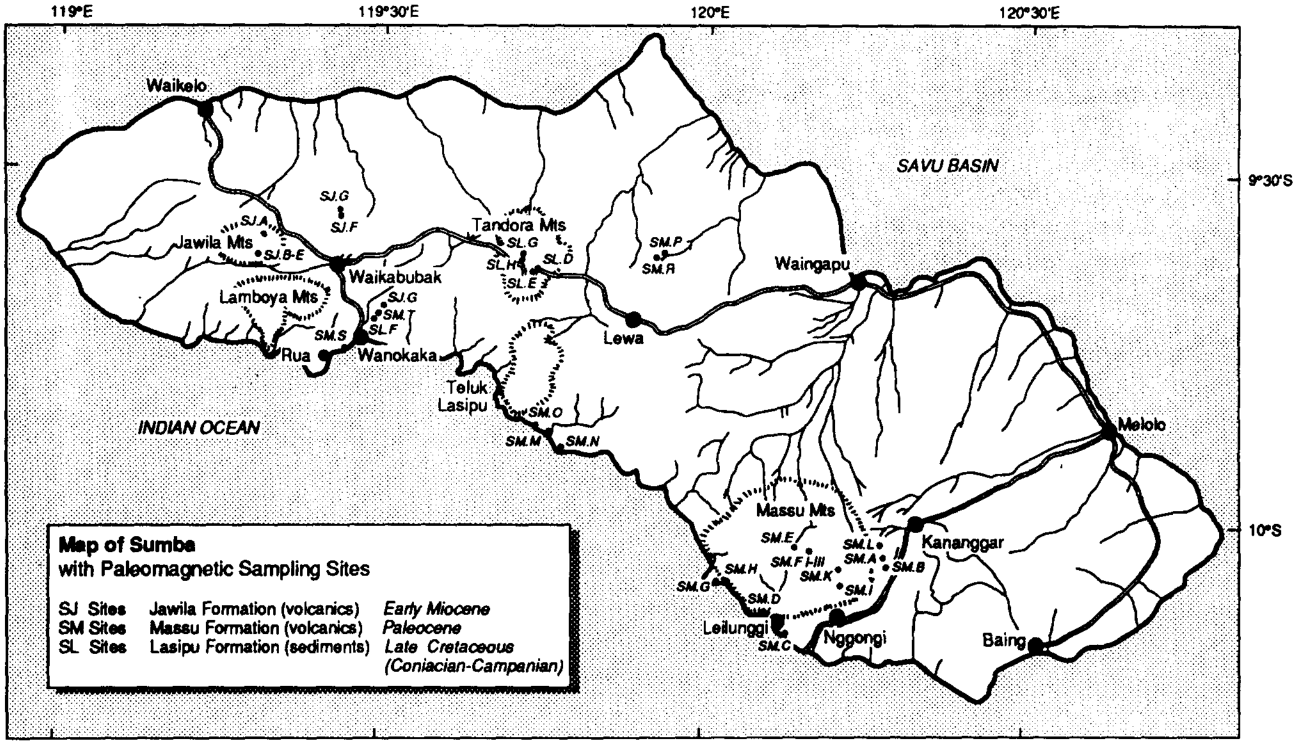

Fig. 3. Map of Sumba with the sampling localities for paleomagnetic research.

of a major submarine fan complex which, in Sumba's present position, progrades to the southwest or to the south (von der Borch *et al.* 1983). The late Cretaceous sediments are intruded by igneous rocks of a great variety. The Tanadaro granodiorite is a large intrusion in Central Sumba with augite, hornblende, biotite, andesine and orthoclase, to which an age of 64 Ma has been assigned (Burollet and Sallé 1982). Andesitic and dacitic dykes accompany the main intrusion. In the South Coast Mountains igneous rocks occur with intrusives of gabbros, some of them quartz-bearing, and with extrusives of agglomerates, tuff-breccias and basalts. The small occurrences of metasomatized albite-basalts—e.g. Palahonan, north of Lewa (Fig. 3)—could belong to the same magmatic period (Laufer and Kraeff 1957). The early Tertiary–Paleocene, possibly including early Eocene, was a period with extensive basaltic and andesitic volcanism. The volcanics with lavas, agglomerates and tuffs overlie the older rocks with an angular unconformity (Veenhof 1990) and are exposed in a rather restricted area in the southern part of East Sumba in the high (up to 1100 m) Massu Mountains after which the formation has been named. The volcanics are associated with some intrusions of gabbros and granodiorite. The gabbroid rocks of the South Coast Mountains are probably the oldest intrusives in the Lasipu sediments; the granodiorites of the Tanadaro could be a little younger, and the basalt magmas must have risen after the granodiorite intrusions.

The older rocks are covered by shallow marine, fossiliferous limestones and sandstones of the Paumbapa Formation and have an Eocene and Oligocene age (Effendi and Apandi 1981). In the early Miocene there is another period of volcanic activity. This volcanism of the Jawila Formation, after the Jawila volcano (888 m), is restricted to West Sumba. Large areas are covered with tuffs, tuff-agglomerates, tuff-sandstones and lahars while rather fresh basalts and basaltic andesites occur as well. In the tuffs fossil wood has been found, indicating that the area was above sea level (Laufer and Kraeff 1957). There are small exposures of the middle Miocene Pamalar Formation with claystone and limestone, the latter both in lagoonal and in reef facies. An enormous pile of sediments with a thickness of at least 800 m covers large areas on Sumba. These sediments, which slightly unconformably overlie older rocks, belong to the Sumba Formation and have a late Miocene to early Pliocene age (Fortuin *et al.* 1992). The deposits show a general shallowing from east to west. The eastern facies of the Sumba Formation—often called Kananggar Formation—consists of basal conglomerates, overlain by volcanoclastic turbidites, sands, gravels and intercalated white, pelagic chalks. In East Sumba the formation contains many slumps. The western facies is mainly shallow marine; here, deposits of the Waikabubak Formation are found with carbonate platform sediments of reef and lagoonal origin. The Quaternary is represented by coral-reef terraces which fringe the island on the west, north and east coasts. At least six terrace levels can be distinguished, the highest of which extends to about 500 m above sea level. Several raised terraces have been dated, the oldest having an age of 1 Ma. Thus, one can deduce a rapid uplift of the island with a rate of 0.5 cm/yr (Pirazzoli *et al.* 1991).

In general, the pre-Tertiary sediments of the Lasipu Formation are mildly deformed, exhibiting broad, open folds. In the South Coast Mountains on West Sumba, however, the sediments are rather strongly folded, possibly due to large-scale slumping. Cleavage has not been found. In some areas the Cretaceous sediments are slightly metamorphosed in prehnite-pumpellyite meta-greywacke facies (Chamalaun *et al.* 1981). The pre-Tertiary basement of Sumba reveals faulting with rifted blocks. In the Massu Mountains two fault systems could be detected: (a) steeply south dipping WNW–ESE faults with a consistent downthrow to the south, and (b) steeply dipping to vertical NNE–SSW faults which do not reveal a consistent throw (Veenhof 1990). A clear angular unconformity is seen at the base of the Eocene sediments. Synsedimentary tectonism with normal faulting and large-scale slumping occurred during the Neogene. A section from south to north on Sumba shows all formations dipping to the north. Since the Pliocene the uplift of Sumba amounts to approximately 3 km.

The elongated dome of Sumba represents an uplifted part of the fore-arc basin. This dome is a diapiric nappe in process of formation. The squeezing effect of the converging Australian continent as well as the continuous subduction below this fore-arc region might be responsible for the post-Miocene uplift of Sumba as a large diapir (Audley-Charles 1985).

Outline of the Sumba fragment

The exact delineation of the Sumba fragment is not known. Towards the west in the Lombok Basin, Sumba extends below sea level for approximately 50 km until it is cut off by a NE–SW fault system (van der Werff, pers. commun.). Faulting and tectonically induced deformation in the eastern part of the Lombok Basin hampers the exact delineation of the Sumba fragment (van Weering *et al.* 1989). In the Savu Fore-Arc Basin east of Sumba seismic reflection reveals a submarine ridge, the North Savu Ridge (Silver *et al.* 1983). The ridge begins at Sumba's easternmost end and runs to the ESE towards the island of Savu. Here, deformed sediments of Permian and Mesozoic age of Australian origin are thrust northward along the Savu Thrust, of late Pliocene to Quaternary age. This thrust postdates the Pliocene strata of the basin (Reed *et al.* 1986). Seismic reflection has shown that the North Sumba Ridge is built up of a basement of probably pre-Tertiary age covered by a thick sequence of sediments correlative with the Neogene deposits of Sumba (Karig *et al.* 1987).

In the Savu Basin at longitude 122° 30′E a S–N trending zone approximately 50 km wide occurs, where "individual features cannot be interpolated" (Karig *et al.* 1987). East of this zone, in the South Savu Basin, basement ridges have been discovered trending SW–NE which probably can be followed onto the island of Timor.

