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PALEOMAGNETIC RESULTS FROM LUZON AND THE CENTRAL PHILIPPINES

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Abstract. Samples were collected from 86 paleomagnetic sites from the islands of Luzon, Marinduque, Mindoro, Panay, Negros, Cebu, and Mindanao in the Philippine Arc. The sampling sites range in age from Pleistocene to Jurassic. Characteristic directions of magnetization of the samples were determined by the use of vector plots. Curie temperature determinations, thin section studies, and hysteresis studies showed that remanence of these samples is carried by fine-grained (pseudo-single domain) magnetite. Positive fold tests from Miocene data from Panay, Jurassic data from Mindoro, and Cretaceous data from Cebu suggest that the magnetization of these regions was acquired prior to folding. Rotations reported below are measured with respect to the axial goecentric dipole field. The Plio-Pleistocene data set shows no resolvable rotation for the 22 sites. This data set suggests that the various terranes that make up the Philippine Arc have behaved as a single unit during the past 5 m.y. or that deformation has been below the limits of resolution. The inclination data from the Plio-Pleistocene sites have anomalously shallow inclination and are consistent with other Plio-Pleistocene data from Vietnam, Taiwan, and the Marianas. These data support earlier suggestions for a late Neogene offset dipole effect. The late Miocene sites fall into two separate groups. Ten sites from western Luzon show evidence for around 20° of clockwise rotation. In contrast to this, late Miocene samples from the Bicol region, Negros, Marinduque, and Mindanao are not rotated. The cause of the post-late Miocene clockwise rotation of Luzon is unknown, but a Pliocene collision of the North Luzon Arc with Taiwan is suggested. Early Neogene results also separate into two different populations. The population from Marinduque shows evidence for a large counterclockwise rotation. The second early Neogene population comes from Panay, Cebu, and Mindanao and clearly shows evidence for a clockwise rotation. The validity of this rotation is further supported by a fold test and a reversal test. These early Neogene data sets are consistent with a middle to late Miocene collision of the Palawan Continental Terrane and the Central Philippine Arc. Data from six dikes of possible Oligocene age from the Zambales Ophiolite are highly discordant from the present field, being rotated approximately 60° clockwise. The directions from these dikes are similar to a direction reported earlier from late Oligocene sediments also from the Zambales region. These two data sets support the interpretation that the Eocene direction from Zambales is recording a large clockwise rotation of the region. Data from the Mesozoic sites are from two regions. Data from the Cretaceous Pandan formation of Cebu are discordant with data from the Upper Jurassic from Mindoro. The presence of a fold test from each region and a reversal test from Mindoro supports the interpretation that each of these data sets is reliable. The VGP of Mindoro is displaced southward from the Late Jurassic VGP of South China, suggesting a post-Jurassic southward migration of Mindoro.

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Introduction

The present configuration of the Philippine Arc (Figure 1) is the result of two major Neogene tectonic events: (1) the early Neogene to late Tertiary collision between the North Palawan Continental Terrane and the west facing Philippine Arc [Hamilton, 1977, 1979; Holloway, 1981; Taylor and Hayes, 1980, 1983; McCabe et al., 1982a, 1985; Karig, 1983] and (2) Neogene strike-slip faulting associated with the left-lateral Philippine Fault [Allen, 1962].

Paleomagnetic data from the islands of Luzon and Marinduque suggest that both these islands rotated counterclockwise with respect to the direction predicted from a time-averaged axial geocentric dipole field for this location. This rotation occurred during the late Paleogene and early Neogene times [Hsu, 1972; De Boer et al., 1980; Fuller et al., 1983]. In contrast to this, paleomagnetic studies from Panay Island [McCabe et al., 1982a] show declination values deflected clockwise from the direction predicted from the average axial geocentric dipole field. On the basis of (1) these three paleomagnetic data sets [Hsu, 1972; McCabe et al., 1982a; Fuller et al., 1983], (2) late Neogene paleomagnetic results from Luzon [McCabe et al., 1982b], and (3) Neogene structural trends of the central portion of the Philippine Arc, we presented a model [McCabe et al., 1982a; McCabe, 1984], which explained both the paleomagnetic rotations and the bending of major structural trends in the central Philippine Arc as a result of the collision-related deformation of the upper plate.

In order to discuss paleomagnetic data in such a tectonic framework, it is important to discuss the directions with respect to some expected directions of the region. For example, in western North America, where paleomagnetic

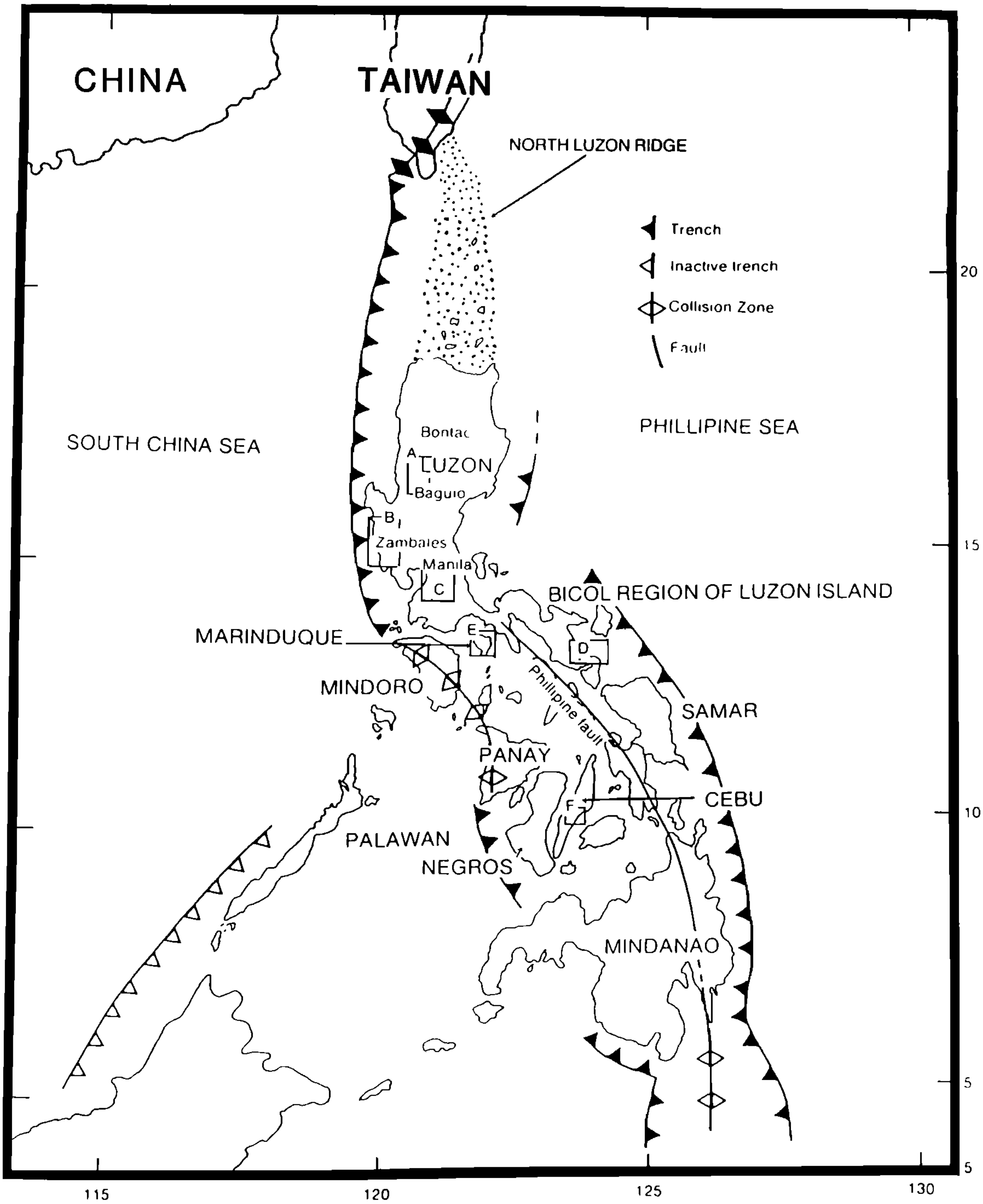


Fig. 1. Simplified tectonic map of the Philippine region. Insert areas A-E are areas studied by Hsu [1972]. Insert area F (located in central Cebu) shows the region studied by Noritomi and Almasco [1981].

directions are used to support rotations resulting from oblique convergence, directions are discussed in terms of being discordant to the predicted value of the North America reference pole [Beck, 1976, 1980; Irving, 1979]. Unfortunately, both the presence of numerous active margins around the Philippines and the lack of a Cenozoic reference pole for Asia do not allow us to use the above definition. In order to discuss the paleomagnetic results from the Philippines, we will make the reasonable assumption that all islands that make up this island arc are close enough together in space that relative discordances can be defined as a variation of the magnetic declination values within the trend of the arc.

In this paper, we summarize these older preliminary results [McCabe et al., 1982a,b;

McCabe, 1984] in a more final form. We will also discuss additional results from Neogene sites sampled between 1982 and 1984. These data allow us to place better constraints on both the timing of the collision-related deformation and the size of the rotating block. In addition, preliminary paleomagnetic poles from the Jurassic of Mindoro are compared with paleomagnetic poles from the South China Block [Lin et al., 1985]. These data are consistent with the suggestion that the North Palawan Continental Terrane was translated southward (with respect to South China) during the middle Cenozoic [Taylor and Hayes, 1980] opening of the South China Sea.

Previous Studies

Hsu [1972] performed the first paleomagnetic investigation of the Philippine Arc. Hsu's study concentrated on five different areas: Central Cordillera, Zambales, the Manila region, Bicol, and Marinduque (Figure 1, areas A,B,C,D, and E, respectively). Hsu obtained useful results from all but the Zambales region.

Hsu's collection from the Central Cordillera was made between Baguio and Bontac. His collection focused on sequences of Neogene volcanic flows, Miocene to Recent quartz diorites, and rocks he labelled Cretaceous volcanics. The early Tertiary/Cretaceous (?) rocks from this region are metamorphic schists (R.J. McCabe, unpublished field notes, 1981) and inconsistent with Hsu's sample descriptions. Hsu's descriptions of the sites suggest that the sites he labelled as Tertiary/Cretaceous were probably collected from the lower section of the Zigzag formation, which consists of pyroclastics of early Miocene age [Balce et al., 1980] and/or the Pugo Volcanics, which are epidotized volcanic rocks believed to be of Oligocene age [Balce et al., 1980]. Both of these formations are well exposed in the region and overlap Hsu's collection sites.

The most convincing results reported by Hsu for the Baguio region come from the Pliocene to Recent volcanic rocks. The data from these rocks, excluding sites with α 95 larger than 20°, show both reverse and normal polarity directions that are consistent with the present field direction, suggesting that the region has not rotated since the Pliocene.

Most of the older sites reported by Hsu from the Baguio region are characterized by anomalously high inclinations (nearly vertical), which Hsu suggested were related to a VRM (viscous remanent magnetization) acquired between the time of drilling and measuring of the sample. The results from the samples that did not show these anomalous inclination values are one site from the late Neogene diorite, which showed 15° of clockwise rotation, and four sites from the older volcanics, which are deflected approximately 55° westward from the axial dipole direction. Hsu suggested that these older results are reflecting a counterclockwise rotation of Luzon. These older sites are also characterized by relatively shallow inclinations (approximately 5°).

Hsu also studied Pliocene basalts from southern Manila and Quaternary basalts from around Taal volcano (30 km south of Manila). The data comprised 15 sites of post-Pliocene age and two sites of upper Miocene diorites. Hsu's results from this region suggested that this region has not experienced a significant rotation since Pliocene times.

Hsu's data from the southern Luzon Bicol region (Figure 1, point D) were limited to samples from two major Quaternary volcanoes (Mount Isarog and Mount Mayon), which are located north of Lagaspi City, in Albay province. The results from 13 flows of Quaternary age suggested no significant rotation of this region. In contrast to the younger results, Hsu's data from four Pliocene volcanic sites in this region showed evidence for significant counterclockwise rotation of the region.

To date, the best evidence for a Neogene counterclockwise rotation of the Philippines came from Hsu's work on Marinduque Island (Figure 1, point E). Hsu's collection from this island was restricted to Oligocene and Miocene volcanic rocks. The results from this collection suggest that Marinduque Island rotated nearly 65° counterclockwise since the Oligocene.

De Boer et al. [1980] worked on samples from central Luzon. These workers, who were mostly concerned with late Neogene crustal movements of the region, restricted most of their collection to rocks younger than late Miocene. De Boer et al.'s study was a combination of paleomagnetic studies and K-Ar age dating, which allowed them to impose very tight constraints on the age of these rocks. The results showed a direct relationship between the K-Ar age and the polarity of magnetization. The declination values reported by these workers showed a progressive westward deflection with increasing age. Based on paleomagnetic data and other geophysical data, De Boer et al. argued that Luzon translated northward and rotated counterclockwise since the early Miocene. De Boer et al. [1980] suggest that this rotation resulted from subduction of the South China Sea beneath the Philippine Arc.

To date, the most extensive paleomagnetic data collection was reported by Fuller et al. [1983]. Fuller et al.'s pre-Pliocene results from the Baguio region are from three late Miocene sites, which show about 20° of clockwise rotation. In contrast to this post-late Miocene clockwise rotation, early to middle Miocene sites from Baguio suggest approximately 20° counterclockwise rotation of the region but give no evidence of detectable N-S translation. Results from the Oligocene sites reported by Fuller et al. [1983] are conflicting. The results from three sites from Baguio support the counterclockwise rotation model. However, results from an Oligocene site from the Zambales region argue for nearly 80° of clockwise rotation. Eocene sites are reported only from the Zambales Ophiolite. These sites including sediments, gabbros, dikes, and volcanic rocks yield consistent directions and show evidence for a strong rotation. Fuller et al. [1983] interpreted these results to indicate a continuous post-Eocene counterclockwise rotation of the Baguio and Zambales region. However, these authors called for a degree of caution in using their interpretation for tectonic studies because of the ambiguous polarity involved in working with the shallow Eocene inclination data. Besides this problem with polarity, other things that argue for the use of caution before using the counterclockwise rotation interpretation for the entire western Luzon are (1) the possible lack of structural correlation between Zambales and the Central Cordillera, (2) possibilities of large strike-slip faulting in the Central Cordillera [Philippine Bureau of Mines, 1964], and (3) the possibility of remagnetization of much of the pre-late Miocene Baguio data [McCabe, 1984].

