Paleomagnetism of Borneo

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Abstract

The paleomagnetism of Borneo remains controversial, although the preponderance of results, both from the island itself and from the surrounding regions, suggest that counterclockwise (CCW) rotation has taken place. CCW rotations are seen in minor intrusions in Sarawak, Sabah and Kalimantan, which increase systematically with the age of the intrusion to a maximum value of $51.8 \pm 3.7^\circ$. The rotation can be no older than 25 Ma, which is the age of the intrusion showing the maximum rotation. The rotation appears to have neared completion by 10 Ma. Similar CCW rotations are seen in sites from Peninsular Malaysia through Borneo to Sulawesi, the Celebes Sea and Palawan in the Philippines, but the ages of these rotations are, for the most part, unknown. In Mesozoic rocks in Kalimantan and Sarawak, a stronger declination rotation of nearly $90^\circ$ CCW is recorded at seven sites, including sites which pass fold and reversal tests. This strong rotation is no older than youngest Cretaceous, and although seen over a wide region in Borneo, it is not seen in Peninsular Malaysia, nor in the Celebes Sea or Palawan, where only the weaker CCW rotation is seen. The widespread occurrence of this strong rotation in Western Borneo suggests that it is essentially a rigid plate, or microplate rotation, and not a series of local rotations caused by distributed shear in limited deformation zones. The rotation of Borneo appears to be a consequence of convergence between the Australian and Eurasian plates, which is accommodated by subduction along the northwest margin of Borneo. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Borneo lies in a central position in SE Asia and hence is a key element of tectonic models and paleogeographic reconstructions of the region. The rotational history of Borneo is controversial. Various possible rotations with respect to stable Eurasia have been suggested: No rotation (Lee and Lawver, 1993, 1995); CW rotation (Rangin et al., 1990); CCW rotation (Haile et al., 1977; Hall, 1996; Hamilton, 1979; Schmidtke et al., 1990); Mixed rotations (Briais et al., 1993).

To the north of Borneo lies the South China Sea marginal oceanic basin, to the east the Sulu and Celebes Seas marginal oceanic basins and the Makassar Straits and Sulawesi (Fig. 1). To the south and southwest are the islands of Java and Sumatra. In the west lie the Sunda Shelf and ultimately the Palaeozoic and Mesozoic continental crust of Peninsular Malaysia. The tectonostratigraphic framework of Borneo bears little resemblance to that of Peninsular Malaysia and previous workers have postulated a Mesozoic terrane boundary within the Sunda Shelf (Metcalfe, 1991). Thus, Borneo is surrounded to the north, east, and south by plate boundaries, marginal ocean basins and arc systems, which are presently active, or which have been active during the Tertiary, and to the west by an under-explored shelf region. It is therefore only by establishing the paleomagnetic history of Borneo that we can hope to determine its rotation history.
Fig. 1. A. Geologic map of SE Asia. B. Geologic map of Borneo.
2. Geological background for paleomagnetic studies

An overview of the geology of Borneo is given in Fig. 1B. Much of the southern half of the island consists of a Sundaland cratonic core of Triassic and Jurassic metamorphics and volcanics. To the north of this lie the arcuate tectonostratigraphic belts of the Cretaceous to Paleogene Rajang–Embaluh Groups and beyond it the turbidite sequences of the Oligocene to Miocene Crocker-Temburong Formations, usually considered to have an accretionary complex origin, although some parts of the Embaluh Group have recently been re-interpreted (Moss, 1998). For the most part, these units are not suitable for paleomagnetic work, but there are substantial sections in the Crocker Formation that are not structurally disturbed on a fine scale and have yielded useful paleomagnetic data. In South Kalimantan, the Meratus and Bobaris ophiolites and volcanic island arc rocks are exposed in the Meratus mountains (Fig. 1B), having been emplaced by the late Cretaceous (Sikumbang, 1986, 1990). Several phases of NNE–SSW oriented strike-slip deformation have affected these rocks during both the Cretaceous and Tertiary (Kusuma and Darin, 1989; Sikumbang, 1986, 1990). Following ophiolite emplacement, arc volcanism in SE Kalimantan then jumped outboard to the Sulawesi arc system. The first paleomagnetic studies in Borneo were in the Schwaner mountains granites and tonalites intruded into Palaeozoic metamorphic rocks of the Sundaland core. The Schwaner mountains granites have been radiometrically dated mainly by K–Ar techniques at 130–80 Ma (Amirruddin, 1989; Amirruddin and Trail, 1993; Keyser and Rustandi, 1993; Pieters and Sanyoto, 1993; Williams et al., 1988). They have been recognized geochemically as volcanic arc granites (Amirruddin, 1989; Amirruddin and Trail, 1993; Keyser and Rustandi, 1993; Pieters and Sanyoto, 1993; Williams et al., 1988). They have been recognized geochemically as volcanic arc granites (Amirruddin, 1989; Amirruddin and Trail, 1993; Keyser and Rustandi, 1993; Pieters and Sanyoto, 1993; Williams et al., 1988). They have been recognized geochemically as volcanic arc granites (Amirruddin, 1989; Amirruddin and Trail, 1993; Keyser and Rustandi, 1993; Pieters and Sanyoto, 1993; Williams et al., 1988). They have been recognized geochemically as volcanic arc granites (Amirruddin, 1989). The finely crystalline nature and limited contact aureoles of these intrusions imply a high level of emplacement. Andesitic breccias and agglomerates are typically associated with the plugs. Pieters et al. (1993) correlate the Sintang intrusives with the compositionally similar coeval Oligo-Miocene intrusives of Kirk (1968) in Sarawak. In Sabah in northern Borneo, the intrusive which forms Mount Kinabalu, the highest mountain in the region, is of a similar age to the younger Sintang intrusives. A satellite stock of the Kinabalu intrusive with a K/Ar age of 13.3 ± 5.3 Ma has been sampled paleomagnetically (Table 5).

Other smaller granitic plutons of Cretaceous age are located north of the Schwaner Mountains in Kalimantan (Fig. 1B). During the Middle Eocene the Melawi–Ketungau basins, the Upper Kutai Basin, and the Kutai Basin (Fig. 1B) formed along the southern margin of the Rajang–Embaluh belt. Paleomagnetic studies have been reported from these basins (Lumadyo et al., 1993) and others are underway. The Barito, Pasir, Asem-Asem, Muara and Tarakan sedimentary basins also were formed at this stage. This period has for some time been recognised as a time when basin opening and extension affected much of the region (Daly et al., 1990, 1991; Hall, 1996; Van der Weerd and Armin, 1992). Sedimentation continued throughout most of the Neogene in these basins, although sedimentation in the Melawi–Ketungau basins had ceased by the end of the Oligocene. The Melawi and Kutai basins have yielded paleomagnetic data and further work is underway.

At least three phases of igneous activity affected Borneo during the Tertiary. Three suites of volcanic and intrusive rocks are recognised within the Tertiary of Kalimantan: the Nyaan Volcanics, the Sintang Intrusive Suite and the Metulang Volcanics (or Plateau Basalts). The felsic Nyaan Volcanics in the Upper Kutai Basin (Fig. 1B) have K–Ar ages of 48–50 ± 1 Ma (Pieters et al., 1987, 1993). The basaltic to andesitic Muller Volcanics, north of the eastern extremity of the Schwaner Mountains (Fig. 1B), have a K/Ar radiometric age of 41 ± 0.4 Ma (Pieters et al., 1993). These represent an important paleomagnetic target for absolutely dated paleomagnetic directions from the Eocene.

