

## Palaeomagnetic data of late Cretaceous rocks from Sumba, Indonesia; the rotation of the Sumba continental fragment and its relation with eastern Sundaland

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Received 18 October 1996; accepted in revised form 30 July 1997

### Abstract

Sumba island forms part of a continental fragment, located near the transition of the Sunda Arc to the Banda Arc. It lies within the forearc region, between the active volcanic arc to the north and the Java Trench to the south. Palaeomagnetic studies of Cretaceous (late Albian-early Campanian) Lasipu sediments revealed a mean characteristic remanence (ChRM) direction with  $D = 42.5^\circ$ ,  $I = -23.0^\circ$ , and  $\alpha_{95} = 6.1^\circ$ , indicating a palaeolatitude of  $12^\circ$  S. This ChRM is, most likely, a secondary magnetization, possibly caused by the intrusion of the 65-Ma-old Tanadaro granodiorite. This granodiorite gave a mean ChRM direction with  $D = 44.7^\circ$ ,  $I = -16.3^\circ$ , and  $\alpha_{95} = 12.2^\circ$ , pointing to a palaeolatitude of  $8.3^\circ$  S.

Eastern Sundaland with Borneo, west and south Sulawesi, and Sumba formed one continental unit in the late Mesozoic, most likely attached to the southeast Asian mainland. Borneo and west and south Sulawesi underwent large counterclockwise (CCW) rotations since the Jurassic with  $\sim 45^\circ$  during the Cretaceous, and  $\sim 45^\circ$  during the Palaeogene. The Sumba microcontinent, most likely, became detached from eastern Sundaland soon after deposition of the Lasipu sediments. Palaeomagnetic data show that Sumba underwent subsequent clockwise (CW) rotations of up to  $96^\circ$ :  $53^\circ$  between 82 and 65 Ma, and  $38^\circ$  between 65 and 37 Ma. Since the late Eocene, only small rotations occurred. The data indicate that eastern Sundaland, including Sumba, remained close to the equator since the Jurassic. CW rotations occurred in Sundaland both in the north (Indochina) and in the west (Sibumasu) as a consequence of the India – Eurasia collision. The same sense of rotation is seen further east in Sulawesi's East Arm and the Philippine Sea plate. Eastern Sundaland (Borneo and west Sulawesi) with CCW rotations is being trapped between these CW rotating plates.

### Introduction

The Sunda–Banda Arc forms a continuous subduction system that extends over some 3000 km from Burma to eastern Indonesia; the system has a conspicuous, arcuate form. Along the western part of the Sunda Arc, up to long.  $118^\circ 30'$  E, Upper Jurassic and Lower Palaeocene oceanic crust of the Eastern Indian Ocean plate (Van Orman et al. 1995) is subducted beneath the continental crust of Sundaland (Figure 1). The eastern part of the Sunda Arc between  $118^\circ 30'$  and  $120^\circ 30'$  E forms a transition zone with marginal, continental plateaus of the Eastern Indian Ocean–Australian plate being involved in the subduction. From  $120^\circ 30'$  E toward the east, Australian continental crust subducts below the Banda Arc (Hamilton 1988).

Subduction along the Sumatra–Java–Bali segment of the Sunda Arc began in the late Oligocene with development of a volcanic arc. The eastern part of the arc from Lombok to central Flores came into existence in the early Miocene (21–19 Ma; Barberi et al. 1987). The Banda Arc is much younger, with volcanism starting about 10 Ma ago (Abbott & Chamalaun 1981).

The Sunda–Banda Arc forms a classical example of a subduction system with a well-developed trench, forearc ridge, forearc basin, volcanic ridge and backarc basin. These morphological elements can be distinguished even in the transition zone between the Sunda and Banda Arcs and further eastward.

Interpretations based on either palaeomagnetic results or geological data have been at logger heads regarding the provenance of Sumba. It has been argued

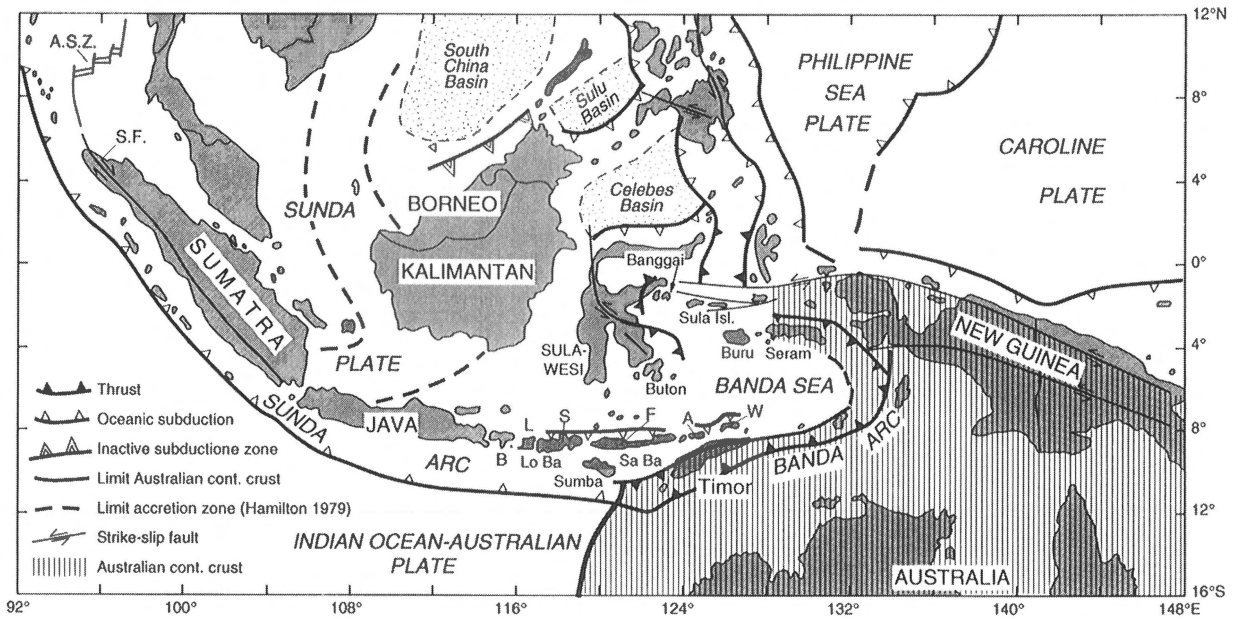


Figure 1. Structural map of Indonesia showing the limits of two Cretaceous accretion zones according to Hamilton (1979). A: Alor; A S Z: Andaman Spreading Zone; B: Bali; F: Flores; L: Lombok; Lo Ba: Lombok Basin; S: Sumbawa; S. F.: Semangko Fault; Sa Ba: Savu Basin; W: Wetar.

that Sumba detached from Australia's northwestern margin in the late Jurassic (Audley-Charles 1975, Otofuji et al. 1981, Hartono & Tjokosapoetro 1984). Another hypothesis favours that Sumba broke away from SE Sundaland in the early Cenozoic (Hamilton 1979). The latter view is now the more generally accepted (Von der Borch et al. 1983, Rangin et al. 1990). If Sumba did belong to Sundaland in the late Mesozoic one would expect to find comparable rock successions in Sumba and for instance Kalimantan and/or Sulawesi (Simandjuntak 1993, Wakita et al. 1996, Bergman et al. 1996).

The late Mesozoic southern boundary of Sundaland and its latitude are not well established (Audley-Charles et al. 1988, Rangin et al. 1990). Originally Sumba may have formed part of Sundaland, but it is unclear whether it was positioned north or south of the equator.