In conclusion one can say that the submarine continuation of Sumba can be followed towards the east until 122° 30′E, and towards the southeast to the Savu Thrust. The marine data obtained from the Savu Sea indicate that since middle Miocene times there have been large-scale vertical movements, but there has been very little horizontal displacement. There has been a regional tilt to the north both in Sumba and in the North Sumba Ridge. It is likely that the Sumba fragment has occupied approximately its present position since at least the Miocene.

The Sumba enigma (Audley-Charles 1985); the origin of the crustal fragment

The island of Sumba with a Bouguer gravity anomaly of +160 to +200 mgal is underlain by a continental type of crust with a thickness of 24 km (Chamalaun *et al.* 1981). The origin of greater Sumba, of which the oldest rocks exposed have a late Cretaceous age, is still a matter of dispute. There are three different views for the original location of this 400 km long and 200 km wide crustal fragment.

(1) *Australian origin*—Sumba has been derived from the Australian continent, where it occupied a position near the Scott Plateau. Along a SW–NE fracture zone at the eastern side of the Wharton Basin a fragment broke away. It is well known that along Australia's west coast, rifting started some 160 Ma ago, resulting in the opening of the Wharton Basin (Falvey and Mutter 1981). Sumba became detached and performed a clockwise rotation (Audley-Charles 1975). In a reconstruction of Eastern Indonesia, Norvick (1979) located Sumba near Australia to the west of a S–N running fault that he called "Sumba Fracture". Based on paleomagnetic research of rocks from Sumba, Otofuji *et al.* (1981) came to the conclusion that the island has an Australian origin. The main objection for a southern provenance of Sumba is that is difficult to explain the significance of the granodiorite intrusives and related rocks which have an age of approximately 64 Ma, as well as the Paleocene volcanics of the Massu Formation. The rifting along Australia's coasts took place in the Jurassic and the early Cretaceous, thus the referred igneous rocks of Sumba are too young for correlation with the Australian rifting.

(2) *Asian origin*—Sumba came from the north and was originally located at the rim of Sundaland. At present, many authors are in favor of a northern provenance of the Sumba fragment (von der Borch *et al.* 1983, Audley-Charles 1985, Audley-Charles *et al.* 1988, Rangin *et al.* 1990a, b). Von der Borch *et al.* (1983) carried out a detailed study on the sediments of the Lasipu Formation and suggested that a northern provenance is more likely, because the shallow-marine intercalated siliciclastics contain a tropical fauna with a Tethyan affinity; the quartz-rich clastics are derived from a continent. The late Cretaceous Lasipu sediments can be interpreted as large-scale continental margin deposits with submarine fans prograding southwest or south, and are related to rifting of a pre-existing continental margin. We think that the igneous activity with intrusions and subsequent extrusions of late Cretaceous–Paleocene age complies rather well with the scenario of von der Borch *et al.* (1983). However, it is very difficult to indicate more precisely the possible place of origin of the Sumba fragment. A locality on the former Southeast Asian margin can be considered. The eastern Sunda Shelf is built up of sediments of Tertiary age, which during the Paleocene

were deposited in an extensional regime with normal faulting. In the very eastern part of the shelf, to the south of Sulawesi and near the island of Salajar these faults have a N–S trend. Since the middle Miocene a compressive regime has been active in the eastern Sunda Shelf (Letouzey *et al.* 1990). The Sunda Shelf is underlain by strongly deformed rocks of Mesozoic age. It is possible that in this region or further north towards South Sulawesi, the provenance area for the Sumba fragment must be sought. However, a late Mesozoic reconstruction for South and East Sulawesi is hampered by the very strong tectonism in these areas which has obliterated many older structures (Hamilton 1979, Letouzey *et al.* 1990). In the reconstructions published by Rangin *et al.* (1990b) the Sumba fragment forms part of Southeast Asia at least as late as the early Miocene (20 Ma).

(3) *Isolated fragment*—There is also a default solution for the provenance of Sumba. It has been proposed that the fragment in Mesozoic times had an isolated position within the Tethys. However, the geology of the island shows that it is likely that there were relations with other continental units. The composition and structure of both the Lasipu and the Sumba sediments are indicative for such relations.

Sumba and Timor

The islands of Sumba and Timor lie only some 400 km apart. Both islands are situated south of the Sunda–Banda volcanic arc and north of the deformation front in the Java Trench and the Timor Trough.

The outline of the geology of Sumba as given above shows that both the stratigraphy and the tectonics of the island are rather simple. On the contrary, the geology of Timor is very complicated, both in stratigraphy and in tectonics (Chamalaun and Grady 1978, Hamilton 1979, Barber 1981, Johnston and Bowin 1981, Wensink *et al.* 1987). In Timor two main rock units can be distinguished which have nothing in common: (1) rocks which are largely exposed in the southern part of the island, and (2) rocks which occur in northern Timor.

The southern rocks are considered to be Australian continental rise and slope deposits with Jurassic sandstones, Cretaceous calcilutites of the Kolbano Units, and an incomplete sequence of pelagic rocks of Tertiary age. There are also shallow marine sediments and volcanics of Permo-Triassic age; these rocks could have been separated from the Australian Gondwana border during the period of rifting in the Jurassic (Hartono 1990, Wensink and Hartosukohardjo 1990b).

Northern Timor is built up of rock units which are completely unrelated to the southern series and, moreover, are quite different among themselves (Barber 1981, Audley-Charles 1985, Wensink and Hartosukohardjo 1990a). The basal sequence consists of metamorphics of possible Paleozoic age of the Lolotoi Complex (Table 1). The Palelo Series is associated with this complex (Tappenbeck 1940), a succession of rocks ranging in age from Jurassic to Paleocene and representing an upwards shallowing sequence. In Northern Timor there are volcanics of the Metan Formation and nummulitic limestones of Eocene age which are overlain by Oligocene reefal limestones. These rock sequences of Northern Timor are considered to have a northern provenance (Audley-Charles' 'Banda Allochthon') with a Southeast Asian origin. The rocks may have been incorporated in the early Banda Arc and may have come in collision with the Australian margin approximately 3 Ma ago.

A comparison of the stratigraphic sequences of Sumba with those of Timor shows that there are some resemblances between the Sumba rocks and the North Timor Palelo Series (Audley-Charles 1985). Table 1 illustrates that there are similarities between the late Cretaceous to early Miocene sequences, but that there are strong differences as well. The main difference is formed by the occurrences on Sumba of large granodiorite intrusions of latest Cretaceous age, the equivalents of which are not found on Northern Timor. Since the middle Miocene there are no similarities anymore between the geological development Sumba and Northern Timor.

It cannot be excluded that both the Sumba fragment and the allochthonous units of Northern Timor have a northern provenance with their area of origin located at the Southeast Asian margin. The Banda Allochthon could include a Sumba fragment and the Lolotoi–Palelo Series of Northern Timor.

PALEOMAGNETIC RESEARCH

Paleomagnetic research of suitable rocks can be a valuable tool for the unravelling of tectonic problems. It can be helpful to elucidate the rotation and the translation of the Sumba fragment. It is important that the ages of the studied rocks are rather well known and the tectonics are properly understood. The geology of Sumba reasonably satisfies both conditions. Paleomagnetic research in tropical areas is often hampered because of extensive weathering which may prevent the collection of fresh samples. In Sumba, however, the rapid uplift of the island caused strong erosion. Good outcrops with fresh rocks can be found, especially along the south coast.

The interpretation of paleomagnetic data from rocks collected in areas of low latitude can be very difficult. When paleolatitudes are near the equator, the polarity ambiguity may play a role. This is of importance for the decision to be made whether the studied area was located in the northern or the southern hemisphere. It can be difficult to determine the sense of rotation, if any. For instance, an easterly declination near the equator can be explained as a clockwise rotation if the polarity was normal, as a counterclockwise rotation if the polarity was reversed. This problem can be avoided if a sequence of formations of successive age can be studied; then, it is usually possible to determine the sense of rotation because of its progression through time (see e.g. Schmidtke *et al.* 1990).

Earlier paleomagnetic research on rocks from Sumba has been carried out by Otofuji *et al.* (1981) and Chamalaun and Sunata (1982). Their most important results will be discussed later.

Paleomagnetic sampling on Sumba

In November and December 1989 we made a paleomagnetic sampling trip to the island of Sumba (Fig. 3). Two hundred hand samples were collected from three formations.

(1) A collection was made in the mainly dark colored, siliciclastic mudstones of the late Cretaceous Lasipu Formation at two localities: (a) near the Tanadaro Granodiorite, where the sediments are slightly metamorphosed (sites SL.D, SL.E, SL.H, SL.J); (b) along the Wanokaka river (sites SL.F, SL.G).