Plio-Pleistocene results from 14 sites from Luzon were reported by McCabe et al. [1982b] and Fuller et al.[1983]. These results are consistent with the findings of Hsu [1972] and argue for no discernible rotation of Luzon during the past 5 m.y. In this paper, we will discuss these earlier results and other Plio-Pleistocene sites from the Central Philippine Arc. In addition, we will present a more comprehensive treatment of the paleomagnetic studies from these sites that showed shallow inclination values. All but one site (which lies close to the dipole field direction) are deflected westward from the present dipole field direction. As all of these sites are characterized by shallow inclinations, the sense of rotation is unknown. It must be pointed out that the Cretaceous rocks in this area are folded. Although the inclination values argue for shallow Cretaceous latitudes for Cebu, Noritomi and Almasco [1981] did not use bedding corrections. Therefore until further work is done in this region, care must be taken when interpreting these results.

Field and Laboratory Techniques

A total of 550 oriented samples were collected from the Philippine Arc. These samples, which range in age from Jurassic to Pleistocene, were collected between 1981 and 1984. Samples were collected either by portable drill or as oriented hand samples.

For most samples, the remanent magnetization was measured on a Schonstedt spinner magnetometer located at Kyoto University. Samples that possessed weak magnetization less than 10^{-2} Amp/meter (A/m) were measured with a cryogenic magnetometer located at the University of California at Santa Barbara. Alternating field (AF) and thermal demagnetization techniques were used to isolate the stable magnetization from secondary magnetizations. For the sites that showed little directional change in the magnetic vector during demagnetization, three samples were demagnetized and served as pilot samples. If all of the pilot samples from a site showed similar behavior on demagnetization (determined by vector plots), an optimal level of demagnetization was determined by calculating a precision parameter κ for each step of the demagnetization. The demagnetization step with the greatest κ value was taken as the optimal value. The rest of the samples from the site were then demagnetized at this optimal value. In no case was an initial magnetization (NRM) used as the optimal value. For samples from individual sites that contained either a low intensity of initial magnetization or that showed complex directional changes on demagnetization, stepwise demagnetization was carried out on all samples.

Analyses of the demagnetization behavior of the samples were done with vector diagrams [Zijderveld, 1967] for individual samples and with stereographic projections for all samples from a site. Stability was indicated by samples that showed unidirectional decay of the magnetization on higher levels of demagnetization and by clustering of the direction of magnetic vectors for all samples from a site. On the basis of the above criteria, a characteristic direction was determined for each sample. These directions were combined using Fisher [1953] statistics to calculate site mean directions. Many sites were characterized by a low coercivity or low blocking temperature secondary component(s) that were easily removed by AF demagnetization of 10-20 mT or by thermal demagnetization of 250°C. Forty-three sites were rejected during this study. These sites were characterized by either erratic behavior of the magnetic vector during demagnetization (defined by vector plots) or by large α_{95} values ($\alpha_{95} > 25°$). Neither AF demagnetizations of up to 100 mT nor thermal demagnetization over 600°C was able to remove the complex magnetization behavior of these rejected sites.

For many of the older sites, bedding corrections were required. Before applying bedding corrections, none of the reported sites had primary directions characteristic of the present axial geocentric dipole field. All of the Plio-Pleistocene volcanics and most of the late Miocene sites did not require bedding corrections. Most of these younger sites were characterized by magnetizations near the present field or reversed position of the dipole field. On the basis of the following observations, we believe that these magnetizations are primary directions and do not represent present field overprints: (1) the lower coercivity magnetic components in most of these sites showed varying degrees of scatter, which were removed by demagnetization; (2) thin section studies show that these rocks are free from secondary alteration; and (3) at two locations the stratigraphically lower site was characterized by a normal direction of magnetization while the stratigraphically upper unit was characterized by a reversed magnetization.

Geology of Sampling Sites and Sample Localities

The Philippine Archipelago is a complex mixture of tectonic fragments. These fragments include segments of continental margins, ophiolitic fragments, and stratigraphic sequences from at least five or more separate Cenozoic arcs [Hamilton, 1979; Balce et al., 1981; Karig, 1983; Hawkins et al., 1985; McCabe et al., 1985]. Although it has long been recognized that the islands consist of a complex agglomeration of distinct stratigraphic units [Irving, 1951; Corby, 1951; Gervasio, 1971], the relationship between these individual units is still unknown. The lack of reliable geologic data for large portions of the region and complex structural relationships in some portions of the archipelago make any detailed discussion of the geology of the region beyond the scope of this paper.

Because of dense tropical vegetation, difficulties in transportation, and intense weathering, only a limited number of sampling sites could be located from many of these regions. The limited number of possible sampling sites that existed from some of these regions argued for the "broad geographic grid" type of study as we

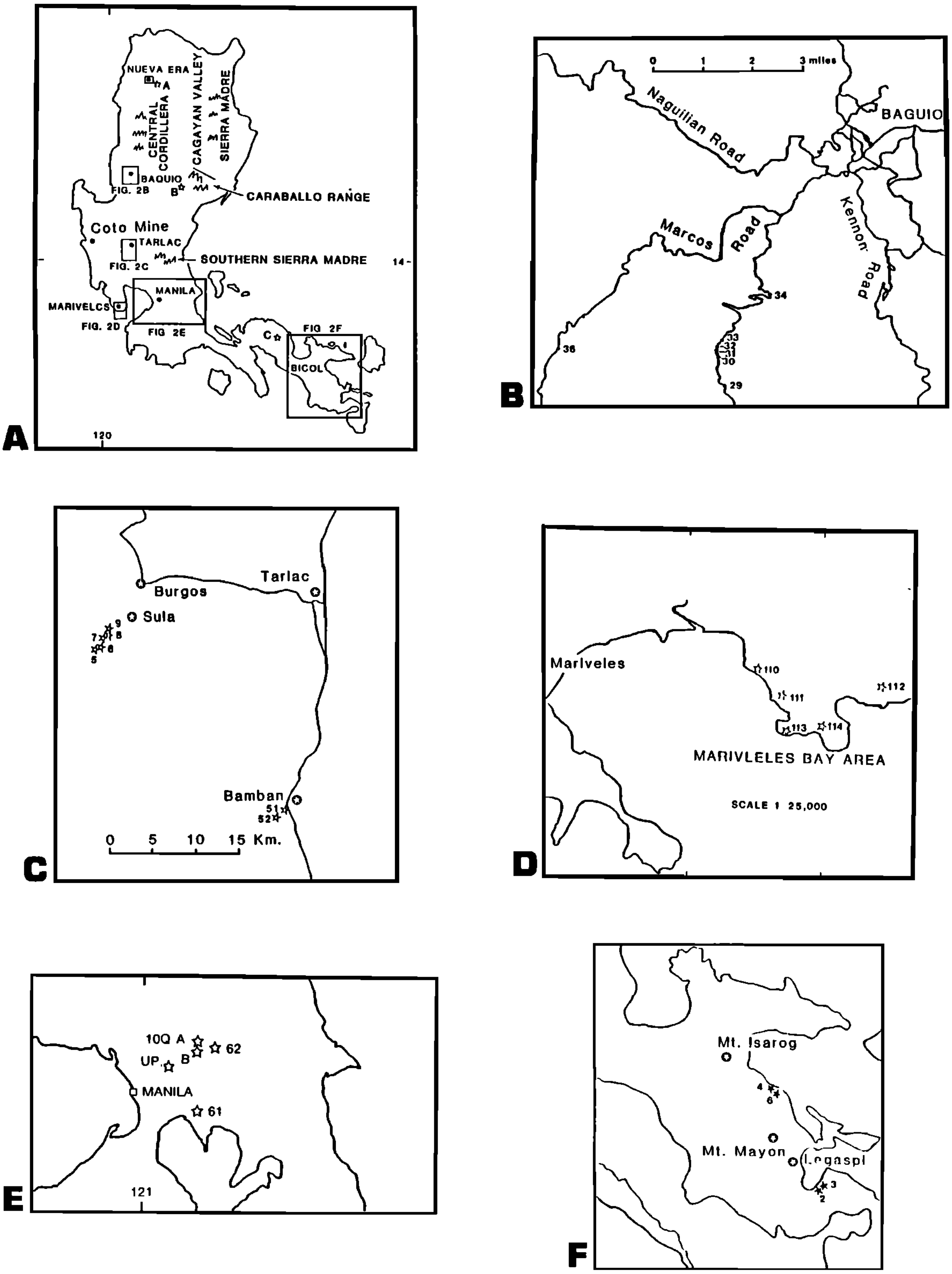


Fig. 2. Location map of sites collected from Luzon. Figure 2 shows location of areas in Figures 2b through 2f.

present here. In addition, this grid-type approach allowed us to look for regionally consistent trends between islands. Figures 2 and 3 show the general location of the sampling sites. A description of the sampling sites and the age critera used for each site are given in the appendix.

Paleomagnetic and Rock Magnetic Results

Paleomagnetic Results

Most of the samples used in this study were taken from sites that, based on field and cursory thin section examinations, were considered free

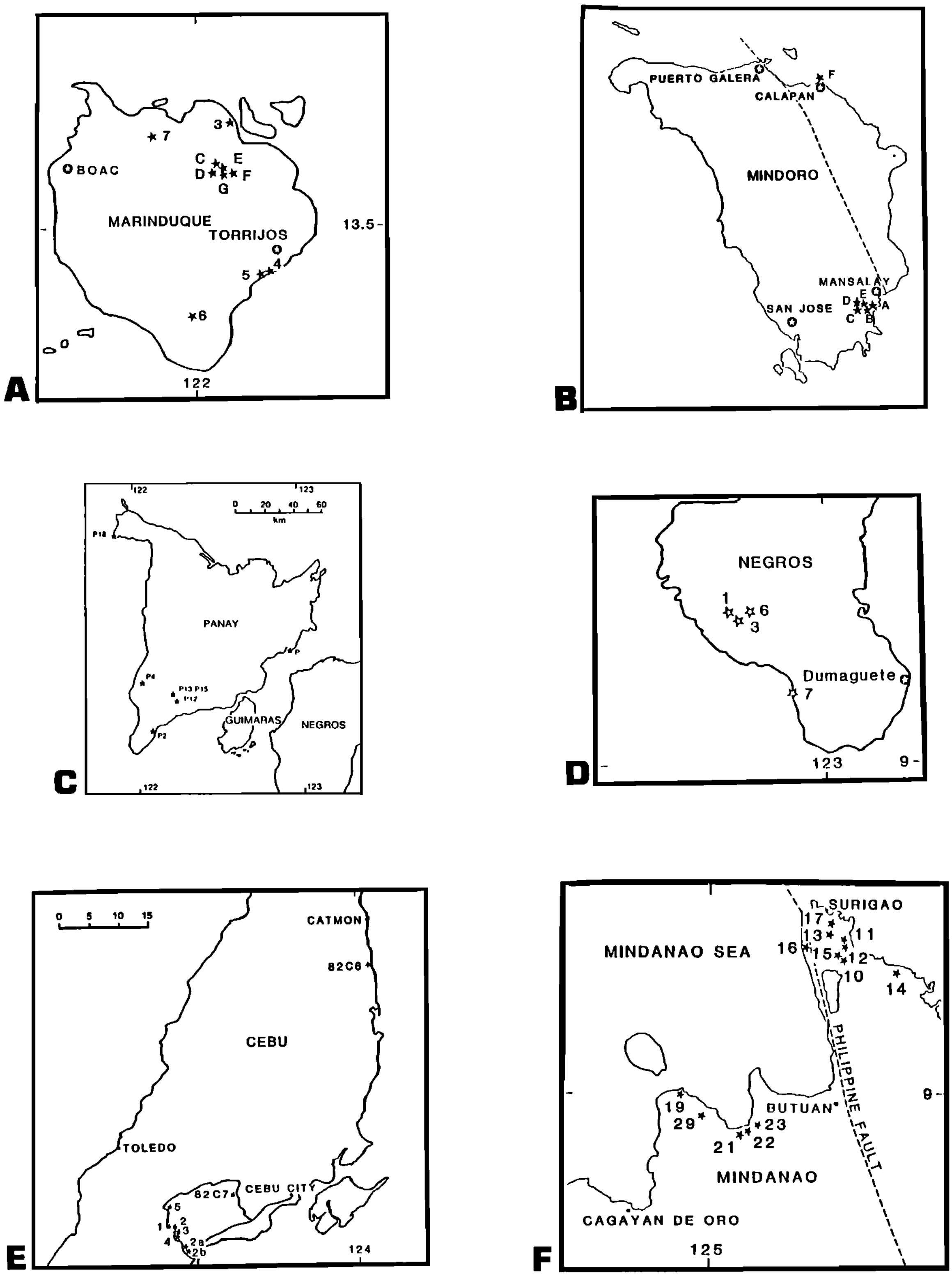


Fig. 3. Location map of sites collected from (a) the islands of Marinduque, (b) Mindoro, (c) Panay, (d) Negros, (e) Cebu, and (f) Mindanao.

from secondary alteration. The samples were collected from numerous lithologies including volcanics, basic dikes, diorites, volcanic tuffs, limestones (packstones and wackestones), and shales. Due to these lithological differences, a large variation in initial remanent intensity and magnetic behavior was noted during demagnetization. The initial magnetic intensity of the igneous rocks ranged between 10 and to 10^{-3} A/m. A large variation was noted in the initial intensity of magnetization of the sediments, which ranged from 0.1 A/m for the tuffaceous rocks to 10^{-5} A/m for the fine-grained shales and limestones.

Alternating field (AF) demagnetization proved to be an effective method for removing the secondary magnetization behavior from 80 of the 86 sites reported (Table 1). The demagnetization behavior of the samples was checked with vector diagrams. From these diagrams, three different types of behavior were observed. A few of the reported sites (<10%) were characterized by a single component of magnetization (Figure 4a). The most common behavior observed is shown in Figure 4b. Here, the sample contains one or more low-coercivity secondary components that were eliminated between 10 and 30 mT of demagnetization. After these low-coercivity components were eliminated, a single-direction component was isolated that showed a straight-line decay toward the origin on higher levels of demagnetization. The fact that many of these low-coercivity components did not show consistent directions (even between samples from a single site) suggests that these secondary components are caused by the samples being magnetically viscous. All the samples displaying either behavior 1 or behavior 2 contained less than 15% of their initial intensity of magnetization after demagnetization of 60 mT. The third magnetic behavior observed (not shown in Figure 4) was characterized by a complex mixture of magnetic vectors. AF demagnetization treatment up to 100 mT was unable to isolate any single component of magnetization for any of the members of this group.

