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A preliminary Neogene paleomagnetic data set from Leyte and its relation to motion on the Philippine fault

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Abstract

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Leyte Island is bisected by the left-lateral Philippine fault. Paleomagnetic samples were collected from nineteen lava flows in Leyte and nearby islands to the north. The data collected from these sites were combined with previously reported results from northeastern Mindanao. The paleomagnetic data from Neogene rocks within or very near the Philippine fault zone on Leyte, Mindanao, Biliran, Maripipi, and Genuruan Islands fall into two populations. Seventeen late Neogene sites (fourteen normal polarity and three reversed polarity) yield a mean direction $D = 358.9°$, $I = 20.1°$ ($\alpha_{95} = 6.6°$, $k = 30.1$) and a paleomagnetic pole $\lambda = 88.9°$N, $\phi = 12.5°$E ($A_{95} = 4.8°$, $K = 56.1$). Eight early Neogene sites (three normal polarity and five reversed polarity) give a mean direction $D = 23.2°$, $I = 13.9°$ ($\alpha_{95} = 9.3°$, $k = 36.2$) and a paleomagnetic pole $\lambda = 66.5°$N, $\phi = 220.5°$E ($A_{95} = 7.1°$, $K = 62.0$). The late Neogene pole is indistinguishable from Plio-Pleistocene poles from the Philippines, Taiwan, and Vietnam, and the late Miocene pole of the central Philippines suggesting there have been no significant rotations or translations of this region with respect to other Southeast Asian regions during the past 5 M.y. The early Neogene paleomagnetic pole is statistically indistinguishable from the middle to early Miocene pole of the central Philippines. The early Neogene pole is statistically distinguishable from early Miocene pole of Marinduque Island (Philippines) as well as the late Miocene pole of the central Philippines and the Plio-Pleistocene pole of the entire Philippines. This preliminary paleomagnetic data set suggests that Leyte and adjacent islands to the north have been a portion of the same tectonic block as northeastern Mindanao, Cebu, and western Panay since early Neogene. There are also no paleomagnetically detectable fault-related rotations associated with the Philippine fault given the resolution of this data set. No consensus exists as to the amount of offset or the age of inception of the Philippine fault. The 110 km offset between ophiolitic basement in northeast Leyte and that in southwest Leyte suggests this amount of left-lateral displacement has occurred along the Philippine fault since the middle Tertiary. In contrast to data from continental regions, no shear-related rotations are found associated with the Philippine fault. This observation suggests that the hot, immature, transitional island arc/continental crust of the Philippine region deforms differently in response to shear than well developed continental crust.

Introduction

Leyte Island in the central Philippines (Fig. 1) is elongate in a NW–SE direction, parallel to the left-lateral Philippine fault which bisects the island. Although seismic observations do not clearly delineate the fault (Cardwell et al., 1980), offset streams, airphoto investigations (Allen, 1962), and

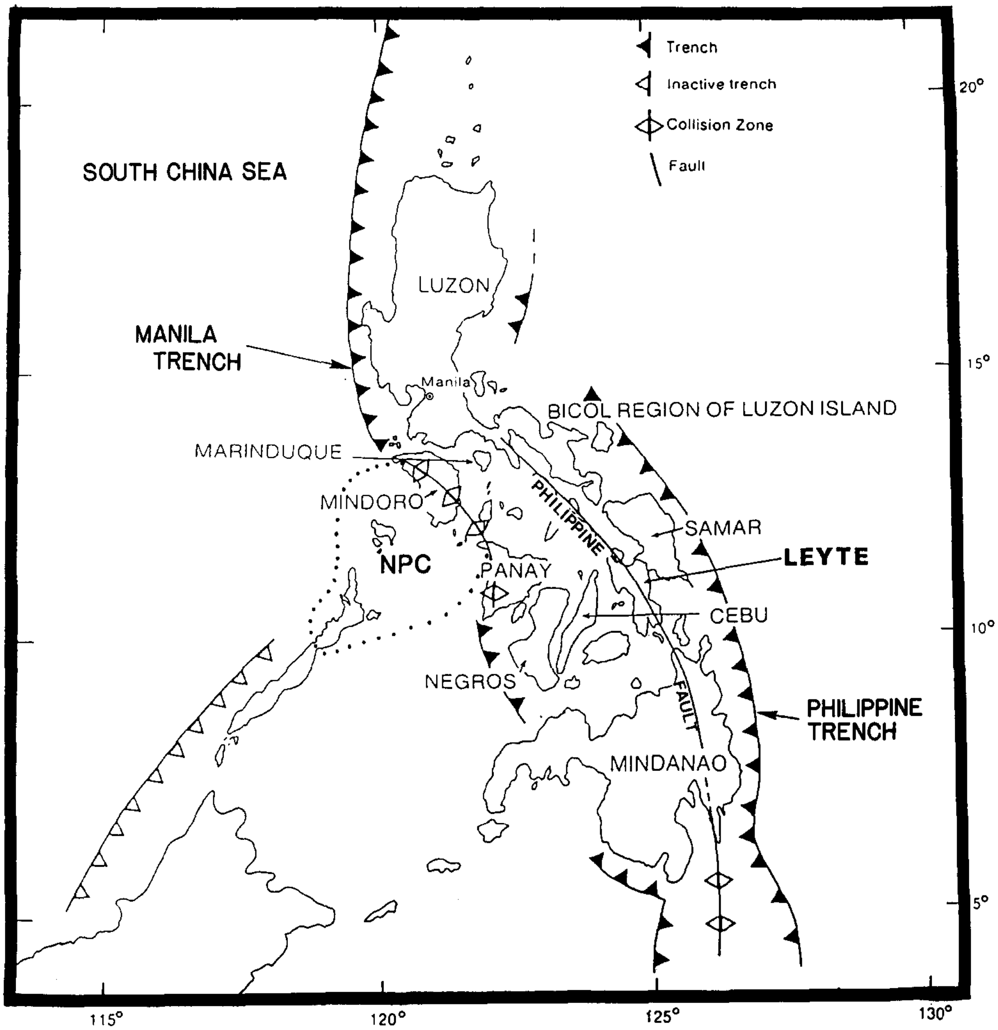


Fig. 1. Simplified tectonic map of Philippine Region. Samples reported in this study are from Leyte Island in the central Philippines. The island is bisected by the left lateral Philippine fault. *NPC*—North Palawan microcontinent.

local geologic mapping (Barcelona, 1980; Bayrante, 1981; Aquino et al., 1983) clearly indicate that the fault cuts through central Leyte. Hamilton (1979) questioned whether or not the Philippine fault is presently active in Mindanao. However, focal mechanism solutions showing left-lateral strike-slip motion in the southern Bicol region (Cardwell et al., 1980) and microseismic activity along the fault in central Leyte (Philippine National Oil Corp., pers. commun., 1985) suggest the fault is active along much of its trace.

