Paleomagnetism of Miocene Volcanic Rocks of Guam and the Curvature of the Southern Mariana Island Arc

JAPAN–UNITED STATES PALEOMAGNETISM PROJECT IN MICRONESIA

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ABSTRACT

Directions of paleomagnetism in dikes and flows in Miocene age on Guam (lat. 13.3° N., long. 144.7° E.) deviate considerably but systematically from the present Earth field direction. The mean inclination of the eight sites is 24° (downward), which is nearly exactly that of the axial dipolar field for this latitude; but the mean declination lies 55° clockwise from true north (α_{95} = 21°). A simple explanation is that the southernmost portion of the Mariana island arc has been tectonically rotated about a vertical axis in a clockwise direction about 50° to 60° since Miocene time but has undergone little, if any, latitudinal shifting. These conclusions are also consistent with available interpretations of seismic data for the southern Mariana arc which suggest components of right-lateral strike slip as well as thrust movement along the generally east-west zone separating the Philippine Sea plate on the north from the Pacific plate on the south.

INTRODUCTION

The geologic setting, seismicity, volcanic history, and petrology of island arcs have been important considerations in the formulation of recent theories of global tectonics (see, for example, Morgan, 1968; Isacks and others, 1968; Dewey and Bird, 1970; Dickinson, 1970). The curvature of island arcs, however, has never been fully explained. Not only are they arcuate, but most are convex toward the ocean basins they rim (Fig. 1).

Lake (1931) suggested that island arcs are curved because they are formed at the intersection of low-dipping thrust planes with the Earth's spherical surface. Frank (1968) demonstrated that the bending of a thin segment of a sphere through 45° (corresponding to the Benioff zone) intersects the surface of the sphere in an arcuate expression of a 22° radius of curvature. On the other hand, Hess (1948) suggested that the curvature of island systems was indicative of deformation along shear zones of transcurrent faulting at the terminations of arcs. Scholz and Page (1970) have suggested that the arcuate form of archipelagos is in part due to a lateral buckling of the downward-moving oceanic slab as it bends sharply and descends at the trench.

If the curvature of arcs is actually the result of tectonic rotation or bending, it should be discernible in paleomagnetic studies of rocks of the island chain if the remanence was acquired prior to or during the early or middle stages of rotation. Furthermore, the paleomagnetic technique could be used, if rotation were indicated, to provide evidence about the orientation of the axis of rotation.

A detailed paleomagnetic study of Cretaceous plutonic rocks in Japan led Kawai and others (1969, 1971) to conclude that the arcuation of Japan was the result of varying amounts of rotation of four discrete blocks that formed an initially linear feature. In a study of the Scotia arc, Dalziel and others (1971) presented paleomagnetic evidence for about 90° of post–late Mesozoic bending of the southernmost Andes. Their results, however, do not indicate any such bending of the arcuate Shetland Islands and the Antarctic Peninsula.

In an attempt to further understand island-arc tectonism, we undertook a paleomagnetic study of Guam and Saipan, Mariana Islands, during the summers of 1971 and 1972. Guam and Saipan were selected because they are situated at the large bend near the southern extremity of the Mariana arc (Fig. 2) and because early and middle Tertiary volcanic rocks are present on the islands.

Because of poor accessibility and lack of exposure, only three sites could be established on Saipan. The directions of remanence from these sites, after af demagnetization, were completely inconsistent and displayed large within-site and between-site dispersion. Apparently the rocks have been affected by lightning, unresolvable structural dislocation, and perhaps chemical alteration. Because of the paucity and inconsistent nature of the data, we have excluded them from our paleomagnetic analysis.

Suitable samples of basic volcanic rocks were obtained from eight different sites on Guam. K-Ar dating was attempted on several of the fresher samples, but the abundance of H_2O in the samples (commonly producing a noticeable condensation during heating) precluded obtaining reliable dates. Fortunately, there is sufficient fossil evidence for a relatively accurate age classification (Tracey and others, 1964).