AF demagnetization was ineffective in removing the secondary components of magnetizations from six of the sites reported. Samples from these six sites responded well to thermal demagnetization. Figure 4c shows a vector diagram obtained from thermal demagnetization of one of these samples. For this particular sample, 250°C was effective in eliminating the low blocking temperature components. After the elimination of these components, the sample showed a characteristic unidirectional decay on further thermal demagnetization up to 550° C. At this temperature, only about 10% of the magnetization remained. In addition to the direction of these AF unstable sites, the reported direction for many of the sites that yielded stable directions to AF demagnetization were also checked by thermal demagnetization. In all cases, the direction obtained by thermal demagnetization was indistinguishable from the mean direction obtained from AF demagnetization.

We believe that the characteristic components obtained by either AF and/or thermal demagnetization represent magnetic directions acquired at or near the time of origin of these rocks. This hypothesis is supported by the following.

1. The decrease of within-site scatter after demagnetization.

2. The general lack of secondary alteration as observed by optical microscopy.

3. The presence of both normal and reversed polarity samples which are antipodal at the 95% confidence level.

4. Positive fold test results for samples from Panay (κ increases by a factor of 2.6 after bedding correction), Mindoro (κ increases for the Jurassic samples by a factor of 2.5 after bedding correction), and Cebu (κ increases for the Cretaceous samples by a factor of 2.0 after bedding correction).

5. With the exception of the horizontal Plio-Pleistocene late Miocene rocks, none of the sites' characteristic directions are near the position of present average axial geocentric dipole field direction (with the exception of sites 82CEBU01, 82CEBU04, and 82MINDA09).

6. All of the late Miocene sites that required a bedding correction (sites from Baguio and Negros) are also characterized by directions that are distinguishable from the present field prior to bedding correction. In addition, the Plio-Pleistocene samples contain normal and reversed polarities, and the Jurassic to late Miocene sites contain sites collected from sedimentary units. This suggests that insufficient averaging of secular variation can be ruled out as the cause for these observed rotations.

Rock Magnetism Results

Igneous samples of different compositions and different Neogene ages were selected for rock magnetic studies. Similar studies were also attempted on the sedimentary samples, but because these rocks were too weak to yield useful magnetic property measurements, the studies were abandoned.

Curie temperature determinations were made on small chips (approximately 100 mg) from several different igneous rock samples by an automatic torque balance in a field of 450 mT. The Curie balance is located at the Ocean Research Institute of the University of Tokyo. All of the thermomagnetic curves were characterized by reversible curves on heating and cooling through 600° in a vacuum of 10^{-5} to 10^{-6} torr. Two representative curves are shown in Figure 5. For each sample, an easily saturable component exhibiting low-Ti titanomagnetite behavior was observed. Figure 5b shows a small amount of irreversible behavior between the heating and cooling curves, indicating the possible occurrence of titanomaghemite. Considering the small difference between the heating and cooling curves, the relative amount of this phase is probably small. The Curie temperatures for the samples measured ranged between 500° and 560° C. None of the samples were characterized by a pure T_c=578° magnetite.

Polished thin sections from the various representative rock types within the study area were examined under reflected light at magnifications of 1000X. All of the samples examined were found to contain abundant fine-grained primary titanomagnetites. In a few of the samples, fine ilmenite lamellae and a small degree of low-temperature oxidation were observed. The relatively high Curie point of these samples and the polished thin section observations indicate that the dominant magnetic carriers of these samples are fresh low-titanium magnetites that have been subjected to only minor low-temperature oxidation.

Hysteresis measurements were also carried out on the same suite of representative samples. All of the samples studied were characterized by hysteresis loops that become saturated in relatively low fields (between 200 and 400 mT). The coercive force of the samples ranges from 10 to 40 mT. The relatively low field saturation value

TABLE 1. Paleomagnetic Results From the Philippines

Location	Sample	N	Rock Type	Demag AF/TH	Dec BBC	Inc BBC	Dec ABC	Inc ABC	α95	κ
				Plio-Pleistocene						
Luzon										
Central Cordillera										
Ilocos Norte	81-2	5	SILT	20/300	181.6	9.8	180.2	-17.5	9.4	21.4
Baguio	81-36	7	BAS	--/480	170.0	-18.3			10.1	23.9
	81-31	11	BAS	20/450	0.1	13.4			5.5	68.8
Central Luzon										
Bamban	81-51	7	TUFF	20/450	359.0	26.1	Horizontal		7.4	26.2
	81-52	9	TUFF	20/450	176.3	-16.3	Horizontal		9.8	28.5
Bataan	81-110	6	AND	30/--	4.2	3.3	Horizontal		6.7	189.8
	81-111	11	DAC	30/350	171.1	-22.3	Horizontal		1.9	518.4
	81-112	9	DAC	30/--	177.5	-19.7	Horizontal		3.2	259.7
	81-113	5	DAC	30/--	175.6	-12.3	Horizontal		4.1	345.6
	81-114	6	DAC	30/--	165.2	- 4.6	Horizontal		7.4	82.7
Manila	81-61	6	BAS	30/--	175.4	-27.8	Horizontal		5.1	174.7
	81-UP	9	TUFF	20/--	182.1	-12.9	Horizontal		7.7	45.2
	81-100A	11	TUFF	15/--	183.8	-18.2	Horizontal		8.1	36.4
	81-100B	8	TUFF	--/450	173.4	-23.9	Horizontal		10.7	24.2
South Luzon										
Bicol	81-B10	5	BAS	20/--	359.8	10.0	Horizontal		6.3	114.6
	81-B4	6	AND	30/--	357.6	15.3	Horizontal		5.8	132.3
Mindoro	82MY20	8	DAC	30/--	187.2	-16.8	Horizontal		8.3	54.7
Cebu	82CEBU06	5	LMS	20/--	174.5	-20.9	Horizontal		10.4	36.1
Mindanao	82MINDA19	6	BAS	20/--	359.0	25.0	Horizontal		2.0	790.9
	82MINDA20	5	BAS	30/--	8.9	6.1	Horizontal		6.2	88.0
	82MINDA21	6	BAS	20/--	8.2	-10.0	Horizontal		5.7	101.0
	82MINDA22	5	BAS	20/--	353.0	33.6	Horizontal		4.7	217.8
	82MINDA23	6	BAS	20/--	181.4	-15.4	Horizontal		4.5	97.2
				Late Miocene						
Luzon										
Baguio	81-29	4	AND	20/425	8.8	-4.2	9.3	12.3	11.9	60.0
	81-30	7	AND	30/--	20.9	-0.9	22.8	21.4	5.3	132.0
	81-32	5	AND	20/--	7.8	27.4	19.4	44.3	8.7	78.3
	81-33	6	AND	15/--	27.9	11.1	25.9	28.1	13.2	18.8
	81-34	6	AND	40/--	9.4	-10.6	8.4	32.6	5.2	101.2
Zambales	84-T-4	5	DAC	30/--	190.1	-21.1	Horizontal		12.3	25.8
	84-T-5	4	DAC	30/--	200.9	-23.5	Horizontal		10.0	39.1
	84-T-6	5	DAC	20/--	202.2	-23.5	Horizontal		10.8	41.6
	84-T-7	7	DAC	30/--	193.7	-46.5	Horizontal		5.0	110.1
	84-T-8	7	DAC	20/--	195.3	-28.6	Horizontal		8.3	89.4
South Luzon										
Bicol	81-B2	8	AND	30/500	352.5	13.4	Horizontal		3.5	254.2
	81-B3	9	AND	30/450	352.6	19.1	Horizontal		4.8	116.2
	81-B6	8	AND	30/--	359.6	24.9	339.6	24.3	6.8	67.0
Marinduque	81MAR03	9	SILT	15/--	0.2	21.6	Horizontal		9.1	38.3
	81MAR04	5	DAC	20/--	6.6	5.1	Horizontal		5.1	211.9
Negros	81N-7	9	SILT	20/350	18.0	10.9	358.2	16.8	9.4	27.3
Mindanao	82MINDA17	7	LMS	30/400	354.3	19.2	Horizontal		3.1	302.4
				Early to Middle Miocene						
Marinduque	81MAR05	2	TUFF	20/350	281.5	-20.0	278.6	-1.5	--	--
	81MAR06	3	AND	30/--	325.6	2.2	Horizontal		13.2	28.2
	81MAR07	5	DIO	15/400	141.2	-28.6	Horizontal		17.7	20.0
	81MAR1C	2	DIKE	30/--	110.5	-36.1	Horizontal		--	--
	81MAR1D	2	DIKE	30/--	100.0	2.0	Horizontal		--	--
	81MAR1E	2	DIKE	30/--	140.0	-1.9	Horizontal		--	--
	81MAR1F	3	DIKE	30/--	135.0	-11.8	Horizontal		12.8	98.6
	81MAR1G	2	DIKE	30/--	109.9	5.6	Horizontal		--	--
Panay	P-13	11	LMS	20/450	198.1	13.8	195.5	-16.6	5.7	65.0
	P-15	15	BAS	20/450	198.2	6.5	202.2	-18.7	4.2	82.7
	P-02	7	SILT	10/350	22.3	-16.9	10.0	24.3	12.1	16.6

TABLE 1. (continued)

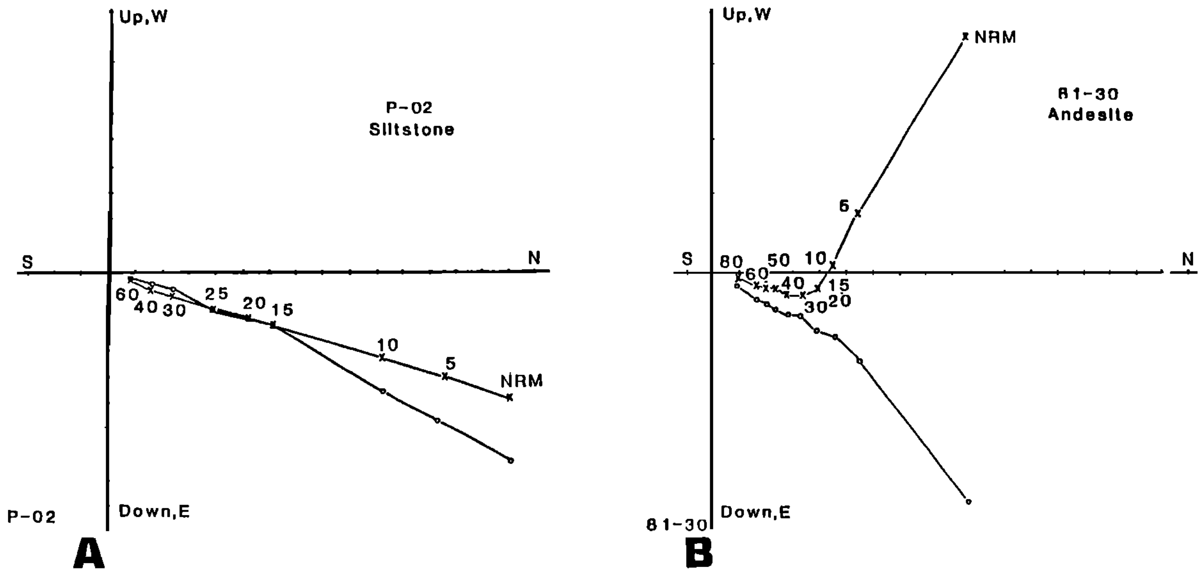
Location	Sample	N	Rock Type	Demag AF/TH	Dec BBC	Inc BBC	Dec ABC	Inc ABC	α95	κ
				Early to Middle Miocene (continued)						
	P-04	10	SILT	20/350	16.8	22.7	34.0	23.9	6.7	23.9
	P-12	9	SILT	10/450	12.2	-0.9	26.3	26.1	17.2	9.9
	P-06	6	SHAL	10/--	12.6	9.2	10.3	19.9	12.0	32.2
Cebu	81CEBU2A	5	SILT	25/--	226.7	4.9	216.7	-21.9	10.4	36.0
	81CEBU2B	5	SILT	15/--	54.7	2.6	56.1	27.6	13.8	20.5
	82CEBU03	4	LMS	20/--	226.9	-15.7	216.9	-18.8	11.7	36.0
	82CEBU04	5	SS	15/--	346.5	68.8	317.5	14.8	20.1	9.6
Mindanao	82MINDA09	4	LMS	30/--	181.1	-25.8	178.8	-20.8	11.9	17.3
	82MINDA10	7	LMS	30/--	13.4	-7.8	14.5	-5.8	6.5	66.6
	82MINDA11	6	LMS	20/--	204.4	-13.7	202.4	-9.7	12.0	22.8
	82MINDA12	9	BAS	--/400	211.6	-11.0	209.6	-9.0	5.9	78.2
	82MINDA14	10	BAS	30/--	199.5	-14.3	Horizontal		2.9	345.9
	82MINDA16	13	DAC	30/--	210.5	-10.5	Horizontal		7.4	57.3
				Oligocene-Eocene						
Luzon										
Caraballo	81-42	7	AND	20/500	325.7	29.0	326.7	2.5	3.6	147.8
Zambales	84-Z-1	8	BAS	20/450	60.0	20.0	Horizontal		10.4	30.3
	84-Z-2	6	BAS	15/--	62.0	22.0	Horizontal		9.5	63.4
	84-Z-3	7	BAS	20/--	53.0	10.0	Horizontal		5.9	236.4
	84-Z-4	9	BAS	20/500	55.0	20.0	Horizontal		7.4	93.5
	84-Z-5	5	BAS	20/--	64.0	10.0	Horizontal		12.8	22.6
	84-Z-6	8	BAS	25/--	50.0	15.5	Horizontal		8.9	73.6
Panay	P-11	8	DIO	15/--	72.7	20.0			11.7	23.5
	82PAN18	9	SILT	20/--	342.3	31.5	331.6	11.0	5.7	66.7
Negros	81N-1	6	DIKE	15/500	332.1	8.2	Horizontal		12.4	21.3
	81N-2	2	DIKE	20/500	330.3	-6.8	Horizontal			
	81N-6	4	DIO	--/450	5.5	62.8	Horizontal		6.6	110.0
				Cretaceous						
Central Luzon										
Manila	81-62	7	TUFF	30/--	329.2	11.4	330.3	3.0	11.8	27.2
Cebu	82CEBU01	6	BAS	40/--	344.7	7.2	347.7	-8.2	21.0	17.3
	82CEBU02	4	SILT	--/320	316.2	-29.1	302.2	-26.1	14.4	31.9
	82CEBU05	5	SILT	--/320	284.3	15.8	295.3	-10.8	32.9	3.6
	82CEBU07	8	SILT	20/--	299.3	37.0	296.6	-10.6	12.4	18.0
				Jurassic						
Mindoro	81MY02	6	SILT	20/--	73.5	60.5	49.5	35.5	10.6	28.9
	81MY03	2	SILT	20/--	88.0	-10.3	88.0	11.3		
	82MY10	4	SILT	15/--	250.4	12.7	254.4	-27.7	25.3	7.7
	82MY12	5	SILT	20/--	77.3	32.3	84.3	47.3	18.4	9.1
	82MY13	6	SILT	20/--	258.8	-5.5	259.8	-13.5	18.1	9.9

N, number of samples; Demag, demagnetization method; AF, alternating field demagnetization level used to obtain characteristic direction given in mT; TH, thermal demagnetization -- temperature is given in degrees centigrade; Dec, declination; Inc, inclination; BBC, before bedding correction; ABC, after bedding correction; α95, radius of 95% confidence circle (only given if three or more samples reported from a site); κ, precision parameter.

and the low coercive force of the samples suggest that hematite is not a major magnetic carrier in these samples [Nagata, 1961].

