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17. *A Paleomagnetic Reconnaissance of the Bonin Islands.*

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Abstract

A paleomagnetic study has been carried out on the volcanic rocks of the Bonin Islands (27°N, 142°E). A total of 15 sites were visited for sampling; eight sites on Chichi-jima, four on Haha-jima, two on Muko-jima and one on Yome-jima. The directions of natural remanent magnetization of the samples after alternating field demagnetization not only deflect considerably from the present geomagnetic field but they clearly show that Chichi-jima differs from the other islands. That is, the mean direction for the eight sites on Chichi-jima is $I=15°$, $D=90°$, $\alpha_{95}=27°$, while that on the other islands is $I=3°$, $D=207°$, $\alpha_{95}=18°$. The offset declinations and shallow inclinations may be explained tectonically by a clockwise rotation and northward drift of the islands since Early Tertiary, although the anomalous geomagnetic behaviors in a transient stage can be an alternative interpretation at the present stage of investigation.

1. Introduction

About 1000 km the south of Tokyo are situated several islands named the Bonin Islands (or Ogasawara Islands), which apparently form a part of the Izu-Mariana arc-trench complex (Fig. 1). The islands consist of three groups of islands lying about 50 km apart from north to south and they are called the Muko-jima, Chichi-jima and Haha-jima islands respectively. Each group is made up of a few inactive volcanic islands and small islets. Several are up to 20 km in size, among which Chichi-jima is the largest, followed by Haha-jima, and both are inhabited at present.

Since the end of the 19th century, the Bonin Islands have been of interest to a number of scientists mainly from the petrological and paleontological viewpoints. KIKUCHI (1890) first reported the high content of MgO in certain rocks on Chichi-jima, and PETERSON (1891) named these

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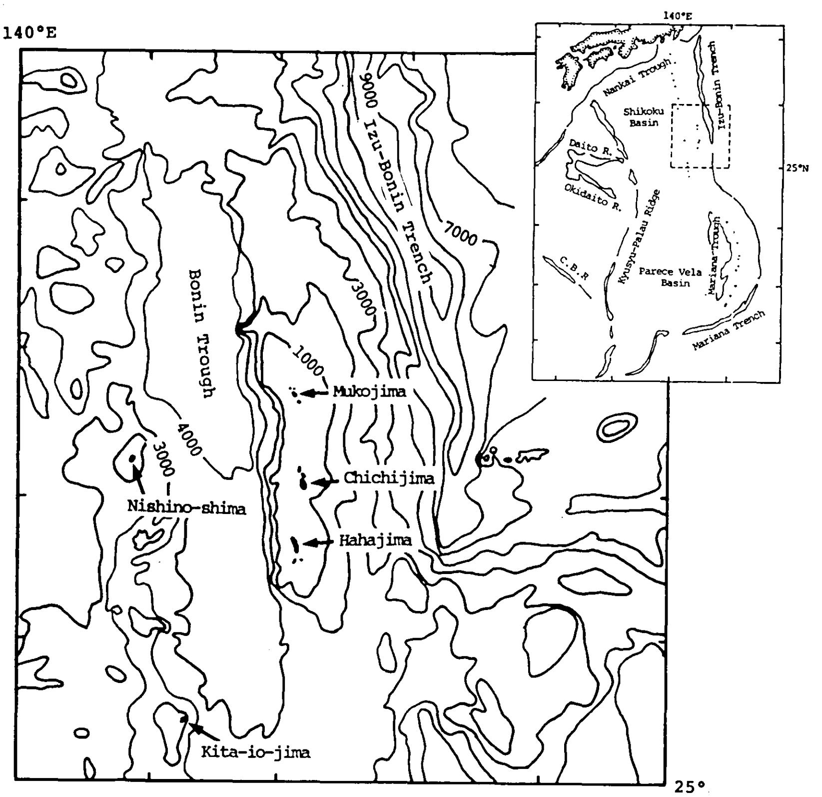


Fig. 1. Index map of the Bonin Islands, showing the major geomorphological outline of the Philippine Sea and bathymetry (unit; meters) around the Bonin Islands. Reproduced partly from the chart by the Hydrographic Office, Maritime Safety Agency of Japan (1966).