Like much of the rest of the Philippines, Leyte is composed of middle to late Tertiary and Quaternary island arc-related volcanic and volcaniclastic rocks intercalated by pyroclastic rocks and limestones. The volcanic rocks on Leyte are mostly middle to late Tertiary hornblende pyroxene andesite flows with occasional dacites and basalts. The islands to the north of Leyte (Biliran, Maripipi, and Genuruan Islands; Fig. 2) are also composed of hornblende pyroxene andesite and basaltic andesite volcanic rocks as well as reefal limestones (Cole, unpublished field notes, 1985; Philippine National Oil Corporation petrographic analyses, 1985). Stratigraphic relations with sedimentary rocks suggest the volcanic rocks are Pliocene in age (Espiritu, 1981). The fact that these volcanic rocks outcrop along much of the trace of the Philippine fault in Leyte and on the small islands to the north suggests a causal rela-

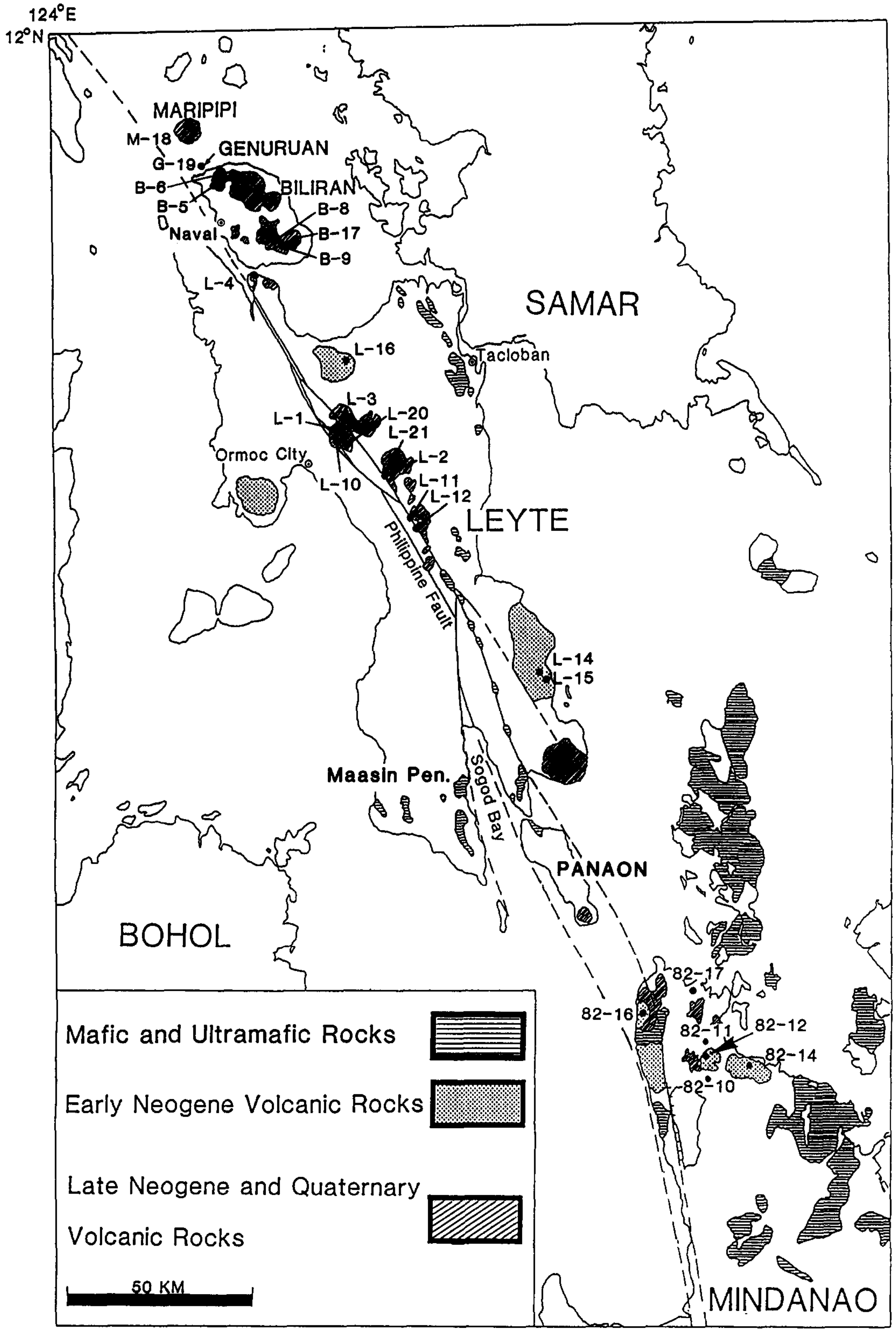


Fig. 2. Map of Leyte and smaller surrounding islands. Location of sites reported in this study (Table 1) are shown. The locations of outcrops of mafic and ultramafic rocks and late Neogene and early Neogen volcanic rocks are also shown on figure. Mafic and ultramafic outcrops in Samar were excluded from the figure.

tionship between faulting and volcanism. However, the lack of good age-control and detailed structural observations limits any conclusions about the nature of this relationship.

On Leyte, these Tertiary and younger volcanic rocks overlie basement rocks consisting of serpentinites, schists, mafic plutonic rocks, and undifferentiated ultramafics (Bayrante, 1981). These mafic and ultramafic rocks outcrop in northeastern Leyte northwest of the city of Tacloban, in central Leyte within the Philippine fault zone, and in southern Leyte on the Maasin Peninsula (F. Florendo, pers. commun., 1984) and the eastern coast of Sogod Bay (J. Cole, unpublished field notes, 1985). Exposures of mafic and ultramafic rocks were also noted along the northern coast of Panaon Island southwest of Leyte (J. Cole, unpublished field notes, 1985).

No paleomagnetic data have previously been reported from Leyte. However, paleomagnetic investigations have been carried out on other islands in the central portion of the Philippines (Noritoni and Almasco, 1981; McCabe et al., 1982a, 1985, 1987) and from Luzon and Marinduque islands in the northern portion of the archipelago (Hsu, 1972; DeBoer et al., 1980; McCabe et al., 1982b, 1987; Fuller et al., 1983). Data from the islands of Marinduque, Mindoro, Panay, and Negros support an early to middle Miocene collision of the North Palawan microcontinental fragment (*NPC* in Fig. 1) with a subduction zone along the western side of the central Philippines. Late Oligocene to middle Miocene data southeast of the collision site in Panay show 20° of clockwise rotation (McCabe et al., 1982a), which is consistent with early to middle Miocene data from Cebu and northeastern Mindanao (McCabe et al., 1987). In Marinduque, Oligocene to middle Miocene sites northeast of the impinging continental fragment exhibit approximately 45° of counterclockwise rotation (Hsu, 1972; Fuller et al., 1983; McCabe et al., 1987). Similar results are also found in south-central Luzon (J. Almasco, pers. commun., 1985). Late Miocene and Plio-Pleistocene directions from Marinduque, Mindoro, northeastern Mindanao, Cebu, as well as northern Negros are indistinguishable from the present dipole field direction (McCabe et al., 1982b, 1987).