The hysteresis observations, Curie point determinations, and polished thin section studies suggest that a low-titanium magnetite is the dominate magnetic carrier in these samples. Jr/Js determinations were calculated from the hysteresis loops. The Jr/Js values range from 0.07 to 0.33. Comparison of these values with those of Day et al. [1977] for pure magnetite grains suggests that the magnetic carriers are magnetites in the psuedo-single domain grain size.

From the above studies it is suggested that the dominant carrier of magnetization in igneous samples is a titanium-poor titanomagnetite whose grain size is in the psuedo-single domain size range. These magnetic studies and the fact that these samples pass paleomagnetic field tests (i.e., reversal test and fold test) strongly argue that the magnetization is a primary



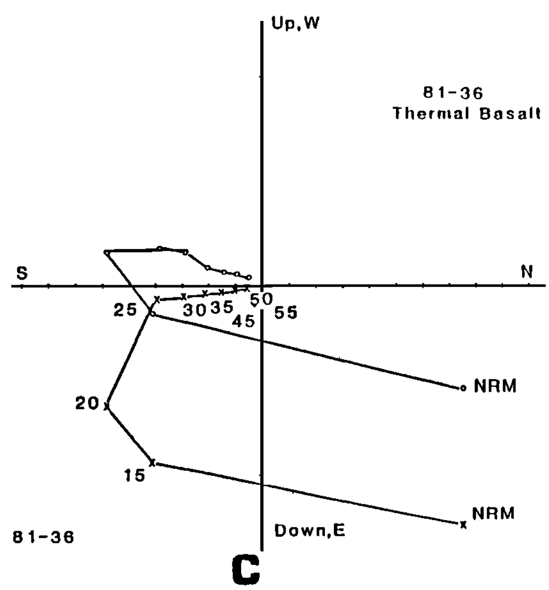


Fig. 4. Orthogonal vector projection of (a and b) AF and (c) thermal demagnetization illustrating the general behavior of the sites reported in this study. (a) Approximately 10% of the samples were characterized by a direction of magnetization that showed nearly unidirectional decay on demagnetization. (b) The most common behavior was characterized by a large secondary component(s) that was easily removed; the samples were characterized by unidirectional decay upon further demagnetization. (c) Some of the samples that did not respond to AF demagnetization responded well to thermal demagnetization. Solid symbols are projections on the horizontal plane, open symbols projections on the north-south vertical plane.

thermoremanent magnetization (TRM) that was acquired at or near the time of cooling of these units. Although we do not have rock magnetic tests from the sediments, many of them are interbedded with these volcanic units and have consistent characteristic directions with similarly aged igneous units from the region. The fact that they pass paleomagnetic field tests with similarly aged igneous units argues that the detrital remanent magnetization of these samples was acquired fairly near the time of deposition.

Discussion

We have presented paleomagnetic results from seven islands of the Philippine Arc. Sites range in age from Jurassic to Pleistocene, with the majority of sites being of Neogene age. We will

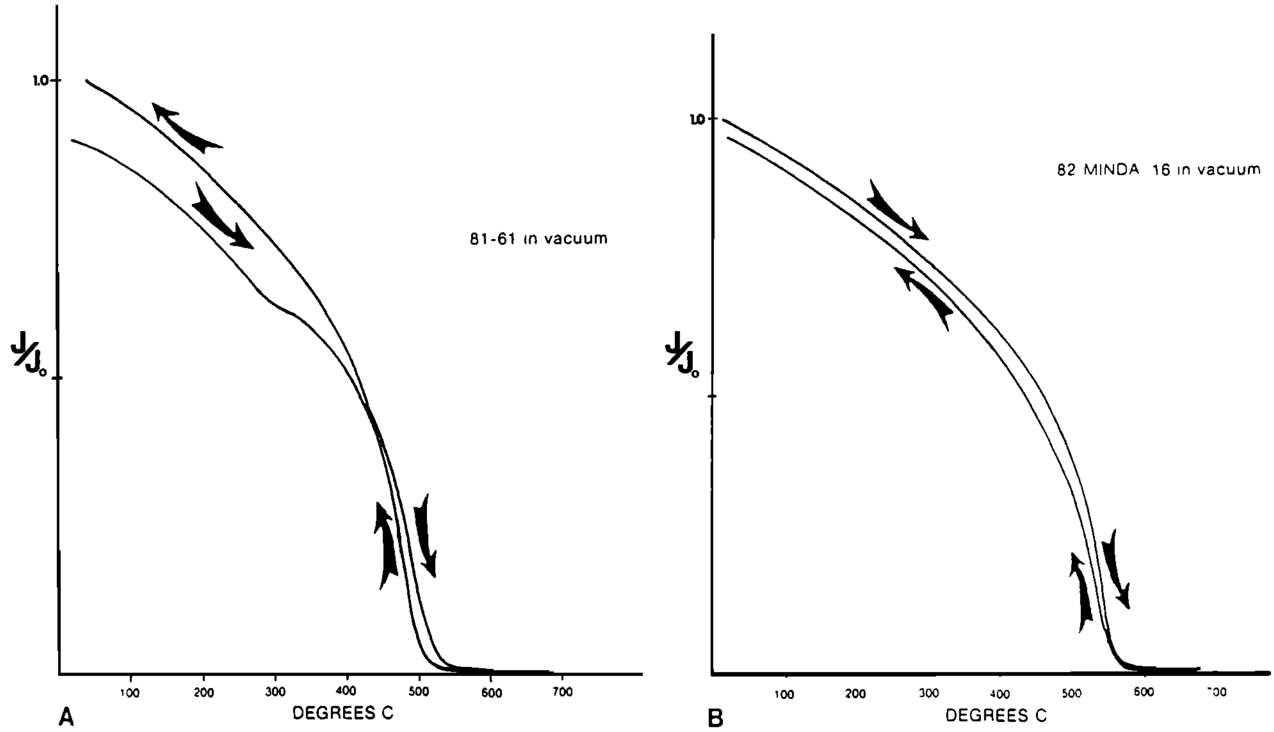


Fig. 5. Strong field thermomagnetic curves for two representative samples. Heating was done in vacuum of 10^{-5} to 10^{-6} torr in field of 450 mT. A small amount of irreversibility is noted in Figure 5a. This observation is consistent with observations made in polished section studies.

now discuss the entire data set in reverse chronological order, beginning with the Plio-Pleistocene. The results will be used to constrain the relative motion between various portions of the Philippine Arc.

Plio-Pleistocene

With the exception of 81-2 and 82CEBU06, all of the Plio-Pleistocene samples reported in this study were taken from volcanic rocks. All samples were characterized by a stable magnetization that was easily isolated by either AF or thermal demagnetization techniques. The declination values from these samples are shown in Figure 6.

In this figure, and the four that succeed it, declinations are shown as a black compass needle with north at the top of the figure. Sites with reversed polarity are reflected to their antipodal direction. The size of the wedge in each figure represents the α 95 error limits. Figure 6 supports the conclusion that during the past 5 m.y. the Philippine Arc has behaved as a single tectonic unit or that deformation has occurred at levels that are not detectable given the resolution of the paleomagnetic data. The mean declination values for the 23 sites (Table 2) are indistinguishable from the present field. Hence the data strongly support the conclusion that there has been no discernible rotation of this region since the Pliocene.

Although the mean declination value is clearly indistinguishable from the present field direction, the mean inclination value for these sites is shallower than the expected axial dipole inclination (30°) for this latitude. Anomalously shallow inclination values are also reported from other Plio-Pleistocene data sets from the southeast Asian region. Table 3 gives the inclination and declination values from Taiwan [Hsu et al., 1966], Vietnam [Giang, 1982], and the Mariana Arc [McCabe and Uyeda, 1983]. The mean declination values listed in Table 3 are indistinguishable at the 95% confidence interval from the direction of the present geocentric field. However, the inclination values differ significantly from the inclination values predicted by the dipole formula for that latitude and are also statistically distinguishable at the 95% confidence interval. It is not the purpose of this paper to address the cause of these late Neogene shallow inclinations; however, neither secular variation nor plate motions are likely causes. The southeast Asian Plio-Pleistocene data set comes from these four different areas and comprises 88 sites collected from volcanics and sediments with both normal and reverse directions of magnetization. These facts argue that it is highly unlikely that these shallow inclinations represent insufficient averaging of secular variation. In addition, since the majority of the sites reported in Table 3 are from the Asian mainland (the Taiwan and Vietnam sites), a 5° northward drift of Asia during the past 5 m.y. would be required to produce these values. This motion does not seem likely.

Two possible explanations for these shallow inclinations are either a strong g_2^0 effect [Wilson, 1970, 1971; Merrill and McElhinny, 1977] or other long-term non-dipole effects that exists in the region. At present, the magnetic equator

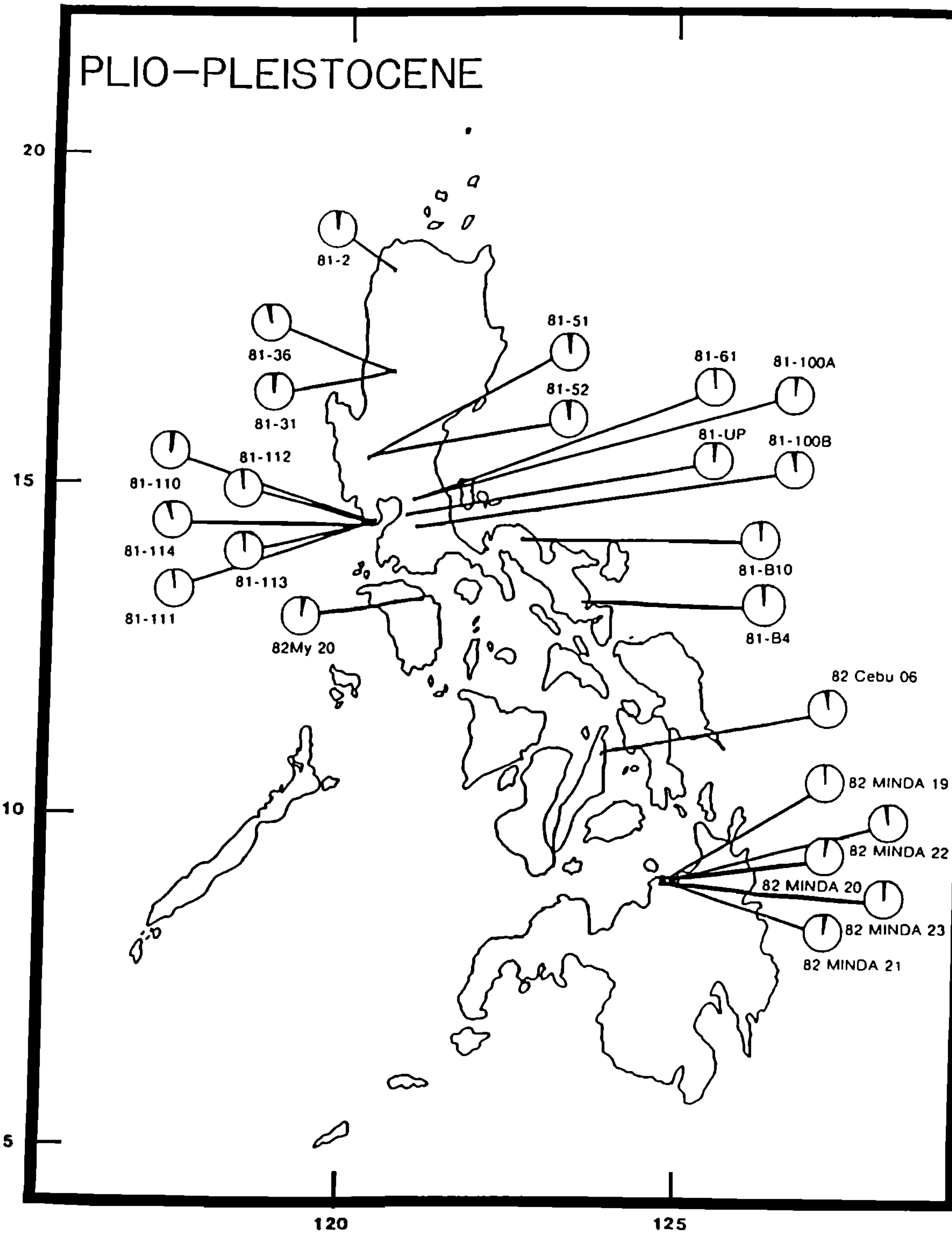


Fig. 6. Map showing location of Plio-Pleistocene results. The small circles on this and the next four figures show the direction of magnetic declination values (shown as midpoint of the darkened section) for each site. The size of the wedge corresponds to the α 95 error bars corrected by the method of Cox and Gordon [1984]. Because of the univariance behavior of declination on these figures, negative polarity samples are reflected through the origin to their antipodal position. This figure suggests that the Philippines has behaved as a single unit during the past 5 m.y.

is deflected 10° to the north in this region [McElhinny, 1973]. The coincidence between the present-day northward deflection in the magnetic equator and shallow inclinations recorded by Pliocene to Recent rocks from the region suggests that the northward deflection of the magnetic equator may not be caused solely by some local transient effect of the field.

