

## Paleomagnetism of the Nakfunu Formation of Early Cretaceous age, Western Timor, Indonesia



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Received 3 October 1986; accepted in revised form 8 March 1987

*Key words:* Timor, Banda Arc, Paleomagnetism, Early Cretaceous

### Abstract

A paleomagnetic study has been carried out on deep sea sediments of the Nakfunu Formation of Early Cretaceous age. The sediments have an allochthonous position in the south-central part of Western Timor, Eastern Indonesia. To determine the characteristic remanence samples were partially progressive demagnetized by applying alternating magnetic fields and by heating. The following results were obtained:  $I = 34.7^\circ$ ,  $\alpha = 5.7^\circ$ , which implies a paleolatitude of  $19.1^\circ$ , derived from the mean of 11 sites; and  $I = 37.8^\circ$ ,  $\alpha = 8.3^\circ$  implying a paleolatitude of  $21.2^\circ$ , derived from a selection of the mean of 6 sites. Therefore, the original site of deposition of the Nakfunu sediments must have been  $10^\circ$  south of its present position on the island of Timor. The sediments have moved about 1200 km in a northerly direction since deposition in an oceanic environment, north of the former rim of the Australian continental margin. The remanence carriers in the sediments are both magnetite and hematite.

## Introduction

The Indonesian Archipelago is bordered in the south-west and the east by the Sunda and Banda Arc Systems, respectively. The Sunda Arc is a classic example of active subduction, with a northward underthrusting of the Indian Ocean plate beneath the Sunda plate. It consists of a nonvolcanic outer arc made up of mélanges (the accretionary wedge) and a volcanic inner arc with extrusives of intermediate composition (Hamilton, 1979). The System continues east of 120° as the Banda Arc, which has developed differently, because here the Australian plate collides with the Arc System (Fig. 1).

The island of Timor with its complicated structural evolution plays an important role in the Banda Arc System. The island forms part of the non-volcanic outer arc of the System, but Timor is not built up exclusively of an accretionary wedge of sediments scraped off from a subducting crust. The island is completely underlain by a continental crust; Timor can be considered to be a microcontinent with a very intricate structural history.

In Jurassic time rifting took place along the north-eastern rim of Gondwana resulting in the separation of a continental mass which later broke up into several smaller parts (Pigram & Panggabean, 1984). It is possible that in Late Mesozoic time one of these parts – the present island of Timor – drifted towards the Asian continent to subsequently move back towards the south during the Tertiary (Barber, 1981).

A number of models of the structural evolution of Timor have been presented: (1) the 'imbricate model', collision with an island arc (Fitch, 1972; Hamilton, 1979); (2) the 'overthrust model', collision with a detached margin of Asia (Audley-Charles et al., 1979); and (3) the 'upthrust model', uplift of the continental margin on reaching the zone of subduction without collision (Chamalaun & Grady, 1978). A feature common to all of these models is that the island of Timor is underlain by or built up of continental crust with a slab of oceanic crust descending northwards at the frontal, i.e. the northern side of the island, below the Strait of Wetar. In some models this slab is detached.

In the Timor area earlier than 3 Ma ago – and

possibly as long as 53 Ma when Australia broke away from Antarctica – oceanic crust that was situated north of the Australian continent subducted. About 3 Ma ago the continental margin of Australia approached both the subduction zone and the continental fragment of Timor north of it. Continuing plate motion has led to thickening and uplift of the deformation wedge of continental margin sediments and of the crust associated with the pre-collision outer arc ridge, viz. the island of Timor (Johnston & Bowin, 1981). The Timor trench, south of the island, is not a classic subduction trench, because there is no active thrust-boundary separating two lithosphere plates.

In Timor several tectonic units can be distinguished (Barber, 1981). In the southern part of the island one comes across the Kolbano Unit, which consists of bathyal sediments with radiolarites, calcilutites and cherts. The area of deposition of these deep-sea sediments of Cretaceous and Tertiary age was located in an oceanic environment, most probably north of the former front of the Australian continental margin. During the northward movement of Australia these sediments were scraped off and subsequently were added to the accretionary prism. The sediments of the Kolbano Unit show fairly strong tectonism (Johnston, 1981). In southern Timor the bathyal sediments of the Kolbano Unit now cover deformed sediments originating from the Australian continental margin.

The Nakfunu Formation, with sediments of Early Cretaceous age, belongs to the Kolbano Unit. These red-coloured, bathyal sediments have a lithology which is usually suitable for paleomagnetic analysis. In order to determine the location of the original deposition area, the natural remanent magnetization (NRM) of the sediments has been studied, in particular the inclination values, because they are a measure for the latitude where the rock received its magnetization.