GEOLOGY OF GUAM

Geologically, Guam can be separated into three regions: late Tertiary reef limestone at the north end, Eocene volcanic rocks in the central part, and Miocene volcanic rocks at the south end (Fig. 3). These provinces have been block faulted, particularly in the central and southern parts, and are separated from each other by major fault zones (Tracey and others, 1964). Poor accessibility and exposure and the common occurrence of deep weathering limited our collecting to the early Miocene Umatac Formation in the southern part of the island. Tracey and others (1964) based the Miocene age on foraminifera recovered from sporadic interbeds of limestone within this unit, which is composed mostly of

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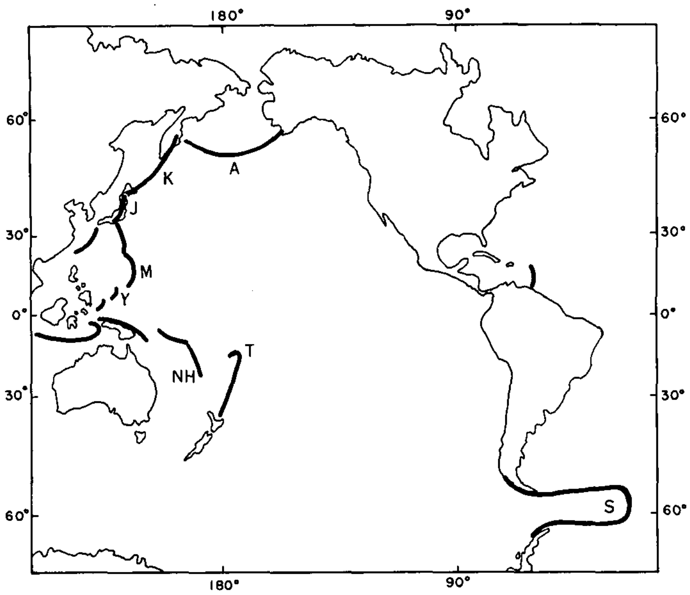

Figure 1. Island arcs of the world. Letters designate those discussed in text: A = Aleutian; K = Kuril; J = Japanese; M = Mariana; Y = Yap; NH = New Hebrides; T = Tonga; S = Scotia.

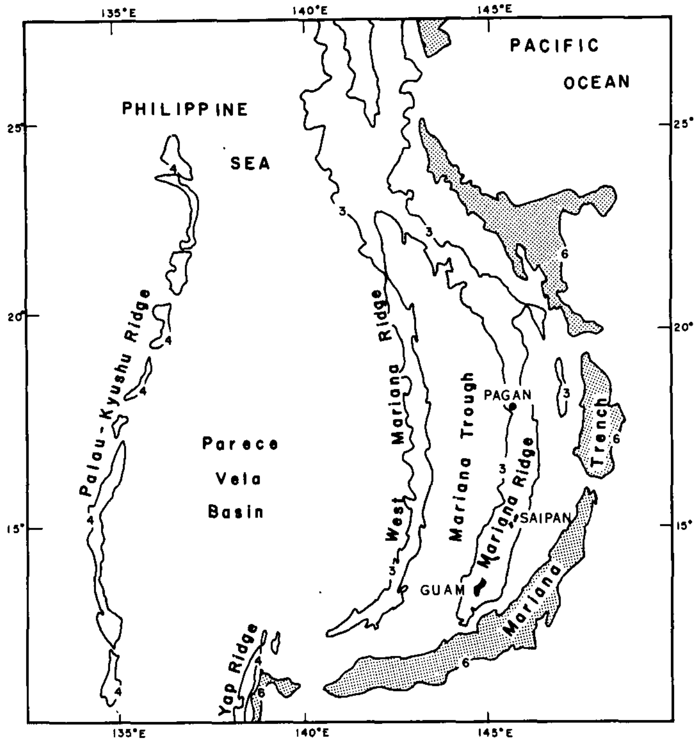

Figure 2. Tectonic and geographic features of eastern Phillipine Sea region. Depth contours in kilometers (after Karig, 1971, Fig. 1).

basaltic and andesitic lava flows and pyroclastic rocks. They interpreted the Umatac Formation as flank eruptives, pyroclastic ejecta, and derived pyroclastic materials of a large volcano that existed to the southwest of the present island. They concluded that this volcaniclastic formation has been only slightly structurally complicated by subsequent uplift, block faulting, and minor folding.