The Sintang Intrusive Suite of Kalimantan and its equivalent in Sarawak have been sampled paleomagnetically (Haile, 1979; Moss et al., 1997; Schmidtke et al., 1990) and more work is underway. They are defined as Late Oligocene to Middle Miocene, although a wider range of K/Ar radiometric ages (41 to 8 Ma) has been obtained from rocks assigned to this suite (Heryanto et al., 1993; Pieters et al., 1993). The Sintang intrusives have a mafic to felsic composition and consist of diorites, microdiorites, dacites, microgranites and andesites. Intrusions of the Sintang Intrusive Suite are widely distributed as plugs and other hypabyssal intrusions throughout parts of west, central and east Kalimantan, often forming conical hills. The finely crystalline nature and limited contact aureoles of these intrusions imply a high level of emplacement. Andesitic breccias and agglomerates are typically associated with the plugs. Pieters et al. (1993) correlate the Sintang intrusives with the compositionally similar coeval Oligo-Miocene intrusives of Kirk (1968) in Sarawak. In Sabah in northern Borneo, the intrusive which forms Mount Kinabalu, the highest mountain in the region, is of a similar age to the younger Sintang intrusives. A satellite stock of the Kinabalu intrusive with a K/Ar age of 13.3 ± 5.3 Ma has been sampled paleomagnetically (Table 5).

Pliocene–Pleistocene volcanics of the Metulang Suite are common throughout the centre of Kalimantan and parts of Sarawak and have been termed the Metulang or Plateau Basalts. They have been studied paleomagnetically by Lumadyo et al. (1993). The Metulang Volcanics have K/Ar radiometric ages of between 2.4 and 1.7 Ma (Pieters et al., 1993). The basalts of the Nuit Volcanics in West Kalimantan, with a K/Ar radiometric age of 4.9 ± 0.1 Ma (Supriatna et al., 1993), belong to this suite.
3. Present tectonic models for Borneo

For much of the last decade the extrusion tectonic model (Peltzer and Tapponnier, 1988; Tapponnier et al., 1982, 1986) has dominated tectonic and paleogeographic discussions of East and Southeast Asia. This model predicts small CW rotations and southeastward extrusion of Southeast Asia as a consequence of the collision of India with Eurasia during the Eocene. Current paleogeographic and plate tectonic reconstructions for the region, therefore, show Borneo rotating clockwise as a portion of an extruding Sundaland block (Briais et al., 1993; Daly et al., 1990, 1991; Lee and Lawver, 1993, 1995; Rangin et al., 1990; Tapponnier et al., 1982, 1986). The extrusion hypothesis has been widely accepted, but the relationship of Borneo to the extruding Indochina block has rarely been questioned.

Prior to the extrusion tectonic hypothesis, Haile et al. (1977), Haile (1979) and Hamilton (1979) proposed plate wide CCW rotations in Borneo. Several subsequent models followed Hamilton and Haile in treating Borneo and eastern Peninsular Malaysia as a separate microplate dominated by CCW rotations (Haile et al., 1983; Holcombe, 1977; Richter, 1996; Schmitdke et al., 1990). Interestingly, small (10–20°) CCW rotations of Borneo have also been shown in reconstructions based dominantly upon the extrusion model (Briais et al., 1993). The difficulty, however, of understanding the substantial (45–90°) CCW rotations indicated by the paleomagnetic data have hampered attempts to merge the two contrasting hypotheses. Current tectonic reconstructions (Hall, 1996; Richter, 1996) incorporate a rigid body CCW rotation of all of Borneo, but recognize that this approach leads to difficulties in accommodating the rotation of Peninsular Malaysia and Borneo: the Thai and Malay basins appear to preclude rotations as late as 30 Ma, while the absence of structural evidence for a break between Peninsular Malaysia and Borneo make later rotation of Borneo alone difficult.

4. Paleomagnetic data from Borneo

As these results are discussed, it is worth remembering that (1) high sensitivity paleomagnetic measurements are by now relatively routine, so that very few rock types are too weakly magnetized to be measured, (2) paleomagnetism is not good at detecting small changes in latitude, i.e., 1000 km displacement requires very accurate studies, (3) paleomagnetism is good at detecting tectonic rotations, but it is often not clear whether the rotations took place in local shear zones or are plate wide, and (4) to interpret a paleomagnetically determined rotation, the age of magnetization, which is not necessarily simply the age of the rock, is critical. If the age is known, then the rotation must have taken place after that time.

In the tables and figures, the results are presented in uncorrected in situ coordinates if there is no tectonic correction, as is the case with most intrusives, or if the results fail a fold test. They are presented in tectonically corrected coordinates if the results pass a fold test or regional attitude test. A true fold test is distinguished from a regional attitude test because only in the former are the sites known to come from a single fold, whereas in the latter the timing of the acquisition of the observed structural attitude is not necessarily synchronous.

The paleomagnetic measurements were made in a variety of laboratories over a period of more than two decades so that they are by no means a data set of uniform quality. However, in all cases some indication of the response to AF and thermal demagnetization is given and reported here.

The statistics of the paleomagnetic data are described by the confidence interval $z_{0.5}$ and $k$, the estimate of Fisher’s precision parameter $\kappa$. The former is the cone about the mean direction defining the area within which there is a 95% probability of finding the true mean of the population sampled. The latter is a measure of the variance in direction obtained from the formula \( (N-1)/(N-R) \), where $N$ is the number of samples or sites and $R$ is the resultant vector obtained by adding all of the unit vectors. Clearly, if the $N$ unit vectors are perfectly aligned, $k$ is infinite; if they are random, it is zero. Values of $k$ less than 10 reflect large scatter and are generally regarded as too badly scattered to be useful. Values of $k$ in excess of 100 for samples at a site, or of sites in a collection, represent very tightly grouped distributions. Values much larger than this in sedimentary rocks suggest remagnetization and, in igneous rocks, indicate that dispersion due to secular variation is not being recorded.

In more recent studies, demagnetization results have been analysed using the principal component analysis technique introduced by Kirschvink (1980). With this technique the directions of lines of best fit along the demagnetization paths are estimated and assigned a measure of collinearity—the Maximum Angular
Deviation or MAD angle. Values of MAD angles of less than 5° are well defined lines, but with increases to larger than 10°, the line is poorly defined and larger than 20° the results are not useful.

In describing the paleomagnetic data from Borneo, we present results in terms of following regions: (1) Northwest Borneo, (2) West Kalimantan—Schwaner Mountains, (3) Central and East Kalimantan—Barito and Kutai Basins (4) South Kalimantan—Barito and Kutai Basins, and (5) Sabah (Fig. 2). For each region, we describe the results beginning with the youngest and working back in time. The results are summarized in Fig. 3, 4, 5, 6, 7, 8 and 9 and in Table 1, 2, 3, 4 and 5; the reader should refer to the original publications for more details.

5. Northwest Borneo

This area is predominantly in Sarawak, but includes some of West Kalimantan. It has been studied paleomagnetically in some detail (Schmidtke et al., 1990) and affords a coherent record which provides a framework against which records from elsewhere in the island can be compared. The area consists of the metamorphic Sundaland Craton upon which Mesozoic clastic and limestone sediments lie (Fig. 1). In the Cenozoic, the Melawi and Ketungau basins developed and a suite of shallow Oligocene-Miocene stocks were intruded; these are known as the Sintang intrusives in Kalimantan. Results are discussed in groups organized as follows: Oligocene-Miocene shallow intrusives, Silantek Formation, Cretaceous intrusives, Jurassic-Cretaceous: Bau Limestone, Pedawan and Kedadom Formations, and Triassic volcanics; the data are listed in Table 1 and shown in Fig. 3.

5.1. Oligocene–Miocene shallow intrusions

These intrusives are small enough and were intruded at shallow enough depths to have cooled relatively rapidly and are excellent paleomagnetic recorders giving in most cases a single stable direction of magnetization by either AF or thermal demagnetization (Schmidtke et al., 1990). The results, shown in Fig. 3a and Table 1, are either unrotated and oriented parallel to the present field or to the reversed field direction, or are rotated counterclockwise. As discussed in a later
section, there is a progression of the maximum rotation found in rocks of a particular age; however, there are also older intrusives which are not rotated.