## The Nakfunu Formation

Exposures of the sediments of the Nakfunu Formation are restricted to an area between Nikimiki and

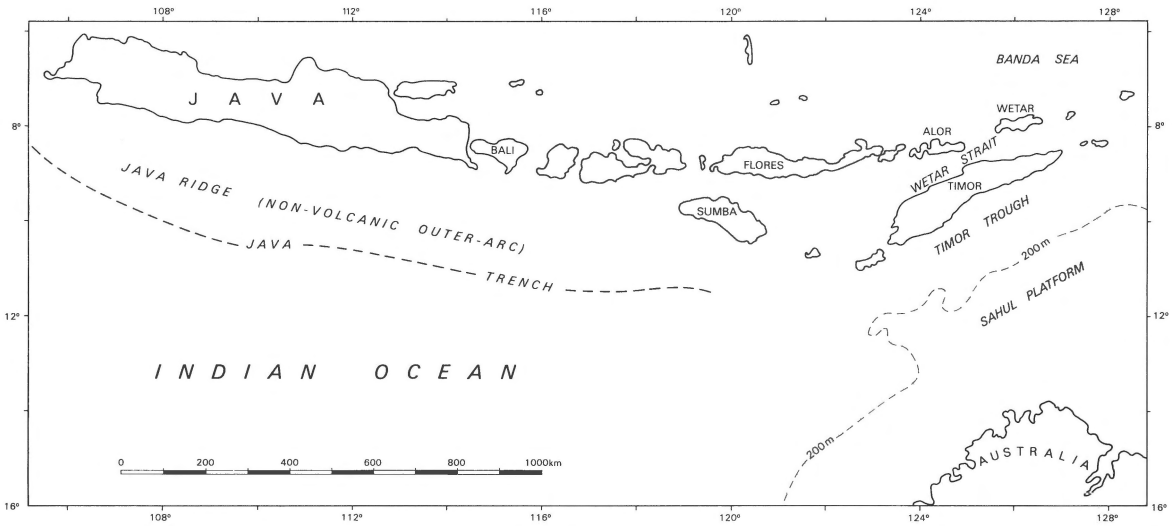


Fig. 1. Map of the eastern part of the Sunda Arc and the western part of the Banda Arc from Flores onwards, with the position of the island of Timor near the Australian continental margin.

Kolbano in the south-central part of Western Timor. The NE-SW striking zone of outcrop has a length of about 30 km and a maximum width of about 5 km; the centre of the zone is located at a latitude of 124.2° East and a longitude of 9.9° South.

The Formation is composed of both reddish, slightly silicified calcilitites in beds of about 25 cm thickness, and pinkish laminated silts with an often clearly visible graded bedding. These sediments alternate with beds of shale or silty marl; intercalations of chert levels do occur. Microfossils point to an Early Cretaceous, possibly Albian age (Rosidi et al., 1979).

The sediments are strongly folded, and broken into innumerable tectonic units. More competent blocks are floating amidst incompetent shales and marls. The Formation resembles the Bobonaro Olistostrome, which covers extensive areas on the island of Timor. The Bobonaro Scaly Clay (Audley-Charles, 1968) or Bobonaro Complex (Barber, 1981) consists of variegated, scaly clays which form the matrix of exotic blocks of various sizes. The clays contain foraminifera of Mesozoic to Pliocene age; the embedded blocks are derived from a great number of formations exposed in Timor. Unlike the Bobonaro Complex, the Nak-

funu Formation only contains intraformational rock fragments. According to Rosidi et al. (1979) the Nakfunu Formation has a thickness of about 600 m. It is correlatable with the Waibua Formation in Eastern Timor (Audley-Charles, 1968).

### Paleomagnetic sampling

Oriented samples were taken from the excellent exposures of the Nakfunu Formation along the banks of the Noil (river) Tuke near the village of Beoti. In the opinion of T.R. Charlton (pers. comm.), who carried out a detailed geological survey in this area, the sampling sites are in sediments which are not tectonically overturned.

In the field we used a portable drill provided with a coring tube of 25 mm inner diameter. However, since the silicified calcilitites were too hard for drilling, hand samples were collected. From 11 sites a number of 43 oriented cores and a number of 27 oriented hand samples were obtained (Fig. 2).

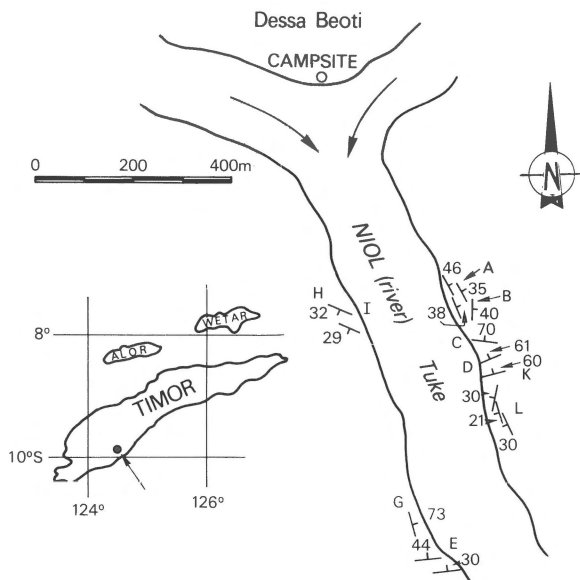


Fig. 2. Map of Timor showing the location of the outcrops of the sediments of the Nakfunu Formation of Early Cretaceous age (arrow). Detailed map shows the sampling sites TCN (A–L) for paleomagnetic research, the attitude of the beds and the amounts of dip.