FIELD AND LABORATORY PROCEDURES

The Umatac Formation is divided into four members (Tracey and others, 1964), the lower two of which are suitable for paleomagnetic sampling. Samples were taken at eight localities (Fig. 3; Appendix 1). The lowermost unit, the Facpi Member, consisting mainly of basaltic columnarly jointed flows, pillow flows, and dikes, provided the best exposures for sampling (Appendix 1, locs. G1 to G7). Only one site (G8) was established in the overlying Bolanos Member, which consists primarily of pyroclastic sandstone, siltstone, and volcanic breccia and conglomerate.

To determine the nature of the magnetic oxides, one sample from each site (with the exception of G6) was examined under reflected light and by thermomagnetic analysis. At least five oriented hand samples were taken at each site for use in the paleomagnetic study. Specimens drilled in the laboratory from the samples were measured on a spinner magnetometer with a sensitivity of about 5×10^{-6} emu/cc. After the natural remanent magnetization (NRM) was determined, all samples were subjected to af demagnetization, once in a peak field of 100 Oe and subsequently in a peak field of 200 Oe. Remeasurement of the remanent magnetization followed each treatment.

ROCK MAGNETISM

The mineralogy as seen in polished section is remarkably similar for all samples. Most opaque grains are elongate to subequant and optically homogeneous, and they vary from dark reddish brown to light gray-brown; a few grains are bluish gray. The lightening in color appears to be indicative of low-temperature oxidation of an initial titanomagnetite (or magnetite) to titanomaghemite. No ilmenite lamellae were observed in any of the opaque grains. Most of the grains are less than 5 μ in diameter, reflecting rapid quenching of the melt.

Thermomagnetic analysis was performed on magnetically separated concentrates. During the experiments, the atmosphere surrounding the sample was controlled by mixing H_2 and CO_2 gases so that little or no oxidation of titanomagnetite should have occurred (Larson and others, 1974). However, the J_s versus T curves are not reversible (see Fig. 4); the cooling curve in every case returns along a higher path. Moreover, the dominant Curie point during heating is about 400°C, whereas on cooling it is about 580°C. These results are indicative of the presence of titanomaghemite (see Ozima and Larson, 1970). During heating, the Curie temperature of the titanomaghemite is reached near 400°C. Continued heating causes the thermally unstable titanomaghemite to dissociate into Fe_3O_4 and $FeTiO_3$. Upon cooling, the material displays the 580°C Curie temperature of magnetite. The saturation moment is increased by the decomposition of titanomaghemite to magnetite; this is reflected in the higher return path of the cooling curve. The amount of titanomaghemite as compared to relict

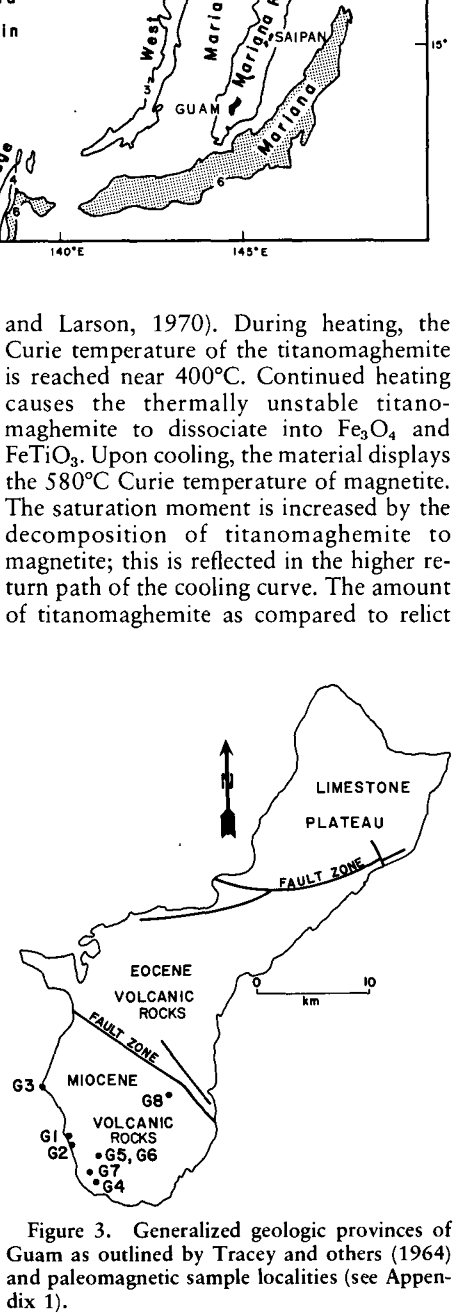

Figure 3. Generalized geologic provinces of Guam as outlined by Tracey and others (1964) and paleomagnetic sample localities (see Appendix 1).