(2) Volcanics of the Paleocene Massu Formation consisting of basalts and andesitic basalts have been sampled mainly in the area southwest of Kananggar both in the mountains and along the coast (sites SM.A–SM.L); other sampling localities are the south coast near Omamahoe (sites SM.M, SM.N, SM.O), north of Lewa with rhyolites (sites SM.P, SM.R), and in West Sumba in the area near Wanokaka (site SM.S, SM.T).

(3) Basalts from the early Miocene Jawila Formation in West Sumba are from two localities: (a) in the Jawila Mountains, 20 km west of Waikabubak (site SJ.A on the northern slope, sites SJ.B, SJ.C, SJ.D, SJ.E on the southern slope); (b) at the Poronubu Mountains, 10 km north of Waikabubak (sites SJ.F, SJ.G).

Paleomagnetic procedures

At the Paleomagnetic Laboratory cores have been drilled from the hand samples; the cores were cut into specimens of standard size. The specimens have been measured on a high sensitivity JR-3 spinner magnetometer with modified electronics. The specimens have been progressively demagnetized according to standard paleomagnetic procedures.

The Lasipu Formation. The specimens collected from the late Cretaceous Lasipu Formation have been treated either with progressive heating only or with alternating magnetic fields (af) and subsequent heating. The first

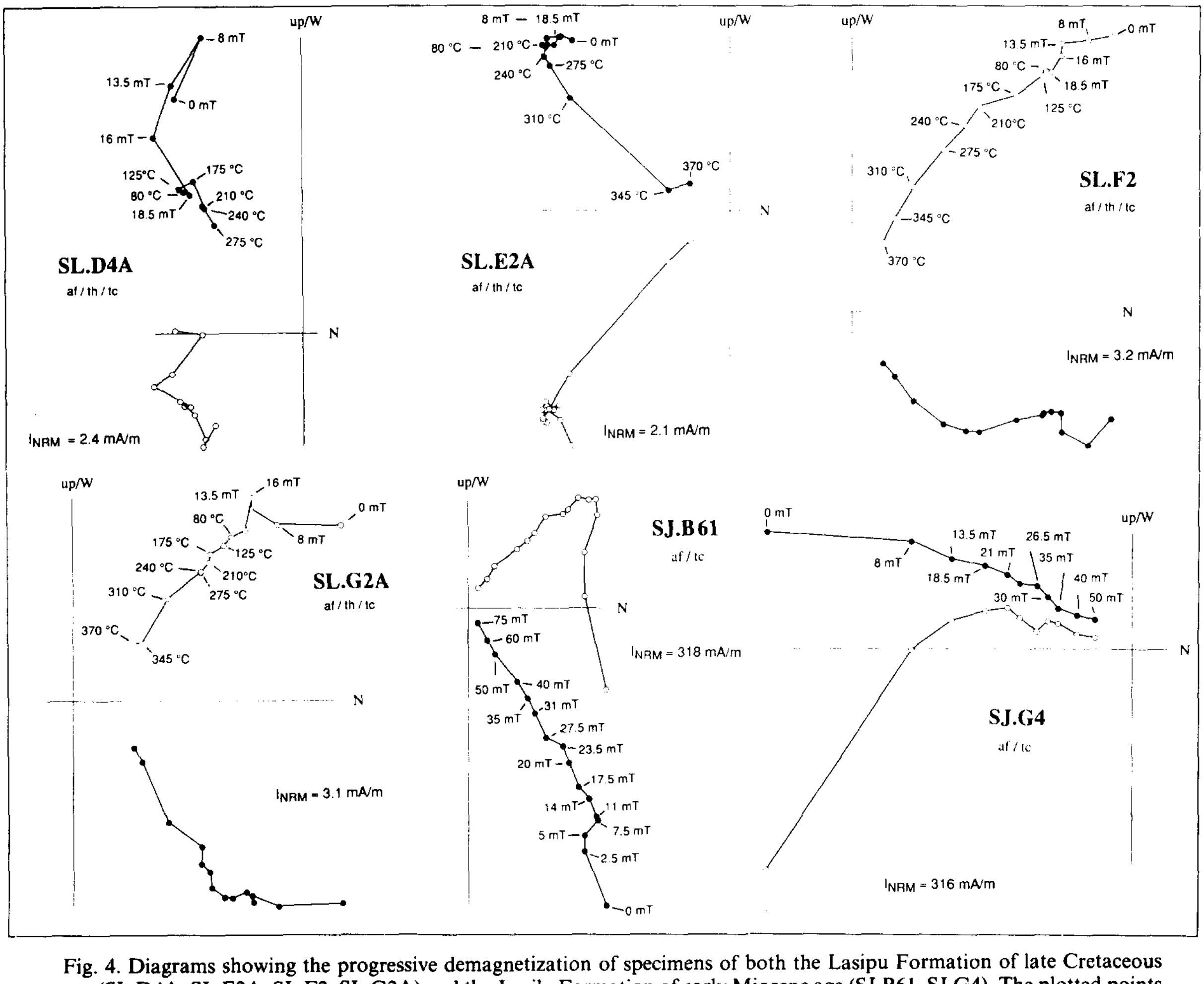

Fig. 4. Diagrams showing the progressive demagnetization of specimens of both the Lasipu Formation of late Cretaceous age (SL.D4A, SL.E2A, SL.F2, SL.G2A) and the Jawila Formation of early Miocene age (SJ.B61, SJ.G4). The plotted points represent successive positions of the resultant remanence vector in orthogonal projection. Dots and open circles denote the projections on a horizontal and on a vertical plane, respectively. Field peak strengths are given in mT (1 mT = 10 Oerstedt), and temperatures are given in Celsius. I_{NRM} is the initial remanence intensity in mA/m (milliampères per meter). af and th are treatments with alternating magnetic fields and with heating, respectively; tc indicates that bedding plane correction has been applied.

group has been heated in 9–12 successive steps up to a maximum temperature of 500°C. The second group has been demagnetized in 3–5 successive steps up to 16 mT peak value, and has been heated subsequently in up to 10 steps to a maximum value of 500°C. The demagnetization diagrams (Fig. 4) show that the initial remanence is built up of two or three components: (a) viscous, (b) secondary and (c) a characteristic component of magnetization (ChRM). It is not always possible to make a distinction between components (a) and (b). Very often, after heating at approximately 200°C the (a) and (b) components have been eliminated, and the ChRM component remains.

More than 60 specimens have been analyzed. Consistent results could be obtained from sites SL.E, SL.F, SL.G; the quality of the data from site SL.D is slightly less. From the majority of the specimens of the SL.H and SL.J no ChRM directions could be obtained, possibly due to the effects of contact-metamorphism of the Tanadaro Granodiorite.

The Massu Formation. From each site of the Paleocene volcanics of the Massu Formation one specimen has been progressively heated in 13 successive steps up to a maximum value of 585°C. The majority of the specimens, however, have been demagnetized with af in 7–12 successive steps up to maximum values between 50 and 90 mT. There is good agreement between the results from heating and those from af. The initial remanence may contain a small viscous component; very often, a secondary component of magnetization is present. Heating to about 300°C usually is sufficient to isolate the ChRM component; specimens treated with af needed a peak field between 20 and 30 mT (Fig. 5).

From the volcanics of the Massu Formation a total number of 240 specimens have been analyzed. The results derived from the sites SM.M and SM.N are poor (Table 3). The outcrops of these sites occur as promontories on the south coast with compact rocks showing a coarse columnar jointing. However, from thin sections one could conclude that these volcanics are hyaloclastics, very fine grained tuffs with an opaque groundmass. The individual specimens of site SM.N have stable remanence directions, but the combined specimens of this site show a large dispersion in directions, indicating that the components of the tuff picked up their remanence earlier. A large dispersion in ChRM directions is observed in site SM.K, a rather fresh porphyritic plagioclase-bearing andesite which appeared to be an agglomerate!

The Jawila Formation. Progressive heating of specimens of the early Miocene volcanics of the Jawila Formation was not always successful, because some specimens fell apart during thermal treatment. The majority of the specimens have been treated with progressive af demagnetization with a maximum number of steps between 7 and 16 and maximum peak fields between 40 and 90 mT (Fig. 4). During the demagnetization procedure a new magnetic component was introduced in a number of specimens which hampered the detection of a ChRM component. Therefore the data were discarded from some sites.