## Paleomagnetic procedures

### *Detection of the Characteristic Remanent Magnetization*

In the laboratory we drilled oriented cores from the hand samples. From some of the calcilutites we were unable to obtain any core, because of the brittle character of the rock, e.g. at site TCNB. All cores were cut into specimens of 22 mm length. To determine the characteristic component of the natural remanent magnetization (ChRM) samples were partially progressively demagnetized, applying both alternating magnetic fields (AF method) and heating (Th). Thirty-one specimens were treated with AF in 11 successive steps up to 100 mT (1000 Oersted) peak strength. We heated 54 specimens progressively with a minimum of 7 and a maximum of 14 successive steps up to a maximum temperature of 650°. Finally, 7 specimens were treated first with AF and were heated subsequently, because AF treatment in fields of 100 mT peak strength was not sufficient to determine the ChRM

component. To detect the direction of the ChRM of a specimen its demagnetization curves were plotted in orthogonal projection (Zijderveld, 1967).

In general, the total Natural Remanent Magnetization (NRM) consists of three individual components: (1) a viscous, laboratory induced component which can be removed after treatment with AF in fields between 2.5 mT and 5.0 mT, or after heating at a temperature of 100° C; (2) a secondary component, removed after 25 mT or after heating to 250° C to 300° C; and (3) a characteristic component which usually cannot be removed with AF, but disappears after heating at temperatures in the range between 570° C and 650° C. Examples are given in Fig. 3. Progressive demagnetization with alternating fields only is shown in specimen TCNA 3; after application of a field of 25 mT peak strength the secondary components of magnetization were eliminated. An enlarged orthogonal projection of the endpoints of the magnetization vectors of specimen TCNA 3 from 25 mT onwards shows slight irregularities due to measuring errors. Specimen TCNA 7 and TCNF 2 were treated with progressive heating; after heating at 250° C or 300° C both the viscous and secondary components of magnetization were removed. Specimen TCNA 7 then showed a considerable change in its direction of magnetization. Examples of progressive AF treatment and subsequent heating applied to the same specimens are seen in the projections of specimens TCND 2 and TCNE 3; here, subsequent heating up to about 350° C was necessary to eliminate the secondary component of magnetization.

### *Magnetic properties of the Nakfunu sediments*

The initial NRM intensities of the specimens of the Nakfunu Formation can be divided into two groups: specimens from sites TCNA, –B, –C, –H, –I, and –K with fairly high initial intensities, mainly between 40 and 120 mA/m, and specimens from sites TCND, –E, –F, –G, and –L with considerably lower initial intensities, between 2 and 12 mA/m (Fig. 4). There is no relation between the initial NRM intensities and the quality of the ChRM data. Specimens from sites with both high