titanomagnetite can be judged approximately by how much higher the cooling path is than the heating path; the greater the difference, the greater the amount of titanomaghemite. Curves of the type shown in Figure 4 are typical of submarine basalt (Ozima and Larson, 1970; Ozima and Ozima, 1971).

PALEOMAGNETISM

The remanence directions of specimens after af cleaning, for each of the seven sites in the Facpi Member, are well grouped in normal and reversed directions (Fig. 5; Table 1). Partial af demagnetization led to a decrease or essentially no change of within-site dispersion. The mean directions shown in Figure 5 represent those corresponding to minimum dispersion; in some cases this was attained after demagnetization in a 100 Oe peak field and in some cases after application of a 200 Oe peak field.

Figure 5 shows that the mean directions all are offset clockwise from the present Earth field direction for Guam. Preliminary results similar to these were reported by Kobayashi (1972) from three samples from the Facpi Member at Umatac Bay (our locality G1).

Even the volcanic breccia (G8) in the Bolanos Member yielded well-grouped NRM directions that are closely similar to the normal directions of magnetization of the Facpi Member (Fig. 5; Table 1). The amount of dispersion of remanence directions from this site increases progressively after af cleaning to 100 and 200 Oe, but the mean direction is not substantially changed. Because we suspected that the volcanic breccia was a hot mudflow (lahar) deposit, we made thermal demagnetization studies on a different set of cores from the same hand samples. The grouping of remanence directions is maintained up to 275°C; some scattering occurs after heating to 310°C, and extreme dispersion occurs after heating to 325°C. Unfortunately, because of the presence of titanomaghemite in these samples, firm conclusions concerning the origin of the remanence in G8 cannot be made.

Sandstone and siltstone (37 samples) directly underlying this volcanic breccia in the Bolanos Member showed a pronounced scatter of direction about the present Earth field direction at Guam. Stepwise af cleaning at peak fields of 50 to 200 Oe produced increasingly greater dispersion. Apparently, the remanence of these sedimentary deposits is related primarily to the present Earth field, and they are unusable for paleomagnetic study.

Although within-site grouping of sites G1 through G8 is reasonably good, the dispersion between sites is quite marked. The α_{95} cone of confidence for the combined means of the eight sites is 21°. Sun compass readings indicate that the declination dispersion is not the result of strong local magnetic anomalies. A high degree of geomagnetic secular variation during Miocene time could explain this scatter. More likely, the between-site dispersion stems from a combination of secular variation and ambiguity regarding the amount of structural correction to be applied to the remanence directions. Even where flow features or interflow sedimentary deposits could be identified, it was difficult to determine how much of the dip was initial and how much was structural. Where the igneous rocks were poorly exposed massive flows (commonly composed largely of pillows) or in the form of dikes and sills, only intuitive estimates could be made. Structural corrections, based on best estimates, were made for all but one site. As is evident from the strikes and dips associated with each site (see Appendix 1), the structural corrections have no preferred directionality, and no biasing of our results should have occurred from this source. In fact, the final mean direction of the eight sites is essentially the same (within the 95 percent confidence cone) as the structurally uncorrected mean direction of the sites. The corrected mean direction from the eight usable sites is $D = 55°$, $I = 24°$ (downward), $\alpha_{95} = 21°$.

It is evident from polished section and thermomagnetic analyses that the principal carrier of remanence in these rocks is titanomagnetite that has been variably affected by titanomaghemitization. Accordingly, the remanence appears to be a mixture of thermal remanent magnetization (TRM), chemical remanent magnetization (CRM), and perhaps thermochemical remanent magnetization (TCRM). Inasmuch as all site mean directions, including both normal and reverse polarities, show a large clockwise deflection from the present Earth field direction at Guam, it is unlikely that much CRM or TCRM has been acquired in the recent past. Even the more highly weathered rocks show little evidence of acquiring a CRM in the present field. We conclude, therefore, that most of the remanence, regardless of its nature, must have been acquired at or soon after the time of the initial cooling of the igneous rocks during early Miocene time.