5.2. Silantek Formation

The youngest sediments, apart from the recent alluvium, are the Plateau Sandstones in the Tertiary basins. Below this are the Late Cretaceous and Eocene Kayan Sandstone and its equivalent the Silantek Formation, a sequence of clastics including red beds. Results from the Silantek Formation are shown in Fig. 3b and Table 1; all are from red mudstones with the exception of one site, which was a grey fluvial mudstone. The most effective demagnetization method was thermal, which either isolated a single direction carried by both magnetite and hematite, or yielded two directions. In samples for which two directions were isolated, the direction blocked between 45°C and 63°C was similar to that isolated as a single direction in other samples, whereas the direction blocked between 150°C and 450°C was the less strongly rotated direction. The more strongly rotated direction is shown in Fig. 3b, as is one site at which directions parallel to the reversed present field direction were found. The bedding dips in the Silantek are weak, so that no convincing fold or regional attitude test is possible.

5.3. Cretaceous intrusives

Throughout Northwest Borneo there are scattered Cretaceous intrusives. In Sarawak, samples from these Cretaceous intrusions carried a weak and scattered magnetization and no useful paleomagnetic record was obtained from them. However, in Kalimantan about 20 km northwest of Sanggau, an intrusion and a dyke cutting the intrusion gave results with MAD angles between 2° and 15° after thermal demagnetization (Fuller, unpublished data, 1998); a K/Ar date of 93.2 ± 3.5 Ma was obtained for the dyke. The mean of 6 samples from the dyke was Dec. 280.8°, Inc., 7.2°, α95 10.9°, k 38.7 (Table 1, Fig. 3c).

5.4. Jura-Cretaceous: Bau Limestone, Pedawan and Kedadom formations

These formations overlap in age and grade laterally into each other, representing a period of basin development. The Kedadom is the nearshore equivalent of the Bau Limestone; both grade upward into the dominant basin-filling clastic Pedawan Formation. The basin was inverted and the Kayan Sandstone of Late Cretaceous–Early Eocene age was deposited unconformably upon it. The most extensively studied formation is the Bau Limestone from which 11 of 21 sites yielded interpretable paleomagnetic data. Thermal demagnetization was again the most effective treatment. Sometimes, a low blocked phase was demagnetized between 50° and 100°C and then the vector stabilized between 250° and 450°C, while in other samples there was no low blocking fraction. The resulting data fell into three groups, which were inti-
mately mixed spatially. Group 1 exhibited present field or reversed field directions. Group 2 consists of five sites in the Bau Limestone and two in the Kedadom formation, which show an average deflection of about 30° CCW; these results failed a fold test and are therefore secondary and post Late Cretaceous. Group 3 is represented by two sites on a syncline near Bunuk and passed a fold test; two sites in the Pedawan also passed a fold test. A third site yielded results that, after tectonic correction, were antipodal to the direction from the fold test sites. These five sites define a CCW rotation of some 90° and are illustrated in Fig. 3c and listed in Table 1.

From Kalimantan, a declination of 267.1° and inclination of 2.6° with χ₀₀ 13.4°, k 21 was reported from Jurassic sediments (Sunata and Wahyono, 1991), which were analysed both with AF and thermal demagnetization.

5.5. Triassic volcanics

In Sarawak, the Triassic Serian Volcanics are always found to be metamorphosed, or the field relations are sufficiently unclear that they are not useful for paleomagnetism. In contrast, in Kalimantan their equivalents are less deformed and have yielded paleomagnetic data (Sunata and Wahyono, 1991). Two results are from Suti Semarang and Gunung Bawan, which yielded almost 90° of CCW rotation after AF and thermal demagnetization (Fig. 3c, Table 1).

5.6. Summary of results from Northwest Borneo

The paleomagnetic record from the Northwest Borneo domain is relatively straightforward. Intrusions are increasingly CCW rotated with age, reaching a maximum of 51° in an intrusion dated by K/Ar to be 25.8 ± 1.9 Ma. The Late Cretaceous–Eocene Silantek Formation gives 41° of CCW rotation. The eight Mesozoic results which come from the Bau Limestone, the Kedadom and Pedawan Formations in Sarawak and from the Jura-Cretaceous and Triassic sites in Kalimantan, all indicate a strong rotation of about 90°.

5.7. Summary of results from Central and Eastern Kalimantan

The paleomagnetic record from Central and Eastern Kalimantan is relatively straightforward. Plateau basalts of Miocene–Pliocene age show no rotation; Oligocene–Miocene igneous rocks show mixed results; Eocene sediments show a weak rotation; Jurassic sediments show a strong rotation (Fig. 5).

5.8. Summary of results from South Kalimantan–Meratus Mountains

The paleomagnetic record from South Kalimantan–Meratus Mountains is relatively straightforward. Oligocene–Miocene igneous rocks show mixed results; Jurassic sediments show a strong rotation (Fig. 6).

5.9. Summary of results from Sabah

The paleomagnetic record from Sabah is relatively straightforward. Miocene miocrodiore suggests weak rotation; Jurassic sediments suggest weak rotation (Fig. 7).

References

Table 1: Results from Northwest Borneo

Table 2: Results from Central and Eastern Kalimantan

Table 3: Results from South Kalimantan–Meratus Mountains

Table 4: Results from Sabah

Table 5: Results from Sarawak
which took place sometime after 93 Ma, the age of the Cretaceous dyke. Among these results there are unro-
tated directions in the sediments and the intrusives. At least in the Bau Limestone and the Silantek
Formation, it is very likely that they are secondary magnetizations and do not constrain the rotations at
the time of formation of the rocks. In the intrusives, it is less clear that they are necessarily secondary direc-
tions and further work is being undertaken to test this suggestion.

6. West Kalimantan: Schwaner Mountains

The Schwaner Mountains were studied by Haile et al. (1977) in their pioneering paleomagnetic and geo-
chronological study. They obtained sixteen K/Ar ages, which ranged from 75 to 112 Ma, mainly from the
granitic plutonic rocks, and were able to get satisfac-
tory paleomagnetic results from 39 of 48 hand samples
collected from dykes, tuffs, lavas and intrusives. The
overall mean of the paleomagnetic results they

obtained was similar to those obtained earlier from Peninsular Malaysia and they concluded that the two regions have behaved as a unit since the main intrusive event at about 80–85 Ma.

We present the results in a slightly different manner. We divide them into three groups: unrotated, weakly rotated and strongly rotated. The strongly rotated group is defined as having rotations greater or equal to the smallest rotation seen in the strongly CCW rotated group from the Northwest Borneo domain. The latter two groups are shown in Fig. 4 and are listed in Table 2.

The difference in interpretation of these results between the original authors and ourselves turns on the question whether the two datasets are sampling the same population or two separate populations. Given the present data set, it is probably not wise to press the case too strongly. Rather the suggestion should be tested with a new collection using modern techniques. Nevertheless, there are directions comparable with the strongly and weakly rotated directions seen in the Northwest Borneo domain.

6.1. Summary of results from West Kalimantan

In the Schwaner Mountains results, we see a similar pattern of directions to that seen in the Northwest Borneo domain with unrotated, weakly and strongly rotated directions all represented. However, the results are based on a collection of only 48 hand samples, so that additional studies are needed to substantiate these results.

7. Central and Eastern Kalimantan

This region includes the Barito and Kutai basins, which were formed during the Middle Eocene in a period of widespread extension and basin formation. Paleomagnetic results have been reported by Lumadyo et al. (1993), Moss et al. (1997) and Sunata and Wahyono (1991).

7.1. Plio-Pleistocene

The study by Lumadyo et al. (1993) of Plio-Pleistocene sites in the Plateau flows from the Kelian, Magerang and Bigung localities in East Kalimantan reported that all sites carried a reverse polarity magnetisation indistinguishable from the reversed present field. The magnetic recorders are shown to be fine magnetite. No tectonic correction is applied (Fig. 5a, Table 3).

7.2. Oligo-Miocene

Lumadyo et al. (1993) reported unrotated declinations in seven Late Oligocene–Early Miocene igneous rock sites (Dec. 178.8°, Inc. –4.7°, χ95 13.4°, k 21). The behaviour of the magnetic recorders was good; magnetisation was interpreted as primary because of a positive fold test. The age of the folding is not known, but probably was Early to Middle Miocene and coincident with a series of structural inversions in the Kutai Basin where the study sites were located (Chambers and Daley, 1995; Cloke et al., 1999).