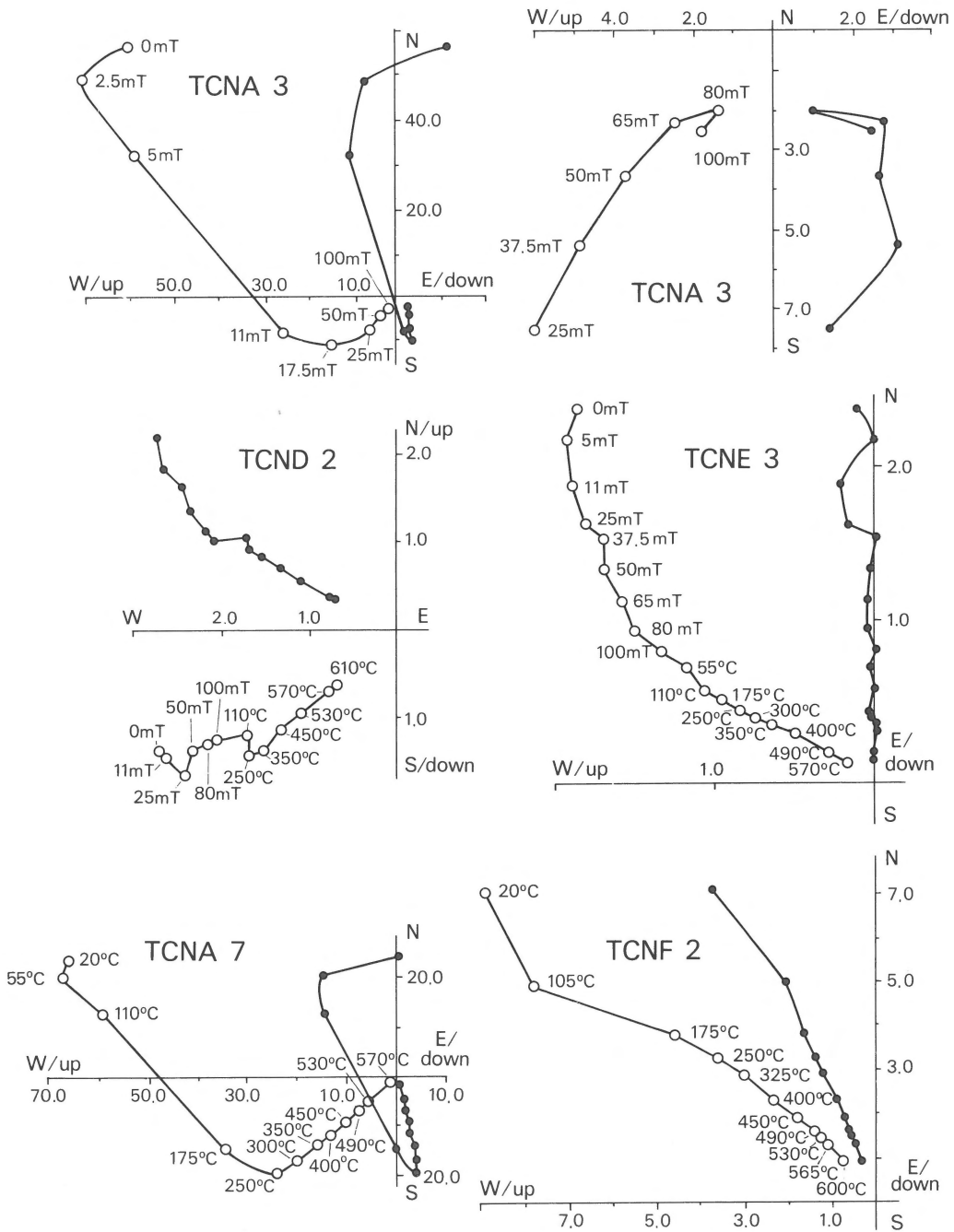


Fig. 3. Diagrams showing the progressive demagnetization of specimens of the Nakfunu Formation, with alternating magnetic fields (AF) of TCNA 3, with AF and subsequent heating of TCND 2 and TCNE 3, and with heating only of TCNA 7 and TCNF 2. The plotted points represent successive positions in orthogonal projection of the end of the resultant NRM vector. Solid circles denote the projections on a horizontal plane, and open circles those on a north-south or east-west vertical plane. Field peak strengths are given in mT (1 mT = 10 Oerstedt), and temperatures are given in degrees centigrade. The numbers on either axis represent the intensities in  $10^{-3}$  A/m ( $10^{-6}$  emu/cc). Note the enlarged diagram of specimen TCNA 3 from 25 mT onwards.

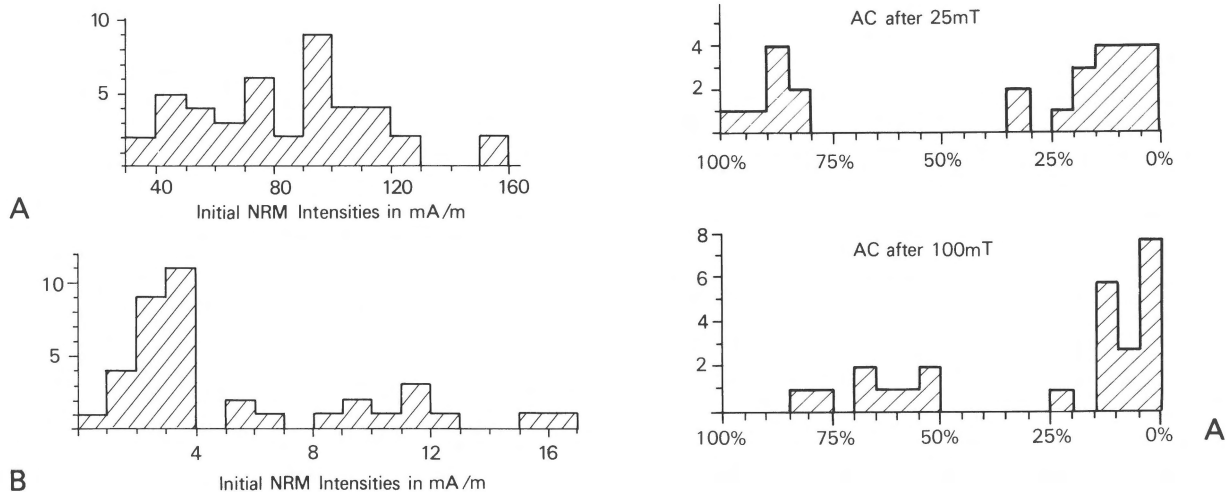


Fig. 4. Histograms with the initial NRM intensities. A) the specimens from sites TCNA, -B, -C, -H, -I, and -K with fairly high initial values; B) the specimens from sites TCND, -E, -F, -G, and -L with substantially lower initial NRM intensities.

and rather low initial intensities can thus supply paleomagnetic data of good quality. Neither the initial NRM intensities nor the reliability of the final paleomagnetic data are dependent on the rock type, silicified calcilutite or laminated silt.