rocks "Boninite". The boninite, vesicular and feldspar-free glassy andesite with high contents of MgO (6~12%) (SHIRAKI and KURODA, 1977) is found on several of the Bonin Islands. No volcanic rock exactly equivalent to boninite has yet been found elsewhere, although quite similar rock has been reported in the fore-arc area of the Marianas (HUSSONG, UYEDA *et al.*, 1981). On the other hand, early in the 20th century, some paleontological studies on *Nummulites* on Haha-jima were made by such workers as YOSHIWARA (1902), YABE (1920) and HANZAWA (1925), suggesting Middle Eocene for the age of this island. A similar age was reported later by SAITO (1962) and UJIIE and MATSUMARU (1977), based on the study of planktonic and larger Foraminifera on Haha-jima. A slightly younger age of 40 m.y.b.p. (Late Eocene) was obtained for the two-pyroxene andesite of Haha-jima by KANEOKA *et al.* (1970). They also reported the absolute age of 26 m.y.b.p. (Late Oligocene) for the slightly altered andesite of Chichi-jima. More recently TAKAYANAGI and KATAYAMA (1979) discovered planktonic Foraminifera of Lower Eocene age from the tuffaceous sediments in Chichi-jima. Moreover, H. TSUNAKAWA (1980, personal communication) obtained K-Ar ages of 38 and 42 m.y.b.p. from dacites and 41 m.y.b.p. from a boninite on Chichi-jima. Therefore, the true age of Chichi-jima is unlikely to differ significantly from that of Haha-jima, although some differences are recognized between fossil and absolute ages. The inferred age of the Bonin Islands (Early Tertiary) can, thus, be compared to the oldest ages for the Mariana Islands such as Guam and Saipan.

Geophysically, the Bonin Islands and the surrounding areas are characterized by very large positive Bouguer and free-air gravity anomalies. KARIG and MOORE (1975) reported that a free-air gravity anomaly with the peak value of over 300 mgal was observed across the Bonin Ridge. TANAKA *et al.* (1974) also observed free-air and Bouguer anomalies over 300 mgal in the central and northern parts of Chichi-jima. These positive anomalies are the largest known in the oceans and island arcs. From the viewpoint of tectonics it is suspected that the Bonin Islands may have been transported northward since Early Tertiary, possibly resulting from the oblique subduction of the Pacific plate underneath the Philippine Sea plate in a NNW direction. The inferred northward movement of the Bonin arc would be explained by FITCH's model (FITCH, 1972). Moreover, northeasterly trending ridges and troughs extending west of the Bonin Islands (KARIG and MOORE, 1975) may have caused some regional tectonic dislocations for the Bonin arc.

The geological and geophysical characters of the Bonin Islands led us to attempt to make a paleomagnetic study on the islands, and we made the first reconnaissance work on several of the Bonin Islands in 1980.

2. Geology of the Bonin Islands

In spite of the various characteristics of geoscientific interests mentioned earlier, the geology of the Bonin Islands has never been investigated, except for the two major islands of Chichi-jima and Haha-jima. Detailed geologic descriptions covering the whole of both islands have not been accomplished. In the following we summarize briefly the geology of these islands, based on the limited bits of geologic information so far reported.

Haha-jima

Haha-jima, or Hillsborough island, is mainly comprised of andesitic, partly basaltic, lava and volcanic breccia together with a number of dikes. Andesitic lavas and tuff breccias are developed in the northern area, while tuffaceous sandstone and sandy limestone are intercalated in the volcanics in the southern part (IWASAKI and AOSHIMA, 1970). Volcanic layers are interrupted by several faults running obliquely in the island and are gently dipping or warping (UJIIE and MATSUMARU, 1977). Marine sedimentary layers distributed in the southern half of the island bear fossils of larger and planktonic Foraminifera, both indicating nearly the same age of late Middle Eocene (SAITO, 1962; UJIIE and MATSUMARU, 1977).

Chichi-jima

Chichi-jima is composed mainly of boninitic and andesitic pillow lavas, hyaloclastites, dikes and subordinate sedimentary rocks such as sandstone and limestone. Volcanic breccias are composed of boninite, hypersthene andesite and dacite. The lower successions are comprised dominantly of pillow lavas accompanied by a number of dikes, and the middle to upper horizons are composed of an alternation of pillow lavas and glassy hyaloclastites. In the uppermost horizon, andesitic and dacitic lavas are distributed locally. Throughout the successions from lower to upper, boninitic and andesitic dikes are frequently distributed, especially in the eastern part of the island (S. MARUYAMA, 1980 personal communication). The dip of volcanic layers are gentle, generally less than 20° toward the west, except for a few local dislocations. Sedimentary rocks are distributed in the southwestern part and in other restricted areas. The reef limestone of Oligocence to Early Miocene age composing Minami-jima and its vicinity seems to be unconformably underlain by major volcanics of Chichi-jima (e.g., HANZAWA, 1925), while the age of the basal volcanics is likely to be Lower to Middle Eocene as suggested by the K-Ar age and fossil age.