TABLE 2. Summary of Paleomagnetic Data

Location	Number of Sites	Stability Test	Average Dec.	Average Inc.	α95	κ	VGP Latitude	VGP Longitude	dp	dm
				Plio-Pleistocene						
	23	R	358.9	16.2	4.2	54.0	N85.2	E314.7	1.8	3.0
				Late Miocene						
West Central Luzon	10	R	16.7	28.3	7.2	46.1	N73.8	E210.9	3.9	5.1
Central Philippine Arc	7		357.7	17.2	6.0	100.7	N80.8	E218.1	3.6	5.5
				Early to Middle Miocene						
Marinduque	8	R	302.4	11.3	16.9	11.6	S29.5	E196.3	8.9	14.5
Panay, Cebu, and Mindanao	15	R, F	23.9	17.6	7.6	26.5	N65.0	E215.4	3.5	5.8
				Oligocene and Eocene						
Coto Mine Dikes	6		57.6	16.6	6.3	115.4	N33.4	E209.6	3.4	4.8
				Mesozoic						
Cebu	3	F	297.1	15.8	14.6	72.3	S25.6	E199.8	7.7	8.1
Mindoro	5	R, F	75.7	27.7	19.4	16.6	N17.2	E198.6	13.6	15.2

R, reversal test; F, fold test.

Late Miocene

The late Miocene collection represents samples taken from 17 sites. These sites included volcanic rocks from Luzon, volcanic and sedimentary rocks from Marinduque, and sedimentary rocks from Mindanao and Negros. Because the collections from Negros and Baguio are clearly distinguishable from the present field prior to bedding correction (the rest of the sites are horizontal and therefore required no bedding correction), we suggest that the rocks recorded a magnetization that was acquired before tilting.

Figure 7 is a diagram that shows the measured late Miocene declination values. The late Miocene population forms two distinct sets (Table 2). The seven sites sampled from the central and eastern portions of the arc are consistent with the Plio-Pleistocene results in that they show no evidence for rotation. In contrast to these sites, results from the 10 sites sampled along the western margin of Luzon argue for approximately 17° of clockwise rotation of this region between late Miocene and Pliocene times (Table 2). Our results are similar to earlier findings [Hsu, 1972; Fuller et al., 1983], which report late Miocene sites from the Baguio region show nearly 20° clockwise rotation.

Until further work is carried out, it is difficult to postulate the cause of this clockwise rotation. The late Miocene samples from Luzon were collected from 10 distinct lava flows from two different areas and contain both normal and reversed magnetized samples. These facts and the consistency between our data and other studies [Hsu, 1972; Fuller et al., 1983] argue that the magnetizations reported are not caused by secular variation of the earth's magnetic field.

The sense of rotation of the Philippine Sea Plate is clockwise [Kinoshita, 1980; Loudon, 1977; Shih, 1980; Jarrard and Sasajima, 1980; Seno and Maruyama, 1984; Keating and Helsley, 1985] and therefore consistent with the sense of rotation observed for Luzon. Our late Miocene data do not allow us to totally rule out that this observed late Miocene rotation is related to Philippine Sea Plate motion. Jarrard and Sasajima [1980] have pointed out that the Philippine Sea Plate has rotated less than 20° during the past 20 m.y. From our late Miocene paleomagnetic data, we would have to argue that almost the entire post-20 m.y. clockwise rotation occurred between 10 and 5 m.y. Although this explanation cannot be ruled out, this explanation seems unlikely. Hence we do not believe the rotation that we are observing is related to

TABLE 3. Plio-Pleistocene Directions From Southeast Asian Region

Location	N	D	I	I*	α_{95}	κ
Vietnam	28	-2.2	18.6	26.5	4.9	32.3
Taiwan	35	3.5	30.5	40.3	5.6	20.0
Marianas	2	353.9	16.2	28.0		
Philippines	23	358.9	16.2	29.8	4.2	54.0

N, number of sites; D, declination; I, inclination calculated by dipole formula; α_{95} radius of 95% confidence circle (only given if more than three sites reported); κ, precision parameter. Sources of data given in text.

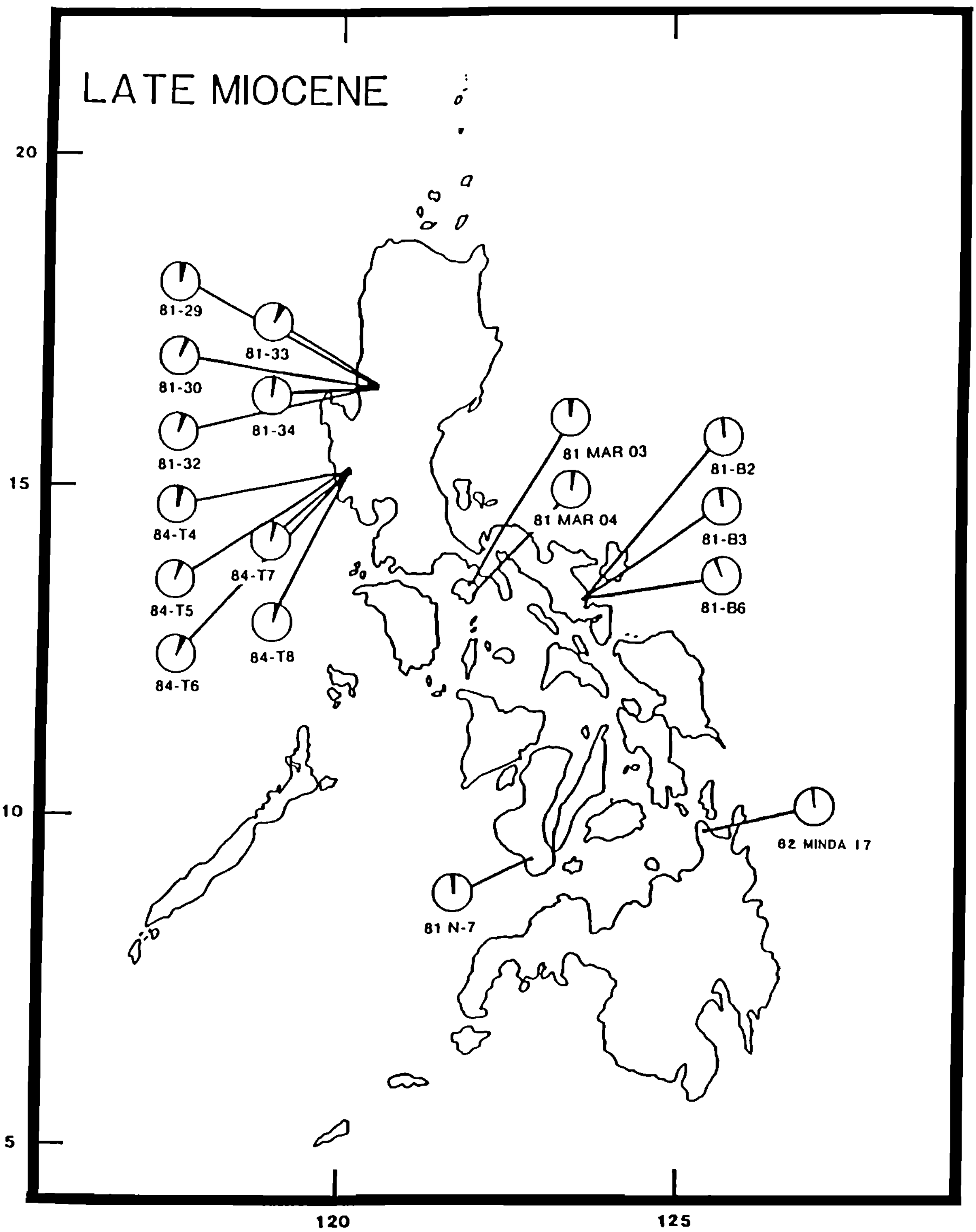


Fig. 7. Location map showing the late Miocene directions. The data fall naturally into two subsets. The directions from north and central Luzon reflect a post-late Miocene clockwise rotation. The remainder of the directions from south and east do not show evidence for this clockwise rotation. The symbols are the same as in Figure 6.

rotation of the Philippine Sea Plate. Instead, we favor that the possible cause of the clockwise rotation of Luzon is the Pliocene collision of Taiwan with the North Luzon Ridge (Figure 1) [Karig, 1973; Chai, 1972; Murphy, 1973]. This collision-related rotation would be consistent with the fact that the rotation is localized to north and central Luzon. Such a cause for the rotation also appears consistent with paleomagnetically detectable rotations observed in other island arc collision zones [McCabe et al., 1982a; McCabe and Uyeda, 1983; McCabe, 1984].

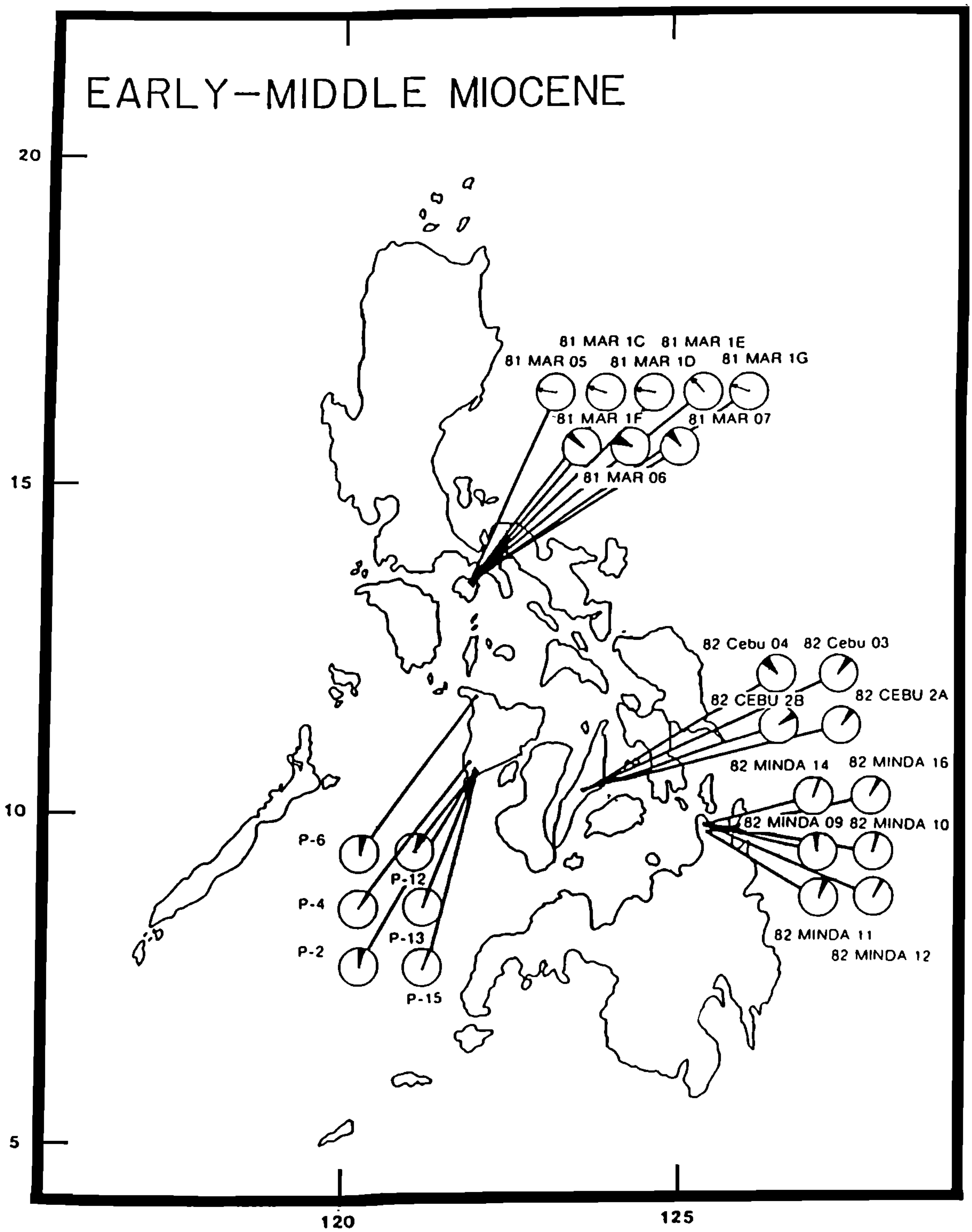


Fig. 8. Location map showing early and middle Miocene directions. The data fall into two groups. Data from Marinduque are consistent with earlier work [Hsu, 1972] and show evidence for a counterclockwise rotation (the small clocklike arrows represent sites less than three samples and therefore no calculated α 95; see text for further discussion). The directions from Panay, Cebu, and northeastern Mindanao show clockwise deflections from N-S direction. The symbols are the same as in Figure 6.

Middle to Early Miocene

Results from samples collected from 24 early to middle Miocene age sites from four different islands are summarized in Figure 8 and Table 2. Like the data from the late Miocene, two different populations are observed. The data from Marinduque Island make up one of the populations. The declinations from all eight sites sampled on Marinduque are deflected approximately 60°

counterclockwise from the present field. These results are consistent with the earlier study of Hsu [1972], who also reported a large counterclockwise deflection in the Oligocene and Miocene results from Marinduque and from the southernmost portion of Luzon.

In contrast to the results from Marinduque, results from Cebu, Panay, and Mindanao (Table 2) show evidence for a clockwise rotation. One site was excluded from the mean given in Table 2. This excluded site is 82CEBU04, which has a direction that is highly discordant (DM=346.5°) to the other 14 sites. The reliability of these data is supported by the Panay data. These data pass fold (κ increases from 28.0 to 72.0) and reversal tests.