A fairly large number of specimens show a rapid decay in remanence intensity during progressive demagnetization procedures. Some specimens lost up to about 90% of their initial NRM intensity after partial progressive demagnetization by AF treatment in fields of 25 mT peak strength, or by heating up to 250°C (Fig. 5). In these specimens it therefore becomes difficult to isolate the characteristic component of magnetization. However, almost every specimen that exhibited a rather slow decrease in remanence intensity during progressive demagnetization revealed a characteristic NRM component. Usually, these specimens still preserve a substantial part of the remanence intensity after AF treatment at 100 mT peak strength or after heating at 525°C (Fig. 5).

A complete, progressive demagnetization procedure leads to both the magnitudes and the directions of the individual components of remanence as can be judged from the orthogonal projection. We can use these orthogonal projections also for the

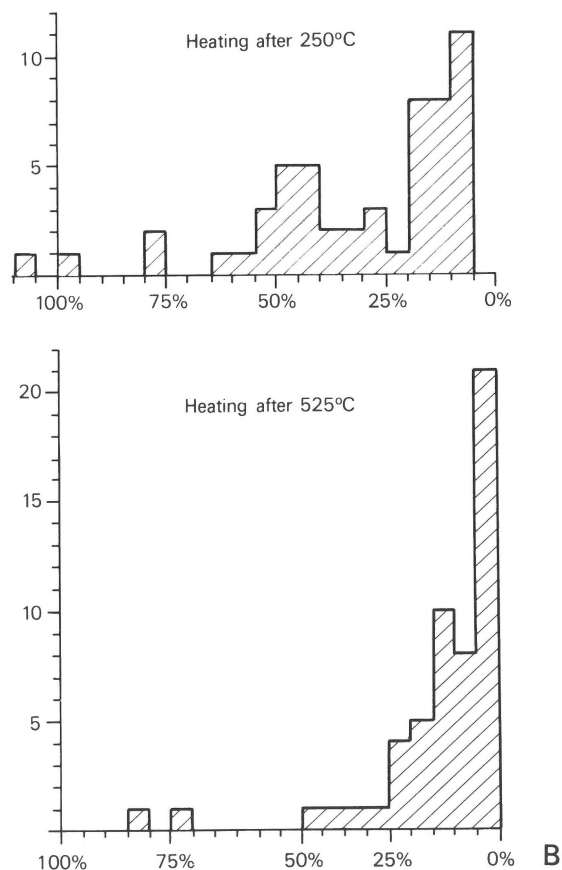


Fig. 5. Histograms showing the percentage of remanence intensity left after progressive demagnetization. A) 26 specimens treated with alternating fields after 25 mT and 100 mT, respectively; B) 54 specimens after heating to temperatures of 250°C and 525°C, respectively.