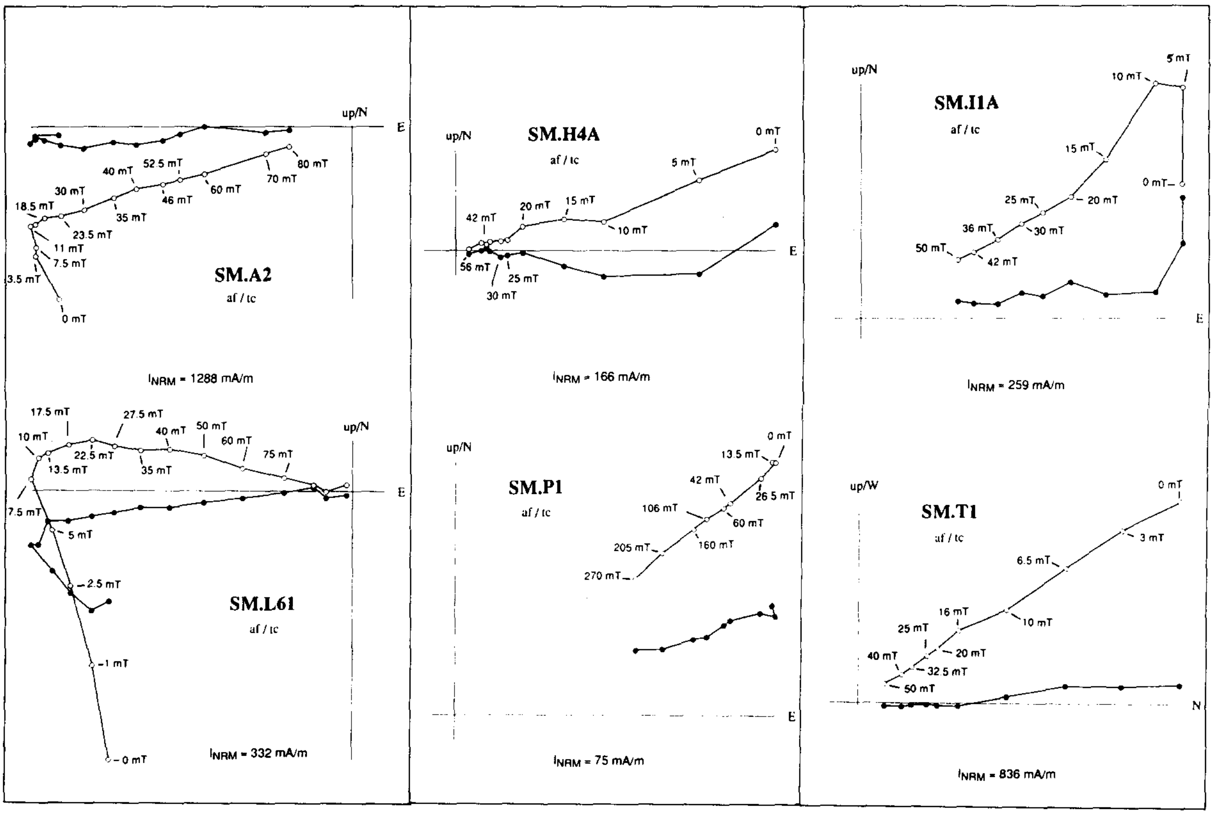

Fig. 5. Diagrams showing the progressive demagnetization with alternating magnetic fields of specimens of the Massu Formation of Paleocene age. See also caption to Fig. 4.

Table 2. Paleomagnetic data from sediments of the Lasipu Formation of late Cretaceous (Coniacian–Campanian) age, Western Sumba

Site	Strike/dip	N	D	I	k	a_{95}
SL.D	106/12.5S	7	234.9	29.5	16.1	15.5
SL.E	112/40S	7	222.9	29.2	80.8	6.8
SL.F	149/26SW	12	43.4	−38	48.6	6.3
SL.G	113/16S	12	45.7	−37.2	107.3	4.2
SL	*no tc*	4	225.9	11.5	30.7	16.8
SL	*tc*	4	226.8	33.5	145.5	7.6

Strike/dip gives the attitude of the strata; N is the number of specimens included in the analysis (for "no tc" and "tc" the number of sites); D and I are the declination and inclination in degrees of the characteristic remanence direction after bedding tilt correction; k is the precision parameter; a_{95} is the semi-angle of the cone of 95% confidence in degrees (Fisher 1953); *SL* is the mean direction of 4 sites; "*no tc*" and "*tc*" is before and after bedding tilt correction, respectively

Paleomagnetic results

The paleomagnetic data, derived from the late Cretaceous Lasipu sediments, are presented in Table 2. The paleomagnetic pole position is listed in Table 5. The sites SL.D and SL.E revealed positive inclinations, whereas sites SL.F and SL.G gave opposite directed declinations with negative inclinations (Fig. 6). The inclinations of the sites with positive inclinations have slightly lower values than those with negative inclinations, for which no explanation can be given. The occurrence of both polarities in the Lasipu sediments—normal and reversed—means that the deposits with reversed specimens should be younger than 82 Ma, because at that time the Cretaceous Normal Polarity Interval ends. This is not in conflict with the age of the sediments of Coniacian through Campanian (Burollet and Sallé 1982). Although the number of sites is small, the fold test is positive with values of k of 30.7 and 145.5 before and after tectonic correction, respectively (Fig. 6; Table 2 in italic).

The paleomagnetic data derived from the volcanics of the Massu Formation of Paleocene age are listed in Table 3. In Table 5 the paleomagnetic pole position is given. For the volcanics the application of a correction for the tectonic position of the lavas is often rather difficult. The area shows block faulting and the individual blocks are usually tilted. We have used flow structures as well as the position of the columnar joints for the detection of the tectonic correction. The majority of the sites revealed declination values of circa 90° and circa 270° with negative and positive inclinations, respectively (Table 3; Fig. 7). We can conclude that the ChRM directions are most likely primary, because both polarities

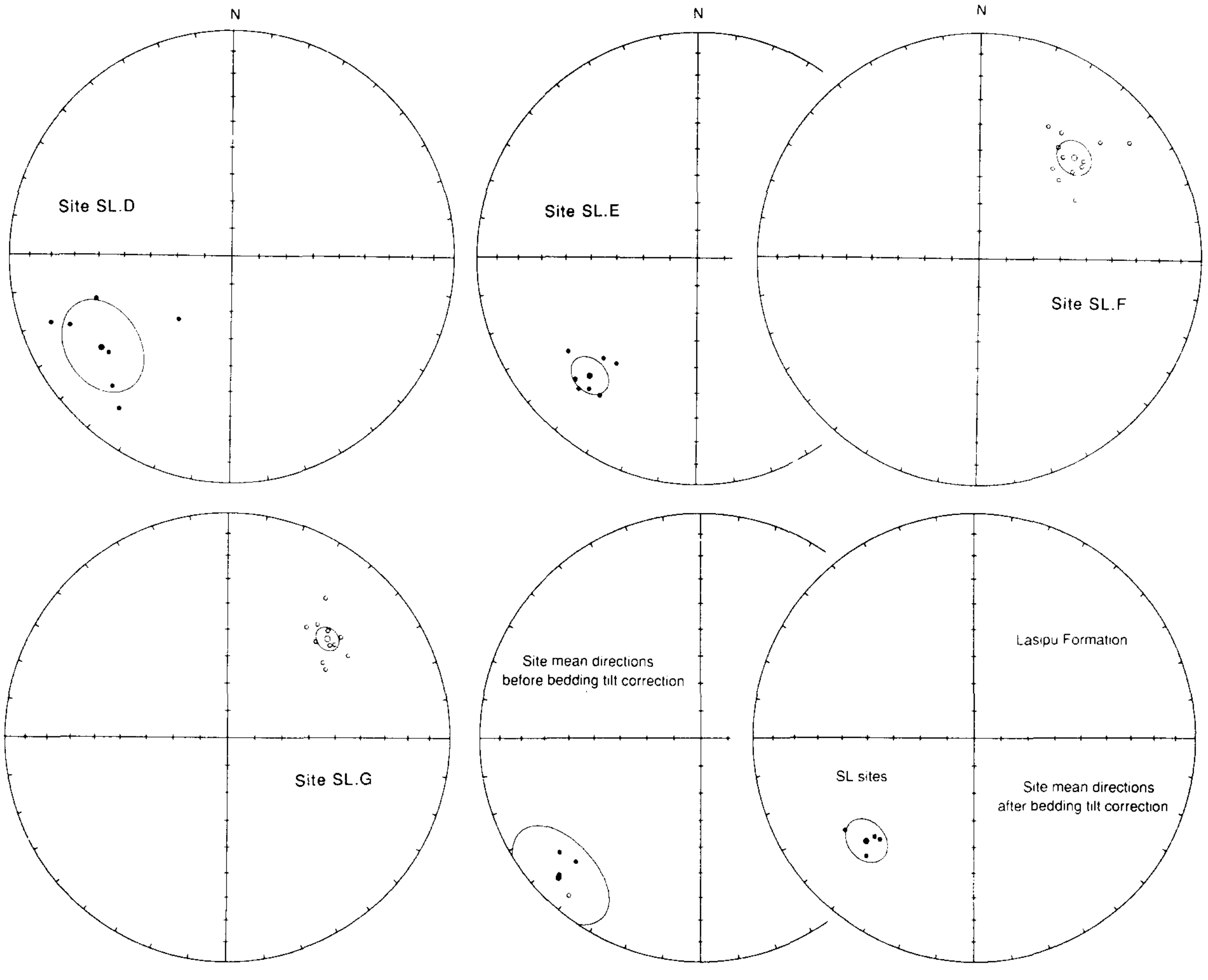

Fig. 6. Stereoplots of the Characteristic Remanence (ChRM) directions of specimens from four sites of the Lasipu sediments (SL.D, SL.E, SL.F, SL.G) with site mean directions provided with the circles of 95% confidence, and plots of the site mean directions with the overall mean both before and after bedding plane correction. Open and closed symbols denote downward-pointing and upward-pointing directions, respectively.

