Paleomagnetism of the Crocker Formation, northwest Borneo: Implications for late Cenozoic tectonics

Andrew B. Cullen1,2, M.S. Zechmeister3,4, R.D. Elmore5, and S.J. Pannalal6
1Shell International Exploration and Production Company, 100 Hoekstade, Rijswijk, Netherlands
2Chesapeake Energy Corporation, 6100 N. Western Avenue, Oklahoma City, Oklahoma 73118, USA
3ConocoPhillips School of Geology and Geophysics, 100 E. Boyd Street, Norman, Oklahoma 73019, USA
4Shell Exploration and Production Company, 150 North Dairy Ashford, Houston, Texas 77079, USA

ABSTRACT

Tectonic models for Borneo’s Cenozoic evolution differ in several aspects, particularly in the extent to which they include paleomagnetic data suggestive of strong counterclockwise rotation between 30 and 10 Ma. Key areas are undersampled. We present the results of a paleomagnetic study of Eocene to Early Miocene sandstones from northwest Sabah, principally from the Crocker Formation. We obtained reliable site means from 11 locations along a 250 km northeast-southwest transect using thermal demagnetization to isolate characteristic remanent magnetization (ChRM) directions. The Crocker Formation sandstones are passively remagnetized; pyrrhotite dominates the ChRM signal. Locations can be grouped into different domains on the basis of the relative sense of rotation about a vertical axis. Mean ChRM directions for seven locations between Kota Kinabalu and Keningau (declination, dec 12°–19°; inclination, inc –22°–23°) indicate minor clockwise rotation and modest tilting, whereas two locations near Tenom (dec 321°–345°, inc –6°–24°) record counterclockwise rotation and modest tilting. Although we cannot precisely date the age of remagnetization, the results of fold tests from 4 locations, interpreted within the regional structural framework, strongly indicate that remagnetization occurred between 35 and 15 Ma, the waning stages of the Sarawak orogeny to an early phase of the Sabah orogeny. Our results pose serious difficulties for current tectonic models in which Borneo rotates 50° counterclockwise as a rigid block between 30 and 10 Ma. With respect to prior paleomagnetic studies, we suspect that an early episode of strong regional counterclockwise rotation (before 35 Ma) was overprinted not only by differential clockwise rotation of crustal blocks during opening of the South China Sea (32–23 Ma), but also locally by a younger (after 10 Ma) counterclockwise rotation.

INTRODUCTION

The Cenozoic tectonic evolution of Southeast Asia reflects the complex interactions of rifting, subduction, continental collision, and large-scale continental strike-slip faulting. The island of Borneo is at the leading edge of several continental blocks that protrude from Southeast Asia as a wedge into the Indo-Australian and Philippine Sea plates (Fig. 1A). There are two end members of tectonic models for Borneo (Figs. 1B, 1C): collision-extrusion (Briais et al., 1993; Replumaz and Tapponnier, 2003) and subduction-collision (Hamilton, 1979; Lee and Laver, 1995; Hall, 1996). These models differ in four principal aspects: (1) the mechanism responsible for rifting and seafloor spreading in the South China Sea ca. 32–16 Ma (Briais et al., 1993); (2) the timing and amount of displacement along the large intercontinental strike-slip faults such as the Red River fault (Leloupe et al., 1995; Searle, 2006); (3) the amount of proto–South China Sea crust subducted beneath Borneo (Rangin et al., 1999; Lee and Laver, 1995; Hall, 2002; Cullen, 2010); and (4) the magnitude and nature of the late Tertiary rotation of Borneo (Hall, 1996, 2002; Murphy, 1998).

In the collision-extrusion model (Fig. 1B), India’s collision with Asia progressively displaces the Sundaland, Indochina, and South China blocks to the southeast along intercontinental strike-slip faults (e.g., Mae Ping and Red River faults). In this model, Borneo, south Palawan, and north Palawan rotate clockwise (CW) ~25° along with the Indochina block as the South China Sea opens as a large-scale pull-apart basin (Briais et al., 1993; Replumaz and Tapponnier, 2003); the amount of seafloor spreading is approximately balanced by 600 km of left-lateral displacement along the Ailao Shan–Red River fault zone. In the collision-extrusion model, there is no Tertiary subduction under northwest Borneo, and mass is conserved by subduction in the Pacific Ocean.

The subduction-collision model (Fig. 1C) features long-lived subduction (Eocene–Early Miocene) beneath northwest Borneo during which an extensive amount of proto–South China Sea oceanic crust is consumed. Subduction terminates progressively (southwest to northeast) as blocks of continental crust (Luconia, Dangerous Ground, and Reed Bank) collide with northwest Borneo and Palawan (Holloway, 1982; Lee and Laver, 1995; Hall, 1996; Longley, 1997). In this model, there is less displacement along the Red River fault and because it largely decoupled from extension in the South China Sea, CW rotation of Borneo is not required. The subduction-collision model has several permutations. The most widely cited reconstructions are those of Hall (1996, 2002); honoring Fuller et al.’s (1999) interpretation of regional paleomagnetic data, these reconstructions show an acceleration in subduction rate driven by strong (~50°) counterclockwise (CCW) movement of Borneo as a rigid block between 30 and 10 Ma. Murphy (1998) and Morley (2002) pointed out, however, that the lack of known regional structures of sufficient magnitude to accommodate such a large rotation poses a challenge to the interpretation of the paleomagnetic data. Hutchison (2010), drawing attention to the lack of paleomagnetic data in key areas of Borneo, suggested that the large oroclinal bend in Borneo’s interior highlands is strong evidence that Borneo did not deform as a single rigid block.

There are two fundamental issues regarding the paleomagnetic evidence for the rotation of

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Although the regional paleomagnetic data compiled by Fuller et al. (1999) included strongly rotated, weakly rotated, and nonrotated sites, their analysis excluded weakly rotated and nonrotated sites older than 10 Ma on the premise that those sites were remagnetized to the modern geomagnetic field direction. The data compiled by Fuller et al. (1999) are heavily weighted toward the southern part of Borneo (136 sites from the Schwaner Mountains, South Kalimantan, Central Kalimantan, and Sarawak) and Palawan (38 sites); only 9 sites are from Sabah. In interpreting the paleomagnetic record from Borneo, Fuller et al. (1999, p. 21) stated, “...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.” The nuance of this statement is significant; south Palawan’s ~60° CCW rotation by the end of the Oligocene (Almasco et al., 2000) predates the proposed CCW rotation of southern and central Borneo, which implies the presence of a significant right-lateral shear zone between northern Sabah and the rest of Borneo. Although such a shear zone has not been identified onshore, the 20 Ma and 15 Ma reconstructions by Hall (2002) show the development of a dextral transform fault offshore along the Balabac line (Milsom et al., 2002).

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study of 40 sites at 14 locations in northwest Sabah that sampled Eocene to Early Miocene sandstones of the Crocker, West Crocker, Meligan, and Kudat Formations (Fig. 2).

REGIONAL GEOLOGICAL FRAMEWORK

Borneo’s geological framework consists of three fundamental parts (Fig. 3): southwest Kalimantan, the interior highlands, and the surrounding coastal lowlands with offshore basins. Southwest Kalimantan, Indonesia, is a Paleozoic cored fragment of Australian Gondwana that was accreted to Indochina during the Cretaceous (Metcalf, 2011). Late Mesozoic continental arc igneous rocks in the Schwaner Mountains of Kalimantan provide suitable paleomagnetic data (Haile et al., 1977). Borneo’s interior highlands are dominated by the Rajang-Embaluh supergroup, a thick succession of strongly deformed Late Cretaceous to Paleogene deepwater clastic sediments lifted to present-day elevations of >1 km. The depositional and structural history of the Rajang-Embaluh supergroup is widely interpreted in terms of an accretionary prism (Hamilton, 1979; Rangin et al., 1990; Tongkul, 1997a; Bakar et al., 2007). Hutchison (1996) and Moss (1998), however, suggested that the younger units of this succession postdate

Figure 2. (A) Stratigraphic column (modified from Cullen, 2010; Lambiase et al., 2008). BMU—Base Miocene unconformity, DRU—deep regional unconformity, SOU—Sarawak orogeny unconformity, SRU—shallow regional unconformity. (B) Simplified geological map of western Sabah (Tongkul, 1997b; Tate, 2001; Hutchison, 2005; Tongkul, 2006) showing locations and units sampled: Cr—Crocker Formation (squares), KD—Kudat Formation (hexagon), Mlg—Meligan sandstone (circles), WCr—West Crocker (circles). Other abbreviations: KoK—city of Kota Kinabalu, KGV—Keningau Valley, MK—Mount Kinabalu pluton, Tbr—Temburong Formation, TO—Telupid ophiolite (ultramafic rocks shown in dark gray), SP—Sook Plains, TBV—Tambunum Valley, TVN—Tenom Valley, BL—Belud (BL) location, TS—TS car wash location, KK—Kota Kinabalu location, BS—Bukit Sepanger, NX—Nexus, JS—Jalan Salaiman, LK—Lok Kawi, KG—Keningau Pass, TN—Tenom, KM—Kampong Mua, KGV—Keningau Valley (see text).
subduction and record deposition in a marginal ocean basin that was subsequently deformed during the Sarawak orogeny (discussed in the following). The coastal lowlands and offshore areas of Borneo are occupied by Neogene foreland basins that contain as much as 10 km of largely shallow-marine successions that record extensive denudation, 4–6 km, of the interior highlands (Hamilton, 1979; Hall and Nichols, 2002; Morley and Back, 2008).