An unrotated result (Dec. 183.8°, Inc 4.6°, χ95 5.2°) was also reported by Sunata and Wahyono (1991) from 22 samples taken from two Oligo–Miocene basaltic sills which intrude the Late Eocene Mandai volcanics near Nanga Raun on the Mandai river. The reported paleomagnetic information on the magnetisations suggests that the remanence is simple and yields statistically consistent data. No fold test was reported.

A reversed weakly deflected result (Ali, unpublished data) comes from a diorite intrusion in the Long
Table 1
Paleomagnetic data from Northwest Borneo. References: 1 = Schmidke et al. (1990); 2 = Mike Fuller (unpublished data); 3 = Sunata and Wahyono (1991). See Fig. 3 for plots of data.

<table>
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<th>Shallow intrusions, Oligocene–Miocene</th>
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<th>Latitude</th>
<th>Longitude</th>
<th>Rock type</th>
<th>Age</th>
<th>N (sites)</th>
<th>n (samples)</th>
<th>Dec (°)</th>
<th>Inc (°)</th>
<th>var (°)</th>
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<td>Gunung Serapi</td>
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<td>110.25°E</td>
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<td>6</td>
<td>128.2</td>
<td>-0.2</td>
<td>3.7</td>
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<td></td>
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<td>Bukit Stabar</td>
<td>1.42°N</td>
<td>110.33°E</td>
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<td>Oligo–Mio</td>
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<td>6</td>
<td>352.0</td>
<td>4</td>
<td>4.4</td>
<td>136  1</td>
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<tr>
<td></td>
<td>Sarawak</td>
<td>Mr. Choo’s Garden, Kuching</td>
<td>1.39°N</td>
<td>110.31°E</td>
<td>?</td>
<td>Oligo–Mio</td>
<td>1</td>
<td>5</td>
<td>154</td>
<td>19</td>
<td>13.7</td>
<td>32   1</td>
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<td>Hua Sun Quarry</td>
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<td>7.4</td>
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<td>Semengo Quarry</td>
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<td>Oligo–Mio</td>
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<td>110.85°E</td>
<td>Red mdst.</td>
<td>Eocene</td>
<td>1</td>
<td>4</td>
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<td>-30.6</td>
<td>6.1</td>
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<td>Moderate rotation</td>
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<td>110.85°E</td>
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<td>1</td>
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<td>-27.0</td>
<td>11.8</td>
<td>33.4  1</td>
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<td>2 km e. Simunjam Jcn.</td>
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<td>1</td>
<td>7</td>
<td>321.3</td>
<td>15.1</td>
<td>7</td>
<td>76.2  1</td>
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<td></td>
<td>Sarawak</td>
<td>Batung Undup</td>
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<td>110.50°E</td>
<td>Fluvial mdst.</td>
<td>Eocene</td>
<td>1</td>
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<tr>
<td>Mesozoic results</td>
<td>No rotation</td>
<td>Kaltimantan</td>
<td>Dusun Bunut Quarry</td>
<td>0.30°N</td>
<td>110.3°E</td>
<td>Dyke</td>
<td>93.2 ± 3.5 m.y.</td>
<td>1</td>
<td>6</td>
<td>280.8</td>
<td>7.2</td>
<td>10.9</td>
<td>38.7  2</td>
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<td>Sarawak</td>
<td>Bau district</td>
<td>1.4°N</td>
<td>110.2°E</td>
<td>Bau Limestone</td>
<td>J-K</td>
<td>4</td>
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<td>Bau district</td>
<td>1.4°N</td>
<td>110.2°N</td>
<td>Bau Limestone</td>
<td>J-K</td>
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<td>Serian–Tebedu Rd. (Ked.)</td>
<td>1.13°N</td>
<td>110.44°E</td>
<td>Marly Limestone</td>
<td>J-K</td>
<td>3</td>
<td>21</td>
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<td>-2.1</td>
<td>22.7</td>
<td>2.9   1</td>
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<td>Bau Limestone, Pedawan and Kedadom Fms: Group 3—strong rotation</td>
<td>Sarawak</td>
<td>Batung fold, Penrissen area</td>
<td>1.4°N</td>
<td>110.2°E</td>
<td>Bau Limestone</td>
<td>J-K</td>
<td>2</td>
<td>17</td>
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<td>-8.6</td>
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<td>Sarawak</td>
<td>Bau-Lundu Rd. (Ped. fold)</td>
<td>1.5°N</td>
<td>109.9°E</td>
<td>Mudstone (Ped.)</td>
<td>J-K</td>
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<td>15</td>
<td>87.9</td>
<td>16.0</td>
<td>7.1</td>
<td>14.5  1</td>
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<tr>
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<td>Pedawan</td>
<td>1.18°N</td>
<td>110.28°E</td>
<td>Limestone lens</td>
<td>J-K</td>
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<td>8</td>
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<td>-15.9</td>
<td>13.3</td>
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<td>Tengwe</td>
<td>0.70°N</td>
<td>110.1°E</td>
<td>Black mudstone</td>
<td>Jurassic</td>
<td>11</td>
<td>40</td>
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<td>2.6</td>
<td>6.9 — 1.3</td>
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<td></td>
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<tr>
<td>Kalimantan</td>
<td>Suti Semarang</td>
<td>0.9°N</td>
<td>109.8°E</td>
<td>Blackshale</td>
<td>Triassic</td>
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<td>21</td>
<td>278.5</td>
<td>-20.8</td>
<td>11.8 — 3</td>
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<tr>
<td>Kalimantan</td>
<td>Gunung Bawan</td>
<td>1.2°N</td>
<td>109.6°E</td>
<td>Basalt &amp; shale</td>
<td>Triassic</td>
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<td>30</td>
<td>286.7</td>
<td>31.7</td>
<td>11.5 — 3</td>
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</table>

measured in the UCSB laboratory by C. Anderson. In London University SE Asia Research group and reliable data. These samples were collected by the Kutai Basin, two sites in minor intrusives yielded Ar ages of 23.6–21.3 Ma (Moss et al., 1998).

Along the Telen River on the northeastern edge of the Kutai Basin, two sites in minor intrusives yielded reliable data. These samples were collected by the London University SE Asia Research group and measured in the UCSB laboratory by C. Anderson. In a hornblende andesite, a soft overprint was completely removed by 150°C. The single direction blocked above this temperature gave a site mean in situ direction of Dec. 143.6°, Inc., 45.4° with an z\(_{95}\) of 11.6° and k 34. A biotite microgranite about 30 km upstream was also well behaved with a soft overprint removed by 15 mT, leaving a single component. With one outlier discarded, the in situ mean was Dec. 342.6° and Inc. 42.4° with z\(_{95}\) 9.0° and k 73 (Fig. 5b, Table 3).