Although the above discordant declination values have been related to a middle Miocene collision along the western edge of the Philippine arc, workers in other regions have shown that discordant paleomagnetic directions can result from tectonic events other than collisions. For instance, discordant declination values can also result from the rotation and translation of small coherent crustal fragments or larger microcontinental blocks within a transcurrent fault zone. This zone may be a region of distributed shear where rotations of crustal fragments within the fault zone are accommodated by similarly rotating antithetic strike-slip faults (Beck, 1976, 1980; Luyendyk et al., 1980, 1985; Ron et al., 1984).

This study is a preliminary paleomagnetic investigation carried out on Neogene volcanic rocks collected from the island of Leyte, as well as the adjacent islands of Biliran, Genuruan, and Maripipi to the northwest. The similar Tertiary stratigraphy of Panay, Cebu, northeastern Mindanao, and Leyte (McCabe et al., 1985) and proximity of the islands suggest that Leyte may be part of the same tectonic unit. Paleomagnetic directions from a late Miocene site (backreef limestone) and five early Miocene sites (two pelagic limestone horizons, two basalt flows, and one dacite flow) within or in close proximity to the Philippine fault zone in northeastern Mindanao (McCabe et al., 1987) were combined with the data of this investigation. We believe it is justifiable to include these Mindanao data for three reasons. First, this portion of Mindanao is proximate to Leyte (~ 60 km SE). Second, the sites in Mindanao are located within or adjacent to the Philippine fault zone. And third, the ages of the rocks from which the Mindanao samples were collected are the same age as samples collected in Leyte.

The purpose of this study was to look for shear-related rotations assoicated with motion on the left-lateral Philippine fault. As stated above, late Miocene and younger rocks from the central Philippines are indistinquishable from the present dipole field direction. Since Leyte and northeastern Mindanao are transected by the left-lateral Philippine fault, late Miocene and younger rocks within or very near the fault zone could show paleomagnetic evidence for sinistral shear-related rotations and translations. This preliminary study was an attempt to utilize paleomagnetic techniques to discern strike-slip related crustal movements within the Philippine fault zone in order to gain insight into the amount of past activity as well as the age of inception of the fault. The paleomagnetic directions determined from Leyte, Biliran, Maripipi, and Genuruan Islands also enhance the late Tertiary paleomagnetic data base for the central Philippines.

Philippine fault zone

Prior to the study of Allen (1962), no consensus existed as to whether or not the Philippine fault represented a significant regional tectonic feature or was even an active sinistral transcurrent fault. Allen (1962), using aerial photographs and limited field geologic observations, proposed that the Philippine fault zone was indeed a physiographically and structurally prominent feature. He further suggested that Quaternary movement along the fault has been dominated by sinistral transcurrent motion as evidenced by offset streams and stream gravels. Allen also stated that the pronounced linearity of the fault suggests that horizontal displacement has been the predominant motion throughout its history. Finally, Allen noted that the parallelism and proximity of the Philippine fault zone to the Philippine trench indicates a causal relationship between the two.

Rutland (1968) and Barcelona (1980) utilized not only aerial photography but also more extensive geologic field mapping to study portions of the Philippine fault zone. Rutland concentrated on the fault zone in southeastern Luzon. He suggested that two episodes of faulting has occurred; late Miocene movements along N–S faults, and Plio-Pleistocene motion along north-northwesterly faults. Rutland further reported that movements were primarily of a dip-slip nature, and saw no structural evidence to support any major post-Miocene strike-slip movements. However, Rutland admitted the possibility of earlier strike-slip motion along the fault zone. Barcelona (1980) agreed with Rutland (1968) that motion along the Philippine fault zone was predominantly left-lateral horizontal slip with a relatively small amount of displacement (at most several kilometers) during the Neogene. Barcelona also suggested that the fault may have originated in early Eocene time.

Several workers (Allen, 1965; Kaneko, 1966; Katili, 1970) have noted the presence of major transcurrent faults on overriding plates in zones of plate convergence. Fitch (1972) developed a model in which oblique convergence between lithospheric plates results in the formation of a nearly vertical transcurrent fault on the overriding plate parallel to the plate margin. Fitch's (1972) model related oblique, west-northwesterly subduction of the Philippine Sea plate beneath the Philippines to the development of the Philippine fault. Other workers (Karig, 1973; Acharya, 1980) suggested that slip along the Philippine fault developed in response to those stresses, generated by movement between the Eurasian and Philippine Sea plates, that are not accommodated by underthrusting in the Philippine trench. Hamilton (1979) believed that the Philippine fault is merely the result of internal shearing deformation. Cardwell et al. (1980) argued that the fault represents a combination of Hamilton's model and Fitch's model, whereby the Philippine fault acts as a boundary that divides the Philippines into two distinct plates.

Although many geologic and geophysical investigations have been carried out on the Philippine fault, there is still no agreement as to its exact length and total amount of horizontal displacement. Hamilton (1979) found no physiographic evidence that the fault zone extends either northwestward into northern Luzon or southeastward into Mindanao. Other investigators (Ranneft et al., 1960; Allen, 1962; Rutland, 1968; Rowlett and Keller, 1976; Karig, 1983; Hawkins et al., 1985), employing physiographic, field geologic, or seismicity data suggested that the fault does indeed extend into both north-central Luzon and Mindanao. Estimates of the total amount of horizontal displacement along the Philippine fault range from as little as hundreds to thousands of meters (Pilac, 1965; Barcelona, 1980) to as much as hundreds of kilometers (Allen, 1962; Karig, 1983). Gervasio (1973) noted that a Mobil Oil Corporation exploration team measured a 28 km left-lateral offset within a Miocene sedimentary facies along the Philippine fault zone in Mindanao.

McCabe, Cole, and Malicse (unpublished field notes, 1985) have noted that much of Leyte east of the Philippine fault zone is underlain by mafic and ultramafic basement. However, well data on Biliran Island, north of Leyte and east of the fault, failed to find any ophiolitic material. Instead, the basement of this island is composed of Tertiary island arc rocks (Philippine National Oil Corporation, pers. commun., 1986). In contrast to the data from northeastern Leyte, west of the Philippine fault mafic and ultramafic rocks are found only at the southwestern side of Leyte near Sogod Bay (Cole, unpublished fieldnotes, 1985) and Maasin (F. Florendo, pers. commun., 1984) (Fig. 2). Drill data and geological investigations from northwestern and west-central portions of the island (Philippine National Oil Corp. pers. commun., 1985) suggest that the the pre-Neogene rocks of this region are composed of granitoid intrusions and thick sequences of Tertiary sedimentary rocks. Assuming that the ophiolitic rocks from northeastern Leyte do not extend to Biliran, as suggested by well data, and that the ophiolitic basement near Sogod Bay west of the fault does not continue northward, the offset in the ophiolitic basement across the fault would suggest 110 km of left-lateral offset has occurred fault since the middle Tertiary. This observation is only correct if these rocks were once continuous across the fault. If this is so, then the amount of offset since the middle Tertiary is consistent with that proposed by Allen (1962) and Karig (1983).