Muko-jima

No geologic outline has been reported until the scientific party including the author visited this uninhabited island in June 1980. It was confirmed at that time that the island is generally comprised of boninitic and andesitic pillows, hyaloclastites and a number of dikes in the same manner as Chichi-jima. No fossil-bearing sediments have been found.

3. Descriptions of sampling localities

We visited the following four Bonin Islands for paleomagnetic sampling; namely Chichi-jima, Haha-jima, Muko-jima and Yome-jima. Most of the samples were collected as oriented blocks, except for several sites on Chichi-jima where a portable rock drill was used. At each site three

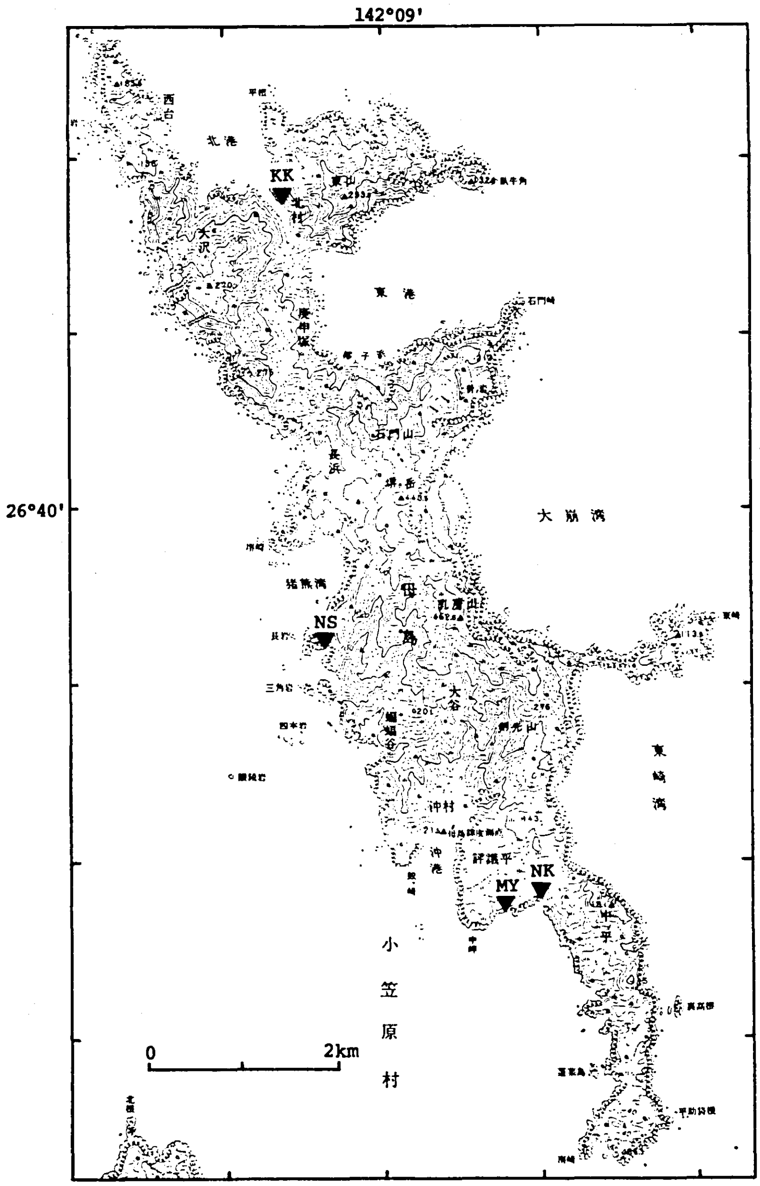


Fig. 2A.

Fig. 2. Topographic map of the four Bonin Islands, showing sampling sites (triangles). A; Haha-jima, B; Chichi-jima, C; Muko-jima, D; Yome-jima. Reproduced from the map by the Geographical Survey Institute (1977).