This paper presents new palaeomagnetic data of rocks of late and latest Cretaceous age from Sumba. Moreover, earlier available palaeomagnetic data have been used to discuss the position and rotation of Sumba since the late Mesozoic, and the relation of the microcontinent with eastern Sundaland.

### The island of Sumba, a continental fragment

Sumba is situated in the transitional segment between the Sunda and Banda arcs, within the forearc basin, to the south of the active volcanic islands Sumbawa and Flores and to the north of the subduction front and corresponding trench (Figure 1). The island does not form part of the outerarc ridge. The Java Trench decreases in depth from 6000 m to the southwest of Sumba to 2000 m in the southeast in the Timor Trough. As a result of the accumulation of shelf sediments at the rim of the Australian continent at long. 122° E the trench veers southwest of Timor toward the south.

Sumba is an isolated microcontinent (Chamalaun et al. 1982) that extends westward in the Lombok Basin up to a major NE-SW dislocation at long. 118° E (Van Weering et al. 1989, Van der Werff et al. 1994). Toward the east in the Savu Basin the submarine continuation of Sumba, the Sumba Ridge, can be identified up to at least 121° E (Van der Werff 1995) where it disappears below a series of north-verging thrusts (Reed et al. 1986). The Sumba microcontinent emerges from the forearc basin and is characterized by tilted and block-faulted Mesozoic basement.

The geology of Sumba is well known (Van Bemmel 1949, Laufer & Kraeff 1957, Effendi & Apandi

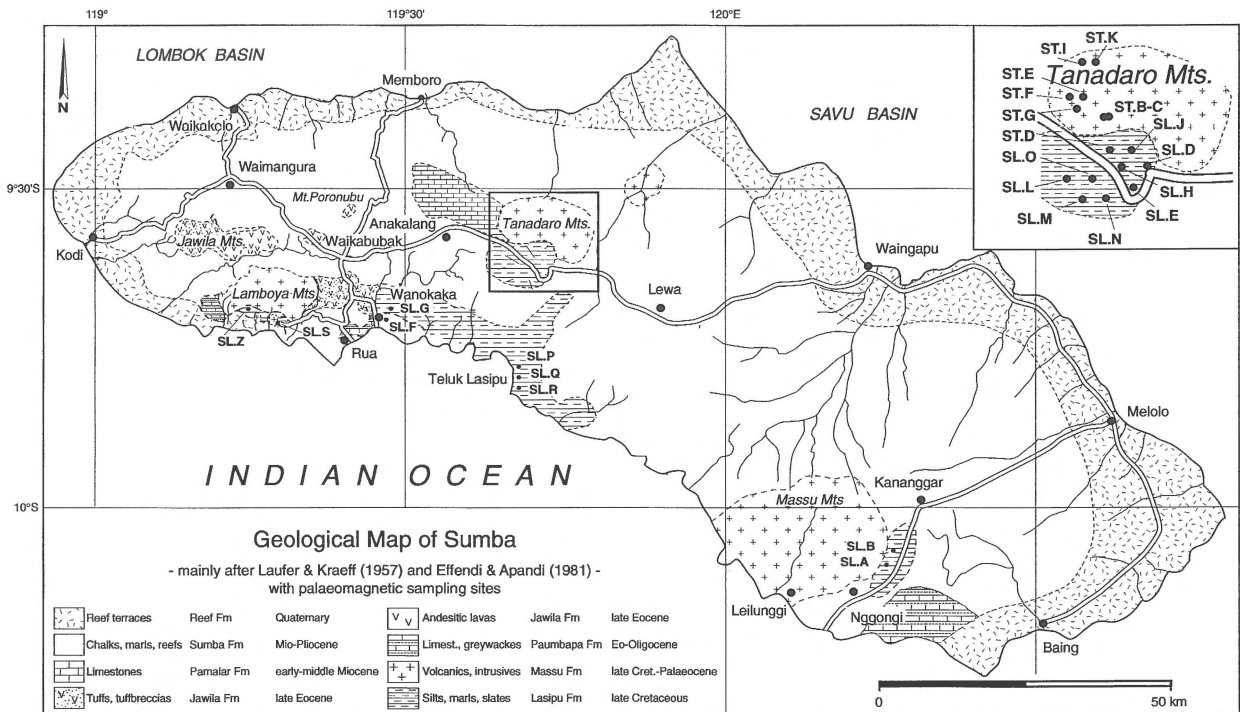


Figure 2. Geological map of Sumba showing the palaeomagnetic sampling sites of the late Cretaceous Lasipu Fm (SL) and the latest Cretaceous Tanadaro granodiorite (ST).

1981, Chamalaun et al. 1982, Von der Borch et al. 1983, Fortuin et al. 1994). The oldest rocks, exposed in the south of the island, are marine sediments of late Cretaceous age of the Lasipu Formation (Figure 2). The sediments are intruded and partly overlain by basaltic and andesitic volcanics which occur both in the Lamboya Mts in the southwest, and in the Massu Mts in the southeast. New  $^{40}\text{Ar}/^{39}\text{Ar}$  laserprobe dating results on volcanic rocks from the Massu Mts show ages of 78 and 76 Ma (Van Halen 1996). Intrusions of granodiorite, diorite, and small stocks of mafic igneous rocks occur as well. The Tanadaro granodiorite of latest Cretaceous age (Buroillet & Sallé 1982, Chamalaun & Sunata 1982) forms a large intrusive massif in west Sumba. Shallow-marine sediments of Eocene, Oligocene and early Miocene age overlie the older successions with a slight angular unconformity. Andesitic lavas and associated tuffs and agglomerates of late Eocene age crop out in west Sumba (Wensink & Van Bergen 1995). Their  $^{40}\text{Ar}/^{39}\text{Ar}$  age is 37 Ma (Van Halen 1996). The volcanics are covered by shallow-marine marls and reef limestones of middle Miocene to early Pliocene age. These sediments merge eastward into a thick pile of pelagic deposits with chalks, marls, shales, some

sandstones and conglomerates. Intercalated turbidites and mega-slides of southern provenance (Fortuin et al. 1994) continue eastward into the Savu Sea (Van der Werff 1995). Sumba is fringed to the west, north and east by Quaternary reefs, which are now at elevations of 500 m, indicating rapid uplift in the order of 0.5 mm/a (Pirazzoli et al. 1991).

Rocks on Sumba are little deformed, apart from some strong tectonic disturbances in the Lasipu sediments. The Sumba continental fragment is slightly tilted to the north, possibly due to the advancing Australian continental margin (Audley-Charles 1985). At present, Australian continental crust subducts beneath Sumba.

## Geology and palaeomagnetism of the Lasipu Formation and the Tanadaro granodiorite

### Geology of the Lasipu Formation

Excellent exposures of the Lasipu Fm occur in cliffs along Lasipu Bay (Teluk Lasipu, Figure 2) on the south coast. The sections consist of volcanoclastic agglom-

erates with interbedded diamictites, coarse conglomerates, sandstones, and medium-grey massive mudstones. Turbidites and slumps are frequent. The coarse layers contain fragments of acid intrusives and rhyolitic to andesitic volcanics as well as of metaquartzites. The sandstones contain grains of unstressed quartz and Na-rich plagioclase. Dykes and sills cut the sediments. Intercalated shallow-marine beds contain a Tethyan, mainly molluscan fauna of a probable Cretaceous age. Palaeocurrent determinations on flute casts with little spread in the readings give a mean azimuth of  $240^\circ$ , indicative for the land-sea distribution at that time (Von der Borch et al. 1983).

The succession along Lasipu Bay forms part of a major submarine fan complex. The sediments are of continental provenance; after rifting along the margin (of Sundaland?), continental-margin sediments were deposited at a large scale onto submarine fans. Rift-related volcanism resulted in additional supply of volcanic debris.