Paleomagnetic techniques and results

Sampling and laboratory techniques

This study is the first paleomagnetic investigation carried out on Leyte. A total of 130 independently oriented samples were collected from nineteen sites of early to late Neogene age (Fig. 2). Each site was from a different lava flow and therefore corresponded to a distinct time unit. Twelve of the sites were drilled on Leyte Island, five on Biliran Island, and one each on Maripipi and Genuruan Islands. Four to ten (typically seven) cylindrical samples (25-mm diameter) were drilled at each site using a hand-held, gasoline-powered portable, rock drill and were oriented utilizing an orienting device and a Brunton compass. When possible, back-azimuths on distant land marks were obtained. The samples were subsequently cut into approximately 25-mm long specimens.

On the basis of field examinations and petrographic analyses by Philippine National Oil Corp. petrologists, the lithologies of the sampled rocks were predominantly unaltered hornblende pyroxene andesites. With the exception of one site, all of the sites were taken from horizontal flows and therefore did not require bedding corrections. The bedding correction used for the one site is given in Table 1. Micropaleotological analyses of sedimentary rocks interbedded with the volcanic rocks yielded late Miocene to Quaternary ages for all but three of these sites. We call these late Miocene to Quaternary sites "late Neogene". The three pre-late Miocene sites are from the older Tertiary section of the region. Stratigraphic data from interbedded sedimentary units from this region (Philippine Bureau of Mines, 1964, 1982) suggest these flows are of early Neogene age. The ages of one late Miocene site and five early Miocene sites in northeastern Mindanao were based on micropaleontological data from the sampled or intercalated sedimentary rocks (Chevron Overseas Petroleum Corp., pers. commun., 1983; Philippines Bureau of Mines, 1984).

Prior to applying demagnetization techniques, the directions of the specimens' natural remanent magnetization (NRM) were obtained using a spinner magnetometer (Minispin by Molspin Ltd.). Stepwise alternating field (AF) demagnetization was carried out on two to four pilot specimens from each site using a Schonstedt GSD-1 single-axis demagnetizer. Orthogonal vector plots were constructed in order to observe the behavior of the remanent magnetization during stepwise demagnetization. A specimen's characteristic component of magnetization was considered isolated when the orthogonal projections showed the magnetic vector components decaying in a unidirectional fashion towards the origin with progressive AF demagnetization and when less than 10% of the initial magnetization remained (Fig. 3a). Stepwise thermal demagnetization techniques were em-

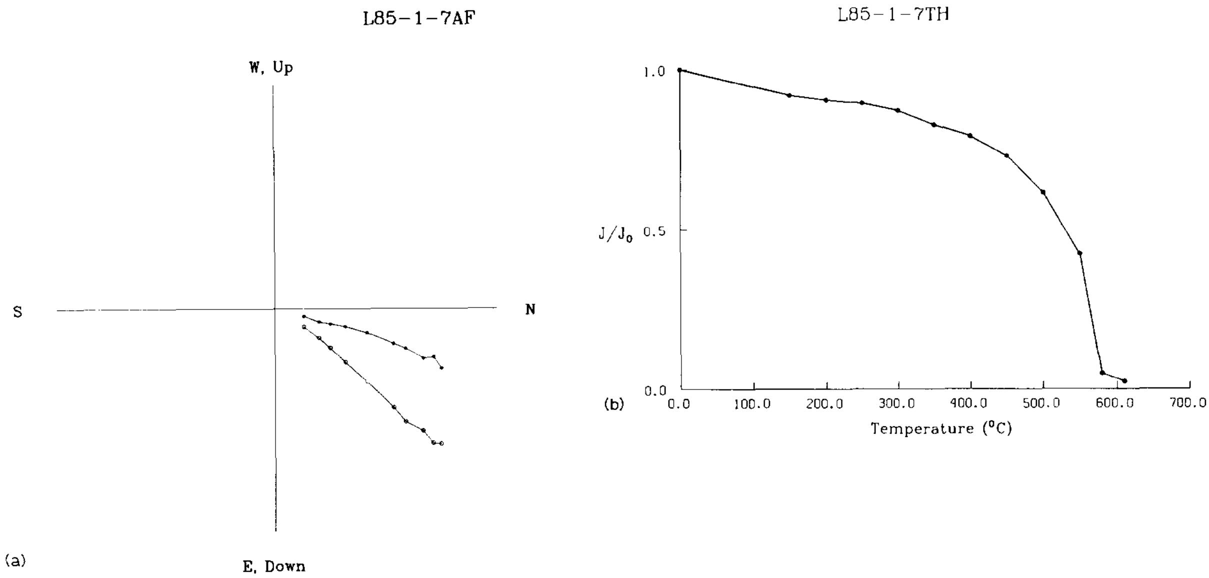


Fig. 3. Typical orthogonal vector projection (a) of AF demagnetization and intensity plots (b) during thermal demagnetization of specimens from a sample. Figure 3a shows a specimen that was characterized by a single component of magnetization; Fig. 3b shows a the intensity of remanent magnetization a specimen from the same sample.

ployed if the pilot specimens failed to respond to AF demagnetization. Specimens from only two sites required thermal demagnetization to obtain a characteristic component of remanent magnetization. Occasionally, specimens were subjected to thermal demagnetization in order to aid in the identification of magnetic carriers. Intensity plots (J/J_0 vs. demagnetization temperature) revealed that the magnetization was carried by a phase which became unblocked by 580 °C (Fig. 3b). This blocking temperature and the fact that the remanent magnetization showed intermediate coercivity (as shown by AF demagnetization) suggest that this magnetization is carried by Ti-poor titanomagnetite. The characteristic directions from each site were combined into a site mean direction using Fisher statistics (Fisher, 1953). Paleomagnetic poles for the seventeen late Neogene sites and for the eight early Neogene sites were subsequently calculated using the virtual geomagnetic poles (VGP's) of sites from this survey as well as northeastern Mindanao (McCabe et al., 1987).

Magnetic results

Table 1 lists the mean directions of each site from the islands of Leyte, Biliran, Maripipi, Genuruan, as well as northeastern Mindanao. We believe the directions of magnetization reported in Table 1 are primary directions and are not secondary overprints. First, the lower coercivity components of magnetization at a few of these sites were easily removed by demagnetization techniques as shown by orthogonal vector plots. Second, in thin-section these rocks are free of secondary alteration. Third, the paleomagnetic pole derived from the eight early Neogene sites is statistically indistinguishable at the 95% confidence level from the early to middle Miocene paleomagnetic pole determined from sites throughout the central Philippines (see below). And finally, sites from widely spaced locations yielded consistent directions.

In any paleomagnetic study involving volcanic rocks it is important to determine whether or not geomagnetic secular variation has been adequately averaged out. There are several reasons why we believe the late Neogene and early Neogene mean paleomagnetic directions represent an accurate sampling of the geomagnetic field and are not solely the products of secular variation of the earth's magnetic field. First, antipolar normal and reversed polarity sites exist within both data sets. Second, the difference in volcanic rock types (i.e.