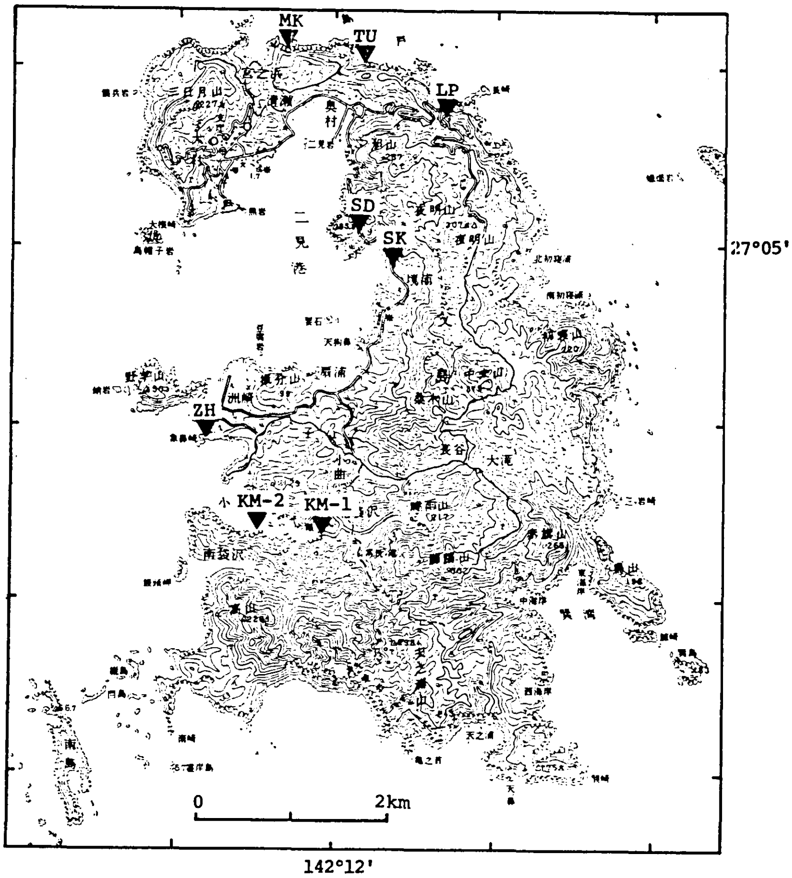


Fig. 2B.

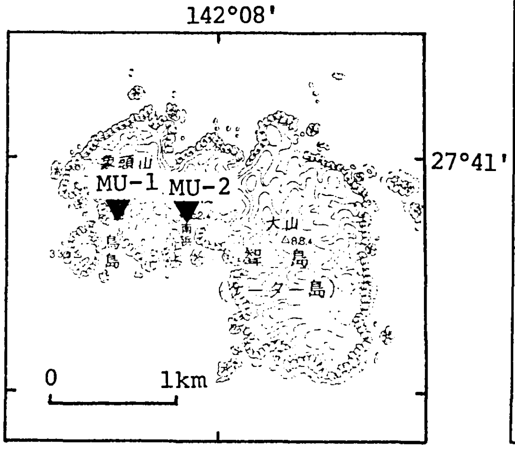


Fig. 2C.

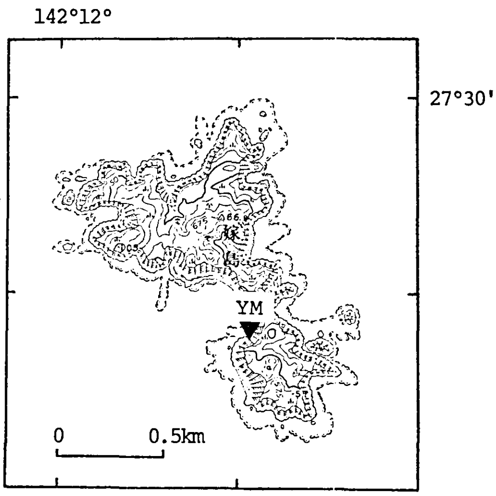


Fig. 2D.

or more block samples were collected, and one to three specimens were cut from each of these. Orientation was made with a magnetic and sun compass. The number of sampling sites on each island is as follows; eight sites on Chichi-jima, four on Haha-jima, two on Muko-jima and one on Yome-jima (Fig. 2). A total of 120 specimens including 18 drilled cores were thus obtained. Sample localities and rock types on each island are briefly described below.

Chichi-jima

LP An outcrop of bronzite-andesite with massive pillows about 50 cm to 1 m in diameter. No reliable bedding correction could be made on this formation because neither sedimentary layers directly overlying or underlying this lava flow, nor three dimensional pillow structure were observed due to restricted exposure. Stratigraphically this formation may be one of the upper horizons, but not the highest one. One to four cores were drilled from each of six pillows several meters apart.