DISCUSSION AND CONCLUSIONS

The mean inclination from the eight sites is 24° (downward), which is the expected value for an axial dipole field at the latitude of Guam today. There is, therefore, no paleomagnetic indication of latitudinal movement of Guam since early Miocene time.

Three simple interpretations can explain the offset declinations of the paleomagnetic data: (1) a post–early Miocene clockwise tectonic rotation of 55° ± 21° (about a vertical axis) of the entire southern Mariana arc-trench system; (2) a post–early Miocene clockwise rotation of the southern part of Guam only, a rotation not affecting the rest of the Mariana island arc system; (3) an anomalous geomagnetic field during early Miocene time, possibly during a geomagnetic transition.

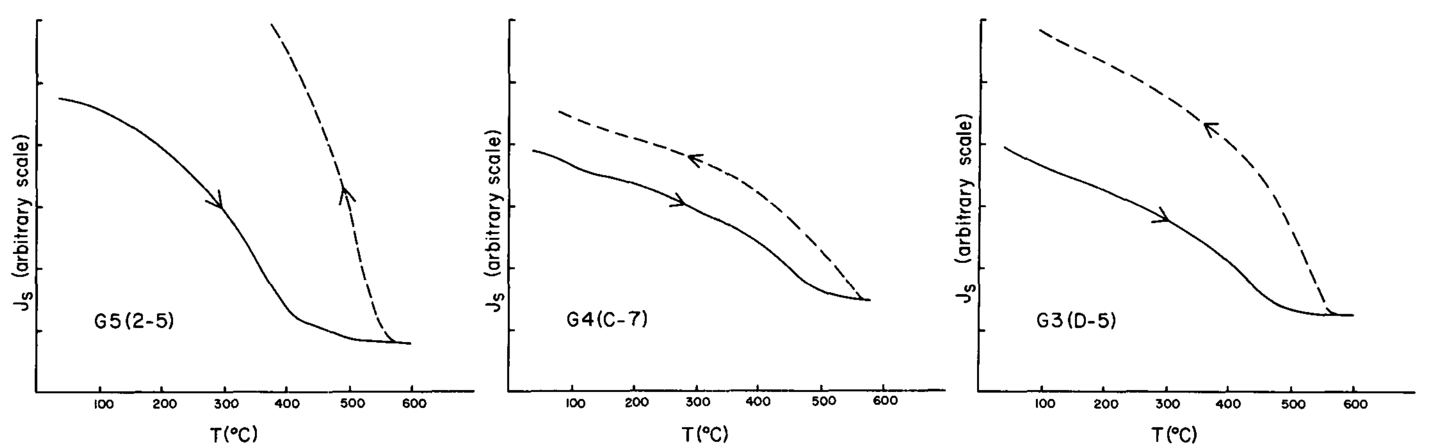

Figure 4. Typical magnetization (J) versus temperature (T) curves, determined in field of about 2,000 Oe.

The time span represented by our samples includes reversals of the Earth field; hence it is sufficiently great to cast serious doubt on the third explanation. The second possibility cannot be discounted by our study. We feel, however, in view of the curvature of the southern Mariana chain and the similar curvature of the Mariana trench oceanward of the island arc and the submerged ridges behind the island arc (Fig. 2), that the first interpretation (tectonic rotation of the southern Mariana arc-trench system) is the more plausible explanation.

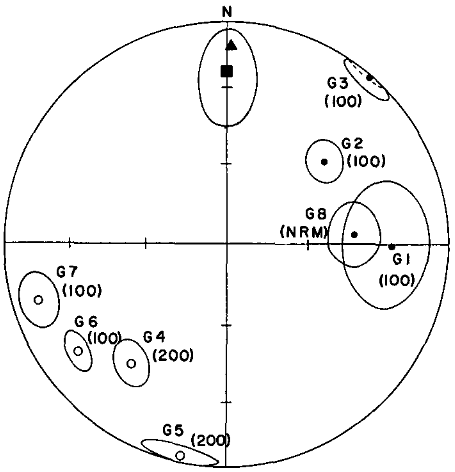

Figure 5. Mean directions of magnetization surrounded by their cones of 95 percent confidence level. Value in parentheses indicates alternating field treatment (in oersteds) that yielded best grouping (highest k value) for that site. Triangle represents present Earth field for Guam. Square represents mean direction of magnetization of site means shown and rotated 55° counterclockwise. Square also coincides with direction of axial dipole component of present geomagnetic field. Open symbols are on upper hemisphere and solid symbols are on lower hemisphere of equal-area net.