Elsewhere in south Sumba several smaller outcrops of the Lasipu Fm occur. These consist of mainly massive dark-grey to green siltstones and mudstones with minor interbedding of fine, immature sandstones, which may indicate a continental-rise setting. A weak regional metamorphism in sub-greenschist facies has been observed (Chamalaun et al. 1982). Everywhere, the sediments are pervasively intruded by dykes and sills. The siltstones locally contain a microfauna indicative of a Coniacian to early Campanian age (Burollet & Sallé 1982).

The total thickness of the formation is estimated at several hundred meters. The stratification is locally disturbed by intrusions. The beds dip generally up to  $40^\circ$  N or NE probably due to regional tilting rather than local faulting.

### *Geology of the Tanadaro granodiorite*

The Tanadaro granodiorite is a large intrusion in western central Sumba (Figure 2). The massif is deeply weathered, but fresh outcrops occur in rivers. The rock is medium to coarse-grained and contains augite, hornblende, biotite, andesine, and orthoclase. Dykes of various composition cut through the main intrusion. At its southern rim the granodiorite intrudes shales and sandstones of the Lasipu Fm. The main intrusion is overlain to the northwest by limestones of the early-middle Miocene Pamalar Fm and to the northeast by sediments of the Mio-Pliocene Waikabubak Fm (western facies of the Sumba Fm). The north-

eastern rim of the granodiorite has been affected by pneumatolytic metamorphism which resulted in silicified eruptives and mica and tourmaline-quartzites. In general, the Tanadaro granodiorite is non-foliated and does not show signs of post-crystallization deformation. Post-crystallization alteration is weak (Laufer & Kraeff 1957). K/Ar determinations show ages of  $64.2 \pm 1.0$  Ma (Chamalaun & Sunata 1982) and 63 Ma (Geological Research and Development Centre, Bandung, in: Chamalaun & Sunata 1982). The result of a new  $^{40}\text{Ar}/^{39}\text{Ar}$  laserprobe dating of  $64.9 \pm 0.2$  Ma (Van Halen 1996) is in good agreement with earlier published ages.

### *Previous palaeomagnetic studies*

Previous palaeomagnetic studies (see Table 3) on the Lasipu Fm gave mean ChRM directions with  $D = 59.2^\circ$ ,  $I = -44.2^\circ$ ,  $\alpha_{95} = 5.7^\circ$ , and  $N = 32/3$  (specimens/sites) (Otofuji et al. 1981), and  $D = 46.8^\circ$ ,  $I = -33.5^\circ$ ,  $\alpha_{95} = 7.6^\circ$ , and  $N = 36/3$  (Wensink 1994), respectively. The two studies showed ChRM directions of both normal and reverse polarity. A study of the Tanadaro granodiorite with five samples gave a mean ChRM direction with  $D = 37.4^\circ$ ,  $I = -25.8^\circ$ , and  $\alpha_{95} = 13.4^\circ$  (Chamalaun & Sunata 1982).

### *Palaeomagnetic sampling*

We collected oriented block samples at various outcrops of both the Lasipu sediments and the Tanadaro granodiorite (Figure 2). In the Lasipu Fm dark shales and mudstones were sampled. In some areas, e.g. the Lasipu Bay, the sediment appeared to be rather friable. We have not sampled near slides and mass movements, thus avoiding possible local rotations of sediment units. From the Lasipu sediments we present palaeomagnetic results for 174 specimens from a large number of block samples collected at seventeen sites (Figure 2). The attitude of the sampled strata was clear; bedding-tilt correction could reliably be applied.

In the Tanadaro granodiorite, we collected block samples at three different localities in small tributaries of the Pamalar river, west of the main massif. Some dykes, mainly of basaltic composition and intruded into the Lasipu sediments, are associated with the Tanadaro Massif. From the Tanadaro granodiorite, palaeomagnetic results are presented for 75 specimens from block samples collected at eight sites (Figure 2). All sites are in the Tanadaro granodiorite, except site D that represents a basaltic dyke intruded into Lasipu

sediments, south of the main massif. The deformation of the Tanadaro granodiorite seems to be restricted to a very slight, regional northward tilt during the Neogene.

### *Palaeomagnetic procedures*

#### *General*

Specimens of standard size (2.5 cm diameter, 2.2 cm height), drilled and sliced from the block samples, were analysed. The Lasipu sediments were measured on a 2G-Enterprises cryogenic magnetometer, the Tanadaro granodiorite specimens on a high-sensitivity JR-3 spinner magnetometer. All specimens were subjected to progressive demagnetization either by applying alternating magnetic fields (AF) in at least eight successive steps up to peak values between 50 and 80 mT, or by heating with a minimum of eight successive steps to temperatures between 450 and 650°C. Some specimens were treated with AF and were heated subsequently (Figure 3: SL.G2A). Demagnetization diagrams illustrate the behaviour of the remanence vector during progressive demagnetization (Figure 3).

#### *The Lasipu Formation*

With progressive demagnetization it turned out that the majority of the specimens contained a small viscous component that was easily removed (at 10 mT or 150°C). A secondary magnetization component, if present, quickly decayed upon subsequent demagnetization (Figure 3). Usually, the demagnetization treatment resulted in the isolation of a characteristic component of remanence (ChRM). There is good agreement between ChRM directions obtained after AF and thermal treatment, respectively. It is conspicuous, however, that the ChRM directions became isolated after progressive demagnetization in relatively low alternating fields or under heating at low temperature.

The specimens showed a large variation in initial remanence intensity with values between 0.3 and 200 mA/m, reflecting a variable supply of volcanic detritus. The rather rapid decrease in remanence during progressive demagnetization indicates that a low-coercivity mineral, e.g. magnetite, prevails as remanence carrier. The ChRM directions of individual specimens and their site-mean directions are shown for a number of sites, as well as the overall means for all 17 sites both before and after bedding correction (Figure 4). The palaeomagnetic results for the Lasipu Fm are listed in Table 1. The palaeomagnetic pole position is present-

ed in Table 3; the latter table also includes data from earlier palaeomagnetic research.

#### *The Tanadaro granodiorite*

The demagnetization diagrams (Figure 3) show that the initial remanence may comprise three components: a) a viscous component which disappeared after treatment in alternating fields between 5 and 10 mT or after heating between 100 and 150°C, b) a secondary component which could be removed after AF treatment up to 20 mT peak field or after heating at 250°C, and c) a characteristic remanence (ChRM) component. The diagrams show that the ChRM components obtained in the Tanadaro rocks are not as soft as those in the Lasipu sediments. The specimens of slightly weathered rocks from Tanadaro sites ST.I and ST.K show southwestern and downward pointing directions interpreted as secondary components of remanence. Unfortunately, the significance of these directions remains obscure.

The initial remanence ranges between 2 and 3500 mA/m. A small stock within the main intrusion (sites B and C) revealed an initial remanence of no more than 2.2 and 3.7 mA/m. A sudden drop in remanence after heating at 560°C indicates that magnetite may be the prevailing remanence carrier. Equal-area projections of the ChRM directions of specimens from two sites are shown in Figure 4, the basalt-dyke site ST.C and the granodiorite site ST.F, together with the site-mean direction and the overall mean direction of six sites included in the final analysis. The palaeomagnetic results and the palaeomagnetic pole positions of the Tanadaro granodiorite are listed in Tables 2 and 3.