7.3. Eocene

The University of London SE Asia Research Group members collected dark grey fine sandstones of Eocene–Oligocene age which were analysed at UCSB by C. Anderson. They showed multicomponent beha-

<table>
<thead>
<tr>
<th>Locality</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Rock type</th>
<th>Age</th>
<th>N (sites)</th>
<th>n (samples)</th>
<th>Dec (°)</th>
<th>Inc (°)</th>
<th>z(_{95}) (°)</th>
<th>k</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shwaner Mtns.</td>
<td>1.5°S</td>
<td>110°E</td>
<td>Tuffs, Porphyry</td>
<td>Cretaceous</td>
<td>4</td>
<td>358.5</td>
<td>16.4</td>
<td>11.7</td>
<td>63</td>
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<td>Schwaner Mtns.</td>
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<td>110°E</td>
<td>Tuffs, Dykes, Volcanics, Granites</td>
<td>Cretaceous</td>
<td>37</td>
<td>311.7</td>
<td>0.3</td>
<td>7.8</td>
<td>10</td>
<td>1</td>
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<td>110°0.0'E</td>
<td>Metatuff</td>
<td>Cretaceous</td>
<td>—</td>
<td>98.0</td>
<td>—</td>
<td>—</td>
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<tr>
<td>Schwaner Mtns.</td>
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<td>110°0.0'E</td>
<td>Hornfels</td>
<td>Cretaceous</td>
<td>—</td>
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<td>17.0</td>
<td>—</td>
<td>—</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Schwaner Mtns.</td>
<td>1.3°S</td>
<td>110°0.0'E</td>
<td>Dyke</td>
<td>Cretaceous</td>
<td>—</td>
<td>282.0</td>
<td>29.0</td>
<td>—</td>
<td>—</td>
<td>1</td>
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<tr>
<td>Schwaner Mtns.</td>
<td>1.3°S</td>
<td>110°0.0'E</td>
<td>Dyke</td>
<td>Cretaceous</td>
<td>—</td>
<td>284.0</td>
<td>22.0</td>
<td>—</td>
<td>—</td>
<td>1</td>
<td></td>
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<tr>
<td>Schwaner Mtns.</td>
<td>1.2°S</td>
<td>110°7.0'E</td>
<td>Dyke</td>
<td>Cretaceous</td>
<td>—</td>
<td>284.0</td>
<td>—25.0</td>
<td>—</td>
<td>—</td>
<td>1</td>
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<td>Mean direction for W. Kalimantan–Schwaner Mtns.</td>
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<td></td>
<td></td>
<td>Cretaceous</td>
<td>1</td>
<td>5</td>
<td>280.1</td>
<td>—5.6</td>
<td>24.5</td>
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</tbody>
</table>

Table 2
Paleomagnetic data from West Kalimantan. Reference: 1 = Haile et al. (1977). See Fig. 4 for plot of data

Table 3
Paleomagnetic data from Central and Eastern Kalimantan. References: 1 = Lumadyo et al. (1993); 2 = Sunata and Wahyono (1991); 3 = Jason Ali (unpublished data); 4 = Moss et al. (1997); 5 = Fuller et al. (1991). See Fig. 5 for plots of data
viour, but a single direction was isolated with Kirschvink’s method (Kirschvink, 1980) giving a mean in situ Dec. 333.8° and Inc. 18.6° with \( \alpha_{95} \) 15.5° and \( k \) 36. When corrected for tilt, the direction becomes Dec. 345.2°, Inc. 18.6°, \( \alpha_{95} \) 14.7°, \( k \) 40.2.

Sunata and Wahyono (1991) reported results from Eocene sandstones and siltstones of the Kalasin region from the tributaries of the Murung River. Thirty-eight samples were collected from which, after AF demagnetization, 27 gave a mean Dec. 322.8° and Inc. 0.6°, with \( \alpha_{95} \) 13.9°.

7.4. Summary of results from Central and Eastern Kalimantan

The results from this area are the most puzzling from Borneo. As in other regions, we see CCW rotated results of some 30° but there are also unrotated directions in rocks of the same age. Among these are directions which pass a fold test reported by Lumadyo et al. (1993).

8. South Kalimantan: Meratus Mountains

This important region is undersampled paleomagnetically. Results from a granodiorite have been reported by Sunata and Permanadewi (1998) and results from the Eocene Tanjung Formation and from the ophiolite are given by Sunata and Wahyono (1998). Lumadyo et al. (1993) reported results from two sites in basaltic flows.

8.1. Miocene

A microdiorite located north of Gunung Kukusan in the Batulicin area with a K/Ar age of 19.6 ± 0.76 Ma was sampled for paleomagnetism by Sunata and Permanadewi (1998). AF demagnetization revealed essentially single component magnetization with five samples yielding Dec. 323° and Inc. 1°, with \( \alpha_{95} \) 7.7° and \( k \) 65.9 (Fig. 6a, Table 4).

8.2. Eocene

Sunata and Wahyono (1998) also reported results from the Late Eocene Tanjung Formation. The formation is widely distributed and passes up from a basal conglomerate into a sandstone. Seven of 14 sites studied yielded reliable data after AF demagnetization with a mean Dec. 344° and Inc. –6°, \( \alpha_{95} \) 7.4° and \( k \) 50.8.

Results from two sites from the Meratus region in South Kalimantan were reported by Lumadyo et al. (1993). They were in basaltic flows of the Kuaro Formation in the northern part of the Pasir Basin; the

Table 4
Paleomagnetic data from South Kalimantan: Meratus Mountains. References: 1 = Sunata and Permanadewi (1998); 2 = Sunata and Wahyono (1998); 3 = Lumadyo et al. (1993). See Fig. 6 for plots of data

<table>
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<th>Locality</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Rock type</th>
<th>Age ( \pm ) error</th>
<th>( N ) (sites)</th>
<th>( n ) (samples)</th>
<th>Dec (°)</th>
<th>Inc (°)</th>
<th>( \alpha_{95} ) (°)</th>
<th>( k )</th>
<th>Ref.</th>
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<tr>
<td>Gunung Kukusan</td>
<td>3.2°S</td>
<td>116.0°E</td>
<td>Microdiorite</td>
<td>19.6 ± 0.76 Ma</td>
<td>1</td>
<td>5</td>
<td>323.0</td>
<td>1.0</td>
<td>7.7</td>
<td>65.9</td>
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<td>Tanjung and Kuaro Fms., Eocene</td>
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<td>Mixed results</td>
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<td>116.0°E</td>
<td>Sandstone</td>
<td>Eocene</td>
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<td>—</td>
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<td>1.0</td>
<td>–16.8</td>
<td>12.3</td>
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<tr>
<td>Batulicin</td>
<td>3.4°S</td>
<td>115.9°E</td>
<td>Ultrabasic</td>
<td>Cretaceous</td>
<td>1</td>
<td>5</td>
<td>321.0</td>
<td>–13.0</td>
<td>14.4</td>
<td>18.9</td>
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Table 5
Paleomagnetic data from Sabah. References: 1 = Fuller et al. (1991); 2 = Mike Fuller (unpublished data). See Fig. 7 for plot of data

<table>
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<th>Rock type</th>
<th>Age ( \pm ) error</th>
<th>( N ) (sites)</th>
<th>( n ) (samples)</th>
<th>Dec (°)</th>
<th>Inc (°)</th>
<th>( \alpha_{95} ) (°)</th>
<th>( k )</th>
<th>Ref.</th>
</tr>
</thead>
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<td>Kapu Quarry</td>
<td>Adamelite</td>
<td>13.3 ± 5.3 Ma</td>
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<td>9</td>
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<td>2.4</td>
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<tr>
<td>NW coast</td>
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<td>3.7</td>
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<td>Chert</td>
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<td>Spilite</td>
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<td>–9.1</td>
<td>27.4</td>
<td>7</td>
<td>2</td>
</tr>
</tbody>
</table>

8.3 Mesozoic

Sunata and Wahyono (1998) reported one site from the ultrabasic of the ophiolite. Five samples gave a site mean Dec. 321° and Inc. −13°, with $\alpha_95$ 14.4°, and $k$ 18.9 (Fig. 6c, Table 4). Further work is underway with additional sites in the ophiolite.

8.4 Summary of results from South Kalimantan

This area is clearly undersampled, but the limited results seem to show a similar pattern to Central and Eastern Kalimantan with rotated and unrotated directions mixed. The weak rotation is seen in all three units, which Sunata and Wahyono (1991) report, i.e., the Miocene microdiorite, the Eocene Tanjung...
Formation and the Cretaceous ultrabasic rocks; there is no report of the strong rotation from this region. Since there is a range in age from Mesozoic to Miocene in these units, there has either been remagnetization of the older units in the direction of the intrusion, or there was no rotation here between the Mesozoic and the Miocene. The two sites reported by Lumadyo et al. (1993) from Eocene Kuaro Fm. basalts are unrotated, so that they are inconsistent with the results of Sunata and Wahyono (1998).