Table 3. Paleomagnetic data from volcanics of the Massu Formation of Paleocene age, Sumba

Site	Rock type	Strike/dip	*N*	*D*	*I*	*k*	a_{95}
SM.A‡	Basalt/andesite	103.5/24S	13	271.1	20.5	304	2.4
SM.B‡	Basalt	86/28S	11	265.2	37.9	128	4.0
SM.C‡	Basalt/andesite	63/27SE	13	88.5	−18.6	107	4.0
SM.D‡	Basalt/andesite	43/15SE	8	103.4	−24.0	17	13.7
SM.E‡	Basalt	126/41SW	9	92.9	−21.4	5	24.6
SM.F1‡	Basalt/andesite	98/18S	9	95.3	12.3	28	9.9
SM.F2‡	Basalt/andesite	21/30E	8	91.2	−34.7	12	16.3
SM.F3‡	Basalt/andesite	345/16E	14	90.4	3.8	39	6.5
SM.G‡	Basalt	8/18S	16	110.9	−9.1	18	9.0
SM.H‡	Andesite	313/32NE	11	98.7	−18.3	25	9.3
SM.I	Basalt	228/82NW	8	74.4	−26.8	84	6.1
SM.K	Andesite	320/47NE	12	344.6	33.6	2	35.7
SM.L‡	Basalt	106.5/33.3S	11	270.4	−4.7	93	4.8
SM.M	Tuff	214/25NW	10	63.1	−37.0	3	31.6
SM.N*	Tuff	—	9	12.1	−8.8	1	−82.4
SM.O‡	Basalt/andesite	322.5/30NE	14	286.4	9.5	6	17.8
SM.P	Rhyolite	240/80NW	11	70.6	−30.9	232	3.0
SM.R	Rhyolite	243/39NW	9	317.6	−45.2	7	20.1
SM.S†	Basalt	124/25SW	15	47.5	−9.1	63	4.9
SM/T	Andesite	—	10	355.5	−24.4	35	8.3
SM		*no tc*	*12*	*280.2*	*6.1*	*17.2*	*10.8*
SM		*tc*	*12*	*275.6*	*14.6*	*22.4*	*9.4*

*Strike/dip is not clear; †dyke in Lasipu sediments; ‡site included in the final analysis; *SM* is the mean direction of 12 sites; for further explanation of symbols see footnote to Table 2.

occur. For the ultimate compilation 12 sites have been selected (Fig. 7; Table 3 in italic). The fold test is slightly positive; the value for *k* increases from 17.2 to 22.4 before and after correction, respectively. The rock collections from the volcanics of the Massu Mountains (sites SM.A–SM.L) revealed a majority of stable ChRM directions (Table 3). Also a good result could be obtained from site SM.O near Omamahoe further west

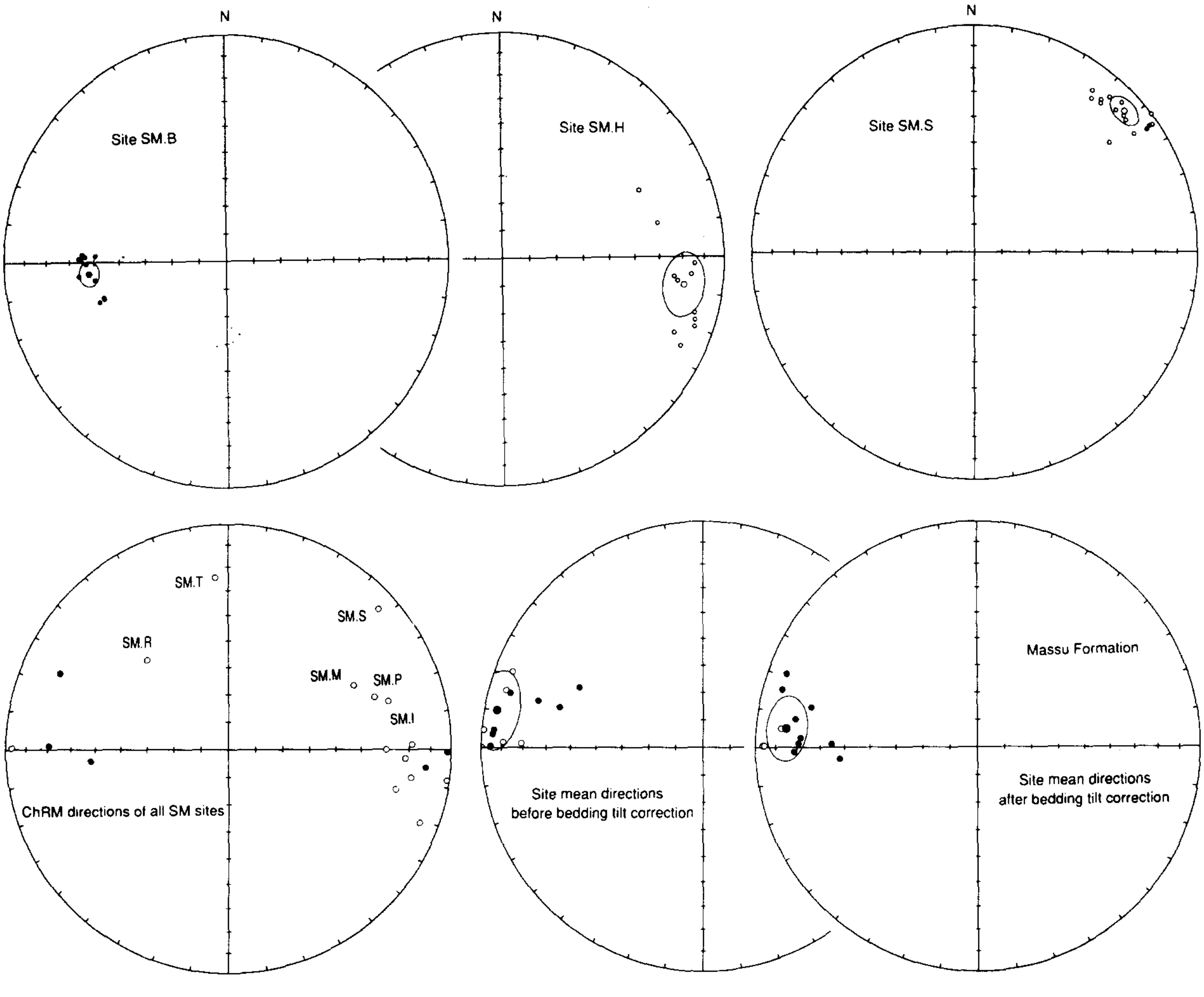

Fig. 7. Stereoplots of the ChRM directions of specimens from four sites of the Massu volcanics as well as site mean directions with the overall mean both before and after bedding plane correction. See also caption to Fig. 6.

at the south coast. The reason why sites SM.K, SM.M, and SM.N produced poor results has been explained earlier. The interpretation of the data derived from the rhyolites collected to the north of Lewa (sites SM.P, SM.R) is difficult, which may be due to inaccurate tectonic correction. Site SM.P showed very stable ChRM directions. It is possible that the rhyolites belong to the volcanic suite immediately related to the Tanadaro granodiorite intrusions, which could be older than the Massu volcanics. Site SM.S is from a basaltic rock, well exposed on the south coast west of Wanokaka, showing a ChRM direction deviating from the Massu directions. This rock could belong to the volcanics of the South Coast Mountains which are probably older than the Massu volcanics. The result from site SM.S corresponds to the overall result for the South Coast Mountains and the Tanadaro Granodiorite, published by Chamalaun and Sunata (1982). The andesitic sill intruded in the Lasipu sediments and exposed in the Wanokaka river (site SM.T) also shows a ChRM direction deviating from those of the Massu volcanics; it is possible that this sill belongs to the early Miocene volcanic suite of the Jawila Formation.

It was difficult to obtain reliable ChRM directions from the basaltic lavas of the early Miocene Jawila Formation. The outcrops on the northern side of the Jawila Mountains (SJ.A) and those in the Poronubu hills (SJ.F, SJ.G) are poor, but the exposures in a stream on the southern slope of Jawila are reasonable (SJ.B, SJ.C, SJ.D, SJ.E) and the rock is fresh. It is possible that large blocks slid downwards which may hamper the application of an exact tectonic correction (site SJ.B; Fig. 4). The paleomagnetic data derived from the Jawila Formation are listed in Table 4; the pole position is given in Table 5.