This early and middle Miocene data set suggests that sometime during the Miocene there was a differential rotation of the central Philippines; the northern portion (Marinduque) rotated counterclockwise with respect to the southern portion (Cebu, northeastern Mindanao, and Panay). These rotations are consistent with Miocene structures in the region and strongly argue for a post-middle Miocene collision along the western margin of the central Philippines.

Additional evidence for this post-middle Miocene collision is observed in lead isotopic studies from the Philippine Arc [Mukasa et al., 1986]. These lead studies show enrichment in radiogenic lead from late Neogene volcanic rocks immediately behind the colliding block. Late Neogene volcanics from the eastern Philippine Arc and northern Luzon do not show such enrichment in radiogenic lead. This evidence suggests that the lavas located close to the collision block are being contaminated by the newly introduced continental crust of the North Palawan Continental Terrane.

Oligocene to Eocene

Early Tertiary results (Figure 9) are from four areas and show no general systematic trends. In addition, the age constraints on four of the 12 sites are poor and based only on stratigraphic arguments. From the central Philippine data set, only the ages of the site from the Buruanga Peninsula of western Panay and the Siplay Diorite of southern Negros are considered accurate. The age from the six dikes from the Coto Mine area of Zambales is based on two K-Ar age dates (25±7 and 36±5 m.y., De Boer et al. [1980]). De Boer et al.'s K-Ar ages on both these dikes are Oligocene but both ages are characterized by rather large errors. Below, we will discuss the directions from the Coto Mine dikes.

The six dikes from the Coto Mine (Figure 9, Table 2) show declination values that are deflected 57° clockwise from the present field direction, suggesting that the region has undergone a strong post-intrusion clockwise rotation. Some degree of caution should be exercised in interpreting the directions from the dikes because they may not average out the secular variation of the earth's magnetic field. Fuller et al. [1983] report the results from Oligocene sediments from the Zambales region. These sediments are rotated over 80° clockwise from the present dipole field direction. The coincidence between the Coto Mine dikes and the Oligocene sediments suggests that the Zambales region of Luzon has rotated clockwise since middle Oligocene. Furthermore, Fuller et al. [1983] reported the results from nine sites of Eocene age from the Zambales Ophiolite (discussed earlier). These authors suggest that Zambales has undergone a post-Eocene counterclockwise rotation. The data we present from Coto Mine and the Zambales Oligocene sediments argue that the sense of the rotation of the Zambales region is clockwise and not counterclockwise, as originally suggested. Further evidence for this clockwise rotation is from preliminary results (R.J. McCabe, unpublished data, 1986) from four sites in the Oligocene portion of the Askitero formation. These sites show evidence for around 50° of clockwise rotation and possess both normal and reversed samples.

Because the geology and the ages are so poorly constrained on the rest of the early Tertiary sites, no tectonic interpretation of these data is possible until further studies are carried out on the early Cenozoic rocks for the region.

Mesozoic

A total of 10 sites of Mesozoic age from three different areas are reported in this study (Figure 10). The late Cretaceous of the Angat area is limited to samples from only five horizons collected at one site (81-62) and is inconsistent with other late Cretaceous results collected a few kilometers away, which show about 45° of clockwise rotation [R.J. McCabe and M.D. Fuller, unpublished data, 1982; Almasco and Fuller, 1984]. Our field work, south of this area, found numerous steeply plunging folds. Recently, preliminary field studies by Haeck and Karig [1985] have identified numerous middle Tertiary strike-slip faults in the region. Because of the conflicting results, the presence of only one sampling site, and the poorly understood, probably complex, structure of this region, we omit these data from tectonic interpretations until more detailed structural studies are reported in the region.

The results from the Jurassic of Mindoro and the Cretaceous from Cebu are considered reliable because they both pass fold tests (κ increases from 6.7 to 16.6 for Mindoro and from 4.8 to 9.9 for Cebu after bedding correction). The data from Cebu are from four distinct units of the Cretaceous Pandan formation. When site 82CEBU01 (whose direction lies close to the present dipole field direction) is removed, the average direction is 297° (Table 2). These data are discordant from the present field direction, being rotated 117° clockwise (or 63° counterclockwise). Care must be taken in the application of this result to a tectonic interpretation of the region until more Cretaceous and early Tertiary data are obtained.

The data from Mindoro come from five separate sites. The VGP of these sites (latitude, 17.2°; longitude, 198.6°; κ=6.7; A95=16.7) is highly discordant from the Cretaceous VGP of Cebu (25.2°N, 17°E) and argues either (1) that a large amount of tectonic movement of the Philippines has occurred between the late Jurassic and the late Cretaceous or (2) that Mindoro and Cebu were distinct tectonic entities until joined at a

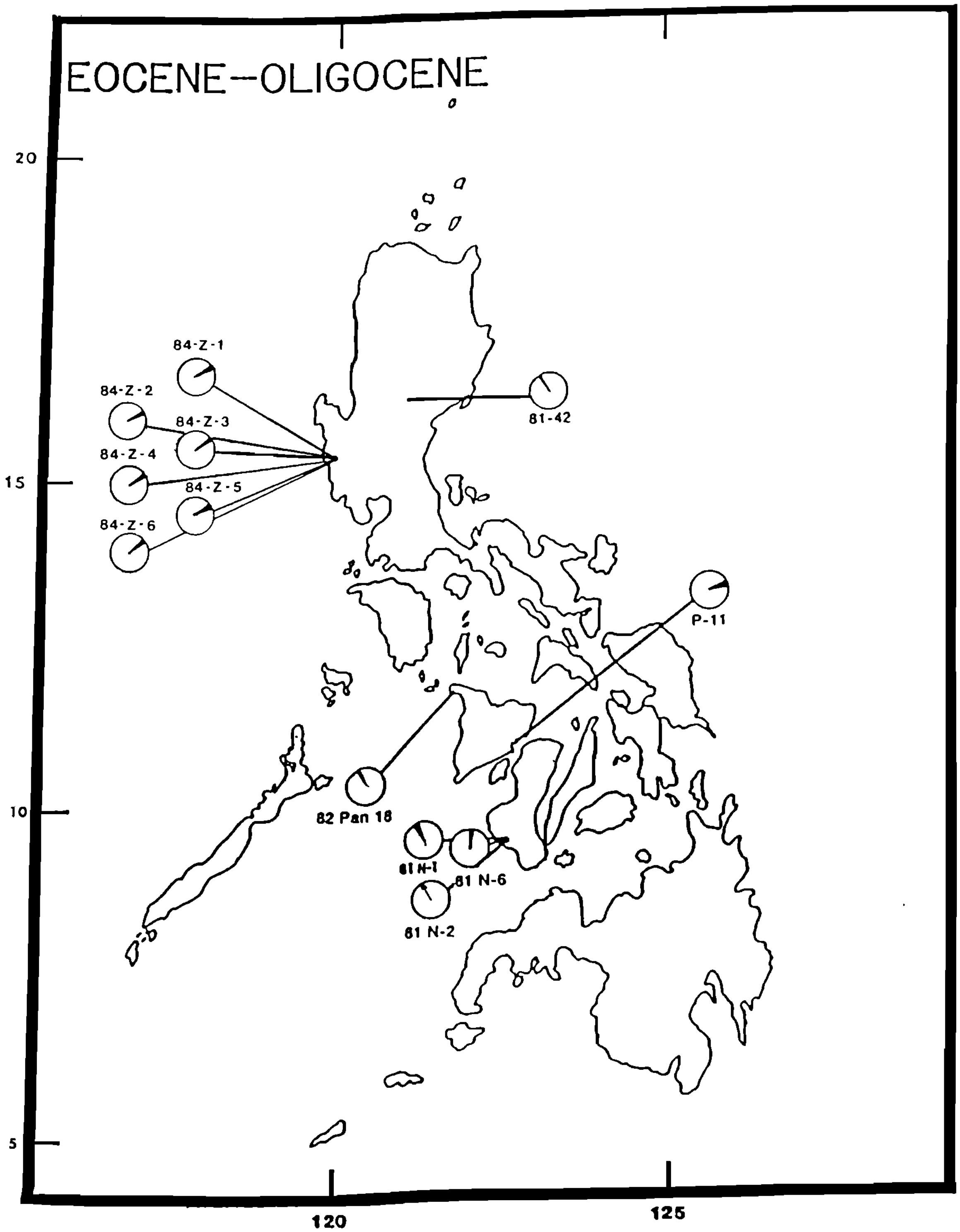


Fig. 9. Location map showing the early Tertiary sites reported in this study. The data do not appear to show any coherent large-scale rotations for the entire Philippines. The data from Zambales show a clockwise rotation of greater than 50. These data and earlier reported Eocene data from the ophiolite [Fuller et al., 1983] suggest that the entire Zambales range has undergone greater than 100° of clockwise rotation since Eocene time. Until further studies are completed, no tectonic significance is attached to this data set. The symbols are the same as in Figure 6.

later time. The second hypothesis is favored. Hamilton [1977, 1979], Taylor and Hayes [1980, 1983], Holloway [1981], McCabe et al. [1982a, 1985], and Karig [1983] have all argued that the pre-Miocene rocks from Mindoro and northern Palawan are distinct from the rest of the Philippine Arc. On the basis of a similarity in stratigraphy between southern China and the North

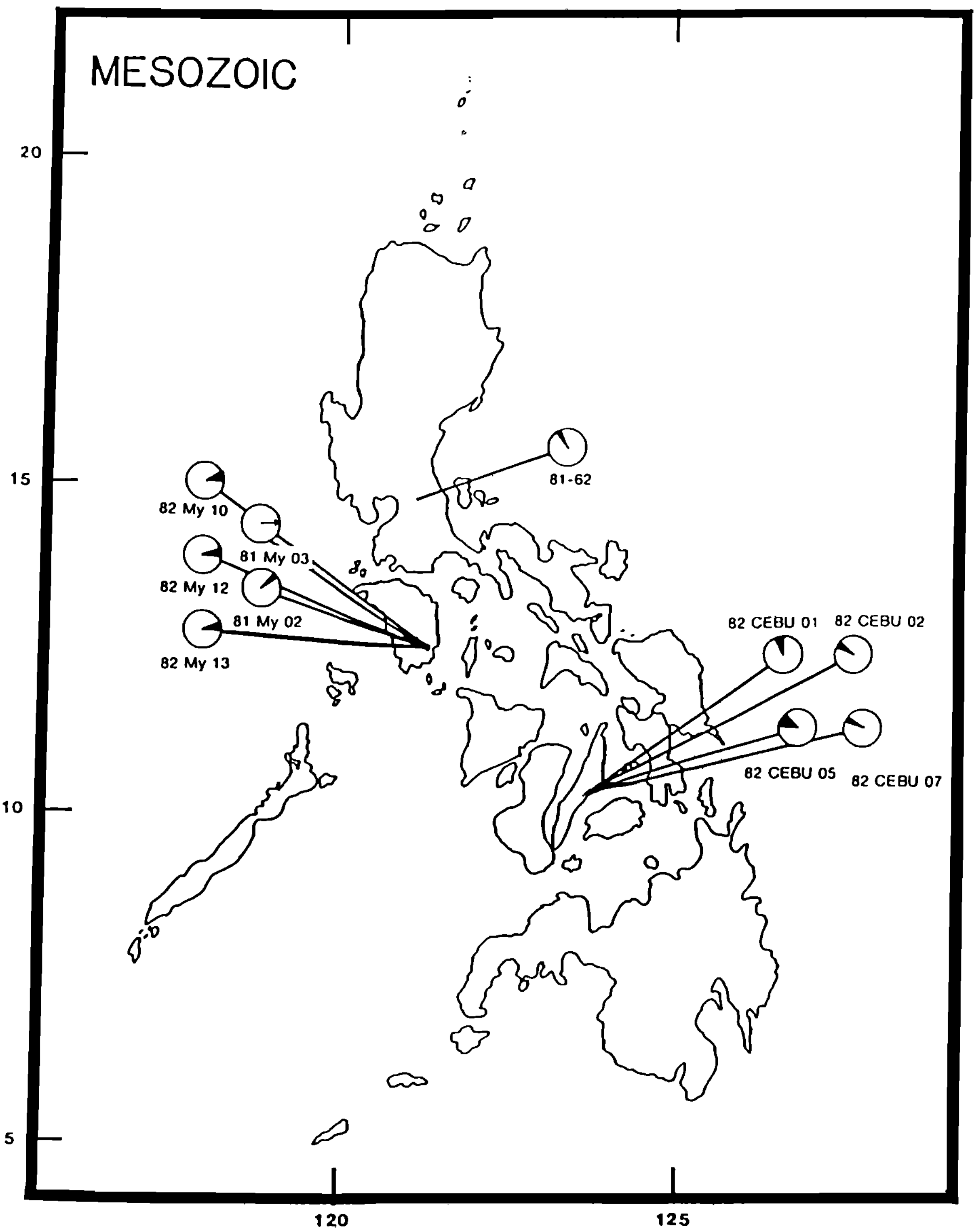


Fig. 10. Location map showing the Mesozoic results. Although the Cebu and Luzon data appear to show a similar rotation, this relationship is suspect until more studies are completed. The Luzon data are inconsistent with other results from that area [Almasco and Fuller, 1984] and suggest more detailed studies of Luzon are required. The symbols are the same as in Figure 6.

Palawan Block, the presence of E-W trending Oligocene to Miocene magnetic anomalies in the South China Sea, and a highly deformed zone along the western portion of the Central Philippine Arc, these authors argue that the North Palawan Block became sutured to the Philippine Arc in the Neogene.