The igneous record of northern Borneo is rather sparse. The oldest igneous rocks are a series of Mesozoic aged variably serpenitized ultramafic bodies and chert-spillite assemblages (Hutchison, 1975) that crop out in north-central Sabah (near the village of Telupid), on islands northeast of Sabah, and on south Palawan (Fig. 3). A regional Bouguer gravity high that extends between these outcrops is interpreted as a regionally extensive late Mesozoic ophiolite complex (Cullen, 2010). Paleomagnetic data indicating very strong CCW rotation of the ophiolites at Telupid and south Palawan (Fuller et al., 1999; Almasco et al., 2000) support that interpretation.

Figure 3. (A) Regional geological framework of Borneo (simplified after Tate, 2001; Hutchison, 2005). Abbreviations as in Figures 1 and 2. SPSO, south Palawan Sabah ophiolite, is outlined in black dashes with ultramafic outcrops shown in dark gray. Sintang igneous suite is in white triangles; Paleogene flysch deposits are in light green with fold belt trend in green dashes showing oroclinal bend in highland; Pliocene–Pleistocene volcanic plateaus are in white with small v symbols; gray X marks—Mount Kinabalu pluton. Plots of previously published paleomagnetic results (Fuller et al., 1991, 1999; Lumadyo et al., 1993; Schmidtke et al., 1990) are grouped into domains (discussed in text). The pie diagram plots show the range of data shaded, with the average declinations shown with arrows. On the plot for Sabah, KQ denotes Kappa Quarry intrusion. Figures with photos refer to locations in Figure 3. CCW—counterclockwise; CW—clockwise; C.E.—central eastern. (B) The regional Bouguer gravity field (Cullen et al., 2010); red corresponds to high Bouguer values, blue to low values.
The Sintang igneous suite in southern Sarawak and central Kalimantan comprises Oligocene–Miocene calc-alkaline stocks and dikes that are an important element of the paleomagnetic record, in part because several of these intrusions have absolute age determinations (Schmidtke et al., 1990; Lumadyo et al., 1993; Fuller et al., 1999; Prouteau et al., 2001).

In northwest Sabah, Mount Kinabalu is a Late Miocene (7.85–7.22 Ma) granitic pluton that intrudes the Crocker Formation and older ultramafic rocks (Vogt and Flower, 1989; Cottam et al., 2010). A satellite stock related to Mount Kinabalu is one of the paleomagnetic sites of Fuller et al. (1999). The central highlands are capped locally by a dissected tabular and flat-lying basalt flows that have whole-rock K-Ar dates between 1.8 and 1.3 Ma (van de Weerd, 1987). The paleomagnetic record from all 17 sites at 3 different locations more than 30 km apart is excellent, and records nonrotated reversed directions and an average inclination similar to those of the present field (Lumadyo et al., 1993).

In the northwest Borneo region, Cenozoic deformation has resulted in the development of several regional angular unconformities (Bon and van Hoorn, 1980; Levell, 1987; Hutchison, 1992) that have been interpreted as the products of two episodes of orogeny: the Eocene Sarawak orogeny and the Middle to Late Miocene Sabah orogeny (Hutchison, 1996). Regional unconformities mark the end of a series of events that occurred prior to the unconformity, not the events themselves; even a short orogeny lasts ~20 m.y. (Dewey, 2005). Thus, although Late Miocene deformation and basin inversion in southeast Sabah has been attributed to the Meliau orogeny (Balaguru et al., 2003; Balaguru and Hall, 2008), the short-term aspect of these events suggests that the Meliau orogeny is a continuation of the Sabah orogeny rather than a third orogeny.

Tectonic models for Borneo’s two principal episodes of orogenesis envision a series of continental blocks progressively colliding with Sarawak, then Sabah, and lastly Palawan (Longley, 1997; Hall, 1996; Murphy, 1998). Two episodes of strong deformation are recognized within our study area (D1 folds are refolded by D2); these episodes can be interpreted as the records of either separate pulses within the continuum of one orogeny or as the products of two distinct orogenies. The expression of orogenesis on Borneo has been strongly influenced by its tropical climate; high erosionally driven denudation rates have prevented building of topographic relief sufficient to trigger tectonic denudation by extensional orogenic collapse and exposure of a metamorphic core (Hall and Nichols, 2002).

In the case of the Sabah orogeny, isostatically driven uplift related to denudation of the lower crust or slab detachment exerted a postcollisional buoyant influence on the orogen (Hutchison et al., 2000; Morley and Back, 2008).

**Sarawak Orogeny**

The Sarawak orogeny is defined by a protracted angular unconformity that truncates isoclinally folded members of the Rajang-Embaluh supergroup (Hutchison, 1996), which makes a large oroclinal bend in the central highlands and then extends into Sabah; the upper member, the Crocker Formation, is the principal unit sampled in this study. Hutchison (2010) interpreted this oroclinal bend as the result of induration owing to collision of the Luconia block during the Sarawak orogeny. The Sarawak orogeny unconformity is diachronous, becoming progressively younger to the northeast. In Kalimantan, the unconformity is capped by the Nyaan Volcanics, dated as 48.6 Ma (Moss, 1998), whereas in Sarawak, biostratigraphic data indicate that the limestone cover sequences are Late Eocene, ca. 38 Ma (Hutchison, 2005). Although outcrops exposing this unconformity were not identified, Hutchison (1996) interpreted the Sarawak orogeny unconformity to extend into Sabah, where Late Eocene to Oligocene sandstones that contain ultramafic rock fragments crop out in central Sabah near the Telupid ophiolite and in northwest Sabah, on the Kudat Peninsula, have been interpreted as being above a Late to Middle Eocene unconformity (Cullen, 2010; Rangin et al., 1990). In addition, Schluter et al. (1996) identified a Late Eocene unconformity throughout the southern South China Sea where Oligocene limestones overlie Late Eocene marine clastic rocks. Thus, the body of evidence suggests that the Sarawak orogeny was of greater regional extent and magnitude than its provincial name implies.

**Sabah Orogeny**

The Sabah orogeny was first proposed by Hutchison (1996) to account for uplift of the Crocker Formation onshore and the formation offshore of the deep regional unconformity (ca. 15 Ma) and shallow regional unconformity (ca. 9 Ma; Bol and van Hoorn, 1980; Levell, 1987). These unconformities are progressively younger to the northwest and their development is attributed to basinward tilting of a set of independently deforming basement blocks (Levell, 1987). An older (20–22 Ma) unconformity identified in southeast Sabah (Balaguru and Nichols, 2004) is in the equivalent stratigraphic position as the top of the Crocker (base of the Miocene) unconformity identified in onshore western Sabah (van Hattum et al., 2006). These older unconformities are a strong indication that the Sabah orogeny commenced in the earliest Miocene. Whether the Sabah orogeny was initiated by collision of the Dangerous Grounds with Borneo owing to CCW rotation of Borneo (Hall, 2002) or by underthrusting of the Dangerous Grounds driven by rifting in the South China Sea is an issue addressed in this study. The Dangerous Grounds are composed of small islands and shallow reefs in the eastern South China Sea that have formed on blocks of rifted continental crust.

**Meliau Episode**

The Meliau orogeny refers to latest Miocene deformation in southeast Sabah that is characterized by sinistral transpression that resulted in minor localized inversion and reactivation of older structures rather than regional uplift and orogenesis (Balaguru et al., 2003; Balaguru and Hall, 2008). Interpreted within the context of a phase of the Sabah orogeny, the Meliau episode corresponds to formation of the shallow regional unconformity, which is characterized by compressive wrench faulting (Levell, 1987). In their study of the deep-water fold-and-thrust belt of the Baram Basin, Hesse et al. (2009) concluded that an along-strike decrease between total shortening and gravity-driven shortening reflects a southwest to northeast increase in the amount of Pliocene to Holocene basement-involved shortening, a conclusion that implies young regional CCW rotation consistent with sinistral transpression.