9. Sabah

In Northern Sabah, the NE/SW strike of the Crocker Belt, which is consistent for several hundred km into Sarawak, turns almost E/W (Tongkul, 1990). This presents the opportunity to test paleomagnetically whether the configuration is brought about by deformation of an earlier continuously NE/SW striking feature. To the east of the Kinabalu intrusion, there are outcrops of the Cretaceous chert-spilite unit of the Telupid ophiolite, but it is badly dismembered so that structural continuity is hard to establish. In the north the chert-spilite unit is again seen. Although a number of paleomagnetic results are available for the region, their interpretation is still far from clear.

9.1. Eo-Miocene

The youngest site sampled is at the Kapa Quarry in a small satellite stock of the Mount Kinabalu intrusion; the K/Ar age is 15.0 ± 5.3 Ma. The rock is an excellent paleomagnetic recorder and gives Dec. 348.9° and Inc. 1° with $z_{95}$ 2.4° and $k$ 422 (Fig. 7, Table 5).

Much of the Eocene–Miocene Crocker Formation consists of turbidites, including relatively coarse sandstones which give a present field directions with some minor CW rotation (Fuller, unpublished data). Among the Crocker sandstones are red mudstones which are excellent recorders; these give the strongly rotated CCW deflected Dec. 277.5° and Inc. 2.8°, with $z_{95}$ 3.7° and $k$ 227, after tectonic correction (Fig. 7, Table 5). Before tectonic correction the result is Dec. 309.3° and Inc 49.7°, with $z_{95}$ 3.4° and $k$ 311. Work is underway with further collections from the mudstones.

9.2. Cretaceous chert-spilite unit

Collections were made from the chert-spilite unit in the vicinity of Telupid in central North Sabah. The chert gave a strongly rotated direction after tectonic correction of Dec. 281°, Inc 0° with $z_{95}$ 6°, and $k$: 66. Tectonic correction has little effect on this direction. In contrast, the spilites fail a regional attitude test giving badly scattered results after correction. The before-correction value, after elimination of 2 outliers is Dec. 313.3° and Inc. ~9.1°, with $z_{95}$ 27.4° and $k$ 7 (Fig. 7, Table 5).

9.3. Summary of results from Sabah

Sabah is a potentially important area for the tectonics of Borneo but requires much more paleomagnetic work. The few results which are available suggest that the magnetization carried by the intrusion at the Kapa Quarry is younger than most of the rotation of the region. The Crocker results are too few and too scattered to provide useful data yet, but additional results from the red mudstone facies could prove important, if they are the youngest units showing the strongly rotated direction. The spread in directions of the spilite magnetizations, from the strongly rotated direction towards the present field, suggests remagnetization. There are insufficient results from north of the region, in which the structure swings from NE/SW to E/W, for interpretation.

10. Discussion of paleomagnetic results from Borneo

In Fig. 8, the Borneo results are presented in the form of maps showing the rotations for the various sites. The figure is in three parts: Fig. 8a shows the results from the youngest sites with ages less than 10 Ma, represented by the Plio–Pleistocene Plateau basalts. Fig. 8b presents all Tertiary sites older than 10 Ma. Finally, in Fig. 8c the results from Mesozoic sites are shown. From this figure it is clear that the rotated and unrotated directions are intimately mixed spatially.

In Fig. 9, the results from igneous rocks are shown in the form of a plot of rotation versus age for sites at which we have absolute age determinations and the data are not interpreted as remagnetizations. The Cenozoic sites which show directions not seen in younger rocks exhibit a trend which gives a rate of rotation of approximately 2° per million years. However, as we have noted elsewhere, there are other well-dated Cenozoic sites of this age which show no rotation. Among the older dated material which is primarily Cretaceous, as well as the strongly rotated directions shown here, there are unrotated and weakly rotated directions. The strong rotation is carried by an intrusive and a cross-cutting dyke of Cretaceous age from Northwest Kalimantan; the dyke has been dated by K/Ar as 93.2 ± 3.5 Ma (Table 1). The second Mesozoic result comes from metatuffs (Table 2) in the contact zone of adamellite dated at 86.2 ± 2.0 Ma (Haile et al.,...
1977). The weak rotation is carried by the youngest granites and associated dykes (see Tables 1–5). The occurrence of rotated and unrotated directions is, therefore, intimately mixed in age as well as in locality. Nevertheless, there is a clear progression of the maximum rotations shown by rocks of each particular age.

Although not shown in Fig. 9, there are also results from sedimentary sites which show a similar pattern of unrotated, weakly and strongly rotated. Using Fig. 9 as a key to direction as a function of age we can, in principle, interpret possible ages of magnetization for sediments. At present this is only useful for age ranges within which we have good control, i.e., from about 10 to 30 Ma. For example, the unrotated sites in the Silantek Formation, Bau Limestone, and Pedawan and Kedadom formations must have been remagnetized after about 10 Ma. Similarly, the Silantek Formation rotated direction and the weakly rotated direction in the Bau Limestone and Kedadom and Pedawan formations must have been remagnetized prior to 30 Ma but after about 80 Ma.

11. Summary of discussion of paleomagnetic results from Borneo

The Sintang results and other data for sites younger than 30 Ma define a CCW rotation trend with a rate of approximately 2° per million years. The Mesozoic strongly-rotated results are also shown, and while they are insufficient to define a trend, it is clear that the rotation rate of 2°/Ma was not maintained throughout the Cenozoic. In the face of this evidence of systematic trends in the observed rotations, we provisionally interpret the data to indicate a rotation of the Sundaland core of Borneo, which can be divided into a strong rotation shown by rocks older than 80 Ma, and a weaker rotation seen in rocks between 30 and about 10 Ma. As a working hypothesis, we propose that all directions in rocks that are also seen in younger rocks are secondary magnetizations and do not carry information about the rotation of Borneo at the time of formation of the rock. They may, however, record particular important periods of remagnetization and reveal the rotation history for that time. For example, it appears that there may have been an important period of remagnetization during a reversed chron in the Plio–Pleistocene, coincident with the extrusion of the Plateau Basalts (Table 3), which would account for the common reversed present field direction seen in many sites of diverse age. Another period of remagnetization appears to have taken place after about 80 and before 30 Ma because the weak rotation is seen in many Mesozoic rocks.

12. Paleomagnetic data from regions surrounding Borneo

If the paleomagnetic results from Borneo are to be interpreted in terms of CCW rotation, then it is important to see how this behaviour fits into local paleogeography and in particular how consistent it is with the paleomagnetic history of nearby regions. Unfortunately, the paleomagnetism of nearby regions is incomplete, but important relevant results are now discussed. The most immediately relevant region is the western part of the south arm of Sulawesi, which is separated from Borneo only by the Makassar Straits (Fig. 1). From this region a number of studies have been reported and are discussed below. To the northeast lies Palawan and again there are paleomagnetic results from that island. While work is underway in Java and Sumatra, the results are presently not sufficiently advanced to warrant inclusion. From Peninsular Malaysia there is a considerable paleomagnetic database, although the absence of a Tertiary section makes interpretation difficult. We now discuss the results from Sulawesi, Palawan, and Peninsular Malaysia and give a brief overview of work underway in Sumatra and Java.

12.1. Sulawesi

Western South Sulawesi and Borneo have been effectively attached throughout the Cenozoic (Fig. 1B). Although extension between the islands took place during the middle Cenozoic (Situmorang, 1982), extensive oceanic lithosphere was not generated along the Makassar Straits and constraining the relative motion between these two crustal fragments is relatively straightforward. The opening of the Makassar Straits reduces CCW rotations in Sulawesi compared with their equivalents in Borneo for data older than the opening event. However, the amount is within the errors of presently available results for sites antedating the opening of the Makassar Straits, i.e., Mesozoic or early Cenozoic data.