The late Jurassic VGP's of Mindoro and South China [Lin et al., 1985] are shown in Figure 11. An examination of this figure shows that the VGP

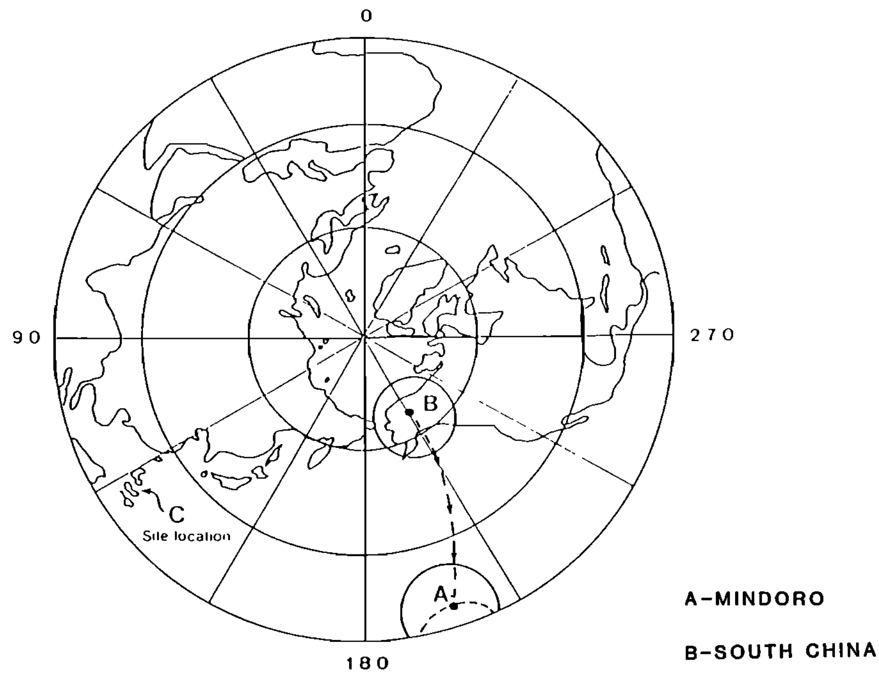


Fig. 11. Location of late Jurassic paleopole positions of (a) Mindoro and (b) South China [after Lin et al., 1985]. The position of the Mindoro pole is consistent with the southward migration of the North Palawan Block with the Oligocene to Miocene opening of the South China Sea [Taylor and Hayes, 1980, 1983].

of Mindoro is displaced southward from the late Jurassic of South China. The inclination data suggest that during the late Jurassic, both these regions were at the same latitude (around 20°). The data are consistent with the model in which Mindoro (and the rest of the North Palawan Block) was part of South China during the Jurassic and later rifted southward (and perhaps clockwise) relative to China. This migration of Mindoro is consistent with the Oligocene to Miocene opening of the South China Sea suggested by Taylor and Hayes [1980]. Although the structural data from Mindoro are not well understood, Sarewitz and Karig [1986] have just mapped a major left-lateral strike-slip shear zone along the axis of the island of Mindoro. In the past, other workers have inferred other major strike-slip shear zones around Mindoro Island [De Boer et al., 1980; Wolfe and Self, 1983; Divis, 1983; Karig, 1983]. These shear couples could produce the observed discordant declinations. In addition, the site locations themselves are at the very edge of the North Palawan Block. This location is likely to be strongly influenced by local collision-related deformation. Such deformation could also provide a possible explanation for the observed rotations.

Paleolatitude of the Philippine Arc

Large differences in directions are observed between different portions of all but the Plio-Pleistocene data sets. Because of the differences, we did not treat the entire population of a particular age with Fisher statistics. However, because the differences in magnetic directions are probably caused by tectonic rotations about a vertical axis, we can still use the inclination values to estimate changes of paleolatitude of the Philippine Arc versus time. This approach is valid because, unlike declination data, paleoinclination values can be recovered by knowing the paleohorizontal of the strata.

Following the discussion by Plumley et al. [1983], we treated our data set and the Eocene results from the Zambales region [Fuller et al., 1983] with the statistical method of McFadden and Reid [1982]. Table 4 lists the paleolatitudes of the variously aged populations. One additional problem encountered with the data set is that the present-day latitudes of the sites vary from 9°N to 18°N, while the older sites vary from 9.8°N to 16.5°N, introducing perhaps a slight southward bias for older paleolatitudes. In order to account for these differences, we assumed a geocentric dipole axial field for the region and a reference latitude (15°N). The difference in inclination between the site latitude and the reference latitude was added (if south of 15°N) or subtracted (if north of 15°N) to the inclination values before calculation of the values listed in Table 4.

An examination of the Cenozoic data is consistent with the conclusion of Hsu [1972] for a Cenozoic northward drift of the Philippine Arc. When the Cenozoic paleolatitude data are plotted against age (Figure 12), the data show a northward drift similar to Philippine Sea Plate inclination data [Louden, 1977; Kinoshita, 1980], suggesting that the Philippine Arc has shared a common Cenozoic northward drift with the Philippine Sea Plate, as originally suggested by Uyeda and McCabe [1983]. Coupland and Van der Voo [1980] have argued that a shallow inclination effect has existed throughout the entire Cenozoic.

TABLE 4. Statistical Analysis of This Data Set and the Data From Zambales

Age	I_{mean}	e_1	κ_1	λ_{paleo}	e_2	κ_3
Plio-Pleistocene	16.3	4.9	35.5	8.3	+2.7 -2.5	52.8
Late Miocene	24.3	5.9	29.0	12.7	+3.5 -3.3	39.3
Early to Mid-Miocene	21.3	6.0	23.0	11.0	+3.5 -3.2	39.3
Oligocene	15.3	8.5	41.7	7.8	+4.6 -4.3	62.4
Eocene	7.3	9.5	21.4	3.7	+4.8 -4.8	33.7
Cretaceous	21.0	11.7	28.6	10.9	+6.9 -6.2	40.5
Jurassic	31.0	16.6	14.3	16.7	+12.0 -9.4	17.5

Zambales data from Fuller et al. [1983]; I_{mean}, e_1 and κ_1 calculated by the dipole method of McFadden and Reid [1982]; λ_{paleo}, calculated from dipole formula; e_2 calculated by using dipole formula on mean inclination plus or minus the error; κ_3 calculated using equation of Cox [1970].

This shallow dipole effect seems to be consistent with the Plio-Pleistocene directions reported above. It is easily seen that such a long-term offset dipole effect would have an effect on the absolute values of the paleolatitudes reported in Figure 12 and Table 4. In the above Plio-Pleistocene section we discussed the fact that the Plio-Pleistocene data show shallow inclination values. Although such an effect may be present in our older data set, this should not affect the interpretation of Figure 12. This last statement is based on the fact that this figure infers that the Philippine samples of a known age have inclination values that are consistent with inclination values reported from similarly aged rocks from the Philippine Sea Plate. The fact that the inclination values for various-aged rocks from both the Philippines and the Philippine Sea Plate have common relative values suggests these two regions shared a common latitudinal history.

It must be pointed out that the error bars in Figure 12 are rather large. Therefore caution is warranted in using this interpretation. At present, the Mesozoic data are too few in number to suggest whether or not the steeper inclinations of the Cretaceous represent a northward drift from south of the equator or a pre-Eocene southward migration of the Philippine Arc.

Conclusions

In this paper we present data collected between 1980 and 1984 from 86 paleomagnetic sites. Rock magnetic tests were conducted on these samples in order to verify that the magnetic phases in these samples are capable of carrying a stable remanence. These studies showed that the dominant magnetic carrier is a low-titanium magnetite with a pseudo-single domain grain size. We suggest that the magnetic carrier acquired its magnetization near the time of cooling (or deposition) of these rocks. These conclusions are further supported by fold and reversal tests. The paleomagnetic data from these samples are used to constrain the tectonic history of the Philippine Arc. From these studies we conclude the following.

1. The entire Philippine Arc has behaved as a single tectonic unit during the Plio-Pleistocene, or has deformed at rates below the level of detection by paleomagnetic studies.

2. Paleoinclination data from over 80 Plio-

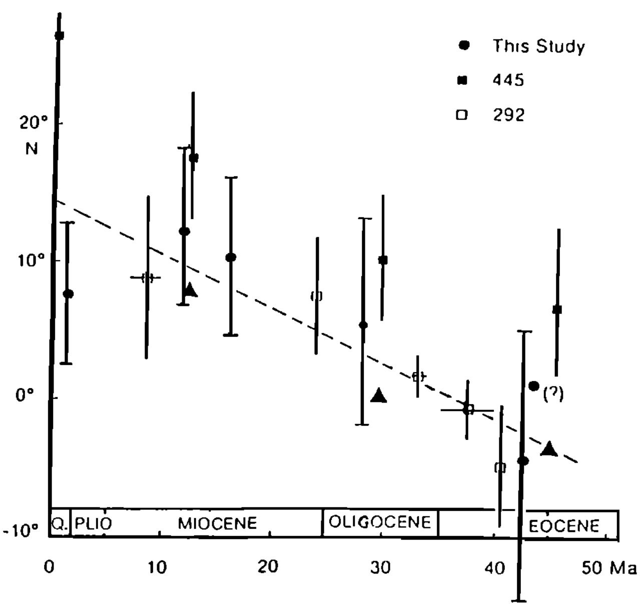


Fig. 12. Comparison of Cenozoic paleolatitudes from the Philippine Arc (this study and Eocene results from Fuller et al. [1983]) and from DSDP site 292 [Loudon, 1977], and DSDP site 445 [Kinoshita, 1980]. Because of shallow inclination values and uncertainty of clockwise or counter-clockwise rotations of the declination data, it is impossible to constrain if the Eocene paleolatitude is north or south of the equator. In the figure, an error bar is placed on south equator for Eocene paleolatitude. The Eocene paleolatitude for the north of equator solution is shown by a point to the right of the Eocene error bar marked with question mark. Until data are collected from the Tertiary section, this problem will be unresolved. Closed triangles are latitudes of site 445 reduced by 10°.

Pleistocene sites from the Philippines, Taiwan, Vietnam, and the Marianas show significantly shallow inclinations and support earlier suggestions [Wilson 1970, 1971; Merrill and McElhinny, 1977; Coupland and Van der Voo, 1980] for an offset dipole.

3. The central and northern portions of Luzon rotated clockwise sometime between the late Miocene and the Pliocene. The cause of this rotation is suggested to be related to the Pliocene collision of the Luzon Arc with Taiwan. Other late Miocene results from the central portion of the Philippine Arc show no evidence for a rotation.

4. The middle to early Miocene data set from Panay, Cebu, and Mindanao shows clockwise rotations. In contrast to this clockwise rotation, data from Marinduque show a counterclockwise rotation. This data set is consistent with a pre-late Miocene collision between the North Palawan Block and the west Philippine Arc.

5. Data from the dikes that intrude into the Zambales Ophiolite at the Coto Mine show evidence for about 60° of clockwise rotation. K-Ar dating of these dikes suggests that the age of these dikes is Oligocene; therefore their directions infer that the Zambales Ophiolite has undergone a clockwise rotation since Eocene time.

6. Jurassic data from Mindoro are consistent with the hypothesis [Hamilton, 1979; Taylor and Hayes, 1980, 1983; Holloway, 1981] that the North Palawan Block rifted away from southern China.

7. Cenozoic paleolatitude data suggest a continuous northward drift of the Philippine Arc and are consistent with Philippine Sea Plate inclination data [Louden, 1977; Kinoshita, 1980]. This northward drift would be consistent with an early Oligocene to Neogene westward facing Philippine Arc forming the westward boundary of the Philippine Sea Plate.

Appendix

Below we describe the location, rock type, age criteria used, and bedding of each of the sampling sites. A more detailed description of the sampling sites is available from the author (R.M.) upon request.

Ilocos Norte

Site 81-2. Alaya formation (Pliocene to late Miocene). Five handsamples were collected from a well-bedded fine-grained brown siltstone (N17°54', E120°41'). This site was dated by foraminifera (Republic of the Philippines and Japanese study, 1981). Bedding is S58°E, 34°W.

Baguio

Sites 81-29, 81-30, 81-32, 81-33, and 81-34. Santo Thomas andesites (late Miocene). Hand samples were collected from fresh hornblende andesite flows located on Mount Santo Thomas (N16°17', E120°34'). The entire volcanic section is reported to sit stratigraphically on top of the middle Miocene [Corby, 1951; Durkee and Pederson, 1961; Balce et al., 1980] Klondyke formation. Bedding used for all five of these flows is N55°W, 18°S and is defined by a Santo Thomas ash layer that underlies site 81-29.

Sites 81-31 and 81-36. Basaltic dikes within the Santo Thomas Volcanics and Rosario formation (Plio-Pleistocene). Hand samples were collected from basaltic dikes that intrude into late Miocene strata around the Baguio region. Site 81-31 is a fine-grained basaltic dike with intersertal texture located on Mount Santo Thomas (N16°17', E120°34'). Site 81-36 is from a dike within the Rosario formation and is located along the Marcos Highway (N16°17', E120°32') west of Mount Santo Thomas. The dikes are assigned a Plio-Pleistocene age because they intrude the late Miocene Rasario Formation. Samples at both sites were collected as handsamples. Bedding is assumed horizontal.

Caballo

Site 81-42. Andesite (post Oligocene). Hand samples were collected from an andesite flow (N16°23', E121°08'). The age of the flow is unknown but must be younger than the underlying Oligocene sediments. Bedding was not observed at the outcrop but was taken from an ash layer that sits upon the volcanics about 250 m to the south. This orientation is N72°E, 28°N. This site was reported by Fuller et al. [1983] as site 81-40.

Zambales

Sites 81-110, 81-111, 81-112, 81-113, and 81-114. Andesites (Pliocene). Hand samples were collected from five sites along the east side of Mariveles Bay (N14°25', E120°28'). Site 110 was collected from a slightly altered plagioclase andesite flow. The other four sites were collected from plagioclase hornblende andesite flows from three different quarries along the sea cliff east of the harbor. All flows were horizontal. De Boer et al. [1980] have reported six K-Ar age dates of Pliocene age from this region (range 2.8-4.1 m.y.).

Sites 81-51 and 81-52. Bamban Tuff (Plio-Pleistocene). Hand samples were collected from two sites (N15°', E120°33'). The Bamban Tuff lies directly on top of late Miocene sediments and is therefore assigned to Plio-Pleistocene. The statigraphically lower site is normal, while the upper site is reversed, suggesting that the sites are at least as old as late Pliocene. The samples collected were crystal tuffs, which were unaltered in thin section. These sites are horizontal.

Sites 84-T-4, 84-T-5, 84-T-6, 84-T-7, and 84-T-8. Andesites (late Miocene). Samples from these five sites were drilled by portable drill from hornblende dacitic flows that crop out along the Moriones River (N15°28', E120°20'). Many of these rocks are exposed as haystack-like plugs that stick up through the middle Miocene Malinta formation. These volcanic features occur stratigraphically beneath the Plio-Pleistocene Bamban Tuff and are tentatively assigned to the late Miocene. The bedding is horizontal.