TABLE 1

Paleomagnetic results from Leyte, Biliran, Genuruan, Maripipi and northeastern Mindanao

Location	Site	N	D (°)	I (°)	α_{95}	k	VGP	
							lat. (°N)	long. (°E)
Late Neogene								
Leyte	L-1	8	20.0	37.0	3.0	344.4	68.6	186.0
	L-2	7	9.8	9.8	4.4	188.0	78.5	246.4
	L-3	4	185.6	−37.4	2.5	1373.7	78.8	152.7
	L-4	7	357.5	11.0	5.1	143.7	83.6	327.3
	L-10	7	357.1	2.0	4.4	193.1	79.5	320.8
	L-11	6	347.2	22.9	3.6	354.3	77.4	40.8
	L-12	7	356.0	43.0	4.6	176.5	75.4	110.4
	L-20	7	180.6	−11.6	9.0	46.0	84.7	298.2
	L-21	5	7.7	7.7	8.0	91.5	79.5	257.6
Biliran	B-5	7	168.3	−22.1	5.5	122.0	78.5	35.6
	B-6	7	358.5	−1.3	4.8	156.7	77.8	311.6
	B-8	7	359.2	24.1	4.0	226.1	88.6	89.3
	B-9	7	354.3	26.0	3.0	409.6	84.0	56.7
	B-17	5	348.9	9.8	9.7	62.9	77.2	4.5
Genuruan	G-19	7	1.7	31.1	2.1	841.3	84.5	141.6
Maripipi	M-18	7	358.4	24.7	3.0	401.4	87.9	77.5
Northeastern Mindanao	82-17 *	7	354.3	19.2	3.1	302.4	84.4	37.3
Early Neogene								
Leyte	L-14	6	17.7	27.1	4.0	285.4	72.3	200.8
	L-15	7	12.8	22.9	2.6	557.3	77.4	207.5
	L-16	6	218.8	−21.8	4.3	248.3	52.0	210.4
Northeastern Mindanao	82-10 *	7	14.5	−5.8	6.5	66.6	71.0	255.5
	82-11 *	6	202.4	−9.7	12.0	22.8	63.7	225.7
	82-12 *	9	209.6	−9.0	5.9	78.2	60.2	223.0
	82-14 *	10	199.5	−14.3	2.9	345.9	70.6	220.9
	82-16 *	13	210.5	−10.5	7.4	57.3	59.5	221.5

N = number of samples; D = mean declination; I = mean inclination; 95 = radius of 95% confidence circle; k = precision parameter; * = sites reported in McCabe et al. (1987); bedding correction for site L-16 was strike = N56°E, dip = 45°NW.

hornblende pyroxene andesite, basaltic andesite, to dacite) between proximate sites suggests that extrusions of the individual flows were temporally distinct events. Third, sites taken from sedimentary rocks show directions which are statistically indistinguishable at the 95% confidence level from the directions obtained from the volcanic rocks. And finally, the amount of dispersion (K) of the VGP's from the volcanic sites suggests suggests secular variation has been averaged out. The dispersion of the late Neogene VGP's is $K_{LN} = 56.1$, and $33.1 \leq K_{LN} \leq 85.1$ at the 95% confidence level (Cox, 1969). The dispersion of the early Neogene VGP's is $K_{EN} = 62.0$, and $28.3 \leq K_{EN} \leq 108.5$ at the 95% confidence level (Cox, 1969). The dispersion of secular variation for the past 5 M.y. (K') as derived using a worldwide data set within a latitude range between 0° and 15° (McFadden and McElhinny, 1984) is $K' = 40.1$ with 95% confidence limits $37.1 \leq K' \leq 44.1$. Not only do the values of K_{LN} and K_{EN} and their 95% confidence limits completely overlap K' and its 95% confi-

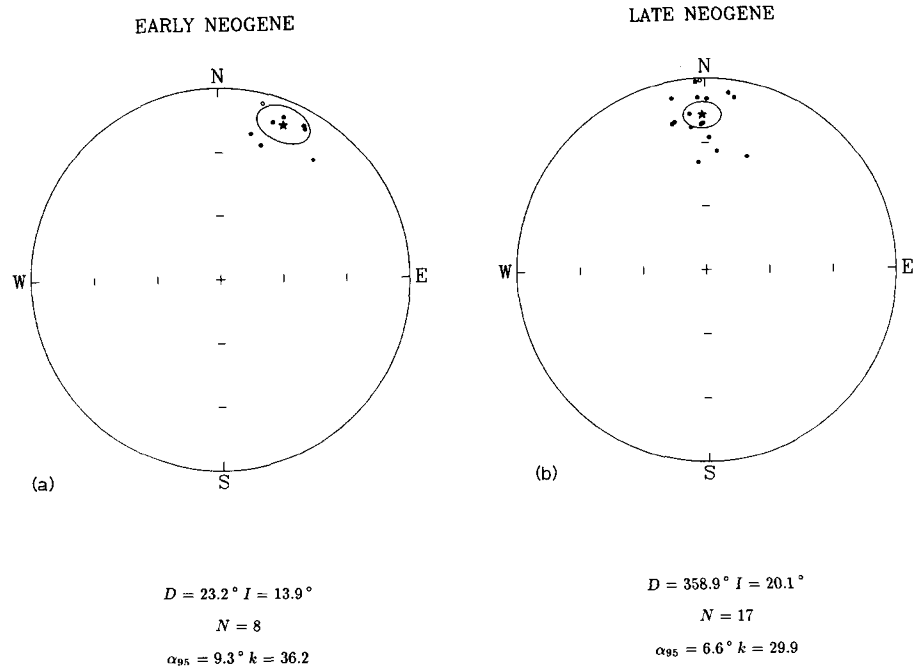


Fig. 4. Late Neogene (a) and early Neogene (b) paleomagnetic directions and 95% confidence ellipses plotted on polar equal-area projections. The antipodal position is given for sites with a reversed polarity.

dence limits, but *F*-tests (McFadden, 1980) reveal that the precisions (K_{LN} and K_{EN} vs. K′) are indistinguishable at the 95% probability level.

Discussion

The paleomagnetic results from Leyte and smaller neighboring islands are of late Neogene and early Neogene age. These results are combined with mean directions of six additional sites in northeastern Mindanao (McCabe et al., 1987) where the Philippine fault transects the island. All of the sites reported in Table 1 were characterized by stable magnetizations that were easily isolated by AF or thermal demagnetization. Site mean directions and the overall mean directions for the late Neogene and early Neogene data sets are shown on polar equal-area projections in Fig. 4. The antipodal position is given for sites with a reversed polarity. We subdivide the data into a late Neogene and an early Neogene set (Table 1) and discuss each of these sets individually.