There have been several paleomagnetic studies carried out on SW Sulawesi (Ali, unpublished data; Haile, 1978; Mubroto, 1988; Mubroto et al., 1994, and Sasajima et al., 1980). In this review, we restrict our analysis to those sites from the western side of the South Arm (Fig. 1B and 2); this avoids the problem of local tectonic complexities associated with the collision of the allochthonous terranes to the east. Ali (unpublished study) has identified nine paleomagnetic sites from the late Miocene Camba Formation of South Sulawesi which have yielded meaningful directional data. The sites are from mainly igneous rocks (thin dykes, lava flows and diorite bodies) but also include
siltstones and clays (van Leeuwen, 1981). Demagnetisation experiments suggest that their magnetisation is primary. Combined with data from eight previously reported sites from Haile (1978) and Mubroto (1988) the new in situ formation mean direction is D 171.6° and I 12.2° with z95 5.8° and k 38.3; correction for tilt results in a mean direction of D 171.3° and I 10.2° with z95 5.3° and k 46.8. The tilt corrected data indicate a small (~9°) CCW rotation and negligible translation of the region since ~10 Ma. These results are consistent with those from Borneo.

Preliminary unpublished work by Ali on the Upper Cretaceous Balang Baru Formation from three sections in the Doidoi region of SW Sulawesi gave Dec. 341.7°, Inc. −21.5°, z95 6.5°, and k 73, with marginally better in situ statistics. This direction is similar to the direction recorded in the younger rocks on Sulawesi. Similar results were obtained by Haile (1978), who obtained Dec. 325° and Inc. −5°, with z95 7.2° and k 60, from brown radiolarian cherts from the Paring River in the Dera Valley. In this same paper, two strongly rotated results are reported, which are similar to those seen in Kalimantan and Sarawak. One came from a dyke which gave Dec. 105° and Inc. 11°, with z95 4.9° and k 624; the other was from grey calcareous siltstone from the same valley with NRM directions of Dec. 121° and Inc. 32°, with z95 14.9° and k 38.6. While these last two results suggest a strongly rotated Mesozoic direction similar to those seen in Borneo, it is clear that more data are badly needed.

12.2. Celebes and Sulu Seas

Shibuya et al. (1991) have reported a period of CCW rotation in late Eocene and early Oligocene time for the Celebes Sea. This result was obtained with orientation of core using the soft magnetisation, which was interpreted to be in the present field direction. The method (Fuller, 1969) is not always reliable, but has been checked elsewhere against the formational microscanner and was found to give similar results (Cisowski et al., 1990). In contrast, samples from the top 220 m at Site 769 on the southern flank of the Cagayan Ridge in the Sulu Sea showed no evidence of CCW rotation from about 8.9 Ma (Hsu et al., 1991). The latter result is consistent with results from Borneo, which suggest that the weak rotation was almost completed by this time. The result from the Celebes Sea is inconsistent with the Borneo results, in that the timing is much earlier than the 30 to 10 Ma seen in Borneo. Thus, the CCW rotated regions in Borneo have a different rotation history from the Celebes Sea during this time.

12.3. Palawan

The elongate island of Palawan lies to the north east of Borneo between the South China Sea and Sulu Seas. It is divided into the Northern and Southern Palawan blocks. The former is dominated by a Mesozoic section, whereas the latter is dominated by ophiolites. Paleomagnetic studies are reported by Almasco (1996) and Almasco et al. (1999). Fig. 10 shows that the directions in the North Palawan Block are predominantly CW rotated, whereas those from the South are predominantly CCW rotated. There is a region at the northern margin of the ophiolites where there is large between-site scatter, probably reflecting local deformation.

The results from the Jurassic Busuanga cherts and the Cretaceous Guinlo Formation on the island of Busuanga in the North Palawan Block and from the Guinlo Formation on the main island of Palawan failed a regional attitude test and gave indistinguishable directions. When combined, the 11 sites yield a declination of 50.9° and inclination of 45.3°, with a k of 26 and an z95 of 9.1°, giving a VGP of 183.4°E and 39.3°N and a paleolatitude of 26.8° ± 4.6°. This VGP is similar to those found in regions of pervasive Cretaceous remagnetisation in South China.

Results from the Cretaceous Espina Basalts of the Calatoguis Ophiolite in the Southern Palawan Block pass a fold test, carry an NRM with AF demagnetisation characteristics consistent with a primary TRM, include Normal and Reversed directions, and yield a mean normal direction of 283.9° and an inclination of 5.8°, with a k of 37.7 and an z95 of 12.6°, which gives a paleolatitude of 3°N ± 6°. The declination is similar to that reported from the Celebes Sea by Shibuya et al. (1991).

Results from the North Palawan Block are consistent with its proposed South China origin, from whence it has moved southward and rotated clockwise. The Espina Basalts of the South Palawan Block have moved northward and experienced counterclockwise rotation. Their origin is less clear, but suggest a Cretaceous spreading center to the south, possibly related to that at which the Sabah Ophiolite was formed. While these paleomagnetic results require different tectonic histories for those parts of the North and South Palawan blocks studied, both the North and South Palawan block basements probably have a common origin, having been moved southward by South China Sea spreading. Subsequently ophiolites were thrust over the Southern Block. The ophiolites in Palawan have an age similar to those of Sabah to the south in northernmost Borneo.
Peninsular Malaysia is dominated by the Main Range granites of predominantly Late Triassic age (Hutchison, 1989). They are deep seated in the east and become more epizonal to the west. In contrast, the Eastern Belt is an epizonal calc-alkaline series of Late Permian to Late Triassic age. Between the two ranges lies the Central Basin separated from the Main Range in the west by the Raub–Bentong suture (Fig. 11). Spectacular uplift associated with the Indosinian Orogeny produced extensive intermontane basins filled with the Jurassic–Cretaceous redbed sequences, which have yielded excellent paleomagnetic results. The other principal sources of late Mesozoic paleomagnetic data have been the Kuantan dykes and the Segamat basalts. The former were intruded into the Permo-Triassic intrusives of the Eastern Belt centered around Kuantan. Towards the southern end of the Central Basin lie the Segamat basalts of probable Late Cretaceous age. The Cenozoic section in the peninsula is confined to a single coal basin at Batu Arang near Kuala Lumpur (Fig. 11) and scattered minor outcrops of coarse sediments.

The published paleomagnetic database for Peninsular Malaysia was reviewed by Haile and Briden (1982). It is primarily the pioneering work of Neville Haile and others (Haile, 1981; Haile et al., 1983; Haile and Khoo, 1980; McElhinny et al., 1974). CCW declinations were found with moderate inclinations (330°–40°) in the Cretaceous Kuantan dykes and Segamat basalts (Haile et al., 1983; McElhinny et al., 1974). CCW rotated declinations with moderate inclinations were also found in Jurassic–Cretaceous red beds near Maran and Kluang (Haile and Khoo, 1980). For comparison, the present latitude spread of Peninsular Malaysia gives shallow inclinations from 2° to 12°. Additional results have been described by Richter and Fuller (1996) and in general there is excellent agreement between the directions listed above and the new data. Fig. 11 gives the results from Jurassic–Cretaceous red beds, from the Cretaceous Kuantan.
dykes and the Segamat basalts. The youngest rocks that have been studied give CCW rotations. Unfortunately the absence of a significant Tertiary section means that the age of these rotations cannot be constrained and we have no information about Tertiary rotation history. There are, however, coal basins such as Batu Arang near Kuala Lumpur (Fig. 11), which give the promise of some Tertiary results. These rocks are very weakly magnetized which hampered earlier studies, but they are being studied at present.

12.5. Java and Sumatra

Despite a number of paleomagnetic studies in Java and Sumatra, it is still too early to use these results to help interpret the results from Borneo. In both areas work is underway and older studies are available. In Java, paleomagnetic results have been reported by Hirooka et al. (1980) and Mahfi (1984). Hirooka et al. (1980) reported results from Bayat which were all of normal polarity and close to the present field, but these were NRM directions before demagnetization. From West Java, they reported results after AF demagnetization, which were widely dispersed. Mahfi (1984) reports results from Bayat, Kalissongo and Karang Sambung, where windows through the blanketing flows which cover the island, permit access to older sections. There is again a mixture of rotated and unrotated sites but no sytematic pattern of rotation with age has emerged comparable with that seen in Borneo. The dominant results from Sumatra give CW rotations (Haile and Briden, 1982) but the situation remains unclear. The results from Sumatra are potentially particularly important because there are plentiful Tertiary intrusives which will aid in the interpretation of the results from Peninsular Malaysia.