### *Discussion of the palaeomagnetic results*

The question should be answered whether or not the ChRM directions detected for the Lasipu sediments are primary. The Lasipu sediments have probably been remagnetized during the intrusion of the Tanadaro granodiorite ~65 Ma ago. Arguments for a primary origin, however, can be put forward as well, because: a) ChRM directions occur with both normal and reverse polarity, and b) the general fold test is positive (Table 1). The occurrence of both polarities should mean that the sediments have been deposited after the end of the Cretaceous Normal Polarity Superchron (Chron C34N) that ended 83 Ma ago (Cande & Kent 1995). Palaeontological evidence for a Coniacian–early Campanian age (88–80 Ma) of the Lasipu sediments (Buroillet & Sallé 1982) concurs with the occurrence of both polarities.

Table 1. Palaeomagnetic data from late Cretaceous sediments of the Lasipu Fm, Sumba.

Site	N	D (°)	I (°)	Attitude	Dtc (°)	Itc (°)	k	$\alpha_{95}$ (°)
SL.A	4	56.0	-25.3	91/31S	49.1	-5.7	289	5.4
SL.B	9	40.8	-8.2	30/29SE	35.5	-12.4	56	7.0
SL.D	12	231.2	14.1	286/12.5N	233.8	24.2	14	11.9
SL.E	15	221.6	-25.6	292/40N	221.0	21.9	24	8.0
SL.F	17	43.3	-14.0	329/26NE	39.3	-38.8	49	5.2
SL.G	15	42.3	-20.4	296/16NE	45.5	-37.1	102	3.8
SL.H	4	223.0	-7.0	286.5/34.5N	225.2	23.2	20	21.3
SL.J	5	233.5	1.3	285/35.5N	239.9	28.2	36	13.0
SL.L	15	217.6	-5.7	302/43NE	218.9	30.5	42	6.0
SL.M	12	226.4	-8.2	295/40NE	229.4	28.9	60	5.6
SL.N	8	193.2	-16.0	285/32N	193.2	16.0	252	3.5
SL.O	3	234.1	-11.0	294.5/39NE	236.3	22.9	13	35.3
SL.P	12	49.0	-12.1	319/12NE	49.0	-24.1	29	8.2
SL.Q	14	43.4	-9.3	345/17E	40.7	-23.6	23	8.4
SL.R	14	35.0	-10.4	328/20NE	31.9	-28.3	22	8.6
SL.S	10	36.7	-2.0	320.5/8NE	36.6	-5.8	430	2.3
SL.Z	8	39.3	-13.5	0/0	39.3	-13.5	103	5.5
SL no tc (F)	17	42.8	-3.2				23	7.5
SL tc (F)	17				42.5	-23.0	35	6.1
SL no tc (M)	17	42.8	-3.2				23	7.5
SL tc (M)	17				42.5	-22.8	32	6.4
SL tc' (M)	17				42.2	-16.0	39	5.7

N: number of specimens included in the final analysis; D, I, Dtc, and Itc are the mean declination and inclination per site before and after tilt correction, respectively; Attitude: strike and dip of bedding; k: precision parameter;  $\alpha_{95}$ : semi-angle of the 95% cone of confidence (Fisher 1953). The overall mean directions of all 17 sites before and after tilt correction are given below with statistics after Fisher (F) and McFadden (M); SL tc': fold-test data showing maximum k (McFadden 1990) at 65% of complete unfolding, indicating that synfolding magnetization cannot be excluded.

Table 2. Palaeomagnetic data from the Tanadaro granodiorite (latest Cretaceous), Sumba.

Site	Rock	N	D (°)	I (°)	k	$\alpha_{95}$ (°)
ST.B	granodiorite	10	225.1	5.8	53	6.7
ST.C	granodiorite	7	221.2	15.9	43	9.4
ST.D	basalt dyke	8	36.6	-9.0	87	6.0
ST.E	granodiorite	10	46.7	-12.9	43	7.4
ST.F	granodiorite	11	38.0	-40.0	30	8.5
ST.G	granodiorite	7	59.5	-14.0	22	13.1
ST.I	granodiorite	11	250.3	-24.6	58	6.1
ST.K	granodiorite	11	241.4	-34.9	109	4.4
ST.B-G		6'	44.7	-16.3	31	12.2
ST.I-K		2'	246.1	-29.8	-	-

For explanation of symbols see Table 1; N': the number of sites in the final analysis of the two groups for which mean directions are given. The magnetization, derived from sites ST.I and ST.K, is, most likely, secondary. The present horizontal is assumed to be the palaeohorizontal; no tilt correction has been applied.

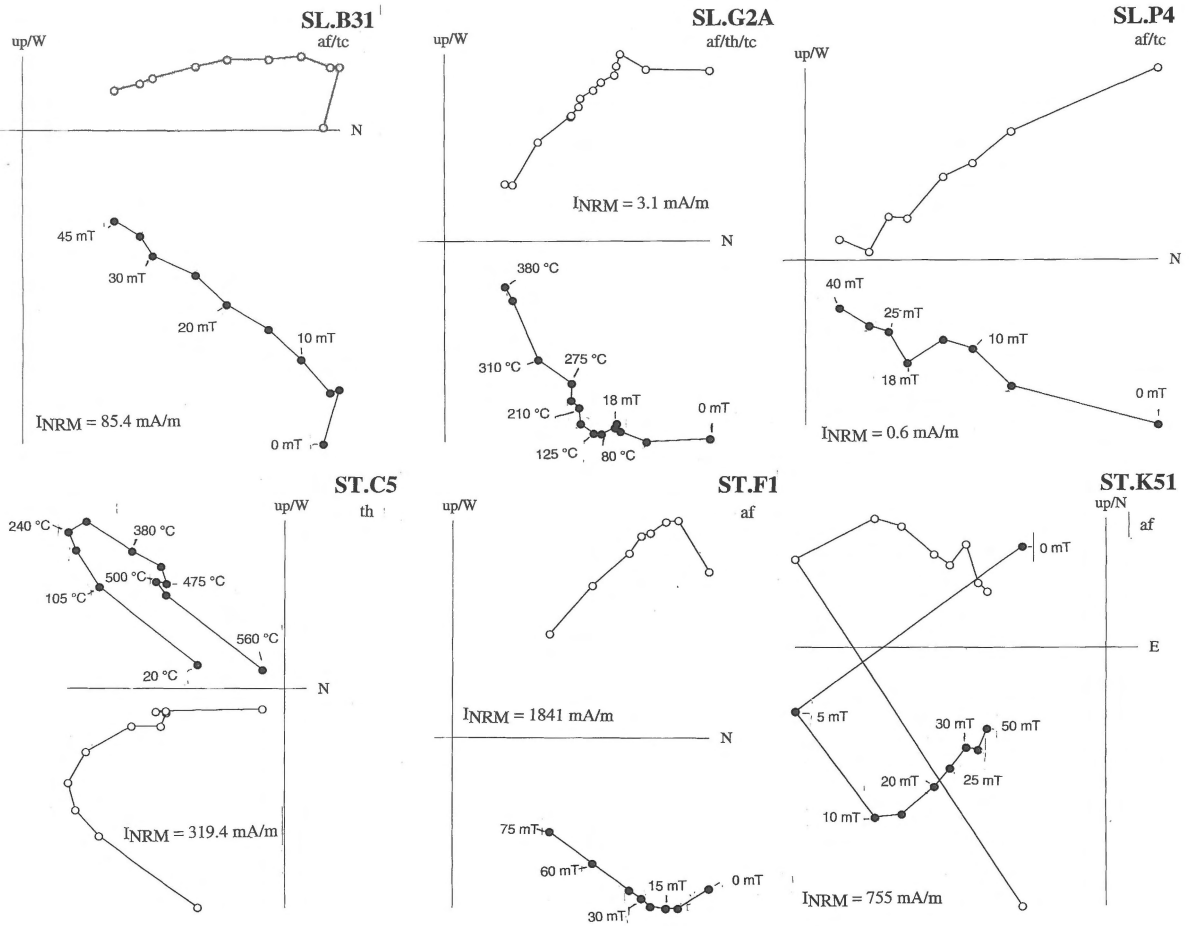


Figure 3. Diagrams showing the progressive demagnetization of specimens from the Lasipu Fm (SL) and the Tanadaro granodiorite (ST). Plotted points represent successive positions of the resultant remanence vector in orthogonal projection. Dots and open circles denote the projections on a horizontal, and a vertical plane, respectively. Field peak strengths are in mT, and temperatures in °C.  $I_{NRM}$  is the initial remanence in mA/m. *af* and *th* indicate treatments with alternating magnetic fields and heating, respectively; *tc* indicates that bedding-plane correction has been applied. Specimen SL.G2A has been demagnetized in alternating fields up to 18 mT peak field and subsequently has been treated thermally. The projection of specimen ST.K51 is different from that of the other specimens.