Table 4. Paleomagnetic data from volcanics of the Jawila Formation of early Miocene age, Western Sumba

Site	*N*	*D*	*I*	*k*	a_{95}
SJ.B	6	50.6	−28.4	86.9	7.2
SJ.C	11	355.6	−13.3	40.4	7.3
SL.D	11	358.9	−25.3	28	8.8
Jawila Fm	*2**	*357.1*	*−19.3*	—	—

*Two sites only (SJ.C and SJ.D) are included in the final analysis; for further explanation of symbols see footnote to Table 2.

The pole positions derived from these three investigated formations are presented in Fig. 8.

COMPILATION OF THE PALEOMAGNETIC DATA FROM SUMBA

A summary of the paleomagnetic data for Sumba from both earlier workers and this paper is given in Table 5.

Otofuji *et al.* (1981) analyzed 32 specimens from shales in West Sumba collected not far from the Tanadaro Granodiorite both with alternating magnetic fields (af method) up to 30 mT peak value and with heating up to 300°C. They assigned a Jurassic age to these shales quoting van Bemmelen (1949); however, these sediments which belong to the Lasipu Formation are now assigned a late Cretaceous age (von der Borch *et al.* 1983). The shales revealed oppositely directed declinations with downward (positive) and upward (negative) directed inclinations, respectively. From the late Cretaceous Lasipu Formation both Otofuji *et al.* (1981) and this paper report remanence directions of both polarities. The ultimate paleomagnetic data derived from both studies agree reasonably; our study revealed lower

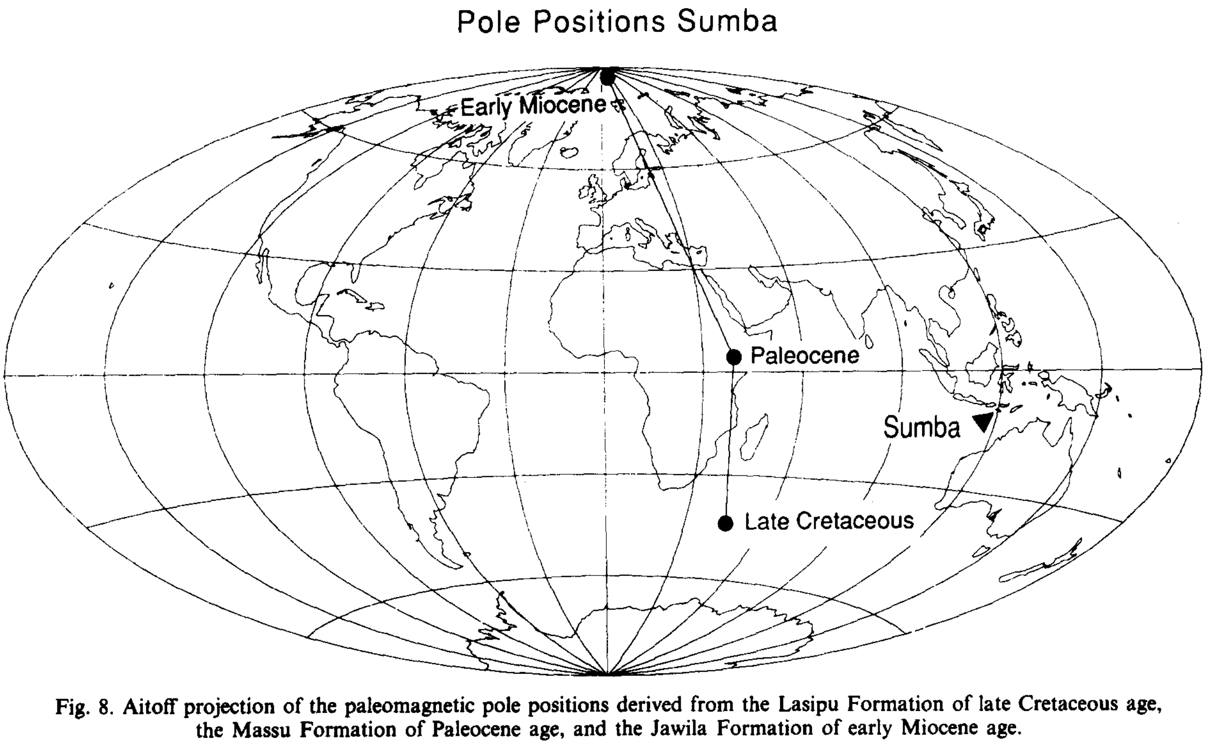

Fig. 8. Aitoff projection of the paleomagnetic pole positions derived from the Lasipu Formation of late Cretaceous age, the Massu Formation of Paleocene age, and the Jawila Formation of early Miocene age.

Table 5. Summary of the paleomagnetic data from Sumba, Indonesia

		Site coordinates						Pole position			
Rock unit	Age	Lat. (°)S	Long. (°)E	N	D	I	a_{95}	Lat. (°)	Long. (°)	Palat.	Data
Sumba Fm (tuffs)	Late Miocene	9.4	120.1	15	6.2	−27.9	8.6	82.3N	249.3E	14.8	[1]
Jawila Fm (volc.)	Early Miocene	9.4	119.2	11	7	−27.5	9.8	81.7N	244.5E	14.6	[1]
Jawila Fm (volc.)	*Early Miocene*	*9.6*	*119.4*	*2*	*357.1*	*−19.3*	—	*87.0N*	*22.5E*	*9.9(S)*	*[2]*
Massu Fm (volc.)	*Paleocene*	*10*	*121*	*12*	*275.6*	*14.6*	*9.4*	*4.2N*	*39.3E*	*7.4(N)*	*[2]*
Tanadaro Fm. (S Coast Volc.)	Late Cretaceous (64 Ma)	9.4	119.3	18	228.8	28.8	8.8	48.0S	41.9E	15.4	[4]
Lasipu F. (sedim.)	Late Cretaceous (Coniac.–Camp.)	9.4	119.4	3	239.2	44.2	5.7	31.8S	54.1E	25.9	[3]
Lasipu Fm (sedim.)	*Late Cretaceous (Coniac.–Camp.)*	*9.7*	*119.6*	*4*	*226.8*	*33.5*	*7.6*	*43.9S*	*45.8E*	*18.3(N)*	*[2]*

N is the number of sites, except at [1] where N is the number of specimens; data [1] and [4] are those from Chamalaun and Sunata (1982); [4] gives the combined data with downward directed inclinations from both the Tanadaro Granodiorite and the South Coast Volcanics; [2] the data from this paper, and [3] are those from Otofuji *et al.* (1981); Palat. is the paleolatitude in degrees; for further explanation of symbols see footnote of Table 2.

negative inclination values. It has been pointed out that the presence of reversed specimens indicates that these sediments must be younger than 82 Ma.

Chamalaun and Sunata (1982) carried out detailed paleomagnetic research on the volcanics of the South Coast Mountains, the Tanadaro Granodiorite, and dykes related to these intrusions. These are considered to belong to one main suite of rocks. These authors found conflicting results. In their summary they presented a combination of all data with southwest declinations and positive inclinations. A comparison between the final result derived from the Lasipu Formation with the one from a combination of the West Sumba igneous rocks shows no significant difference (Table 5). One can conclude that in late Cretaceous time the Sumba fragment did not drift very much.

In the Paleocene volcanics of the Massu Mountains no paleomagnetic sampling has been carried out earlier. We have demonstrated that our extensive paleomagnetic research in the Massu Mountains was successful. ChRM directions of both polarities have been found. Although the inclinations have rather low values one can see that the mean declinations of about 270 and 90° have positive and negative inclinations, respectively. The difference in ChRM directions between the combined Lasipu–Tanadaro formations and the Massu volcanics implies that Sumba performed a rotation of approximately 45° in the early Tertiary (Fig. 9). It should be pointed out that we have no data for a possible regional tilt correction of the Massu volcanics, because there is no contact visible between the sampled volcanics and the underlying Lasipu sediments.

Both Chamalaun and Sunata (1981) and our team (this paper) collected samples from the early Miocene Jawila volcanics. Chamalaun and Sunata also collected to the west of the Jawila Mountains near Edeklara. There is rather good agreement between the results of both studies. Although not coincident, the ChRM directions are very close to the present direction of the Earth's magnetic field. From these results one can conclude that in early Miocene time the Sumba fragment was already in approximately its present position. The island must have performed a large rotation of about 85° between Paleocene and early Miocene times (Fig. 9).

Paleomagnetic data from the Sumba Formation of late Miocene–Pliocene age from both Otofuji *et al.* (1981) and Chamalaun and Sunata (1982) confirm the results derived from the early Miocene volcanics.