**PREVIOUS PALEOMAGNETIC STUDIES**

Since Fuller et al.’s (1999) review of the paleomagnetism of the greater South China Sea region, no significant regional studies have been published. Although Almasco et al. (2000) presented a thorough analysis of the paleomagnetic record of Palawan, major aspects of that work were first discussed by Fuller et al. (1999). Within that discussion of previous work, we highlight uncertainties and problems, some of which were noted by Fuller et al. (1999). To maintain continuity, we retain the same geographic domains and the criterion for site reliability used by Fuller et al. (1999); reliable sites have $\alpha_{95} \leq 20$ (where $\alpha_{95}$ is the 95% confidence ellipse). Rather than displaying separate pie diagrams for strongly rotated, weakly rotated, and nonrotated sites, the data from each domain are plotted on a single diagram to highlight the range of rotational variation (Fig. 3).

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West Kalimantan

Late Mesozoic igneous rocks in the Schwaner Mountains yielded what Haile et al. (1977) considered “satisfactory paleomagnetic data” from 46 of 48 oriented block samples. Haile et al. (1977), interpreting the data as recording a primary magnetization acquired when the rocks originally cooled, determined a Late Cretaceous paleomagnetic pole for West Kalimantan. Although the declinations and inclinations have significant scatter, the results indicate CCW rotation with a maximum and average of 78° and 49°, respectively (Fig. 3). Negligible latitudinal differences between the present-day and Late Cretaceous magnetic poles for West Kalimantan and the Malay Peninsula led Haile et al. (1977) to conclude that these areas have remained close to their present latitudes and have behaved as a unit that rotated CCW ~50° since the middle Cretaceous. These conclusions indicate that the Sundaland block has behaved as a unified tectonic element during the Cenozoic, and imply that paleomagnetic sites from this block should have inclinations close to the present-day geomagnetic field, unless they have undergone rotation about a horizontal axis.

Northwest Borneo

The northwest Borneo domain (Figs. 3 and 4A) refers to the area between the Schwaner Mountains and the coastal area around the city of Kuching (Sarawak, Malaysia), where shallow intrusions of the Sintang igneous suite yield excellent paleomagnetic data that record a range of CCW rotated sites, as well as two weakly CW rotated sites (Schmidtke et al., 1990; Fuller et al., 1999). The average and maximum rotations for the entire data set are 18.9° CCW and 51° CCW, respectively. Using the absolute age determinations from the intrusions at four sites, Fuller et al. (1999) interpreted these data as recording progressively larger CCW rotations of a primary magnetization in increasingly older intrusions, 16.4 Ma to 25.8 Ma. Weakly CCW and CW rotated sites were considered to be remagnetized to the present field, but no analytical data were published in support of that interpretation.

The intrusions near Kuching can be grouped into two categories with respect to composition and age (Prouteau et al., 2001): calc-alkaline diorites (22.3–25.8 Ma) and adakitic microtonalities (14.6–6.4 Ma). The dates reported by Prouteau et al. (2001) are important because absolute ages can be assigned to the Kuching Quarry and Bukit Stabor sites, which were listed as Oligocene–Miocene by Schmidtke et al. (1990). An estimate for the absolute age of other sites can also be assigned on the basis of the composition of the intrusions sampled: calc-alkaline diorites (23.34 Ma) and adakitic microtonalities (11.2 Ma). In addition, red mudrocks of the Eocene Silantek Formation also show a range in CCW rotations (Schmidtke et al., 1990). The Silantek Formation is considered to have been deposited ca. 40 Ma (Hutchison, 2010), but may extend into the Early Oligocene (Hutchison, 2005) and we assign an age of 35 Ma, latest Eocene. A plot of age versus rotation (inset, Fig. 4B) shows that the amount of CCW rotation increases with age in the northwest Borneo domain. For the igneous rocks with CCW rotation the rate is 3.62°/m.y. At the equatorial latitudes of Borneo, this angular rate implies plate motion of ~4 cm/yr.

Several aspects of the data in the Kuching area merit discussion within the context of tectonic models incorporating 50° CCW of a rigid Borneo between 30 and 10 Ma.

1. The Kuching Airport and Kuching Quarry sites (12.2 ± 0.2 Ma, Prouteau et al., 2001) record 2.7° CW and 1.1° CCW rotations, respectively. Fuller et al. (1999) interpreted these weakly rotated sites as being remagnetized to the present magnetic field. However, these sites record

Figure 4. Sintang igneous rocks (filled polygons) and paleomagnetic sites (open circles) of the Kuching area, northwest Borneo domain (Schmidtke et al., 1990; Prouteau et al., 2001). Inset to upper right plots age versus rotation: black diamonds have absolute age determinations, gray diamonds have ages estimated based on composition of igneous rocks (see text for discussion), squares are sites in Kalimantan (Fuller et al., 1999), gray circles are red beds from the Silantek Formation, and dashed line is regression through the four sites near Kuching having absolute age determinations. CCW—counterclockwise.
much shallower inclinations (−2.1° and 2.8°) than that of the present field inclination near Kuching (−2°), which implies rotation about horizontal axes. Because the Kuching Airport and Quarry sites appear to be structurally disturbed, their declination data can also be interpreted as recording rotation to near the present field as an alternative to remagnetization.

2. The Airport and Kuching Quarry sites are ~10 km from the Bukit Stabor site. If the former sites are remagnetized, then remagnetization at the Airport and Kuching Quarry sites is a local event that occurred within the past 10 m.y.

3. Bukit Stabor (12.9 ± 0.3 Ma; Prouteau et al., 2001) records 8° CCW rotation. If CCW rotation ceased ca. 10 Ma, then the Bukit Stabor site suggests that rotation of Borneo ceased abruptly.

4. Gunung Serapi, the oldest site, shows the most rotation (28.8 Ma, 51° CCW), but has a low inclination (−1.2°) relative to that of its paleo-latitude, which should be similar to its present-day latitude if the interpretation of the West Kalimantan data is correct. The inclination at Gunung Serapi suggests rotation about an inclined axis, although Schmidtke et al. (1990) made no structural correction. We suggest that at least part of the observed rotation can be attributed to local deformation, as suggested for the Kuching Quarry and Kuching Airport sites.

5. Sites from Late Eocene to Early Oligocene (ca. 35 Ma) red beds in the upper member of the Silantek Formation are less rotated (maximum of 42° CCW) than the older Gunung Serapi site (51° CCW). This suggests that the Silantek Formation has rotated differentially CCW with respect to Gunung Serapi.

6. In relation to the Siburan site near Kuching, the dated igneous sites from Kalimantan (Fuller et al., 1999) appear to introduce a short-term reversal in the sense rotation between 16 and 19 Ma (Fig. 4B).

The northwest Borneo domain data clearly convey a sense of CCW rotation. In detail, however, the data suggest that the domain did not behave as a single rigid block. The northwest Borneo domain is along a northwest-southeast–striking early Tertiary suture, known as the Lupar line (Fig. 1), which represents a potential complicating factor when interpreting this domain’s paleomagnetic data. We suspect that some measured rotations in this domain reflect localized deformation related to reactivation of faults along this suture. Because the sampled intrusions are represented by only single sites, the hypothesis that some of the observed CCW rotations are related to minor shear zones could be tested by sampling multiple sites from individual intrusions.

Central and East Kalimantan

The central and eastern Kalimantan domain is in the Indonesian highlands of Borneo. Paleomagnetic data collected by multiple workers cover a larger area than the northwest Borneo domain (Figs. 3 and 5A). Flat-lying Pliocene–Pleistocene basalts yield reliable paleomagnetic data from 17 sites at 3 different locations more than 30 km apart that record nonrotated, but reversed, declinations with an average inclination close to that of the present field (Lumadyo et al., 1993). These locations provide an important control point when considering the timing and sense of rotation in other areas. The Sintang suite and older Eocene sites yield rotated and nonrotated sites. The average and maximum rotations are 15° CCW and 60° CCW, respectively (Lumadyo et al., 1993; Fuller et al., 1999; Moss et al., 1998). The overall sense and amount of rotation are similar to those observed in the northwest Borneo domain. The large range of rotations within and between locations having similar ages suggests that central and eastern Kalimantan did not rotate as a coherent rigid block (Fig. 5B).