Sediments of the Balangbaru Formation in south Sulawesi (Wakita et al. 1996), that are identical to Sumba's Lasipu sediments, contained, however, in all their members a radiolarian fauna of late Albian to Turonian (100–93 Ma) age. Such an age range falls within the Cretaceous Normal Polarity Superchron which would exclude the occurrence of both polarities. Findings of planktonic foraminifera of early Turonian to late Maastrichtian age (93–66 Ma, Hasan 1990 as quoted in Wakita et al. 1996) add further confusion. The palaeontological data are not of great help for the exact age determination of the sediments.

Palaeomagnetic results derived from the Tanadaro granodiorite (Table 2) showed a ChRM direction with

$D = 44.7^\circ$ ,  $I = -16.3^\circ$ ,  $\alpha_{95} = 12.2^\circ$ , and  $N = 53/6$  (specimens/sites) which is not significantly different from the results of Chamalaun & Sunata (1982) for Tanadaro rocks (Table 3) with  $D = 37.4^\circ$ ,  $I = -25.8^\circ$ ,  $\alpha_{95} = 13.4^\circ$ , and  $N = 5$  (samples). It is conspicuous that the Tanadaro data are consistent with our palaeomagnetic result of the Lasipu deposits with  $D = 42.5^\circ$ ,  $I = -23.0^\circ$ ,  $\alpha_{95} = 6.1^\circ$ , and  $N = 174/17$ . Palaeomagnetic studies of the Tanadaro granodiorite showed the occurrence of ChRM directions of both normal and reverse polarity. The granodiorite has been dated at 65 Ma, in an interval of mixed polarity. The Lasipu sediments most likely have been remagnetized through the intrusive activity of the Tanadaro granodiorite; if so, the

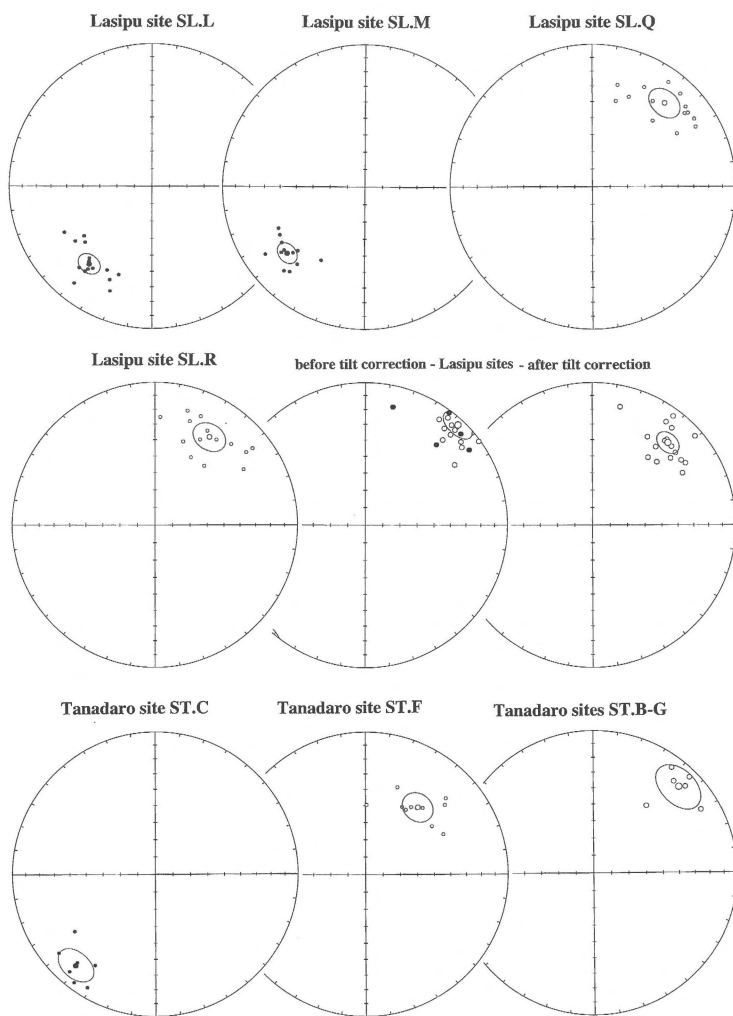


Figure 4. Equal-area projections of ChRM directions for four sites of the Lasipu Fm (tilt corrected) and two sites of Tanadaro granodiorite with site-mean directions (large symbols), and circles of 95% confidence indicated. The overall mean directions of all 17 sites of the Lasipu Fm included in the final analysis are given both before and after bedding-plane correction. For the Tanadaro granodiorite the overall mean direction of six sites is shown. Open (closed) symbols denote upward (downward) pointing directions.

period of magnetic overprinting must have covered a rather long time span in order to explain the occurrence of both polarities. The exact timing of the remagnetization can hardly be given. The majority of the sampled strata dip to the north or northeast; thus there are no fold limbs, hampering the interpretation of fold-test statistics. The application of Fisher statistics (1953) points to a remagnetization earlier than tilting which is confirmed using McFadden's (1990) statistics. The results of McFadden's test may be influenced by the relation between the distribution of site-mean directions about the overall mean direction and the tectonic corrections. Application to the Lasipu data, using maximum  $k$  sta-

tistics ( $k$  is precision parameter, Fisher 1953) gives a  $k = 39$ , but shows no apparent correlation at 65% of complete unfolding (Table 1). Reversal tests using data from Lasipu as well from Tanadaro (Tables 1, 2) are positive (McFadden & McElhinny 1990) and confirm the supposed remagnetization of the Lasipu sediments by the Tanadaro granodiorite. In conclusion, it cannot be excluded that the remagnetization of the Lasipu sediments started at the beginning of the tilting process at the time of the Tanadaro intrusive activity. Then, tilting could have continued subsequent to the remagnetization.

Table 3. Palaeomagnetic data from Sumba.