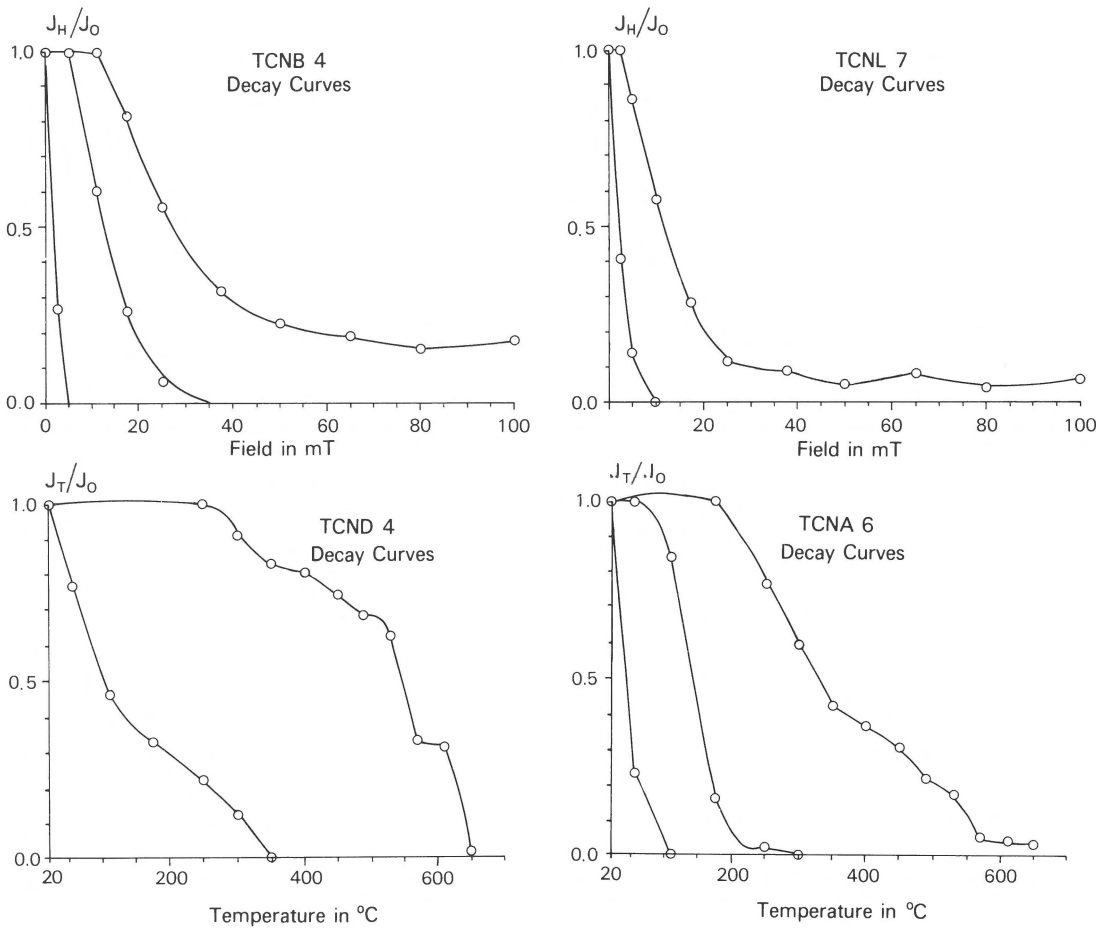


Fig. 6. Normalized decay curves of the individual components of the total NRM intensity. Specimens TCNB 4 and TCNL 7 have been progressively demagnetized with alternating magnetic fields. Note the rapid decay of the characteristic component of specimen TCNL 7. Specimens TCNA 6 and TCND 4 have been progressively heated. Note that the curve of TCND 4 clearly shows the presence of both magnetite and hematite which have Curie temperatures of 578°C and 675°C, respectively. Specimens TCNA 6 and TCNB 4 reveal a viscous component of magnetization that can easily be removed by progressive demagnetization.

collection of data for the decay curves of remanence intensity during progressive demagnetization. The data for the decay curves of the remanence intensity presented in Figure 6 are derived from the orthogonal projections of the respective specimens (Zijderveld, 1967). The curves of the specimens TCNB 4 (AF) and TCNA 6 (Th) reveal three components of remanence: (1) a very soft, viscous component that disappears after treatment at 5 mT peak strength or heating at 105°C; (2) a secondary component that is removed after treatment in AF of 37.5 mT peak strength or by heating at 300°C; and (3) a hard characteristic component. It turns out that both magnetite (Curie tempera-

ture is 578°C) and hematite or titanohematite (Néel temperature is 675°C) are carriers of remanence. In specimens TCNL 7 (AF) and TCND 4 (Th) viscous and secondary components of magnetization cannot be separated.

#### *Isothermal remanent magnetization and coercive force*

An additional study of the saturated isothermal remanent magnetization (SIRM) and the remanent coercive force ( $H_{cr}$ ) of the specimens and the inspection of the acquisition curves of the isothermal

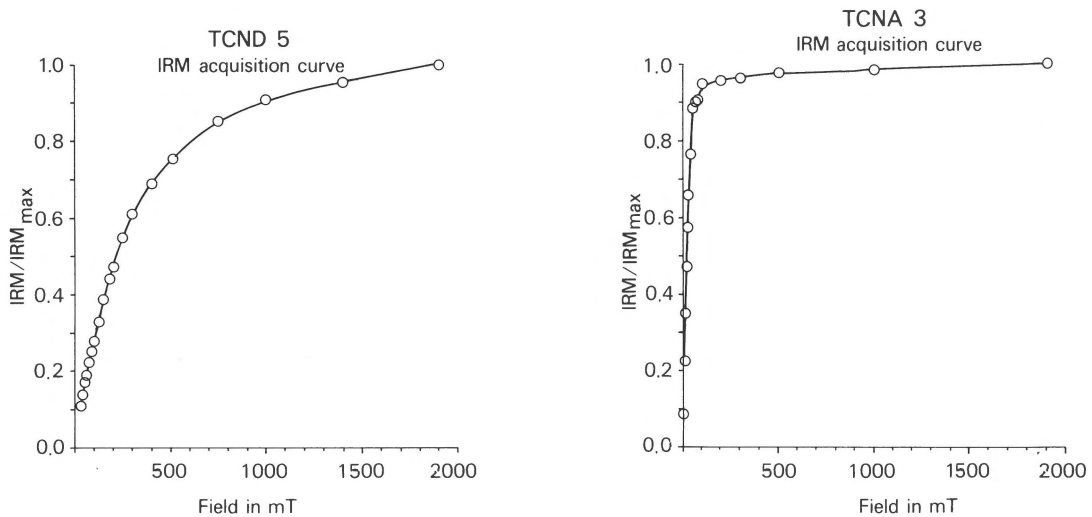


Fig. 7. Normalized acquisition curves of isothermal remanent magnetization.

remanent magnetization can provide information on the carriers of remanence (Dankers, 1981; Hartstra, 1982). We magnetized a number of specimens in 16 successive steps with increasing strength up to a maximum value of 2000 mT. In Fig. 7 the IRM acquisition curves of two specimens are shown: specimen TCNA 3 is nearly saturated after a magnetizing field of 100 mT, whereas specimen TCND 5 shows a gradual increase of IRM with increasing field strength. The rapid increase of IRM in specimen TCNA 3 points to magnetite as the main carrier of remanence; the gradual increase of IRM in specimen TCND 5 shows the presence of hematite as an important carrier of remanence.