In the Telen-Malnyu area, four closely spaced sites from the Sintang intrusions have age determinations that cluster tightly around 23 Ma, yet show rotations that range from 16° to 60° CCW (Fuller et al., 1999; Moss et al., 1997). The observed range in rotations between these sites could be attributed to differing degrees of remagnetization, as proposed by Fuller et al. (1999). The Telen-Malnyu sites are along the Bengalon fault zone, which is described as a complex set of interconnecting

Figure 5. (A) Map showing paleomagnetic sites of the central Kalimantan domain (Lumadyo et al., 1993; Moss et al., 1997; Fuller et al., 1999). Location names refer to nearby villages: Nakan (white triangles), Telen-Malnyu (gray triangles), Long (L.) Bagun (black square), Naga Ruan (white square); gray circles are sedimentary rocks. SFFZ—Sangkulirang fault; BFZ—Bengalon fault zone. (B) Plot of age versus rotation plot with symbols as in Figure 5A. CCW—counterclockwise.
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en echelon normal faults that form the boundary between the northern Kutei Basin and the Mangkalihat Peninsula (Cloke et al., 1999; Moss, 1998). Relatively steep inclinations at the Telen-Malnuy sites (18°–45°) are consistent with rotation from normal faulting. We consider that differential rotation owing to oblique slip within the Bengalon fault zone is an equally valid explanation for the observed range in the declinations at the Telen-Malnuy sites.

In the Nakan area, lava flows in the Sintang suite and Eocene units were sampled at eight locations (Lumadyo et al., 1993); the lava flows in the Nakan area have been dated as 14 and 22 Ma (van de Weerd et al., 1987), and we use the average of these two dates, 18 Ma, for the Nakan sites. Sites from the Nakan area data pass a regional fold test and display weak CW and CCW rotations; magnetite is the primary magnetic carrier (Lumadyo et al., 1993). Lumadyo et al. (1993) interpreted the data to record a non-rotated primary magnetization, whereas Fuller et al. (1999) suggested that the sites record pervasive remagnetization. Eocene sandstones from the Nakan area yield Cretaceous zircons (Moss et al., 1998). Because the onset temperature for annealing zircon (~200 °C) is lower than the Curie temperature of magnetite (580 °C), remagnetization of the Nakan area must be the result of a diagenetic (chemical) event rather than a thermal event. Chemical remagnetization of igneous rocks can be associated with low-grade metamorphism (Ahmad et al., 2001; Yo-ichero et al., 2000). Thin sections of the Nakan samples, however, show little to no alteration to support the hypothesis of a diagenetic and/or epithermal event (Lumadyo et al., 1993). The fact the Nakan sites pass a tilt test requires that remagnetization predated folding, which is related to Early to Middle Miocene inversion in the Kutai Basin (Cloke et al., 1999). Therefore, even if the Nakan sites have been remagnetized, they should still record a component of postfolding CCW rotation. Pending analytical evidence to the contrary, we believe that the Nakan sites represent folded nonrotated primary magnetization.

Palawan and Celebes Sea

Palawan, located north of Sabah and west of the main Philippine archipelago, consists of two blocks of contrasting geology juxtaposed across the Ulugan Bay fault (Figs. 1 and 3). Late Paleozoic and Mesozoic sedimentary rocks compose much of the north Palawan block, whereas the south Palawan block is dominated by the south Palawan ophiolite of Late Cretaceous–Eocene age (Raschka et al., 1985; Almasco et al., 2000). Although only 38 of 147 paleomagnetic sites are rated reliable (e.g., α95 < 20°), those sites provide a reasonable paleomagnetic record for both Palawan blocks. Mesozoic sediments from the north Palawan block have declinations spread to over 40° CW rotation, but only minimal differences in their inclinations, and are interpreted to have been remagnetized prior to opening of the South China Sea (ca. 32 Ma) and to record differential CW rotations about vertical axes during rifting (Almasco et al., 2000). The Espina basalts on the south Palawan block record rotated 65° CCW and have inclinations suggesting a paleolatitude near the present Celebes Sea (Almasco et al., 2000). The Celebes Sea also rotated CCW rotation in Late Eocene and Early Oligocene time (Shibuya et al., 1991); this led Almasco et al. (2000) to conclude that the Celebes Sea and south Palawan block shared a common rotational history. Fuller et al.’s (1999) suggestion that, although they record different paleomagnetic results, the north and south Palawan blocks have a common origin, is in agreement with Hinz and Schluter’s (1985) interpretation that Palawan region is underlain by stretched continental crust and that both the north and south Palawan blocks are parts of a microcontinent carried south by South China Sea seafloor spreading. These blocks are linked by a cover sequence of Late Cretaceous to Eocene quartz-rich turbidites having granitic and acidic volcanic rock fragments that record a South China Sea provenance (Suzuki et al., 2000). Therefore, both Palawan blocks appear to share an early tectonic history involving very strong CCW rotation followed by CW rotation during rifting of the South China Sea.

Sabah

The paleomagnetic record for Sabah is based on a preliminary study by Schmidtke et al. (1985) that was included in syntheses by Fuller et al. (1991, 1999). Although only five locations have reliable data and augmenting analytical work was not published, several important observations can be made (Fig. 3). A single site from a Late Miocene satellite stock (Kappa Quarry) of the Kinabalu pluton near the city of Kota Kinabalu shows weak (11°) CCW rotation (Fuller et al., 1999). Near the village of Telupid in central Sabah, Cretaceous chert from an ophiolitic assemblage record very strong (79°) CCW rotation; although not classified as reliable, associated spilitites also record strong (47°) CCW rotation. Along the coast near Kota Kinabalu, three sites from marine red mudstones in the Crocker Formation record strong (average 77°) CCW rotation. Although no specific data were presented, Fuller et al. (1999) commented that the associated Crocker sandstones are mostly remagnetized close to the present field, and that some sites have minor CW rotation.

GEOLOGICAL SUMMARY OF UNITS SAMPLED

Crocker Formation

The Crocker Formation is an assemblage of deep-water clastic rocks that includes the medium- to coarse-grained sandstones cored for this study. We obtained a sufficient number of cores from the Crocker Formation at 11 different locations to cover a wide geographic area (Fig. 2). At several additional locations along older road cuts (such as the Bukit Melinsung section of Lambiase et al., 2008), the unit was too weathered and argillaceous to collect intact cores.

There are two contrasting models for the paleogeographic setting of the Crocker Formation: (1) a basin-floor megafan of first-cycle sandstones derived from the Kalimantan domain (Crevello, 2001; van Hattum et al., 2006; Jackson et al., 2009), and (2) multiple, smaller, toe-of-slope fans derived largely from older members of the Rajang-Embaluh Group (Lambiase et al., 2008; Cullen, 2010). The Crocker Formation has a steep southeast regional dip, but is deformed locally into large-scale folds. Opposing limbs of individual folds were cored at four locations (Bukit Sepangar, Kota Kinabalu [KK], Kinabalu Industrial [KI], and Tenom). The Crocker Formation records two major episodes of deformation (Fig. 6) that we attribute to the Sarawak and Sabah orogenies, ca. 40 and 20 Ma, respectively.

The age of the Crocker Formation is poorly constrained. At the regional scale, Wilson (1964) assigned an Eocene–Early Miocene age for the formation. Recent studies suggest that the outcrops around Kota Kinabalu are Late Eocene in age (Lambiase et al., 2008; Cullen, 2010). We note that the strong rotation recorded in the Crocker mudstones has sense and magnitude similar to those recorded in older units at Telupid, south Palawan, and the Celebes Sea. Assigning an Oligocene to Early Miocene age for the red mudrocks of the Crocker Formation (ca. 25 Ma) implies rotation rate of 5.1°/m.y., considerably faster that the rate calculated for the northwest Borneo domain, 3.62°/m.y. Thus, the paleomagnetic data are consistent with the Late Eocene age for the Crocker Formation in the area of Kota Kinabalu.

Kudat Formation

The Early Miocene Kudat Formation crops out on the Kudat Peninsula within a series of northwest-southeast–striking thrust sheets (Tongkul, 1994, 2006). Near Kota Belud at the southwest end of the peninsula, where the Crocker Formation has been thrust over
Figure 6. Photographs of the Crocker Formation in the Kota Kinabalu area. (A) Maju East. (B) Bandar Sierra, 3 km east-southeast of Maju East. White lines highlight bedding and yellow arrows point stratigraphically upward. At least two episodes of compressive deformation (D1 and D2) are expressed in the Crocker Formation. At Maju East, a D1 syncline is recumbently folded (D2) to form an antiformal syncline. At Bandar Sierra, moderately plunging small folds (D1) have been cut by a younger thrust fault (D2). High-angle faults (f) may record a third deformational event.
the Kudat Formation, the structural grain changes nearly 90°. Despite poor outcrop exposures on the Kudat Peninsula, we cored four sites, including opposing limbs of an anticline. The site statistics are poor (Table 1). Although these data indicate 45° CCW rotation of a postfolding remanence, we stress that these data are included primarily for the possible interest of others, we stress that these data are included primarily for the possibility of northwest-southeast shear zones. Although the Crocker Formation was the principal unit sampled (12 locations), the end points of this transect included locations from the Kudat Formation (4 sites), the West Crocker Formation (3 sites), and Meligan sandstone (2 sites). Most locations have multiple sites and each site consists of ~8 directed 2.5-cm-diameter drill cores. At five locations the exposures were suitable for paleomagnetic study.