ZH Dacitic dike or sill surrounded by hyaloclastite with various sizes of volcanic breccia. Like the site above, the original bedding could not be identified due to its poor and complicated exposure. This site might have been affected, more or less, by a secondary movement such as slumping. Five cores were drilled.

KM-1 Dacite massive flow congealed in a nearly horizontal position, judging from the surrounding hyaloclastites with no significant tilting. Seven cores were drilled.

KM-2 Massive boninite pillow lavas with long axes of about one meter. Five oriented block samples were taken from the fresh glassy margins of five pillows (one sample from each pillow). Stratigraphically, like the above two sites, this horizon can be regarded as one of the lowest horizons, although the precise stratigraphic relation among them remains obscure.

MK Massive boninite pillows of various sizes (several tens of centimeters to one meter in diameter): one of the lower successions. Six oriented blocks were sampled from glassy margins of separated pillows.

TU Boninite pillows in lower horizons. Five block samples were taken from fresh margins of the pillows.

SD Dacite dike with well-developed columnar joints. Possibly one of the middle to upper successions. Five blocks were taken.

SK Boninite pillows intercalated by hyaloclastic layers bedded nearly horizontally. One of the uppermost horizons, possibly the highest one of boninite pillows. Seven blocks were sampled from fresh margins.

Haha-jima

NK Massive lava flow of fine-grained blackish two-pyroxene andesite. This flow, about 5 m thick, outcrops at the both ends of a small beach, Nankinhama, and is overlain by well-bedded coarse-grained calcareous sandstone rarely containing larger Foraminifera. Bedding is nearly horizontal or 5°S at most. Five block samples were taken, each several meters apart.

MY Fine-grained blackish two-pyroxene andesite exposed at the eastern end of Miyuki-hama beach, about 500 m west of the above site. This flow may be one of the lowest horizons and is overlain by coarse-grained sandstone, about 8 m thick, yielding a large assemblage of *Nummulites*. Five block samples were taken.

KK Massive dark-gray two-pyroxene andesite, about 10 m thick, exposed to the east of the northernmost beach named Kita-ko. Bedding is unclear, but possibly horizontal. Five block samples were taken.

NS Fine-grained dark-gray andesite outcropping as the lowest horizon at the northern end of Nishi-ura beach. Eight block samples were taken. Bedding is considered almost horizontal judging from the overlying hyaloclastic layers.

Muko-jima

MU-1 Massive pillows of boninite, at the lowest horizon of the western cliff: probably one of the lowest successions. Two block samples were taken from fresh glassy margins of separated pillows.

MU-2 Massive pillows of boninite: probably one of the lowest successions. Five block samples were taken from pillow margins.

Yome-jima

YM Greenish andesitic dike, about two meters thick, with well-developed columnar joints. Three block samples were taken. Bedding is unclear.

4. Laboratory procedures

All of the magnetic measurements were made with a Schonsted spinner magnetometer of the Paleomagnetic Laboratory of the Geophysical Institute, University of Tokyo. After the measurements of natural remanent magnetization (NRM) of all the specimens, several pilot specimens were selected from each site and progressively demagnetized in alternating magnetic fields with peak intensities of fifty to several hundred Oe.