DRIFT OF SUMBA

Chamalaun and Sunata (1982) concluded that the combination of the results of Otofuji *et al.* (1981) with their own data did not give a straightforward answer to the question whether Sumba had an Australian or a Sundaland origin, although they have a slight preference for a southern provenance. The Sumba fragment seemed to have occupied its present position at least since the early Miocene.

The paleomagnetic data derived from rocks of Sumba can be interpreted in two different ways (Fig. 9).

(a) In late Cretaceous through Paleocene time, Sumba had a position in the northern hemisphere, if one interprets the paleomagnetic data in terms of a counterclockwise (CCW) rotation, because in the northern hemisphere during a period with a normal magnetic polarity of the Earth's magnetic field the north-seeking magnetization directions are pointing downwards (positive inclinations), whereas during a period of reversed polarity the south-seeking directions are pointing upwards (negative inclinations).

Then, the continental fragment performed a CCW rotation of about 135°, with a drift of about 28° towards the south since the late Cretaceous. Between 80 Ma and approximately 64 Ma the rotation was very small or even absent; it is possible that in this time interval the fragment moved somewhat to the south. After the late Cretaceous, possibly in Paleocene time, Sumba rotated 50° in a CCW sense; the crustal fragment moved approximately 11° southwards. Between the Paleocene and the early Miocene Sumba rotated another 85° CCW;

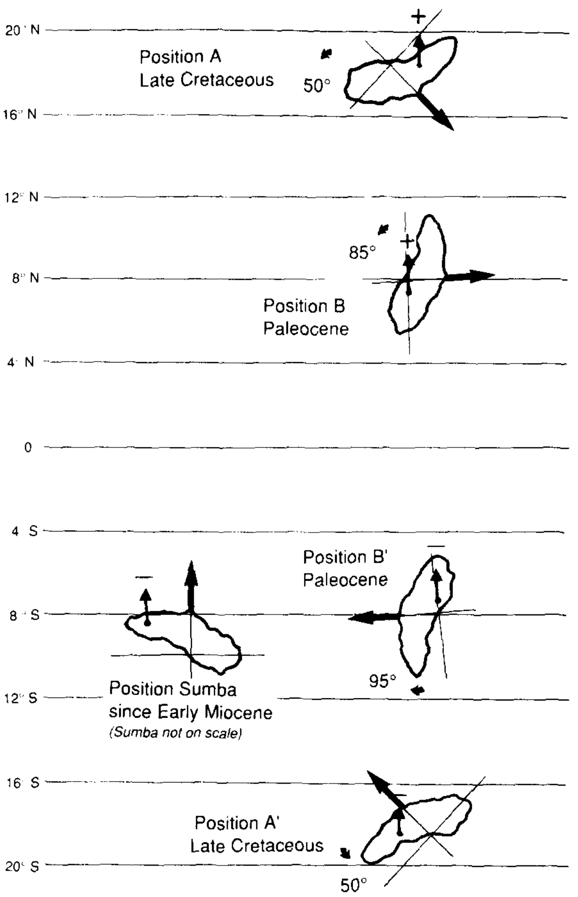

Fig. 9. Paleolatitudinal positions for the island of Sumba derived from paleomagnetic data of three different formations. During a period of Normal Magnetic Polarity the positions in the northern hemisphere during the late Cretaceous and the Paleocene correspond with downward-pointing inclinations of the ChRM directions, whereas the positions in the southern hemisphere correspond with upward-pointing inclinations.

in this time span the island shifted further to the south over about 17°. Since the early Miocene the island of Sumba has been in approximately its present position. The paleolatitudes of Sumba in late Cretaceous and Paleocene times are 18.4°N and 7.4°N, respectively (Table 5).

(b) In the southern hemisphere during a period with normal polarity the north-seeking directions are pointing upwards (negative inclination), whereas during a period with reversed polarity the south-seeking directions are pointing downward (positive inclinations). If Sumba had a position in the southern hemisphere in late Cretaceous times, the island must have performed a more complicated series of rotations, with a clockwise (CW) rotation of 45° since the late Cretaceous, followed by a CCW rotation of 50° after the late Cretaceous in Paleocene time, and again a CW rotation between Paleocene and early Miocene times of 95°. No rotation has occurred since the early Miocene. In this scenario the continental fragment of Sumba was positioned in the southern hemisphere since the late Cretaceous and remained there until the present time. The island moved northwards from latitude 28.4°S in the late Cretaceous to latitude 7.4°S in the Paleocene, and has shifted slightly southwards since that time.

It is difficult to make a choice between possibilities (a) and (b). An original position of Sumba in the northern hemisphere means that the rotation continued its CCW sense. Whether the position of Sumba in the late Cretaceous was in the northern or the southern hemisphere is of little importance for the question whether or not Sumba originally came from Australia. In the late Cretaceous Australia still was positioned rather far to the south (Smith *et al.* 1981); the late Cretaceous paleolatitude data (18.4°S) indicate that at the time Sumba could not have been part of Australia. However, it cannot be excluded that Sumba broke away from Australia in earlier times. The main rifting along Australia's northwest and west coasts took place in Jurassic–early Cretaceous time (Falvey and Mutter 1981, Pigram and Panggabean 1984). In the late Jurassic (160 Ma) large blocks may have rifted from Northern Gondwana and they may have drifted towards Asia, such as South Tibet, Burma, Malaya, and Sumatra (Audley-Charles *et al.* 1988). It has been postulated on the basis of the occurrence of recognizable pre-rift, syn-rift, and post-rift deposits with associated tectonics and volcanics, that in the late Jurassic also smaller fragments separated from Gondwana, and especially from the Australian part of it. These fragments now occur as isolated microcontinents, mainly in Eastern Indonesia with the Banggai–Sula Archipelago, Obi, Bacan, Buton, and possibly parts of Buru and Ceram. It is possible that these fragments originally remained in Australia's vicinity and that they drifted away in early Neogene time. Part of Timor could have the same structural history (Wensink and Hartosukohardjo 1990b). In this scenario Sumba's basement had an Australian origin and the fragment was split off in Jurassic times.

A comparison of the geology of Sumba with that of the allochthonous Palelo Series of Timor has revealed some resemblances (Table 1). Both units in their former position could have constituted the Banda Allochthon (Audley-Charles *et al.* 1988), a postulated landmass in the Banda area [Fig. 10(b)]. The eastern Sunda Shelf which continues to the south of West Sulawesi is underlain largely by deformed Mesozoic rocks (Letouzey *et al.* 1990). Hamilton (1979) proposed an original location for Sumba at the eastern end of the Sunda Shelf. Then, the late Cretaceous Lasipu sediments must have had their source area on the Sunda Shelf, and the submarine fan complexes (von der Borch *et al.* 1983) must have prograded to the north. The granodiorites of Tanadaro and associated intrusive rocks may point to a period of extension along the rim of Sundaland in the latest Cretaceous. If the large volcanic suites of the Massu Mountains on Sumba represent products of a volcanic arc, the rocks could be related to the early Banda Arc, originally located along the rim of the Southeast Asian continent, and including Southeast Sulawesi. The early Banda Arc forms the continuation of the early Sunda Arc (Rangin *et al.* 1990a, b).

According to Rangin *et al.* (1990b) left lateral transform faults were active in the ancient Banda Arc area during the middle Eocene and early Oligocene [Fig. 10(a)].