West Crocker Formation

The West Crocker Formation sandstones are fine- to medium-grained arenites that represent the coarser grained lateral equivalents of the Temburong Formation shales (Wilson, 1964). Although regional structural dip is steep to the southeast, the Temburong–West Crocker strata are complexly folded. The Sipitang-Tenom road, traversing the Crocker Ranges, is dominated by outcrops of Temburong mudrocks. Exposures of the West Crocker Formation along the coastal highway are too deeply weathered to extract intact cores. The Kampung Mua location is our only data point for the West Crocker Formation.

Meligan Sandstone

The Early Miocene Meligan sandstone crops out mainly in Brunei and Sarawak and consists of cross-stratified, well-sorted, coarse to medium quartz arenites that record deposition in shelf-edge to shallow-marine environments (Sandel, 1996; Hutchison, 2005). The Meligan sandstone is preferentially preserved in deeply eroded synclines and its contact with the Temburong is locally unconformable. The Meligan sandstone is considered to document a regression at the top of the Temburong Formation related to the proto-Champion delta (Sandal, 1996).

**Paleomagnetism of the Crocker Formation, NW Borneo**

**TABLE 1. SITE MEANS**

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<th>Dec (°)</th>
<th>Inc (°)</th>
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**Note:** All sites are sandstones. Dips >90° are overturned beds. NC—No characteristic remanent magnetization signal. PGMF—Present-day geomagnetic field (100 yr average). Calculated using National Oceanic and Atmospheric Administration National Geophysical Data Center web site (www.ngdc.noaa.gov/). Dec—declination; Inc—inclination; K—a measure of grouping; α95 is the 95% cone of confidence. Tilt dec and Tilt inc are values after structural correction. Tmax—the maximum temperature that a linear component could be identified on the orthogonal plots. N/N0—the number of specimens with direction versus the number of demagnetized specimens. TN—Tenom, KK—Kota Kinabalu.

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to confidently sample opposed anticlinal limbs to conduct tilt tests. To minimize the effects of tropical weathering and oxidation, our sampling program targeted fresh exposures from new housing and road construction.

Subsets of cores from each site were cut into standard paleomagnetic specimens (2.5 x 2.3 cm) and their natural remanent magnetizations (NRM) was measured using a 3-axis 2G Enterprises DC-SQUID cryogenic magnetometer housed in a magnetically shielded space at the University of Oklahoma. To isolate possible primary and secondary NRM components, our specimens were subjected to stepwise demagnetization: 174 specimens were thermally demagnetized in 35 steps to 700 °C; 36 additional specimens were demagnetized using alternating field (AF) techniques in 12 steps to 100 mT. The AF demagnetized samples tended to have nonlinear decay of NRM, making it difficult to isolate any stable remanent magnetization; therefore only thermally demagnetized specimens were subsequently analyzed. When subjected to thermal demagnetization, more than 98% of the specimens from the Crocker and Kudat Formations showed linear decay of NRM (Fig. 7), and their ChRM was isolated using the least squares method of Kirschvink (1980).

Site mean ChRM was obtained by averaging individual core specimen mean ChRMs with a maximum angular deviation of <15° using Fisher (1953) statistics. For sites from the limbs of single folds, the site means from both limbs were subjected to a fold test following the method of Enkin (2003). This fold test method determines the timing of ChRM acquisition relative folding and potentially provides critical constraints for the relative timing of deformation. Sites are deemed to pass a fold test if the site means are more tightly clustered after correcting for the structural tilt; they fail a fold test if the site means are better grouped in situ and become more scattered as the result of structural correction. Based on the outcome of the fold test, a location ChRM direction was obtained by averaging.

Figure 7. Orthogonal vector plots of thermally demagnetized specimens from the Crocker Formation. (A) Nexus (NX1). (B) Tenom (TN4). (C) West Crocker Formation (Kampong Mua, KM2). (D) Meligan sandstone (Sipitang location specimen-1, SP1). A and B show maximum laboratory unblocking temperatures of 340 °C and 420 °C for isolation of the characteristic remanent magnetization (ChRM), suggesting that pyrrhotite and magnetite are the magnetic remanence carriers, respectively. C and D show absence of a ChRM signal. White symbols—vertical component; black symbols—horizontal component; NRM—natural remanent magnetization.
Following the convention used by Fuller et al. (1999), only those site means with $\alpha_{95} < 20^\circ$ are deemed reliable. Dispersion caused by paleosecular variation of the geomagnetic field is an issue that should be addressed when assessing if a declination could due to tectonic rotation. Secular variation is at a minimum at low latitudes and multiple sites were collected over a large area to average the secular variation. In addition, if the rocks contain secondary magnetization, remagnetization processes commonly take a long enough time to average secular variations. If the ChRM is primary and the age of the rock unit is known, then the calculated directions give an estimate of the paleolatitude at acquisition. If the ChRM is secondary, then the age of remagnetization is critical for interpreting the structural history of that unit.

Selected core specimens (8) representative of the different rock formations were subjected to saturation isothermal remanent magnetization (SIRM) tests, determining the dominant magnetic minerals in each formation. An isothermal remanent magnetization (IRM) acquisition curve for each specimen was obtained by pulse magnetization in 26 steps to 2500 mT. Because magnetic minerals (e.g., magnetite, pyrrhotite, and hematite) acquire IRM at different rates and saturate over a range of specific field intensities, IRM acquisition curves provide information on the presence and relative amounts of the magnetic minerals in a specimen (Kruiver et al., 2001; Heslop et al., 2002, 2004). Analysis of the IRM acquisition curves was conducted using the IRMUNMIX 2.2 software program (Heslop et al., 2002) and cumulative log-Gaussian (CLG) analysis was performed using the IRM-CLG 1.0 (Kruiver et al., 2001) to model the different coercivity contributions (Heslop et al., 2004).

LOCATION RESULTS

The site statistics are tabulated in Table 1. The majority of our locations are within 10 km of Kota Kinabalu, where the averaged magnetic field for the past 110 years is declination (dec) 1.25°E, inclination (inc) –4.35° (Table 1). As previously noted, flat-lying Pliocene–Pleistocene basalts in central Kalimantan have similar small (reversed) declinations and low negative inclinations. Therefore, in discussion of our data, the present-day magnetic field is used the reference field.

Crocker Formation

The Belud (BL) location, a weathered road cut 50 km north of Kota Kinabalu, carried no stable remanence. This was the only such negative result from the Crocker Formation.

The TS car wash location (TS), a fresh quarry 30 km north of Kota Kinabalu, yielded a single site. Stable ChRM directions with maximum unblocking temperatures of 325 °C suggest that pyrrhotite is the magnetic remanence carrier (Table 1). The in situ location mean has dec 37.5° and inc 16.6°; respective tilt-corrected values are 55.5° and 43.4° (Fig. 8A).

Jalan Salaiman (JS) and Lok Kawi (LK) are single site locations; Jalan Salaiman is within Kota Kinabalu and Lok Kawi is 15 km south of Kota Kinabalu and occupies an intermediate geographic position relative to the southern Keningau and Tenom locations (Fig. 2). The maximum unblocking temperatures for specimens from sites JS1 (420 °C) and LK1 (340 °C) indicate that magnetite and pyrrhotite are the respective chief magnetic remanence carriers (Table 1). The Jalan Salaiman in situ location mean has dec 15.6° and inc –0.4°; respective tilt-corrected values are 19.6° and –3.4° (Fig. 8B). The Lok Kawi in situ location mean has dec 19.9° and inc 13.9°; respective tilt-corrected values are 22.9° and –8.3° (Fig. 8C).

The Nexus (NX) location is the westernmost of four locations (NX, KI, Bukit Sepanger [BS]),...
and KK) that traverse two folds 15 km north of Kota Kinabalu (Fig. 9A). The NX specimens show a linear decay indicating a single component of magnetization having a northern ChRM (Fig. 7A); maximum temperature ($T_{\text{max}}$) and IRM data indicate that pyrrhotite is the dominant ChRM carrier (Tables 1 and 2). The NX sites have $\alpha_{95} < 10^\circ$ (Table 1). The in situ site means have dec $10.9^\circ$ and $11.2^\circ$, and inc $13^\circ$ and $2.5^\circ$. The tilt-corrected site means have dec $68.3^\circ$ and $33.4^\circ$ and inc $44^\circ$ and $33.3^\circ$ (Table 1). The $\alpha_{95}$ of the in situ location mean is significantly lower than that for the tilt-corrected location mean, showing that the ChRM was acquired after tilting (Fig. 9B).