Formation (rock)	Age	Site coordinates (°)		N/N'	D (°)	I (°)	$\alpha_{95}$ (°)	Pole position (°)		Palat. (°)S	Data
		Lat. S	Long. E					Lat.	Long.		
Sumba Fm (chalks)	late Miocene to early Pliocene	9.8	120.2	21	356.0	-22.8	3.4	85.4 N	2.6 W	11.9	1]
Jawila Fm (volcanics)	late Eocene (37 Ma)	9.6	119.4	11	4.6	-19.2	9.9	85.5 N	213.3 E	9.9	2]
Tanadaro Fm (granodiorite)	latest Cretaceous (65 Ma)	9.4	119.3	5'	37.4	-25.8	13.4	53.0 S	42.4 E	15.4	4]
Tanadaro Fm (granodiorite)	latest Cretaceous (65 Ma)	9.4	119.3	6	44.7	-16.3	12.2	28.2 S	42.7 E	8.3	6]
Massu Fm (volcanics)	late Cretaceous (78 Ma)	10.0	121.0	12	95.6	-14.6	9.4	4.2 N	39.3 E	7.4	3]
Lasipu Fm (silts)	late Cretaceous (100-82 Ma)	9.4	119.4	3	59.2	-44.2	5.7	31.8 S	54.1 E	25.9	5]
Lasipu Fm (silts)	late Cretaceous (100-82 Ma)	9.7	119.6	4	46.8	-33.5	7.6	43.9 S	45.8 E	18.3	3]
Lasipu Fm (silts)	late Cretaceous (100-82 Ma)	9.4	119.4	17	42.5	-23.0	6.1	48.2 S	36.9 E	12.0	6]

N/N': numbers of sites/samples included in the final analysis; D and I: declination and inclination of the ChRM direction; Palat.: palaeolatitude; 1] Fortuin et al. (1997); 2] Wensink & Van Bergen (1995); 3] Wensink (1994); 4] Chamalaun & Sunata (1982); 5] Otofujii et al. (1981); 6] this paper. For further explanation of symbols see Table 1.

## Regional geological interpretation: Sulawesi and Sumba

### Sulawesi

The four-armed island Sulawesi is dissected by large fault systems that connect the western end of the Sulawesi Trench in the Celebes Sea with the Tolo Thrust in the Western Banda Sea (Figure 5; Silver et al. 1983). These transform fault systems comprise the NNW-SSE Palu-Koro Fault and the WNW-ESE Matano Fault, where a left-lateral displacement of 20 km has been observed, and also the strongly southward bending Tolo Thrust which continues towards northeast Buton. Oceanic lithosphere of the Celebes Sea subducts along the W-E trending Sulawesi Trench which forms the northern boundary of Sulawesi's North Arm.

This arm is built up mainly of island-arc volcanics and associated rocks of late Cretaceous to recent age (Surmont et al. 1994). In central and east Sulawesi large thrust belts occur containing ophiolitic rocks and associated mélanges of possibly Cretaceous age, part of which have a southern-hemisphere origin (Mubrot et al. 1994). These belts also contain Mesozoic pelagic sediments and Tertiary carbonates. Fragments of Aus-

tralian continental crust represented by the Banggai and Sula Islands, Buton, and the Tukang Besi platform, became incorporated in the thrust belt. These fragments have been transported westward from New Guinea by strike-slip movements in the early Miocene and reached Sulawesi by the end of the Miocene (Hall 1996).

Various views exist on the structural evolution of west Sulawesi including the greater part of the South Arm of the island: a) the area has a basement of pre-Jurassic continental crust representing the eastern continuation of Sundaland; b) the area represents a continental fragment of unknown (Australian?) origin, the Mkongga block, which became accreted to the eastern cratonic margin of Sundaland. In south Sulawesi, the Bantimala metamorphic complex, dated between 132 and 106 Ma, is built up of NE-dipping tectonic slices. The stacking of this complex was caused by Neogene subduction (Wakita et al. 1996). Within the complex and locally elsewhere in the South Arm late Cretaceous turbiditic sediments of the Balangbaru Fm have been deposited in a possible forearc basin. Late Cretaceous to Oligocene volcanic rocks and granitic intrusions support the presence of a collision zone and accretion to east Sundaland.

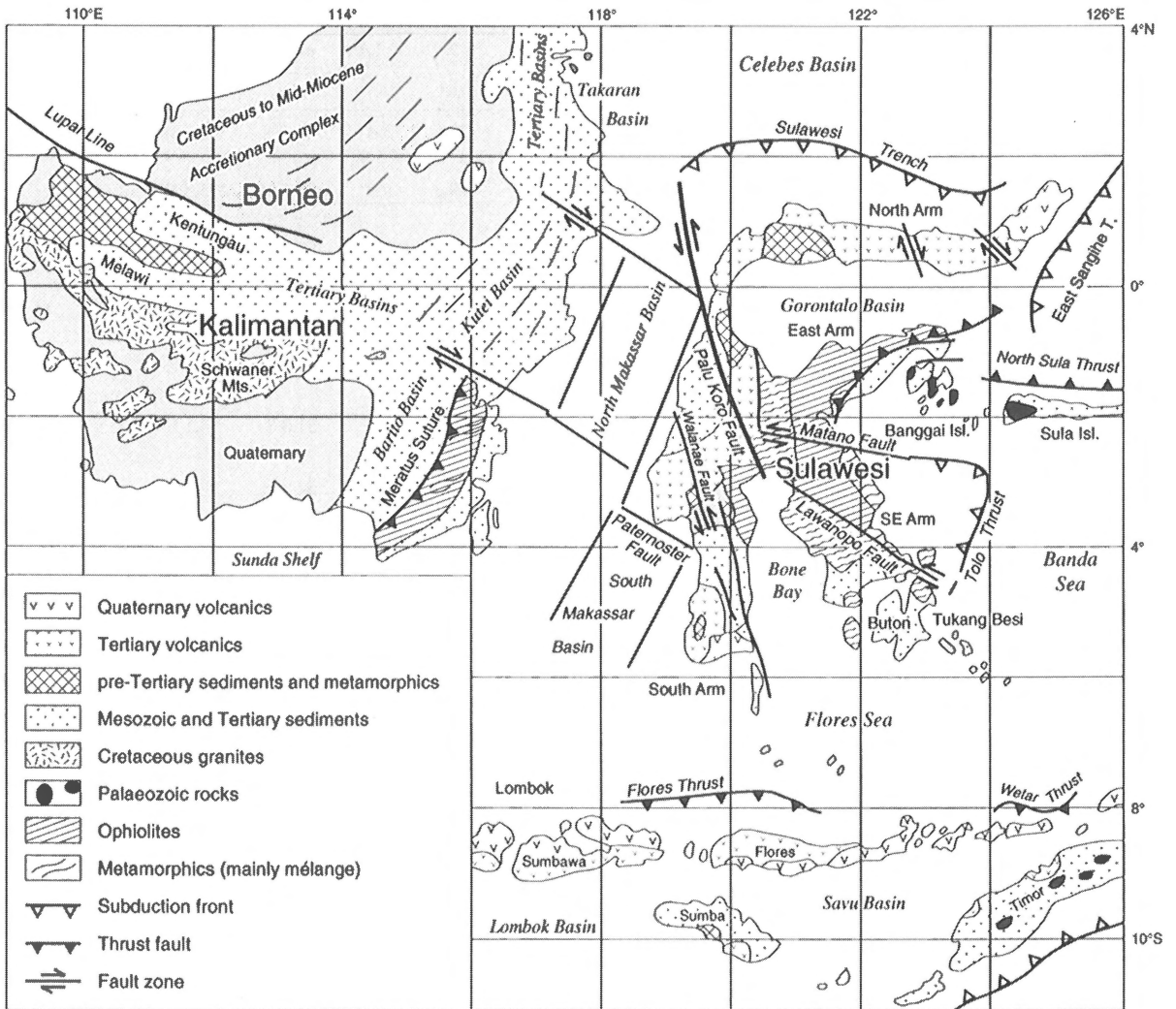


Figure 5. Structural map of central Indonesia including Borneo (Kalimantan), Sulawesi, and the eastern Sunda Arc, mainly after Hamilton (1979) and Silver et al. (1983).