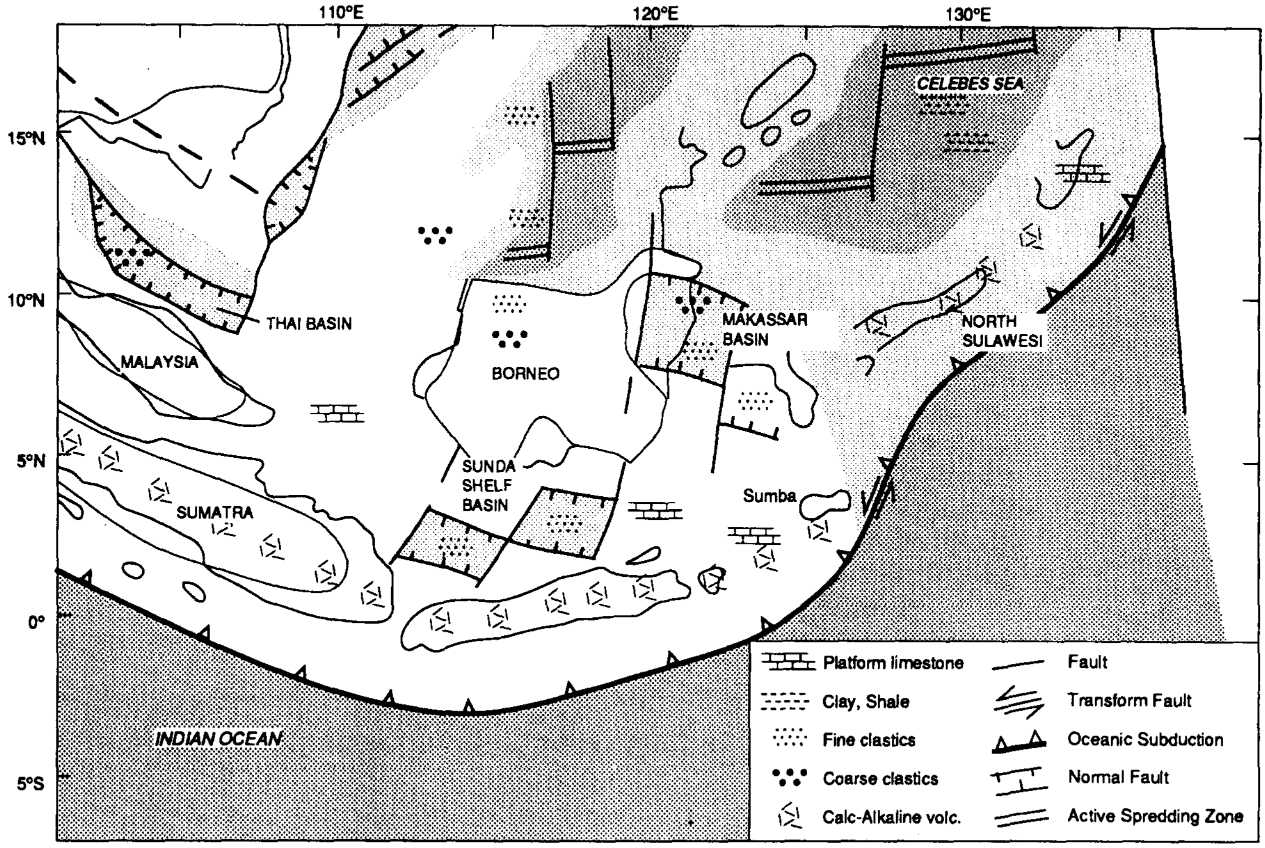

Fig. 10a. Simplified structural map of Indonesia during the middle Eocene (43 Ma) after Rangin *et al.* (1990b) with the position of Sumba.

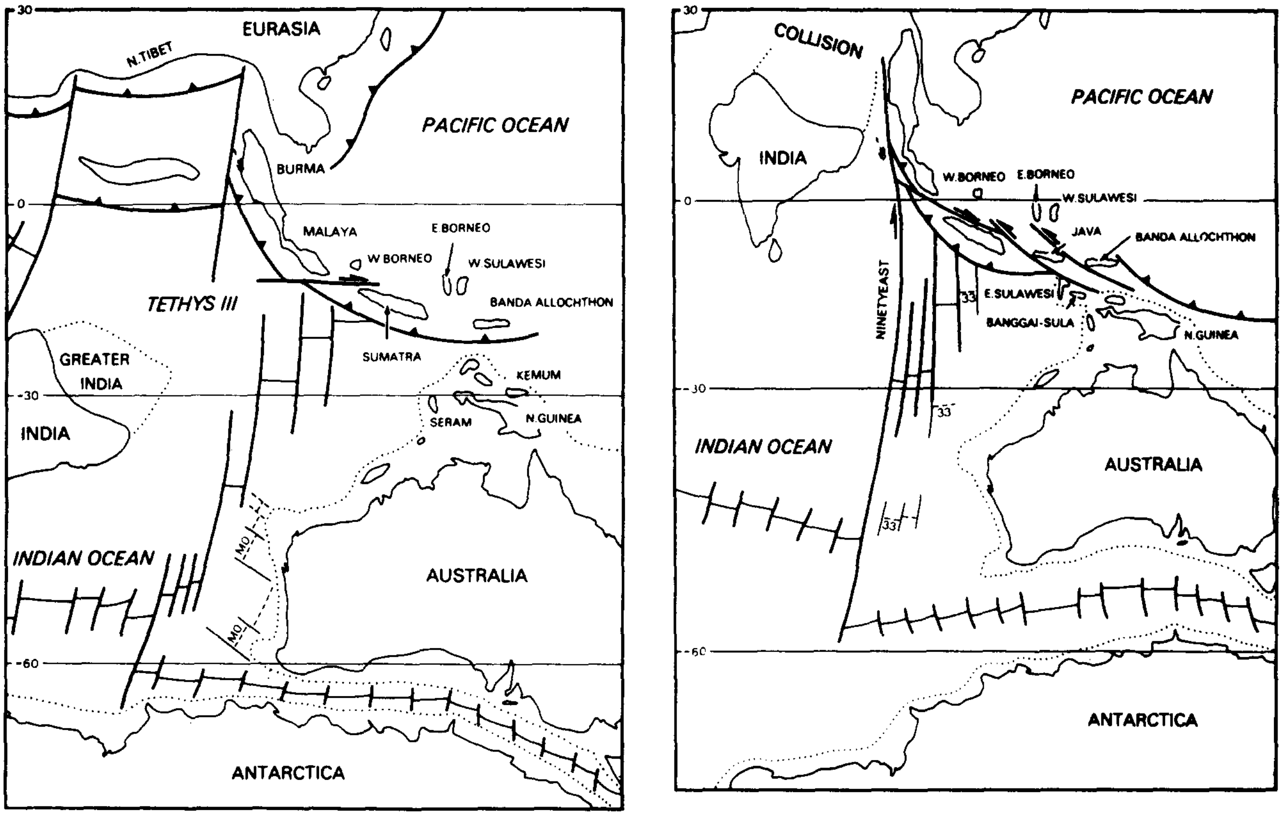

Fig. 10b. Reconstruction of Australian Gondwanaland at 90 Ma (late Cretaceous) and at 40 Ma (late Eocene), left and right, respectively, based on Smith *et al.* (1981) and after Audley-Charles *et al.* (1988).

These faults could have broken up the arc into a number of segments. In this scenario, in Eocene–Oligocene times one of the segments, the Sumba fragment, performed a CCW rotation and moved southward. It is possible that the change of movement of the Pacific Plate some 45 Ma ago from NNW to NW has played a role (Engebretson *et al.* 1985). In the early Miocene, with the approach of the Australian continent, the westwards movements of small Australian fragments could be of influence as well. By that time, Sumba had reached its present position. By the middle Miocene the present Banda Arc came into existence without disturbing the continental fragment of Sumba. The allochthonous units of Timor, which may have formed together with Sumba the Banda Allochthon came in contact with the frontal part of the Australian continental margin 3 Ma ago.

This scenario of the drift of Sumba since the late Cretaceous fits rather well into the structural evolution pattern for Southeast Asia suggested by Rangin *et al.* (1990a, b). In their models [Fig. 10(a)], the southern rim of the Sunda subduction zone remained during the early Eocene to the north of the equator. During the Oligocene the Sunda Arc moved slowly towards the south. In the early Miocene the southern boundary of the Sunda Arc is located at latitude 10°S. Although the authors do not discuss the shift of the Sumba fragment, one can see from their maps, that Sumba was located in the northern hemisphere by Eocene times; in the early Miocene Sumba reached approximately its present position.

Audley-Charles *et al.* (1988), making use of a map-plotting computer program, showed in a series of maps the drift of Gondwana fragments towards Asia since 160 Ma. For the position of Sumba the structural evolution of Southeast Asia since the late Cretaceous is important (their map of 90 Ma). The map shows the Banda Allochthon in a position north of the Sunda Arc. Their next map of 40 Ma [Fig. 10(b)] shows a number of WNW–ESE left lateral strike–slip faults which break up the eastern part of the Sunda Arc (in the region of the present Banda Arc). These faults may be a result of the reorganization of the movement of the Pacific Plate, as outlined before. However, in the reconstruction of Audley-Charles *et al.* (1988) the southern boundary of the Sunda Arc is positioned in the southern hemisphere; the boundary moved towards the north from approximately latitude 20°S to latitude 12°S between 90 and 30 Ma ago. If one accepts the reconstructions of Southeast Asia since 90 Ma presented by Audley-Charles *et al.* (1988) with the position of the larger part of Indonesia in the southern hemisphere, the interpretation (b) of the paleomagnetic data must be considered. Then, one must accept that since the late Cretaceous the Sumba fragment performed both CW and CCW rotations. The shift of the island was first to the north and subsequently to the south.

In conclusion it can be remarked that both scenario's for the structural evolution of Southeast Asia (Rangin *et al.* 1990a, b, Audley-Charles 1988) contain valuable elements for the structural history of Sumba. We have a preference for the reconstructions of Rangin *et al.* in which during the early Tertiary the southern part of Indonesia was situated in the northern hemisphere. Then, one can derive from the paleomagnetic data that the fragment of Sumba performed rotations, with a CCW sense only, from the late Cretaceous till the early Miocene, and that the fragment moved continuously to the south. An original position of Sumba in late Mesozoic times at or near to the Southeast Asian rim is likely.

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