The KI location is an anticlinal fold with a steeply dipping overturned eastern limb (Fig. 9A). The location comprises 3 sites with acceptable $\alpha_{95}$ values. Unblocking temperatures ranged from 460 to 375 °C, suggesting that pyrrhotite and magnetite are the magnetic remanence carriers (Table 1). The KI in situ location mean has dec $16.1^\circ$ and inc $-0.4^\circ$; respective tilt-corrected values are $53.2^\circ$ and $-23.3^\circ$ (Fig. 9C). The in situ location mean has a significantly lower $\alpha_{95}$ indicating that ChRM acquisition postdates folding at this location. The red mudrocks exposed in the overturned limb of the KI anticline (Fig. 9A) represent the same Crocker Formation lithology that records $77^\circ$ CCW rotation (Fuller et al., 1999). Although we were unable to recover intact core specimens of the red mudrocks at the KI location and could not determine chief magnetic remanence carrier(s), Crevello (2001) reported that the red mudrock facies is hematitic. We suspect that hematite is the dominant magnetic mineral and the ChRM in the red mudrocks represents a pre-folding, possibly primary, signal.

The Bukit Sepanger (BS) location consists of 11 sites where more than 500 m of continuous stratigraphic succession is exposed (Fig. 10A). All sites have stable ChRM directions. The tight cluster of unblocking temperatures about a mean of 323 °C (Table 1) indicates that pyrrhotite is the magnetic remanence carrier. The respective in situ and tilt-corrected Bukit Sepanger location mean ChRM directions are dec $12.8^\circ$, inc $4.6^\circ$ and dec $35.5^\circ$, inc $17.2^\circ$. The $\alpha_{95}$ of the in situ location mean, 8.0, is significantly lower than that for the tilt-corrected
Bukit Sepanger sites are within the footwall of the age limit for timing ChRM acquisition. The kink fold offers a way place a lower (younger) ChRM acquisition. Establishing the age of the Sepanger location after making a structural perspective because the northwest strike of the Crocker Formation is nearly orthogonal the main Crocker Range and the Keningau Pass location. The results from the Keningau Valley location are reliable, and maximum unblocking temperatures (400 °C) indicate that magnetite and/or pyrrhotite are magnetic remanence carriers (Table 1).

The in situ location mean has dec 337.5° and inc 18.2°; respective tilt-corrected values are 340.8° and 11.4° (Table 1; Fig. 12B). In the absence of multiple sites for a structural correction, we prefer interpreting the CCW rotation at Keningau Valley as recording post-ChRM acquisition deformation similar to our other locations.

The Tenom (TN) location consists of four sites near the crest of the Tenom Pass in a road recently cut through the Crocker Range between Sipitang and Tenom. Sites TN1 and TN2 are from east-dipping limb and sites TN3 and TN4 are from the steeply west dipping forelimb of an asymmetric anticline, which is locally overturned (Fig. 13A). Of the four Tenom sites, three are deemed reliable. IRM data and maximum unblocking temperatures ranging from 310 to 420 °C indicate that pyrrhotite and/or magnetite are the magnetic remanence carriers (Tables 1 and 2). The respective in situ and tilt-corrected Tenom location mean ChRM directions are dec 331.4°, inc 5.9 and dec 333.1°, inc 0.9. The α95 of the in situ location mean is significantly lower than that for the tilt-corrected location mean (Fig. 13B). A fold test using the 3 reliable Tenom sites gave the best grouping of data at 32.1° ± 14.0° untilting, indicating that magnetization was acquired late synfolding to postfolding.

**West Crocker Formation**

The Kampong Mua (KM) location consists of three sites from a compact anticline along the Sipitang-Tenom road (Figs. 2 and 13A). Although the outcrop exposure was fresh and competent to core, none of the specimens analyzed gave stable magnetic remanence when thermally demagnetized (Fig. 7C). The IRM data indicate that hematite is present (Table 2). These results contrast with the Crocker Formation, which is dominated by pyrrhotite and magnetite in its magnetic mineralogy. Considering the fresh nature of this road cut location, the lack of a preferred magnetic orientation suggests that the hematite reflects primary deposition as a heavy mineral rather than in situ oxidation and/or weathering.

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### TABLE 2. MINERAL MAGNETIC DATA

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**Table Notes:**

- SI RM — saturation isothermal remanent magnetization in 10^3 A/m; B% is the mean remanence coercivity (in mT); DP is the half-width of the distribution (in mT).
- These mineral magnetic parameters were obtained from measured IRM acquisition curves, following Kruiver et al. (2001). Site abbreviations are those used in text.

Location mean, 14.6 (Fig. 10B), which indicates that the ChRM was acquired after tilting. During progressive untilting, optimal grouping for all 5 sites (Fig. 10C), which suggests that ChRM acquisition was late synfolding to postfolding. At the southeast end of this location, the Crocker Formation is locally overturned, forming a small kink fold (Fig. 10C). Sites BS7–BS11 are from a single bed in both the upright and overturned limbs of that kink fold. The ChRMs from the overturned limb (BS9–BS11) have negative inclinations, whereas sites from the upright limb (BS7–BS9) have positive inclination. Because the sites are within a single bed, the simplest explanation for these opposed inclinations is that the kink fold postdates ChRM acquisition. Restoring the overturned limb to the 86° southeast dip it had prior to development of kink fold results in positive inclinations for all 5 sites (Fig. 10C), which indicates that the kink fold postdates ChRM acquisition.

To test our kink-fold hypothesis, we recalculated the in situ location mean for the Bukit Sepanger location after making a structural correction for the kink fold, restoring it to it a prekink dip of 86° southeast. This test reduced the α95 value from 8.6 to 5.9 (Fig. 10D) and supports the hypothesis that kink folding postdates ChRM acquisition. Establishing the age of the kink fold offers a way place a lower (younger) age limit for timing ChRM acquisition. The Bukit Sepanger sites are within the footwall of a thrust fault that postdates tilting (Lambiasi et al., 2008). We interpret the kink fold and small thrusts observed at the location (Fig. 10C) to result from footwall deformation beneath the younger thrust fault. The Kota Kinabalu (KK) location consists of four sites from opposed limbs at the crest of a small upright anticline. The α95 values for the site means from this location are poor relative to the other locations along the NX-KK transect, a circumstance we attribute to a combination of localized crestal faulting and late-stage fluid flow, which is consistent with the postfolding ChRM acquisition from other limbs of the NX-KI-BS-KK folds.

The Keningau Pass (KG) location consists of two closely spaced sites from southeast-dipping outcrops exposed during construction of the Papar-Keningau road over the Crocker Range (Fig. 2). The Keningau Pass site means are reliable, and unblocking temperatures of 420 °C indicate that pyrrhotite and/or magnetite are the magnetic remanence carriers (Tables 1 and 2). The respective in situ and tilt-corrected Keningau location mean ChRM directions are dec 331.4°, inc 5.9 and dec 333.1°, inc 0.9. The α95 of the in situ location mean is significantly lower than that for the tilt-corrected location mean (Fig. 13B). A fold test using the 3 reliable Keningau sites gave the best grouping of data at 32.1° ± 14.0° untilting, indicating that magnetization was acquired late synfolding to postfolding.

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Overturned limb on secondary fold (Fig. 10C)

Figure 10. (A) Outcrop photo of Bukit Sepanger (BS) section. (B) Stereoplots showing in situ and tilt-corrected site mean and location mean characteristic remanent magnetizations (ChRMs) of the BS location. (C) Outcrop photo of overturned kink fold at Bukit Sepanger; small white circles show sites BS7–BS11. Posted to the right are inclinations; values with solid arrows are the post-kink corrected inclinations of the overturned limb. (D) Stereo plot for the BS location ChRM mean and $\alpha_{95}$ values after the overturned limb was restored to its pre-kink southeast dip.
Meligan Sandstone

The Sipitang (SP1, SP2) locations do not carry stable magnetic remanence when thermally demagnetized (Fig. 7D). The IRM signal from the Meligan sandstones shows that pyrrhotite is present (Table 2); we interpret as a primary accessory heavy mineral. At the SP2 location, the Meligan was so tightly cemented that it was necessary to collect an oriented block sample for coring with a drill press in the laboratory; this suggests that it has not been affected by surficial oxidation.

DISCUSSION

This study represents the most comprehensive paleomagnetic sampling program undertaken in Sabah to date; 11 of 15 locations along a 250 km northeast-southwest transect have reliable site means. Our results present us with four straightforward observations. We believe, however, that the paleomagnetic database is not yet sufficient to draw tightly constrained conclusions integrated within a regional tectonic framework. Therefore, we direct our discussion toward framing testable hypotheses drawn from our observations, which if answered should allow more rigorous tectonic models to be advanced.