From specimens TCNA 3 and TCND 5 we have determined both the maximum isothermal remanent magnetization ( $IRM_{max}$ ) and the remanent coercive force ( $H_{cr}$ ) which is the strength of the opposite field that is required to reduce the  $IRM_{max}$  value to zero. Specimen TCNA 3 has a relatively high  $IRM_{max}$  value of 12 A/m and an  $H_{cr}$  of 18.6 mT in contrast to specimen TCND 4 that has a relatively low  $IRM_{max}$  value of 0.8 A/m and a high coercive force of 226 mT. The  $IRM_{max}$  values are not conclusive, because they are dependent on the concentration and the properties of the magnetic minerals. However, the  $H_{cr}$  data show that the main carriers of remanence of TCNA 3 and TCND

4 are magnetite and hematite, respectively. In the orthogonal projections of another specimen of site TCNA (Fig. 3) one observes that after heating up to 570°C there is practically no remanence left (the Curie temperature of pure magnetite is 568°C). Figure 3 also shows the projection of a progressive treatment – AF and subsequent heating – of a specimen of site TCND. Here, about 25% of the initial remanence intensity remains after heating at 610°C (the Néel temperature of pure hematite is 675°C).

## Paleomagnetic results

### *Significance of the ChRM directions*

The characteristic remanence directions could be determined from the greater part of the specimens. From a number of sites the ChRM directions of individual specimens are plotted in equal area projections. In each projection the mean value of the particular site is given together with its 95% circle of confidence (Fig. 8). It can be seen from these plots that even after bedding tilt correction the declinations of the ChRM directions of the respective sites have an irregular distribution. This is due to the complicated tectonic disturbance of the Nakfunu sediments. The within-site results are rather

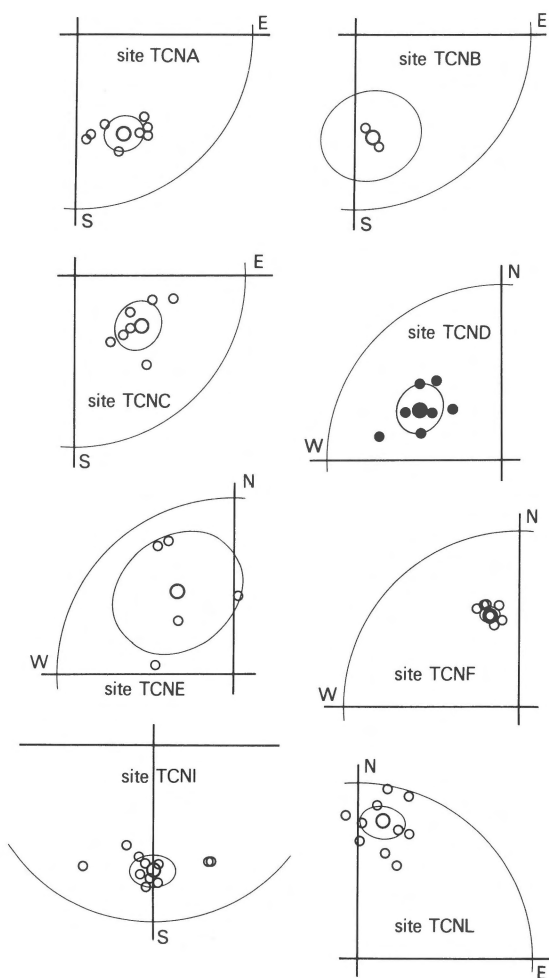


Fig. 8. Equal area projections showing the characteristic remanence directions of the specimens of a number of sites of the Nakfunu Formation; each projection gives the data, their mean direction and the 95% circle of confidence. Open and closed symbols denote upward-pointing and downward-pointing directions, respectively.

good, except for site TCNE, which shows a considerable scatter in the remanence directions. Apart from the sites TCND and TCNH, the specimens of which have downward-pointing directions, the specimens of the remaining sites have upward-pointing characteristic directions of magnetization (see also Table 1). In Table 1 we give a summary of the paleomagnetic data. We see that site TCNB is represented by two specimens only; the brittle character of the rock hampered the drilling. No characteristic remanence could be detected from

the specimens of site TCNK. Site TCNH shows two clusters of ChRM directions. There is no obvious explanation for this scatter. It is possible that for site TCNH we did not use the correct bedding tilt data.

Because of the complicated tectonics, in the final analysis we have made use of the inclination data of the ChRM directions only. The mean value of the inclination is calculated for each individual site; therefore a fictive, but fixed value for the declination of the specimens of a particular site has been assumed. For the calculation of the overall mean inclination all sites have been given an identical, fictive value for the declination. In Table 2 we have listed the mean value of the inclination for all sites as well as the value derived from a selection of best results. In Table 2 we have also listed the values of the paleolatitude as calculated from  $\text{tg } \lambda = 1/2 \text{ tg } I$ , where  $\lambda$  and  $I$  are the paleolatitude and inclination, respectively.