Late Neogene

The late Neogene paleomagnetic pole (star in Fig. 5) is statistically indistinguishable at the 95% confidence level from the Plio-Pleistocene paleomagnetic pole of the Philippines (McCabe et al., 1982b, 1987; solid circle in Fig. 5), Taiwan (Hsu et al., 1966; triangle in Fig. 5), and Vietnam (Giang, 1982; square in Fig. 5). In addition, the late Neogene paleomagnetic pole of Leyte is indistinguishable at the 95% confidence level from the late Miocene central Philippine paleomagnetic pole (McCabe et al., 1987; open circle in Fig. 5). The coincidence of the late Neogene data from Leyte and the late Neogene pole from other nearby regions argues against any major regional rotations or translations of Leyte during the late Neogene. In addition, there are no paleomagnetically detectable shear-related crustal movements associated with motion along the Philippine fault. If rotations or translations have occurred on Leyte, they are not detectable given the resolution of the late Neogene paleomagnetic data set. Although the mean results are indistinguishable from the central Philippine late Neogene pole, three of the younger sites within or very near the fault zone (sites 1, 5, and 11) do show large deflections of their magnetic vectors from the expected late Neogene directions. Presently, we are unable to distinguish if these sites reflect local tectonic rota-

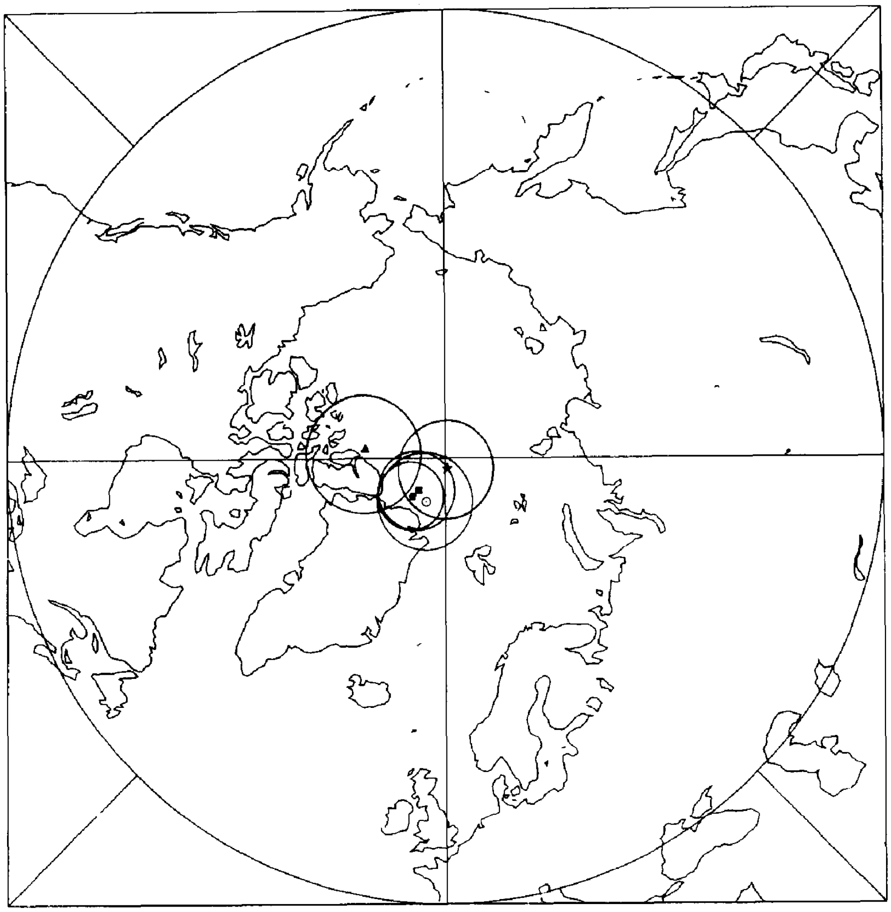


Fig. 5. The late Neogene Paleomagnetic pole from this study is shown with a star. This direction is indistinguishable from the Plio-Pleistocene poles from Philippines (solid circle), Vietnam (square), Taiwan (triangle), and from the late Miocene pole from the central Philippines (open circle). These data suggest that there has not been significant rotations of the study area with respect to these other regions during the late Neogene. Circles surrounding mean directions represent 95% confidence cones around paleomagnetic pole positions.

tions or are caused by secular variation of the earth's magnetic field.

Early Neogene

The early Neogene paleomagnetic pole (star in Fig. 6; Table 2) is distinguishable at the 95% probability level from the early to middle Miocene pole calculated from the islands of Panay, Mindanao, and Cebu (solid circle in Fig. 6). In contrast, the early Neogene pole from Leyte is highly discordant from the early to middle Miocene pole from Marinduque (triangle in Fig. 6) as well as the late Miocene and Plio-Pleistocene poles from all of the Philippines. The fact that the pole of these early Neogene rocks from Leyte and northeastern Mindanao is statistically indistinquishable from the early to middle Miocene pole from Panay and Cebu suggests that these four islands have behaved as a single tectonic block during the past 20 m.y. (within the limit of the resolution of these paleomagnetic data).

Paleomagnetic directions

In Fig. 7 we show the mean declination values reported from the various islands of the Philippines (McCabe et al., 1987; and this study). Figure 7a shows the results from late Neogene sites and Fig. 7b shows the results from early Neogene sites. We should point out that in Fig. 7b, we excluded one of the reported sites from Cebu. The exclusion