The South and the Southeast Arms of Sulawesi, and terranes around the Bone Bay most likely formed part of Sundaland since the late Mesozoic. According to Bergman et al. (1996) the Bone Bay subsided in Neogene times as a result of post-orogenic collapse of accreted terranes. In areas near to the bay, late Mesozoic and Palaeogene sediments and volcanics occur; identical rocks have been described from southeast Kalimantan and Sumba (cf. Simandjuntak 1993). South of the South Arm the crust is still oceanic and forms the southwestern continuation of the Banda Sea. Westward in the Flores Sea there is a gradual transition to the Sunda continental basement which is overlain

by a thick cover of Tertiary sediments (Letouzey et al. 1990). According to Hamilton (1979) the approximately N-S trending North Makassar Basin between Kalimantan and Sulawesi opened in late Eocene times, ~ 40 Ma ago, by oceanic spreading (Figure 5). A large graben formed that became filled with undisturbed sediments. Recently, however, the Makassar Strait has been interpreted as a foreland basin bound on both sides by converging Neogene thrust belts (Bergman et al. 1996).

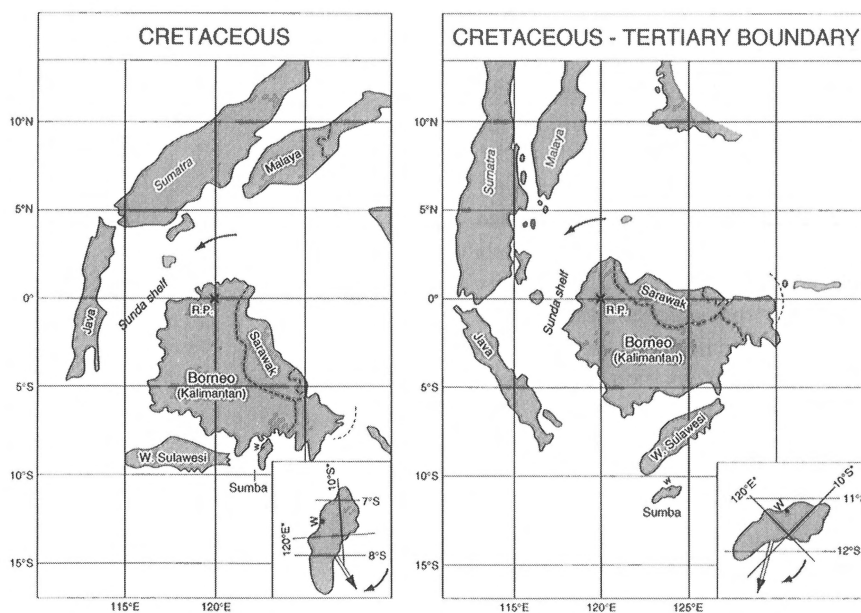


Figure 6. Palaeogeographic reconstructions of the Sundaland protuberance of the southeast Eurasian plate in the Cretaceous (left) and the Cretaceous–Tertiary transition (right), including the Malay peninsula, Sumatra, Java, Borneo and western Sulawesi according to palaeomagnetic data from Borneo and western Sulawesi. Because Borneo remained at equatorial latitude since the late Jurassic a pole of rotation has been chosen as indicated (R.P.). The positions of Malaya, Sumatra and Java relative to Borneo are not exactly known. The approximate (large  $\alpha_{95}$  values) latitudinal positions of the Sumba fragment derived from mean inclination data are given, both to scale and as insets. W: Waingapu, capital of Sumba. The southward directed arrow on Sumba indicates the mean vector of turbidite palaeocurrents in the Lasipu Fm (Von der Borch et al. 1983). \* Asterisks indicate present-day coordinates. Note that since the (late) Mesozoic Sumba rotated CW, in contrast to ongoing CCW rotations of Borneo and western Sulawesi.

### Analogy between south Sulawesi and Sumba

Simandjuntak (1993) discussed the geological analogy of the Bone Bay area of Sulawesi's South Arm with Sumba. The similarity of the late Cretaceous sediments and igneous rocks of both areas indicates nearby, original positions. The volcanic islands Sumbawa and Flores, presently located between Sulawesi and Sumba did not exist before the early Neogene. Stratigraphic studies revealed that the late Cretaceous Lasipu slope sediments of Sumba can be correlated with flysch deposits of the Balangbaru and Marada Fms in south Sulawesi. The latest Cretaceous Tanadaro intrusives on Sumba can be correlated lithologically with coeval rocks in Sulawesi's South Arm. According to Simandjuntak (1993) Sumba's detachment from Sulawesi should have taken place in the middle Miocene, because, in his opinion, corresponding Palaeogene carbonate platform deposits do occur in both regions. The up-to-1000-m-thick Tonasa limestones of middle Eocene to middle Miocene age in south Sulawesi (Wilson & Bosence 1996), however, are not identical to the coeval shallow-marine deposits on Sumba.

Geochemical analyses of the Lasipu and Balangbaru sediments indicate only slight variations in  $^{143}\text{Nd}/^{144}\text{Nd}$  (0.51244–0.51248 and 0.51246–0.51255 respectively), and  $^{206}\text{Pb}/^{204}\text{Pb}$  (18.74–18.77 and 18.67–18.74 respectively). The isotopic signatures do not correspond to the Australian or New-Guinean continental domains, but provide evidence for Sumba's affinity with Sundaland (Vroon et al. 1996).

### Discussion

Before the pre-Tertiary, Sundaland, most likely, formed a protuberance of southeast Asia that had undergone prolonged accretion. Palaeomagnetic data indicate that a large part of southeast Asia, including the South China block, the Indochina block, and Sibumasu (Siam–Burma–Malaya–Sumatra) rotated between 30 and 55° CW (clockwise) since the middle Mesozoic (Haile & Briden 1982, Van der Voo 1993). The palaeomagnetic data derived from post-early Jurassic rocks of eastern Sundaland including the eastern part of the Malayan peninsula, Borneo, and west Sulawesi

point to CCW (counter-clockwise) rotations (Haile et al. 1977, Haile 1978, Schmidtke et al. 1990). The most reliable and most complete set of data comes from Borneo, mainly from the western and central parts of the island. Since the Jurassic, Borneo rotated  $90^\circ$  CCW, whilst it remained at equatorial latitudes (Figure 6). Since late Cretaceous–Palaeogene time Borneo rotated CCW over a maximum of  $50^\circ$ . The Malayan peninsula showed a maximum CCW rotation of  $44^\circ$ . The quality of the palaeomagnetic data from west Sulawesi is poor. The west Sulawesi Langi volcanics with ages between 63 and 35 Ma (!) display a CCW rotation of  $45^\circ$  and a position near the equator (Sasajima et al. 1980).

New  $^{40}\text{Ar}/^{39}\text{Ar}$  laserprobe dating results show ages for the Massu volcanics in southeast Sumba, originally supposed to be Palaeocene–Eocene, of  $76.1 \pm 0.3$  and  $77.7 \pm 0.3$  Ma (Van Halen 1996). The result of an age determination on the Tanadaro granodiorite of  $64.9 \pm 0.2$  Ma confirms earlier reported results. An early Miocene age had been attributed to the Jawila andesites of west Sumba (Effendi & Apandi 1981). These andesites, however, have been dated now at  $37.3 \pm 0.2$  Ma, i. e. late Eocene (Berggren et al. 1995). The new age determinations permit to present a scenario for the drift and rotation of Sumba, different from that presented earlier (Wensink 1994).