From this study we can conclude that the sediments of the Nakfunu Formation were deposited at a latitude of about  $20^\circ$ , most probably in the southern hemisphere. This implies that the sediments, which presently crop out at about  $10^\circ$  S in south-central Timor, have shifted approximately 1200 km ( $\pm 600$  km) to the north since their deposition in Early Cretaceous times.

#### *The magnetic polarities of the Nakfunu sediments*

We shall discuss the magnetic polarities of the Nakfunu Formation, because of the large scatter of the characteristic NRM declinations between individual sites. On the magnetic southern hemisphere downward-pointing directions – positive inclinations – should be directed towards the magnetic south pole corresponding to a period of reversed polarity. The geological arguments are in favour of an area of deposition of the Nakfunu sediments on the southern hemisphere. The majority of the Nakfunu sites have revealed upward-pointing directions – negative inclinations – implying normal polarities on the magnetic southern hemisphere. Nevertheless, at some sites positive inclinations were found. In the Nakfunu sediments there is no

connection between the magnetic polarities of the sites and the declinations of the ChRM directions. This is due to the complicated tectonic history of the sediments. Because the Nakfunu sediments reveal both normal and reversed polarities, it is likely that the deposits are older than 120 Ma, and date back to before the beginning of the Mercanton Normal Polarity Interval, a period that lasted until 82 Ma.

## Conclusions

A paleomagnetic analysis of the Nakfunu Formation of Early Cretaceous age from south-central Timor indicates that the sediments were deposited at a latitude of about 20°, most likely in the southern hemisphere, i.e. about 1200 km south of the present location. Deposition at a latitude of 20° S agrees with the paleogeographic configuration in

the southern hemisphere at that time. During the Early Cretaceous the northern rim of Australia was positioned at a latitude of about 30° S (Smith et al., 1981). Due to the intricate deformation of the sequence, the declination data of the characteristic NRM directions cannot be used for tectonic interpretations.

The study of the magnetic properties of the sediments makes a valuable contribution to the detection of the carriers of remanence. Saturated isothermal remanent magnetization and remanence coercive force studies, together with the inspection of demagnetization diagrams reveal that in site TCNA magnetite is probably the main carrier of remanence while in site TCND magnetite but also hematite is an important carrier of remanence. The sediments of the sites TCNA and TCND are laminated silts and silicified calcilutites, respectively. In summary, the greater part of the laminated silts have magnetite as the carrier of remanence; the

Table 1. Paleomagnetic data from the Nakfunu Formation of Western Timor

Site	Rock type	N	E	AF	Th	D	I	k	$\alpha_{95}$
TCNA	laminated siltstone	8	0	4	4	154.8	-38.0	42	8.6
TCNB	brittle silicified calcilutite	2	0	1	1	170.8	-38.9	-	-
TCNC	calcilutite	7	0	0	7	126.6	-50.5	32	10.8
TCND	silicified calcilutite	7	2	4	8')	302.7	43.7	31	11.0
TCNE	silicified calcilutite	5	1	4	6')	324.9	-40.7	8	29.5
TCNF	siltstone	7	1	0	8	341.4	-42.7	228	4.0
TCNG	laminated siltstone	2	0	0	2	346.6	-28.1	-	-
TCNH (1)	silicified calcilutite	3	3	5	1	348.9	16.3	141	10.4
TCNH (2)	id.	3	0	0	3	108.3	30.3	16	31.8
TCNHI	silicified calcilutite	11	0	3	8	181.1	-27.5	28	8.8
TCNK	silicified calcilutite	0	6	0	6	-	-	-	-
TCNL	laminated siltstone	11	4	6	9	10.2	-24.9	29	8.7

N and E are the numbers of specimens included in, and excluded from the final analysis; AF and Th are treatments with alternating magnetic fields and heating, respectively; ') means that a few specimens are included which were treated initially with AF up to 100 mT peak strength; D and I are the declination and inclination in degree of the characteristic NRM direction after bedding tilt correction; k is the precision parameter;  $\alpha_{95}$  is the semi-angle of the cone of confidence, in degrees (Fischer, 1953).

Table 2. Inclination and paleolatitude data of the Nakfunu Formation of Western Timor

Site	N	D	I	$\lambda$	k	$\alpha_{95}$
All	11	fixed	34.7	19.1	65	5.7
Selection')	6	fixed	37.8	21.2	65	8.3

$\lambda$  is the paleolatitude in degrees; ') the selected sites are TCNA, -C, -D, -F, -I, and -L.

silicified calcilutites in addition have hematite as an important remanence carrier.

### Acknowledgments

This research has been carried out as a part of the Snellius II Expedition, organized by the Netherlands Council of Oceanic Research (NRZ) and the Indonesian Institute of Science (LIPI). The authors are grateful to the staff of the Paleomagnetic Laboratory of the Utrecht State University for their interest in this study. Dr. C.G. Langereis kindly read the manuscript. Thanks are due to two anonymous reviewers.

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