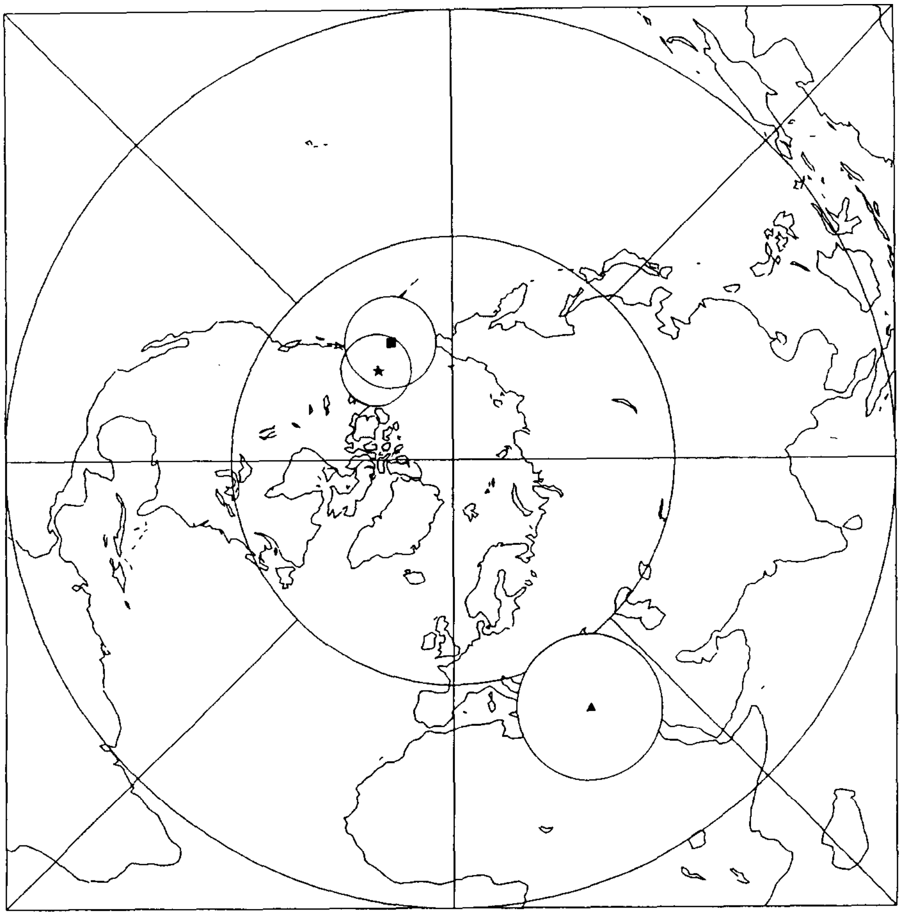
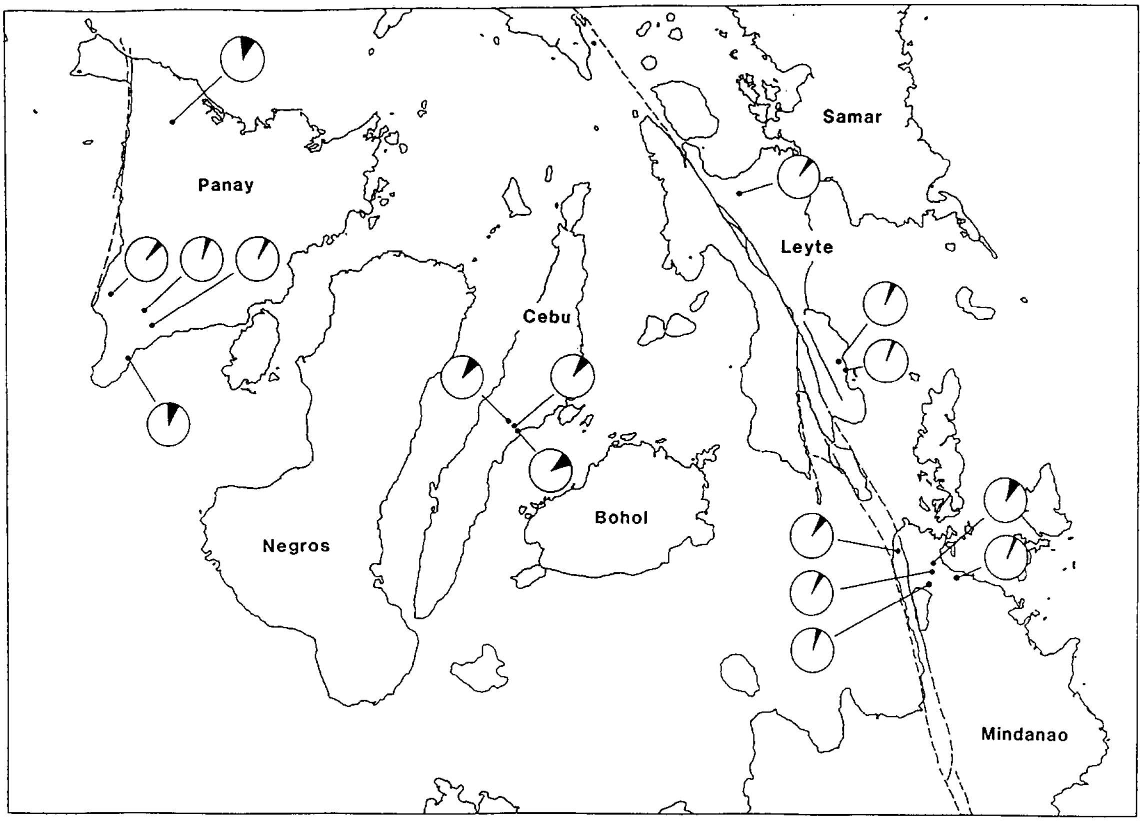


Fig. 6. Early Neogene results from Leyte (circle with star in center) lies within the 95% cone of confidence of early to middle Miocene directions from Panay and Cebu (circle). The early Neogene pole from this study is distinguishable from early to middle Miocene pole from Marinduque (Triangle) and lies outside the 95% cones of confidence of the late Neogene poles (shown in Fig. 4). This data suggest that Leyte has shared a common Neogene translational history with Cebu, Panay, and northeastern Mindanao.

of this site is justified because of the large statistical uncertainty associated with this site ($\alpha_{95} = 20.1°$; $k = 9.6$). In this figure, the mean declinations from a site are shown as a compass needle with north being at the top of the figure. Sites with reversed polarity are reflected to their antipodal direction. The size of the wedge in each circle represents the error in declination as defined by Beck (1980) and Demarest (1983). The fact that the directions of both the late Neogene data and the early Neogene data sets are consistent over the entire region suggests that these islands have behaved as a single tectonic unit during the Neogene.

Crustal rotations

Paleomagnetic studies in strike-slip regions have shown that in many cases, crustal blocks caught in a shear regime show paleomagnetic directions which are discordant from the directions of a paleomagnetic reference frame (Cox, 1981; Fagin and Gose, 1983; Ron et al., 1984; Brown and Golombek, 1985, 1986; Luyendyk et al., 1985: Terres and Luyendyk, 1985; Wells and Coe, 1985; Hudson and Geissman, 1987; Golombek and Brown, 1988). For example, Miocene paleomagnetic directions from much of southern California