Although the oldest rocks exposed on Sumba are Lasipu sediments with ages between 100 and 82 Ma, the oldest non-remagnetized ChRM directions were detected from the 77-Ma-old Massu volcanics. As outlined above, the palaeomagnetic data of the Lasipu sediments should be interpreted in terms of remagnetization upon intrusion of the Tanadaro granodiorite. These sediments revealed magnetization directions that are not significantly different from the ChRM directions obtained from the Tanadaro granodiorite. Palaeomagnetic results are also available from the Jawila andesites (Wensink & Van Bergen 1995), and from the late Miocene–early Pliocene Sumba Fm in east Sumba (Fortuin et al. 1997). The palaeomagnetic data from Sumba revealed large differences in declination indicating substantial rotations. The differences in inclination are small and, moreover, do not deviate much from the inclination of the present geomagnetic field. Most likely, Sumba remained at about the same latitude since the late Cretaceous. A reconstruction of east Sundaland including Borneo and west Sulawesi shows the equatorial location of the region in Cretaceous time (Figure 6). There is a strong geological affinity of south Sulawesi with Sumba. The reconstruction of Sumba relative to east Sundaland in the Cretaceous locates the

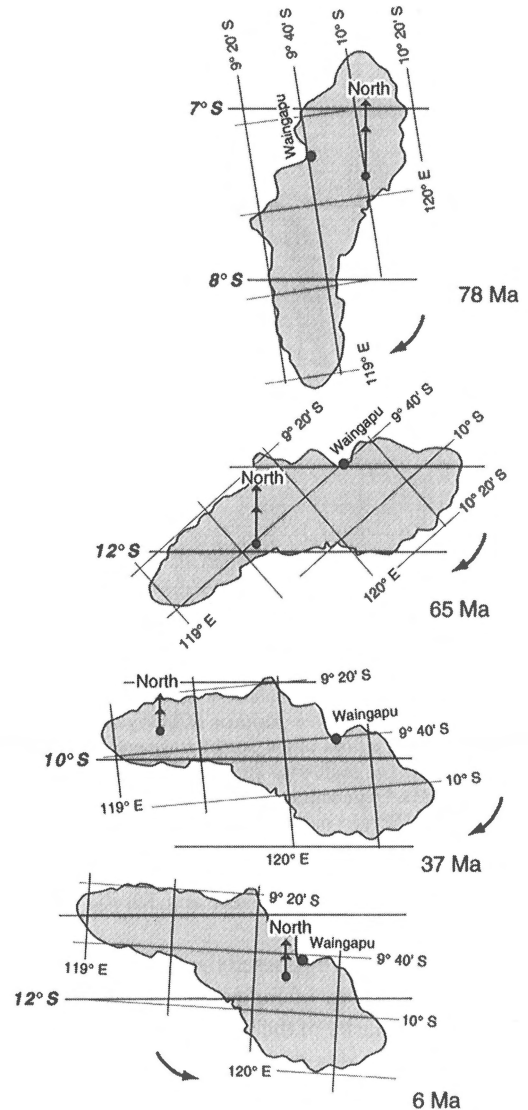


Figure 7. Maps showing the successive rotations of Sumba since 78 Ma ago. The positions are derived from palaeomagnetic results from radiometrically dated rock formations, except the position at 6 Ma, which is based on palaeontologically well-dated sediments. The positions at 78, 65, and 37 Ma are derived from palaeomagnetic studies of the Massu volcanics, Tanadaro granodiorite, and Jawila andesites, respectively. The positions are provided with the present grid of the island as well as with the palaeolatitude and the palaeo-north direction (arrow).

fragment on the southern hemisphere. Although some of the palaeomagnetic data are less accurate (see  $\alpha_{95}$  values in Table 3), the rotation of Sumba through time can be given. The palaeomagnetic data from the Massu volcanics, the Lasipu sediments (remagnetized) and the Tanadaro granodiorite indicate a  $53^\circ$  CW rotation

of the Sumba microcontinent between 78 and 65 Ma ago (Figure 7). The palaeomagnetic data derived from the late Eocene Jawila volcanics point to a further CW rotation of  $39^\circ$  between 65 and 37 Ma. The Sumba fragment rotated subsequently  $9^\circ$  CW between the late Eocene and late Miocene, and approximately  $4^\circ$  CCW since the late Miocene–early Pliocene (Fortuin et al. 1997).

## Conclusions

In southeast Asia three main areas with different rotations can be distinguished, a western area with CW, a central part with CCW, and an eastern area with CW rotations.

Large areas in western Sundaland, such as the South China block, the Indochina block, and the Sibumasu block underwent CW rotations over  $30$  to  $55^\circ$  since the early Cretaceous (Van der Voo 1993). The collision of the Indian subcontinent with the Eurasian plate, initiated in the latest Cretaceous, is probably responsible for these CW rotations. In Indochina old lineaments became re-activated, e.g. the Three Pagodes Fault and the Red River Fault (Tapponnier et al. 1986).

In eastern Sundaland CW rotations occurred with amounts of  $90$  and  $45^\circ$  for Borneo since the late Jurassic (Schmidtke et al. 1990) and the early Tertiary, respectively, and of  $45^\circ$  for west Sulawesi since the early Tertiary. The complicated structural evolution of the South China Sea, located between western and eastern Sundaland, with extension tectonics in successive phases in combination with NW–SE to N–S trending right-lateral transform faulting may have been responsible for the distinct rotations of these main units at both sides (Lee & Lawver 1994, 1995). Peninsular Malaysia was perhaps a separate unit that rotated  $45^\circ$  CCW since the Cretaceous (Haile et al. 1983).

Geological and geophysical arguments favour a position of the Sumba fragment close to south Sulawesi. Palaeomagnetic data indicate that Sumba underwent CW rotations since 78 Ma ago. We conclude that the continental fragment of Sumba became detached from east Sundaland in the late Cretaceous, and that it subsequently underwent CW rotations independently of Sundaland. The latitudinal movements of the fragment are very small; since the late Cretaceous it has occupied approximately its present position. Possibly Sumba's displacement took place along the NNW–SSE trending transform fault, a split-off from the Walanae Fault (Figure 5), situated in the eastern part of south

Sulawesi (Simandjuntak 1993). The mechanism which caused the large CW rotation of Sumba between late Cretaceous and late Eocene is unknown. The N–S displacements of east Sundaland including Borneo and west Sulawesi, and also including Sumba, are small. Since the late Jurassic hardly any change took place in their equatorial positions.

Just like in Sumba, CW rotations have been noted in eastern Sulawesi and further to the east. An interesting palaeomagnetic study on the late Cretaceous–Palaeogene Balantak ophiolites of Sulawesi's East Arm suggested a large,  $60^\circ$  CW rotation and a significant northward shift of the ophiolitic mass from an original position at lat.  $20^\circ$  S (Mubroto et al. 1994). In the Philippine Sea plate CW rotations up to  $80^\circ$ , with a northward shift between 1100 and 1500 km, occurred since the Oligocene (Koyama et al. 1992, Hall 1995).

The late Mesozoic outline of Sundaland to the east and southeast is obscured because of collisions with various structural units. Metamorphic rocks, locally affected by high-pressure metamorphism, developed in an east-dipping Palaeogene subduction zone, are overlain by the westwards obducted east Sulawesi ophiolite. In the Neogene, the Banggai-Sula and Buton microcontinents, separated from Australia, possibly from the region of central New Guinea, were carried westward and reached Sulawesi in the Miocene.

## Acknowledgements

This work was supported by the Netherland's Council for Sea Research (SOZ) in the Hague. It was conducted under the programme of the Dutch national research school, the Vening Meinesz Research School of Geodynamics. The logistic support by the Marine Geological Institute (MGI) under director I. Usna, Bandung, and the Research and Development Centre for Geotechnology (LIPI) under director S. Suparka, Bandung, is gratefully acknowledged. Thanks are due to Wadjoe, Suharno, Saban and H. Berghuis for their assistance in the field and to the staff of the Palaeomagnetic Laboratory of Utrecht University for their interest in this study. Chris Klootwijk and Herbert Haubold are thanked for their critical and useful comments.

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