Pervasive Remagnetization of the Crocker Sandstones

Locations having reliable ChRM site means recorded declinations and inclinations that are distinctly different from the present-day geomagnetic field (Table 1). For example, the mean ChRM direction derived from the 19 reliable sites around Kota Kinabalu (dec 13.39°, inc

Figure 11. (A) Outcrop photo of crest of Kota Kinabalu (KK) location anticline; circles are site locations. (B) In situ and tilt-corrected specimen and location means, characteristic remanent magnetizations (ChRMs), and $\alpha_{95}$ values for the KK anticline location.
3.22°) records a relative CW rotation with a positive rather than negative inclination. Our data demonstrate that the Crocker Formation sandstones record an older remagnetization event, rather than carrying the signal of the present-day field as was suggested by Fuller et al. (1999; commenting on their unpublished data). The widespread geographic coverage of our locations suggests that remagnetization was a regional event. Apatite fission track and vitrinite reflectance data indicate that maximum burial temperatures for the Crocker Formation were ~150–200 °C (Hutchison et al., 2000; Anuar et al., 2003). In thin section, the Crocker Formation sandstones lack quartz overgrowths and sutured grain contacts that would indicate relatively deep and hot maximum burial conditions. These paleotemperature indicators suggest that the burial temperatures never exceeded the Curie temperature for either pyrrhotite or

Figure 12. Stereoplots showing in situ and tilt-corrected specimen mean characteristic remanent magnetizations (ChRMs) and $\alpha_{95}$ values. (A) Keningau Pass (KG) location. (B) Keningau Valley (KGV) location.

Figure 13. (A) Cross section from Sipitang (SP) to Tenom (TN) (modified from Wilson, 1964; Cullen, 2010) through the SP, Kampong Mua (KM), and TN locations. (B) Stereoplots show in situ and tilt-corrected site mean characteristic remanent magnetizations (ChRMs) and $\alpha_{95}$ values for the TN location. Disharmonic folding in the Temburong Formation is schematically depicted, but is in accordance with field observations.
magnetite. Crocker sandstones showed a single linear decay trend during thermal demagnetization, indicating a single event (Fig. 7).

The SIRM data from the Crocker sandstones show that both pyrrhotite and magnetite are present (Table 2) and the range in Tmmax (280–450 °C) suggests that both phases may carry the ChRM (Table 1). In considering these observations in relation to time-temperature remagnetization curves for magnetite and pyrrhotite (Dunlop et al., 2000), we favor interpreting the ChRM in the Crocker Formation sandstones, particularly for pyrrhotite, as a chemical (diagenetic) rather than thermal event. A number of chemical mechanisms have been proposed for the origin of the ChRMs that reside in pyrrhotite and magnetite in sedimentary rocks; pyrrhotite mechanisms include authigenesis caused by preexisting magnetite reacting with pyrite during burial metamorphism under reducing conditions (Gillet, 2003), oxidation of pyrite (Salmon et al., 1988), and thermochemical sulfate reduction (Peirce et al., 1998). These mechanisms can be related to such processes as migration of hydrocarbons (Machal and Burton, 1991), diagenesis of gas hydrates (Housen and Musgrave, 1996), and release of pore fluids (Urbat et al., 2000). Late-stage remagnetization by the diagenetic formation of sulfide-bearing minerals, such as pyrrhotite, is documented on the island of Sakhalin and may be related to migration of hydrocarbons (Weaver et al., 2002). Magnetite ChRMs can be explained by burial diagenetic mechanisms such as maturation of organic matter (Banerjee et al., 1997; Blumenthal et al., 2004) and clay diagenesis (Katz et al., 2000), or by fluid migration events (Elmore et al., 1999, 2001). In light of the orogenic setting of northwest Borneo, we attribute acquisition of the ChRM signal in the Crocker Formation sandstones as the product of large-scale fluid flow in a foreland basin, as has been documented in similar settings elsewhere (e.g., Elmore et al., 2001; Enkin, 2003). Our site mean declinations are all northward with shallow inclinations from the Crocker Formation, indicating that they record normal polarity magnetization. Because the late Cenozoic is a time of rapidly alternating normal and reversed polarity states, we consider crystallization of the phases carrying the ChRM to have occurred in a relatively short interval, 1–2 my.

It is remarkable that the red mudrocks of the Crocker Formation in the Kota Kinabalu area show strong CCW rotation (Fuller et al., 1991), whereas the mean paleomagnetic direction derived for the sandstones around Kota Kinabalu (JS, LK, NX, K1, BS, and KK in Fig. 2) shows weak CW rotation. As a working hypothesis we propose that the ChRM in red mudrocks preserves an older, probably primary, magnetization that was not reset by expelled foreland basin fluids owing to the impermeable nature of the Crocker Formation mudrocks. If so, the amount of CCW rotation in the mudrocks is even greater than reported when corrected for the younger CW rotation recorded in the Crocker sandstones. The strong CCW rotations observed in Eocene and older units in south Palawan, the Celebes Sea, and central Sabah (Fig. 3) lead us to interpret the paleomagnetic data from the Crocker Formation as indirectly supportive of an Eocene age for the Crocker Formation.

No ChRM Signal in the West Crocker and Meligan Sandstones

In contrast to the Crocker Formation, neither the West Crocker nor Meligan sandstones yielded a ChRM signal, even though the IRM data indicate that hematite and pyrrhotite, respectively, are present. The Kampong Mua and Sipitang samples are from fresh outcrops that lacked the argillaceous weathering profile that characterized the Belud location, the only other location that lacked a ChRM signal. We tentatively interpret the West Crocker and Meligan sites as never having acquired a ChRM signal, rather than as having acquired such a signal and subsequently having it obliterated by later events such as weathering. We acknowledge that, owing to the limited number of sites in these units, this interpretation should be tested with additional sampling and analyses.

The supposition that the Meligan and West Crocker Formations were not affected by the same fluids that pervasively remagnetized the Crocker Formation is consistent in treating these units as a tectonostratigraphic element that is distinctly different from the Crocker Formation (Fig. 2). From this viewpoint, the Crocker Formation was thrust over the foreland basin sediments of the Sarawak orogeny (i.e., West Crocker and Temburong Formations) along such faults as the Tenom fault during the Sabah orogeny (Figs. 2 and 13A; Cullen, 2010). Because the Sabah orogeny does not appear to be primary, magnetization that was not reset by expelled foreland basin fluids owing to the impermeable nature of the Crocker Formation mudrocks. If so, the amount of CCW rotation in the mudrocks is even greater than reported when corrected for the younger CW rotation recorded in the Crocker sandstones. The strong CCW rotations observed in Eocene and older units in south Palawan, the Celebes Sea, and central Sabah (Fig. 3) lead us to interpret the paleomagnetic data from the Crocker Formation as indirectly supportive of an Eocene age for the Crocker Formation.

Age of ChRM Acquisition

We treat the Crocker Formation as Late Eocene in age (albeit with a range of uncertainty, 35 ± 5 Ma), similar to the age of the red beds in the Silantek Formation (northwest Borneo domain). Remagnetization of the Crocker Formation sandstones generally postdates folding, although tilt tests from the Tenom and Bukit Sepanger locations suggest remagnetization could be a late synfolding. Working with a relatively small, but extremely well exposed outcrop at Bukit Sepanger, Lambiase et al. (2008) documented two episodes of folding. The earliest episode, D1, records syndepositional folding in an active deep-water fold-thrust belt during generation of the large-scale folds of the NX-KK cross section (Fig. 9A). During the second episode of deformation (D2), the D1 folds were recumbently. The east-dipping limb of our Bukit Sepanger sites has been interpreted as being in the footwall of a younger (D2) thrust fault (Lambiase et al., 2008). Strong D2 deformation cutting across earlier D1 structures is also observed at Bandar Sierra, 3.5 km east of Bukit Sepanger (Fig. 6B). In Cullen (2010), this earlier phase of deformation was attributed to the Late Eocene to Early Oligocene Sarawak orogeny. The structural relations at Bukit Sepanger offer the possibility for establishing the relative timing of remagnetization, if the ChRM signal was acquired prior to the second episode of deformation and if the age of the second deformation can be established.