Panay
Samar
Leyte
Cebu
Bohol
Negros
Mindanao

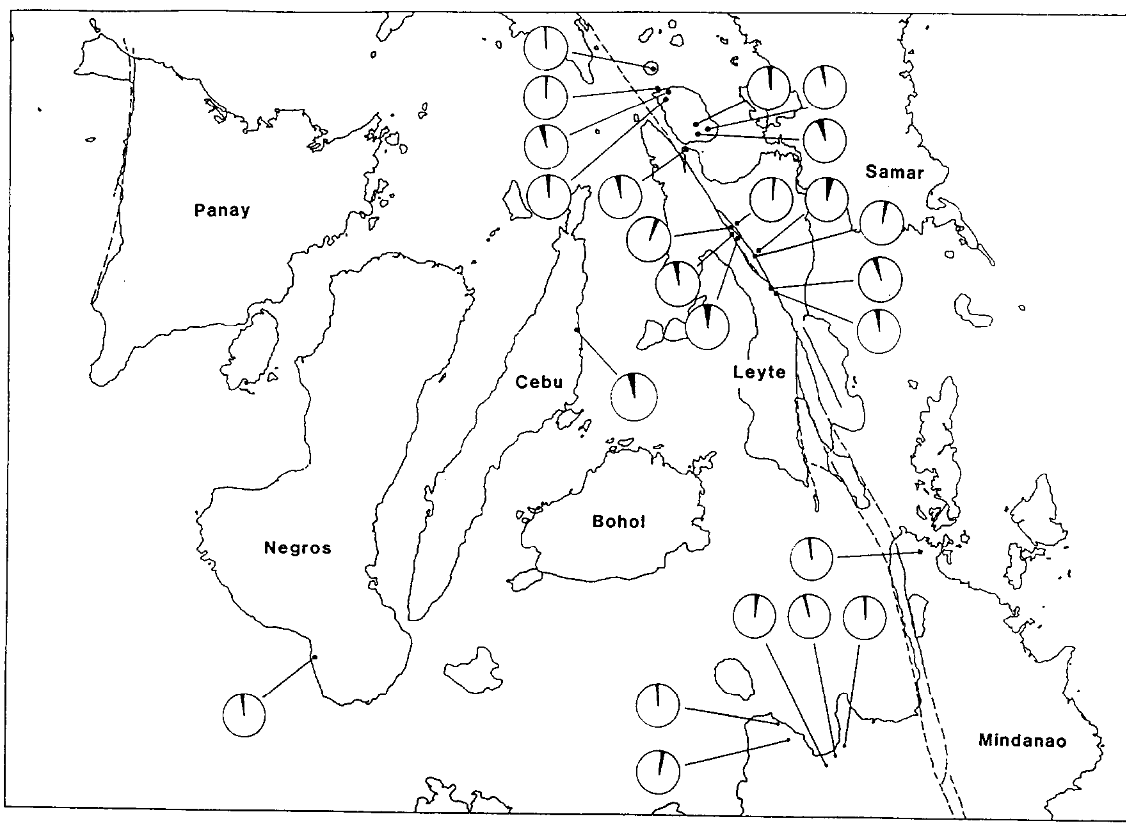

Samar
Panay
Cebu
Leyte
Bohol
Negros
Mindanao

TABLE 2

Summary of Neogene and Pleistocene poles from Philippines and surrounding areas

Age	Ref.	Location	N	Pole lat. (°)	Pole long. (°)	α_{95}
Plio-Pleistocene	a, b	Philippines (1)	23	84.9	318.9	3.0
	c	Taiwan	35	81.7	264.1	5.8
	d	Vietnam	29	85.8	319.9	3.8
Late Miocene	b	Philippines (2)	5	85.0	325.8	6.7
Late Neogene	e	Philippines (3)	17	88.9	12.5	4.8
Early–Middle Miocene	b, f	Philippines (4)	9	63.1	207.8	9.5
	b, g	Philippines (5)	8	32.9	29.3	15.0
	e	Philippines (6)	8	66.5	220.5	7.1

α_{95} = radius of 95% confidence circle about pole. Pole, calculated from site VGP's. N = number of sites.

(1) Data from entire Philippines (does not include data from this survey); (2) data from Marinduque, Negros, and southeastern Luzon (Bicol area); (3) data from Leyte, Biliran, Genuruan, Maripipi, and northern Mindanao; (4) data from Cebu and Panay; (5) data from Marinduque; (6) data from Leyte and northern Mindanao.

References: (a) McCabe et al. (1982a, b); (b) McCabe et al. (1987); (c) Hsu (1972); (d) Giang (1982); (e) this study; (f) McCabe et al. (1985); (g) Fuller et al. (1983).

show declinations which are rotated significantly clockwise from the Miocene North American reference direction (Greenhaus and Cox, 1979; Luyendyk et al., 1980; Terres and Luyendyk, 1985). Such discordant paleomagnetic directions are believed to result from either simple-shear rotations (Beck, 1976, 1980) or rotations of small crustal blocks that are caught between larger parallel fault sets in the region (Freund, 1974; Luyendyk et al., 1980; Ron et al., 1984; Nur and Ron, 1986; Nur and Ron, 1987). In the case of our data from Leyte and Mindanao which are bisected by the left-lateral Philippine fault, such rotation models, as discussed above, predict that we should observe counterclockwise rotations. However, our data are indistinguishable from late and early Neogene directions from other islands in the central Philippines (Fig. 7). These data suggest that crustal blocks near the trace of The Philippine fault (in the study area) are not independently rotating with respect to the rest of the Philippine arc. It is worthy to note that in most areas where crustal rotations have been observed, such as southern California (Greenhaus and Cox, 1979; Luyendyk et al., 1980), Alaska (Globerman and Coe, 1985; Hillhouse et al., 1985), Israel (Ron et al., 1984), and Thailand (McCabe et al., 1988), the crust is mature continental crust. In contrast, the crust of the Philippines is transitional between island arc and continental. In addition, large amounts of volcanism and plutonism is associated with the Philippine fault in Leyte. This may suggest that there is a fundamental difference to the way the crust deforms in strike-slip regimes in these two contrasting regions.

Conclusions

(1) The 110 km offset between ophiolitic basement outcrops in northeastern Leyte on the eastern side of the Philippine fault and those in southwestern Leyte on the western side of the fault may represent the amount of displacement along the Philippine fault if these ophiolitic outcrops were once continuous across the fault zone.

Fig. 7. Mean declination values of (a) late Neogene sites and (b) early Neogene sites located in the central Philippines (this study; McCabe et al, 1987). Mean declinations are shown as compass needles with north being the top of the figure. Directions of reversed polarity sites are reflected to their antipodal position. The size of the wedge within each circle represents the error in declination as defined by Beck (1980) and Demarest (1983). The consistency of directions within each data set suggests that these areas have behaved as a single tectonic unit during the Neogene.

(2) VGP's of seventeen late Neogene sites from Leyte and the adjacent islands of Biliran, Genuruan, Maripipi, and northeastern Mindanao yield a paleomagnetic pole $\lambda = 88.9°$ N, $\phi = 12.5°$ E. This pole is indistinguishable at the 95% probability level from Plio-Pleistocene paleomagnetic poles of the Philippines, Taiwan, Vietnam, as well as the late Miocene pole of the central Philippines. This suggests that during the past 5 m.y., the study area has not experienced rotations or translations with respect to much of continental southeast Asia.

(3) Only three of the late Neogene sites within or near the Philippine fault zone (sites 1, 5, and 11) exhibit any significant declination anomalies relative to the present dipole field direction. However, the data are too sparse to determine if these discordant declinations result from the rotation of independant crustal blocks within the fault zone or from secular variation of the earth's magnetic field.

(4) Eight early Neogene sites located within and outside the Philippine fault zone in Leyte and northeastern Mindanao show clockwise-deflected declinations and yield a paleomagnetic pole $\lambda = 66.5°$ N, $\phi = 220.5°$ E. This paleomagnetic pole is indistinguishable at the 95% probability level from the early to middle Miocene pole of the central Philippines. However this early Neogene pole from Leyte and northeastern Mindanao is highly discordant from the early Miocene pole of Marinduque. It is also distinguishable at the 95% confidence level from the late Miocene and Plio-Pleistocene paleomagnetic poles from the central Philippines, Taiwan, and Vietnam.

(5) Paleomagnetic data from the islands of Leyte, Biliran, Genuruan, Maripipi, and northeastern Mindanao suggest that these areas have been a portion of the same tectonic unit as Cebu and western Panay since early Neogene time. In addition, the late Neogene data also show no paleomagnetically detectable late Neogene to Recent crustal rotations or translations associated with left-lateral Philippine fault motion.

(6) In contrast to shear-related paleomagnetic rotations observed in continental regions, we have not observed similar rotations in this transitional island-arc/continental crustal region. This may suggest that hot, immature crust, like that of the Philippines, deforms differently in response to shear than the crust in continental regions.

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