Sites 84-Z-1, 84-Z-2, 84-Z-3, 84-Z-4, 84-Z-5, and 84-Z-6. Diabase dikes at Coto Mine (late Oligocene ?). Cores were drilled from six dikes that cut through the ultramafic section at Coto Mine (N15°33', E120°07'). The age of the dikes is assigned to the Oligocene on the bases of two K-Ar age dates reported by De Boer et al. [1980]. Since no obvious post-Oligocene bedding correction is known, bedding corrections were not used.

Manila Region

Sites 81-100A, 81-100B, 81-UP, Guadalupe Tuff, and Site 81-61, Antipolo Basalt (Plio-Pleistocene). 81-UP was collected from an ash layer at the University of Philippines, Quezon City campus (N14°37', E121°06'). Hand samples from sites 81-100A and 810100B were collected 15 km east of Quezon City in a rock quarry along the Marcos Highway (N14°42', E121°11'). Sites 81-100A and 81-UP are fine-grained volcanic ash deposits. Site 81-100B is a pyroclastic flow. Hand samples from site 81-61 (N14°33', E121°11') were collected from the Antipolo Basalt, a porphyritic plagioclase basalt with holocrystalline texture. All samples were free from secondary alteration and are horizontal.

Sites 81-62. Pelagic sequence overlying the Angat Ophiolite (Cretaceous). Samples were collected with a portable drill and by hand samples from a sedimentary sequence located at N14°42, E121°14'. Samples were collected from six different horizons. Bedding is N64°E, 10°NW.

Bicol Region

Sites 81-B2, 81-B3, 81-B6, Legaspi and Mount Isarog andesites (late Miocene) and site 81-B4, Mount Isarog flow (Pleistocene). Samples were drilled from hornblende andesite flows. Two of the sites were collected just southeast of Legaspi (N13°4', E123°51') and from an the older flow of Mt. Isarog (N13°31', E123°33'). These flows are dated as late Miocene based on paleontological ages of interbedded sediments [Dumapit, 1973]. Sites are horizontal. Site 81B-6 (N13°31', E123°33') is part of the folded basement of Mount Isarog. The bedding is measured as N5°W, 42°W. The site numbers used here are the same site numbers used in an earlier paper [McCabe et al., 1982b]. In Fuller et al. [1983], these sites were assigned different site numbers: 81-B4=81-203, 81-B2=81-202, 81-B3=81-204, and 81-B6=81-205.

Site 81-B10. Plagioclase basalt from the northern Bicol (Plio-Pleistocene ?). Samples were drilled from a holocrystalline plagioclase basalt (N14°6',E122°38'). Microscopic observation showed rock to be free from secondary alteration. The age of this flow is uncertain and inferred to be post-Miocene (J.A. Wolfe, personal communication, 1980). The flow is assumed to be horizontal.

Marinduque

Site 81MAR03. Gasan formation (late Miocene). Hand samples were collected from a tuffaceous siltstone located at N13°30', E121°57. Age is based on a paleontological age of late Miocene [Loudon, 1976]. Bedding is horizontal.

Sites 81MAR04 and 81MAR05. Dike (81MAR04) intruded to 81MAR05 Sayao Volcanics (early Miocene ?). Dike is believed to be late Miocene. Samples from site 81MAR04 were collected from a dike intruded into a submarine pyroclastic sequence. Both sites were located at N13°20', E122°05'. The dike is dacitic in composition and is partially glassy. Age is poorly constrained and based on inferred age from a local Marcopper geologist (personal communication, 1981). Samples from site 81MAR05 were collected from fine-grained tuffaceous deposits 1 m away from the dike. Because of a loss of samples, only two samples of this tuff were analyzed. The age assigned to the volcanics is based on fossil ages from interbedded limestones (Philippine Bureau of Mines, personal communication, 1981). Bedding of the tuffaceous unit is well defined as N30°W, 24°E. A bedding correction was not applied to vertical dike.

Sites 81MAR1C, 81MAR1D, 81MAR1E, 81MAR1F, and 81MAR1G. Basaltic dikes in Mahinhin Intrusion (middle Miocene). Eleven hand samples were collected from five dikes in the Mahinhin Intrusion (N13°30', E122°01'). When first collected, it was thought that these would represent one time horizon, i.e., one site. Demagnetization of these dikes showed that each dike had a different direction. Since orientation error for hand samples is probably less than a few degrees, this difference in magnetization of the different dikes is probably not caused by an orientation error. Since the directions of each dike showed a large variation in direction, we tentatively assigned each dike as an independent time horizon. The age of the dikes is unknown and assigned to middle Miocene because they intrude the 15.5 m.y. Mahinhin Intrusion [Wolfe, 1981]. Dikes do not intrude the overlying late Miocene sediments. Samples were assigned 81-301 by Fuller et al., [1983] and reported as a single site mean.

Site 81MAR07. Mahinhin diorite (middle Miocene). Hand samples were collected from the Sanyo Volcanics located at N13°15', E122°00'. Three of the six samples collected were badly altered and possessed an unstable magnetization and hence were discarded in calculation of a site mean. The age of the Sanyo Volcanics is considered to be middle Miocene [Loudon, 1976]. Bedding is horizontal.

Mindoro

Sites 81MY02, 81MY03, 82MY10, 82MY12, and 82MY13. Mansalay formation (Jurassic). Samples from these sites were collected from black shale units located at N13°26', E121°12'. Sites 81MY02 and 81MY03 were collected as hand samples. The other three sites were drilled in the field along the small branching tributary just south of the Mansalay River. These three sites are about 200-300 m apart. Bedding of the five sites is: 81MY02 N66°W, 29°N; 81MY03 N7°E, 22°W; 82MY10 N78°W, 54°N; 82MY12 N38°W, 18°S; and 82MY13 N63°W, 10°S. The presence of belemnites and ammonoids at the sites confirms their Jurassic age.

Sites 82MY20. Socorro Volcanics (Pliocene). Hand samples were collected at 13°27', E122°12'. The rock is a fresh hornblende plagioclase dacite. Age is inferred to be Pliocene based on K-Ar dating [De Boer et al., 1980] of similar flows south of collection site. Columnar jointing is well developed and suggests bedding is horizontal.

Panay

Site P-11. Sara diorite (upper Eocene/lower Oligocene). Hand samples were collected at

N11°05', E122°57'. No overlying sediments were seen in the area; therefore no correction for tilting was obtained. Age assignment is based on Oligocene sediments overlying the pluton and the 38 m.y. Rb-Sr date (X. Capiz and G.R. Balce, personal communication, 1981) from the southern Negro Pluton, which is on the same linear trend as the Sara diorite.

Site P-13 and P-15. Seweragan Complex Member of Singit formation (upper Oligocene/lower Miocene). Hand samples were taken from these two sites located at N10°42' E122°11'. Site P-15 is a plagioclase-free augite-olivine basalt flow. Thin section study of this sample showed it to be free of secondary alteration. Site P-13 is a calcareous siltstone about 25 m downsection from P-15. No signs of baking from the nearby lavas were observed in this unit. Samples were collected from two distinct horizons, stratigraphically about 1 m apart. Bedding is N45°E, 53°E.

Site P-2 and P-4. Lagdo formation (lower Miocene). Hand samples were taken from these two widely spaced sites (approximately 50 km apart). Site P-2 (N10°33', E122°05') is a buff colored tuffaceous siltstone. The samples were collected from three horizons about 50 cm apart stratigraphically. Site P-4 (N10°50', E121°57') is a green colored tuffaceous siltstone. Bedding of these sites is: P-2 N16°W, 45°W; P-4 N27°E, 38°E.

Site P-12. Igtalongon formation (middle Miocene). Hand samples were taken from N10°42', E122°11'. The samples were collected from siltstones in repeated interbeds of calcareous silts and sands. The bedding of this unit was the same as P-13. Samples were collected from five stratigraphic horizons. Bedding is N45°E, 62°SE.

Site P-6. Makato formation (middle Miocene). Hand samples from this site were collected 6 km west of the town of Tangalan along Highway 1 (N11°48', E122°05'). Samples were taken from three black shale horizons about 7 m apart stratigraphically. Bedding is N40°W, 13°W.

Site 82PANAY18. Buruanga shale (Eocene). Ten cores were drilled from three different beds of a black shale at N11°43', E121°52'. The age of the site is based on Nummilites species foraminifera identified as Eocene by Hashimoto [1973]. Bedding is N15°E, 30°W.

Negros

Site 81N-7. Limestone (late Miocene). This site is located at N9°17 E122°53. Nine hand samples were collected from four different strata layers. Age is based on foraminifera (Philippine Bureau of Mines, personal communication, 1981). Bedding is N10°W, 20°SW.

Sites 81N-1, 81N-2, Basaltic dikes and 81N-6, Diorite (late Eocene). Hand samples were collected from these three sites around the Consolidated Development Corporation (CDCP) mine site (N9°38' E122°37'). Sites 81N-1 and 81N-2 were taken from basaltic dikes that intrude into a diorite (site 81N-6). Rb-Sr dating on the diorite has yielded an age of 38 m.y. (Philippine Bureau of Mines, personal communication, 1982). Limestone and volcanic ash strata that sit on top of the pluton are horizontal; therefore structural correction was used.

Cebu

Sites 81CEBU2A and 81CEBU2B. Toledo formation (middle to upper Miocene). Ten hand samples were collected from two different units in a quarry located at N10°14' E 123°45'. Sites are well stratified. These sites are separated by about 6 m stratigraphically and are dated by foraminifera (W. Diegor, personal communication, 1981). Bedding is N58°W, 28°SW.

Site 82CEBU01, Canci Volcanics, and sites 82CEBU02, 82CEBU05, and 82CEBU07, Pandan formation (early Cretaceous). Sites 82CEBU01 and 82CEBU02 are separated by 15 m stratigraphically. Both sites are located at N10°14' E123°45'. The samples were collected using a portable drill. Bedding corrections are consistent within the section and are measured from site 82CEBU02. 82CEBU01 is a basalt that shows alteration in hand sample. Some local veining of epidote was noted at this site, and such veins were avoided when sampling. 82CEBU02 is a well-indurated red mudstone. Sites 82CEBU05 and 82CEBU07 are located on the highway that goes from Cebu City and Toledo. Site 82CEBU05 is a red siltstone; 82CEBU07 is a green siltstone. Ages are based on Hashimoto [1981]. Bedding corrections are 82CEBU01 and 82CEBU02 N42°W, 12°E; 82CEBU05 N325°W, 34°S; and 82CEBU07 N12°E, 55°NW.

Site 82CEBU03. Ilag Limestone (lower Miocene). Ten samples were collected with a portable drill. The outcrop is located along the Cebu City-Toledo Highway (N10°14' E123°45'). Site was rich in lower Miocene Orbulina. Bedding is N10°E, 40°W.

Site 82CEBU04. Masaba Formation (lower Miocene). This site is at the Philippine National Oil Company coal mine (N10°14' E123°45'). This limestone is located between a foraminifera-bearing sandstone unit and a coal layer. Ages were provided by the Chevron Overseas Petroleum Corporation (personal communication, 1983). Bedding is N30°E, 49°NW.

Site 82CEBU06. Coastal Limestone (Pliocene). Oriented cores were drilled from a lime wackestone containing coral fragments and red algae (N10°34' E124°02'). Contrasting ages are assigned to this formation. The Chevron Overseas Petroleum Corporation (personal communication, 1983) identified early Tertiary foraminifera (Nummulites species). The Philippine Bureau of Mines fossil dated these rocks as Pliocene. As this wackestone is flat lying (while the nearby pre-late Miocene rocks are folded) and because this limestone appears along the coast, we will use the Philippine Bureau of Mines age and suggest that the early Tertiary fossils are reworked clast. Bedding is horizontal.

Northeastern Mindanao

Sites 82MINDA09, 82MINDA10, 82MINDA11, 82MINDA12. Limestones (early Miocene). Samples were drilled from these sites at N9°35' E125°34'. The rocks exposed in this general region are gently dipping series of pelagic limestones and interbedded basalts. The four sites all lie within 20 km of each other. Sites 82MINDA09, 82MINDA10, and 82MINDA11 consist of pelagic limestones. Samples contain Orbulina species and Globorotalia species foraminifera (Chevron Overseas Petroleum Corporation, personal communication, 1983), confirming the lower Miocene age. Site 82MINDA12 is a slightly altered olivine basalt and lies stratigraphically below 82MINDA11. The bedding of all of these horizons is N2°E, 12°NW.

Site 82MINDA16. Dacite flow (early-middle Miocene). Samples were collected by drill at N9°39' E125°24'. The site is a biotite-hornblende plagioclase dacite. The age of the flow is based on the stratigraphic reltionships between this flow and late Miocene limestones from the region (Philippine Bureau of Mines, personal communication, 1983). The site must be older than the late Miocene reefal limestones (site 82MINDA17) discussed below. Bedding is considered horizontal based on sediments that overlie the flow.

Site 82MINDA14. Basalt (early Miocene). Samples were drilled at N9°32' E125°46'. The rock is a fine-grained basalt. The age of this sample is assigned as early Miocene by the Philippine Bureau of Mines (personal communication, 1983) and based on the age of overlying limestone. Bedding is horizontal as inferred from overlying limestone sediments.

Site 82MINDA17. Reefal limestone (middle to late Miocene). Samples were drilled from this site located at N9°44' E125°32'. Samples are very poorly sorted fine-grained floatstone-packstone. Age is assigned based on occurrence of alga Aethesolithon probematicum (Chevron Overseas Petroleum Corporation, personal communication, 1983). Site is horizontal.

Sites 82MINDA19, 82MINDA20, 82MINDA21, 82MINDA22, and 82MINDA23. Basalts (Plio-Pleistocene). Hand samples were collected from vesicular basaltic flows (82MINDA19 N8°55' E124°59'; 82MINDA20 N8°54' E125°00'; 82MINDA21 N8°50' E125°08'; 82MINDA22 N8°50' E125°09'; and 82MINDA23 N8°51' E125°10'). All sites are horizontal as defined by flat lying sediments that are found both above and below one of the flows (near Gingoog City (82MINDA22)).

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