12.6. Summary of paleomagnetic data from regions surrounding Borneo

Results from the Late Miocene of Western Sulawesi are sufficiently well determined and geologically constrained to provide a useful comparison with the results from Borneo itself and the results are consistent in the two regions, showing the weak rotation. This same direction is seen in some of the Mesozoic rocks, whereas the more strongly rotated direction is seen in a dyke and in Jurassic–Cretaceous siltstones.

The results from North Palawan clearly represent a very different geological history from Borneo. The North Palawan block has a paleomagnetic history consistent with an origin associated with South China and carries the typical CW rotations of that region. As noted above the South Palawan basement probably has a similar history, but the ophiolites which were thrust over that basement have the CCW clockwise rotations similar to the weak rotation of Borneo and the CCW rotation reported in the Celebes Sea (Shibuya et al., 1991).

The comparison between Borneo and Peninsular Malaysia is hampered by the absence of a significant Tertiary section in the peninsula. However, the Jurassic–Cretaceous redbeds, the Kuantan dykes and the Segamat basalts all show CCW rotations similar to that seen in Borneo in the Sintang intrusives. The problem in interpreting these results is that we have no indication of the age of the rotation. It could have taken place at the same time as the weak rotation in Borneo, or it could have been much older. Clearly Peninsular Malaysia cannot have rotated coherently with Borneo throughout the Cenozoic because it shows only the weaker rotation seen in the 30 Ma aged units in Borneo.

13. Discussion

Despite obvious shortcomings, there is now a substantial paleomagnetic data base from Borneo and the surrounding regions. The chief difficulty in interpreting these paleomagnetic data and particularly those from Borneo, is that rotated and unrotated sites are intimately mixed in age and in location. The fundamental difference in resulting tectonic models and paleogeographic reconstructions lies in the interpretation of the unrotated sites. One view assumes that these are faithful records of the field at the time of origin of the rock and that, because there are unrotated directions as well as CCW rotated directions, the island of Borneo cannot have rotated as a single block. Rather the island must have been predominantly fixed with the rotated sites recording local rotations in shear zones, or are anomalous or spurious directions. A second interpretation assumes that the unrotated directions are secondary magnetizations and therefore do not constrain rotations since the time of formation of the rock. In this view, the CCW rotational history of the island is recorded by only those samples and sites which are not remagnetized, i.e. those that show the maximum rotation for each particular age.

The chief difficulty faced by the suggestion that Borneo has remained fixed with respect to stable Eurasia and indeed with respect to the Geomagnetic Axial Dipole from the Mesozoic (e.g., Lumadyo et al., 1993; Lee and Lawver, 1993, 1995) is the internal consistency of the paleomagnetic results. If the island has not rotated, why are similar rotations seen over such a wide region? For example, the strongly rotated Mesozoic results are seen in the Jurassic of Sarawak, the Cretaceous–Jurassic intrusions of the Schwaner Mountains, sediments in Central Kalimantan, and in
preliminary results from the chert-splitle unit in northern Sabah. It seems very unlikely that similar rotations would be seen if the inferred rotations come from simply anomalous or spurious paleomagnetic results. It seems equally unlikely that the observed rotation only took place in localized shear zones because, given the intimate mixing of the locations of rotated and unrotated sites, it is hard to see how zones of distributed shear could thread their way through the island affecting rotated sites and avoiding the unrotated.

The intimate mixing throughout Borneo of rotated and unrotated results is easier to explain in terms of remagnetization than by a special distribution of local shears. This suggests that there was pervasive remagnetization in Borneo through which a paleomagnetic record has partially survived. We take as a working hypothesis, to be tested by further work, that the Cenozoic rocks and Mesozoic rocks which are unrotated, or show the weak 30 Ma rotation, are remagnetized. The identification and detailed understanding of remagnetization remains a major problem in paleomagnetism despite many studies (e.g., Elmore et al., 1987; Fuller et al., 1988; Hart and Fuller, 1988; McCabe and Elmore, 1989; McCllelland-Brown, 1982; Reynolds et al., 1990). That sedimentary rocks are frequently remagnetized is well known, so that there is no difficulty in accepting a major role of remagnetization in the sedimentary rocks studied even though criteria which might have been used to establish remagnetizations were not, for the most, part used. The interpretation of remagnetization in small shallow stocks, such as the Singtang intrusives poses more difficult problems. Preliminary investigations of the magnetization of the minor intrusions in Kalimantan revealed some distinctions between the blocking temperature distributions of the magnetizations which were rotated, and those that were unrotated. Further work is planned to investigate the cause of these blocking spectra, but the presence of such distinctions may be the key to distinguishing primary and secondary magnetizations in this suite of rocks.

If we accept that the paleomagnetic results require a coherent rotation of Borneo, there still remain two possible modes of rotation—a rigid plate rotation, or rotation brought about by distributed deformation in one or more shear zones. One possibility raised by Holcombe (1977) in a discussion of the rotation of Peninsular Malaysia is that a series of concentric slivers rotate. In Peninsular Malaysia the rotation is CCW about a pole to the northeast. A somewhat similar kinematic scheme was advocated by Rangin et al. (1990) in describing CW rotation in SE Asia in response to the India–Eurasia collision. In that example the CW rotation was about a pole at the eastern syntaxis in Assam. It is possible that a similar kinematic scheme might explain the paleomagnetic observations in Borneo. The structure of the island does define a series of roughly arcuate zones, which might be interpreted as rotating slivers. While it is not clear how one could refute such an explanation with paleomagnetic data alone, from a broader geological viewpoint the model is open to criticism. First, there is no evidence of the necessary faults to accommodate such movement, and second there are features which appear to crosscut the arcuate boundaries, thereby precluding the proposed movement. Still another model which could be used to interpret CCW rotations across Borneo is that of Wood (1985) who considered that the dominant tectonic features were a series of NW/SE shears which cut across Borneo. These could then form a region of left lateral shears which would generate CCW rotations across Borneo. However, the evidence for these shears with their associated distributed deformation is not very convincing. We therefore fall back to an essentially rigid plate model with much of Kalimantan, Sarawak and southern Sabah participating in a rotation of about 50° CCW between 30 and 10 Ma, and in an earlier rotation of about 40° sometime between 80 and 30 Ma. The underlying cause of these rotations is convergence between the Australian Plate and Eurasia, which is accommodated in the southerly subduction which gave rise to the accretionary wedge in Sarawak and volcanism in Kalimantan.

14. Conclusion

The paleomagnetic results from Borneo give considerable support to the suggestion of CCW rotation, which is consistent with earlier discussions (Haile, 1978; Hamilton, 1979) and with aspects of more recent tectonic models and paleogeographic reconstructions Hall (1996) and Richter (1996). There are also results which are inconsistent with this idea, but the simplest interpretation of the paleomagnetic data is that there is a CCW rotation of some 50° since about 30 Ma. Directions corresponding to this rotation are also seen in Mesozoic rocks and are interpreted as a secondary magnetization. Other Mesozoic rocks show a stronger rotation of an additional 40° giving a total of almost 90°. The timing of this earlier rotation is not clear, but it cannot be older than 80 Ma, the age of the younger Cretaceous intrusions in the Schwaner Mountains which show the rotation. In comparing the results from Borneo with those from the surrounding regions, we find CCW rotations from Western Sulawesi, the Celebes Sea, Palawan and Peninsular Malaysia. However, these rotations are not as large as the rotation in Borneo, so that the region has not rotated coherently as Borneo appears to have done. The rotation of Borneo is a consequence of convergence between the Australian and Eurasian plates which is
accommodated by subduction along the northwest margin of Borneo.

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