If the arcuation of the Mariana arc resulted from tectonic dislocation since Miocene time, deformation may yet be in progress that might be seismically evident.

Katsumata and Sykes (1969) showed that throughout most of the relatively straight central part of the Mariana island arc, the plane of hypocenters for depths of 200 to 700 km is nearly vertical; to the north and south of this, the seismic zone is inclined westward at 40° to 60°. Relative motions throughout most of the straight part of the island arc are essentially dip slip. Katsumata and Sykes described, however, a focal-mechanism solution for a shallow event in the southern Mariana arc system indicative of a combination of strike-slip and thrust motion between two lithospheric plates. This type of motion could result in the large-scale drag offset (arcing) of the southern Marianas by right-lateral movement along a generally east-west fault zone separating the Mariana arc-trench system from that of Yap (see Fig. 6).

Draglike arcuations have been observed at the terminations of other arc systems in the Pacific. For example, Sykes (1966) showed that the curvature to the north of the Tonga arc and of the South Fiji Ridge was mirrored by curvature of deep and shallow earthquakes and volcanism. Subsequently, Isacks and others (1969) postulated several transform faults connecting the northern end of the Tonga arc with the southern termination of the New Hebrides arc by way of Fiji, and they suggested left-lateral strike-slip motion within this zone.

Similarly, the seismic activity of the westernmost Aleutian arc appears to be right-lateral strike-slip motion (Gumper, 1971), suggesting a trench-trench transform fault between the Aleutians and the Kuril arc system (McKenzie and Parker, 1967).

The Mariana trench defines the surface boundary between the Philippine Sea plate to the west and the Pacific plate to the east and south. S. Uyeda (1972, personal commun.) postulated that the Philippine Sea came into existence in Eocene time as the result of a change in direction of Pacific plate movement. On the basis of the ages of sedimentary deposits filling the basins behind the arcs, Karig (1971) contended that the basin west of the Palau-Kyushi Ridge opened in late Eocene time, the Parece Vela Basin was developed during an early Miocene extensional event, and the Mariana trench and presumably the present configuration of the Mariana island arc developed in late Pliocene and Quaternary times.

Our paleomagnetic results from Miocene volcanic rocks on Guam support Karig's conclusion that the present arcuate form of

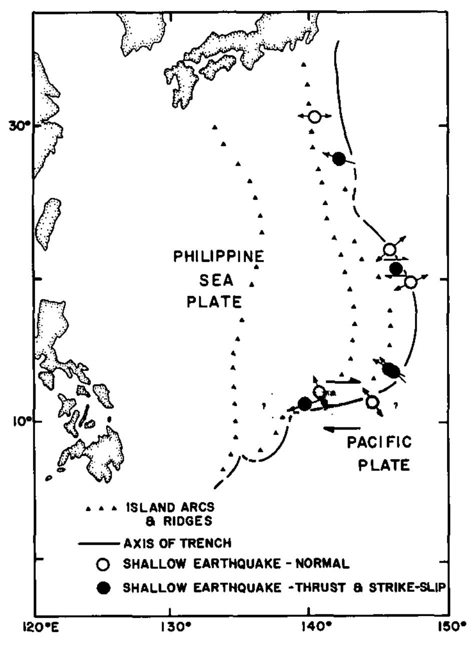

Figure 6. Focal mechanism solutions and inferred directions of relative movements of plates of lithosphere for Mariana-Izu chain (from Katsumata and Sykes, 1969, Fig. 18). Diverging arrows show horizontal projection of tensional axis. Small single arrows show horizontal projection of slip vectors. Large single arrows show suspected right-lateral motion between Philippine Sea plate to north and Pacific plate to south.