As shown earlier, restoration of the overturned limb of the kink fold at Bukit Sepanger improved the pre-tilt location mean (Fig. 10D) and restored the negative inclinations (BS9–BS11) back to the positive inclinations that characterized the site (Fig. 10C). This suggests that development of the kink fold postdates ChRM acquisition. During our reconnaissance program, block samples collected from overturned beds at 2 sites from Maju East, 500 m east of Bukit Sepanger, yielded reliable site means (Table 1; Fig. 14B) that we initially considered to record extremely strong CCW rotation, similar to the Crocker Formation red mudrocks. Subsequent to our full field program, the Maju East site was further cleared for additional housing, exposing an antiformal syncline that records large-scale recumbent refolding of the Crocker Formation (Fig. 6A). This new exposure led us to reconsider our original interpretation at the Maju East location in terms of refolding during D2. Although we do not know the precise orientation of the D2 fold axis, and therefore cannot correctly restore the lower limb of the recurrent fold at the Maju East site, several lines of evidence suggest that the D2 fold axis was subhorizontal. First, outcrop patterns of long linear ridges and the gentle plunge of fold axes (our observations, and map from Crevello, 2001) suggest that tilting is minor. Second, because southwest to northeast paleoflow directions (reviewed by Hutchinson, 2005) are nearly orthogonal to regional
Figure 14. (A) Outcrop photo of Maju East location showing large load casts on overturned limb of antiformal syncline. (B) Stereoplot shows in situ mean characteristic remanent magnetizations (ChRMs) with a notional structural correction for D2 deformation assuming a horizontal fold axis. (C) Horizontal to gently plunging flute marks and load casts in Crocker Formation sandstones.
shortening (southeast-northwest), the amount of plunge on folds can be estimated from the inclination of flute marks and load casts. Over the entire study area, including Maju East, these features plunge gently (Fig. 14C). Our inclination data are also consistent with minimal post-ChRM tilting. Using a horizontal fold axis as a first-order approximation for unfolding D2, the Maju East data restore to a pre-D2 CW rotation similar to that observed at Bukit Sepanger (Fig. 14B), although with larger declinations and inclinations.

We cannot put an absolute age on the timing of D2. It is observed at several locations in the Kota Kinabalu area, suggesting that it not a local event confined to Bukit Sepanger. In the shallow offshore, immediately west of our study area, seismic data (Cullen, 2010, figs. 6, 11, and 23 therein) show that the shallow regional unconformity (ca. 8.2 Ma) is virtually undeformed, which puts a lower limit on D2. In contrast, the section beneath the deep regional unconformity is strongly folded. Although the pre–deep regional unconformity phase of the Sabah orogeny represents a good candidate for the relative timing D2 (between 22 and 15 Ma), we indicated here that the Sabah orogeny did not appear to produce pervasive remagnetization. Therefore, we must also consider D2 as a continuation of the Sarawak orogeny, a strong possibility in light of late-synfolding ChRM acquisition indicated at Tenom and Bukit Sepanger. The preponderance of evidence suggests that remagnetization of the Crocker Formation sandstones occurred between 15 and 35 Ma, that is, between development of the deep regional unconformity and the waning stages of the Sarawak orogeny (Figs. 2 and 15).

**CW and CCW Rotations Observed**

In contrast to the CCW rotations that dominate West Kalimantan, northwest Borneo, central Kalimantan, south Palawan, and the older units in Sabah, both CW and CCW rotations are observed in the Crocker Formation (Fig. 15). The different polarities in rotations are not randomly distributed, but rather can be grouped into three discrete geographic domains (Fig. 16). In the Kota Kinabalu area, the Crocker Formation sandstones record an average of 12° CW rotation. It is interesting that a single site from a Late Miocene (8.2 Ma) granite near Kota Kinabalu

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**Figure 15.** Plot of rotation versus age for all data (this study; Fuller et al., 1991, 1999; Lumadyo et al., 1993; Schmidtke et al., 1990). Dashed vertical lines show uncertainty in the age of the Crocker Formation; open dashed green circles indicate age of sandstones with filled green circles indicating our best estimate for the age of characteristic remanent magnetization acquisition. CCW—counterclockwise; CE—central eastern; SP—south Palawan; NP—north Palawan; NWB—northwest Borneo; SW Kal—southwest Kalimantan.
shows 11° CCW rotation (Fuller et al., 1999); this could be related to the Meliau episode of the Sabah orogeny. If additional sampling confirms that Late Miocene CCW rotation occurred over a larger area of the pluton, then it would imply that the Crocker sandstones in the Kota Kinabalu domain may have actually undergone 23° CW rotation, consistent with the extrusion-collision model for opening the South China Sea. Near the Keningau Pass area (KG1 and KG2), the Crocker Formation sandstones also show mild CW rotation similar to that of the Kota Kinabalu area, indicating a large domain of CW rotation. South of the KG1 and KG2 locations, however, Crocker sandstones from the Tenom and Keningau Valley locations record a change in the polarity of rotation, showing moderately strong CCW rotation. How far this CCW rotated domain extends to the southwest is not known, due to lack of sampling; further work is needed.

The data from the Kudat Peninsula, although of marginal quality, indicate fairly strong (46°) CCW rotation that appears to postdate folding of Oligocene to Early Miocene sandstones. An Early Miocene or younger age CCW rotation of the Kudat Peninsula is problematic not only to the data around Kota Kinabalu, but also with respect to the data indicating that south Palawan’s CCW rotation was concluded by the Oligocene (Almasco et al., 2000). If accepted at face value, the data imply that these areas moved independently at different times.

CONCLUSIONS

Reliable ChRM measurements from Cenozoic sandstones of the Crocker and Kudat Formations at 12 locations along a 250 km northeast-southwest transect on the northwest side of Sabah, Malaysia, show that these sandstones are pervasively remagnetized. Rock magnetic analyses indicate the ChRM signal in the Crocker Formation sandstones resides in pyrrhotite and magnetite. Fold tests at five locations show that ChRM acquisition postdates folding. Sandstones from the Temburong–West Crocker and Meliggan units lack stable remanence, suggesting that these units had a different diagenetic history than the Crocker Formation sandstones.

Placing constraints on the timing for ChRM acquisition is problematic. A mean paleomagnetic direction using 6 locations in the Kota Kinabalu area indicates that the Crocker sandstones record 12° CW rotation that postdates folding related to the Sarawak orogeny (D1). A second episode of deformation (D2), recorded at Bukit Sepanger, Maju East, and Bandar Sierra, appears to postdate ChRM acquisition. D2 deformation was sufficiently intense to recumbently fold the D1 (pre-ChRM) folds.
Paleomagnetism of the Crocker Formation, NW Borneo

Placed within a regional geological context and previous paleomagnetic studies, we suggest the following sequence of events. An early episode (before 35 Ma) of strong regional CCW rotation, recorded in the red mudrocks of the Crocker Formation, ended with the Sarawak orogeny, during which the Crocker Formation was strongly deformed (D1) and its sandstones pervasively remagnetized during regional fluid expulsion. Owing to their impermeable nature, mudrocks of the Crocker Formation were not remagnetized during the Sarawak orogeny. A younger episode of deformation (D2) that postdates ChRM acquisition in the Crocker sandstones may represent an early (ca. 15–22 Ma) phase of the Sabah orogeny or the waning late stages of the Sarawak orogeny (ca. 35 Ma). Therefore, we interpret that acquisition of the ChRM signal in the Crocker sandstones around the Kota Kinabalu area occurred between 15 and 35 Ma. Limited data from the West Crocker and Meligen units indicate that the Sabah orogeny had little effect with respect to remagnetization.

Paleomagnetic data from the Crocker and Kudat sandstones can be grouped in three large-scale domains on the basis of differences in the direction, amount, and timing of rotation. The Kudat domain shows moderate CCW rotation that appears to postdate folding of Early Miocene sediments. In the central domain (Kota Kinabalu to Keningau Pass) minor CW rotation occurred between 15 and 35 Ma, and could be attributed to opening of the South China Sea. The southwest domain (Tenom and Keningau Valley) records late synfolding to postfolding ChRM acquisition and moderate CCW rotation.

The opposed sense of rotation between the central and southwest domains is problematic for interpreting CW rotation of the central domain in terms of opening of the South China Sea. The minor CCW rotation at the single site from the Late Miocene Kappa Quarry stock (Fuller, 1999) adds further complexity to defining the region’s rotational history because it suggests local overprinting of younger rotation related to the Meliai orogeny.

We consider the present data set insufficient to support little more than speculation with respect to interpreting the precise boundaries and origin of the different rotated domains in Sabah in context of a detailed tectonic framework. We believe, however, that the full regional data set (Figs. 3 and 15) is sufficiently robust to support two broad conclusions regarding the region’s tectonic evolution. First, in accord with all earlier studies, Sabah, along with the entire region, rotated CCW prior to 30 Ma. Second, the younger CW and CCW rotations are too complex to reconcile with models that show the entire island of Borneo and south Palawan rotating CCW as a rigid block between 30 and 10 Ma. Instead the data imply that strain has been partitioned in a complex manner with several overprinting episodes of deformation. The present data, including regional geological mapping and age determinations, are not sufficient to resolve the manner in which strain has been partitioned. However, the recovery of reliable paleomagnetic data over a wide area of Sabah should encourage workers to collect additional paleomagnetic data to help resolve remaining structural, tectonic, and diagenetic questions.

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Paleomagnetism of the Crocker Formation, NW Borneo