TABLE 1. REMANENCE DIRECTIONS AND POLE POSITIONS

Locality	Treatment	N	I (°)	D (°)	k	α_{95}	Lat	Long	dp	dm
G1	NRM	9	33	87	6	23	7	142	15	26
	100 Oe	9	27	91	8	20	2	140	12	22
G2	NRM	8	41	47	52	8	45	146	6	9
	100 Oe	7	42	50	55	8	42	146	6	10
	200 Oe	8	40	56	22	12	36	144	9	14
G3	NRM	19	4	29	13	10	60	106	5	10
	100 Oe	19	1	41	17	8	47	112	4	8
	200 Oe	19	- 4	41	9	12	47	108	6	12
G4	NRM	16	-14	174	2	44	-81	171	23	45
	100 Oe	16	-25	216	19	9	-55	309	5	9
	200 Oe	16	-31	218	20	8	-53	316	5	10
G5	NRM	6	- 2	190	28	13	-74	182	6	13
	100 Oe	6	- 2	191	33	12	-74	196	6	12
	200 Oe	6	- 2	192	35	11	-73	191	6	11
G6	NRM	6	-20	233	162	5	-38	237	3	6
	100 Oe	6	-19	233	146	6	-39	237	3	6
	200 Oe	6	-13	237	91	7	-34	234	4	7
G7	NRM	7	-14	256	44	9	-15	239	5	9
	100 Oe	7	-12	253	50	9	-18	237	4	9
	200 Oe	7	- 8	251	25	12	-20	234	6	13
G8	NRM	5	47	81	27	15	14	151	13	19
	100 Oe	5	49	93	7	32	4	155	28	42
	200 Oe	5	40	96	4	42	- 1	147	28	49
	NRM	4	42	86	70	11	10	148	8	14
	150°C	4	30	87	59	12	7	140	7	13
	275°C	4	36	92	41	15	3	145	10	17
	310°C	3	49	87	7	50	9	154	43	65
	325°C	4	41	196	2	86	-50	238	64	..
Site means*		8	24	55	8	21	37	131	12	22

Note: N = number of samples measured;
I = inclination positive downward;
D = declination clockwise from true north;
k = Fisher's (1953) best estimate of precision;
α_{95} = semi-angle of cone of 95 percent confidence level;
Lat = paleomagnetic latitude, positive indicates north latitude;
Long = paleomagnetic longitude, west;
dp = semi-minor axis of oval of 95 percent confidence level;
dm = semi-major axis of oval of 95 percent confidence level;

* One site mean exhibiting best grouping (highest k value) from each locality.

the southern segment of the Marianas developed since Miocene time. Furthermore, these results suggest that the curvature is the result of tectonic rotation about a vertical axis of a segment of the Earth's crust. Possibly the rotation was the result of large-scale right-lateral drag along an east-west shear zone separating the Mariana arc system from the Yap arc system.

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APPENDIX 1. SAMPLE LOCALITY DESCRIPTIONS

G1. Pillow basalt flow exposed in sea-cut terrace on the northwest point projecting into Umatac Bay, 0.3 km due west from center of village of Umatac. Attitude of nearby flow breccias is N. 40° W., 45° NE.

G2. Two pillow basalts (4 samples) and three dikes (4 samples) in coastal exposures, 0.9 km north of G1. Attitude of beds is N. 30° E., 40° SE.

G3. Three pillow basalts (9 samples) and three dikes (10 samples) exposed in sea-cut terrace of Facpi Point about 6 km northwest of village of Umatac. Attitude of beds is N. 40° W., 35° NW.

G4. Dike (2 samples), flow breccia (4 samples), and nonbrecciated flow (10 samples) exposed in roadcut and 70 m southwest of roadcut on road 0.5 km from village of Port Merizo to Memorial Elementary School.

G5. Pillow basalt flow exposed in ridge leading to summit of Mount Schroeder. Attitude of underlying tuffaceous siltstones is N. 01° W., 16° E.

G6. Pillow basalt flow above G5 on Mount Schroeder Ridge.

G7. Massive flow rock exposed in stream gully about 0.4 km northwest of Memorial Elementary School, Port Merizo.

G8. Coarse volcanic breccia exposed in Talofofo River at Talofofo Falls. Attitude of underlying tuffaceous sediments is N. 01° E., 4° E.

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