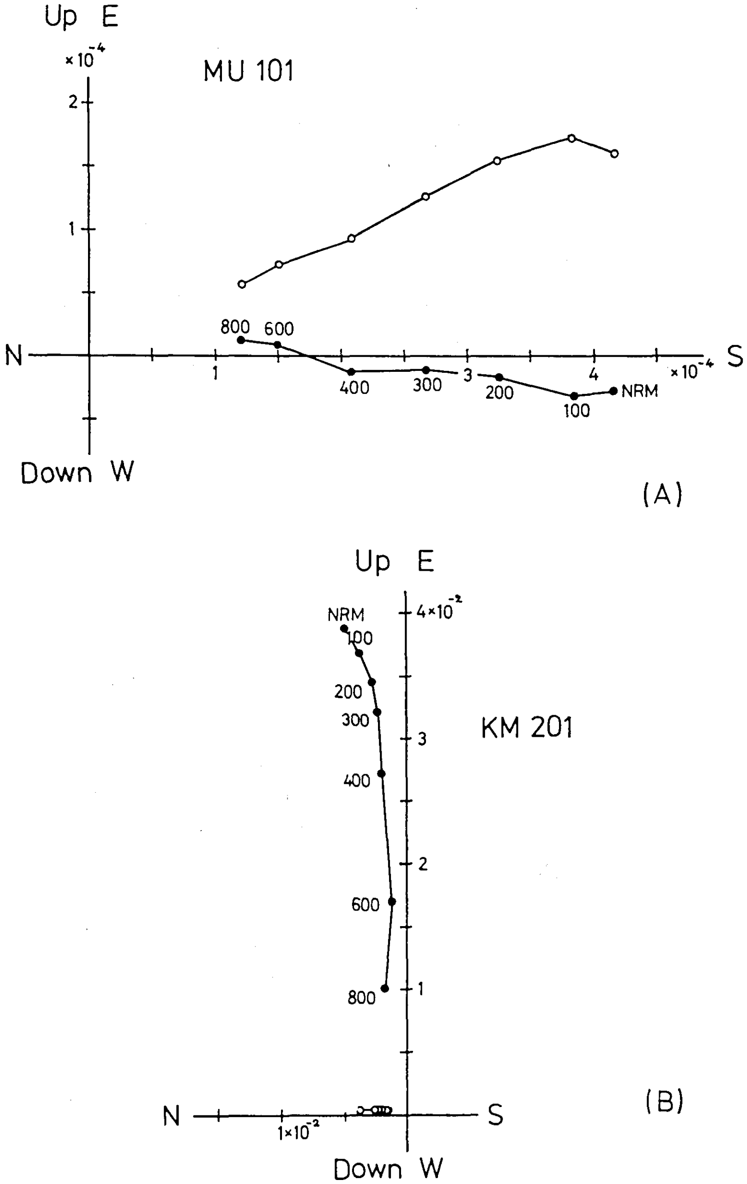
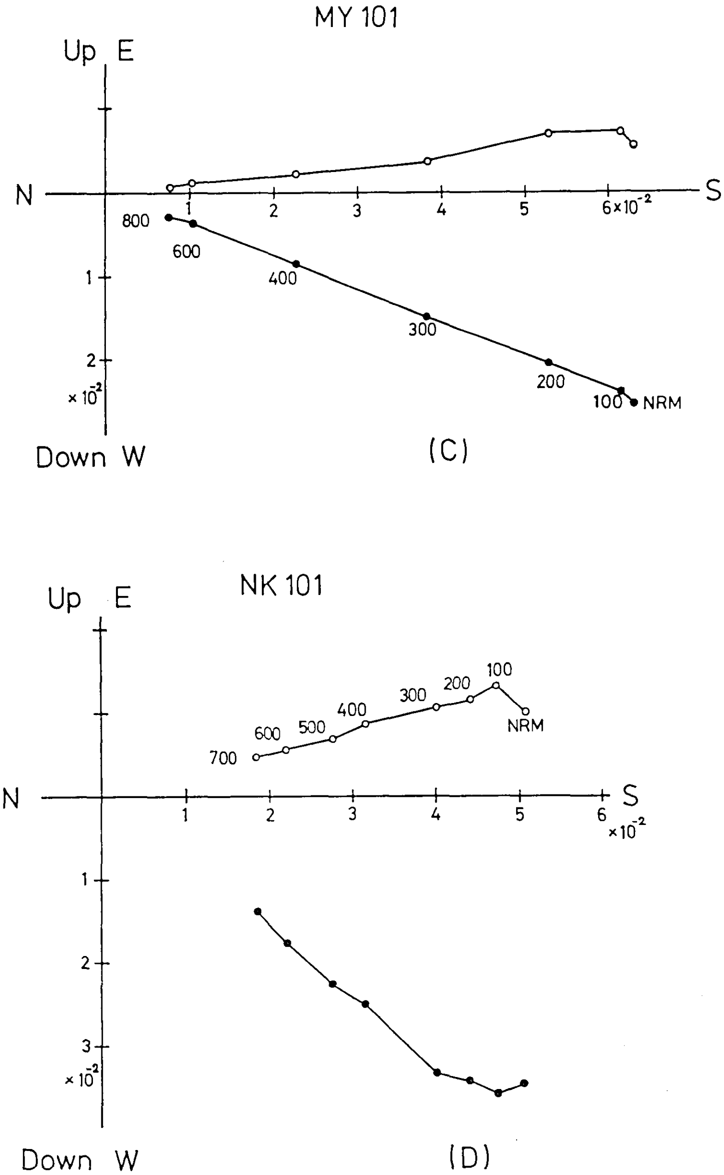
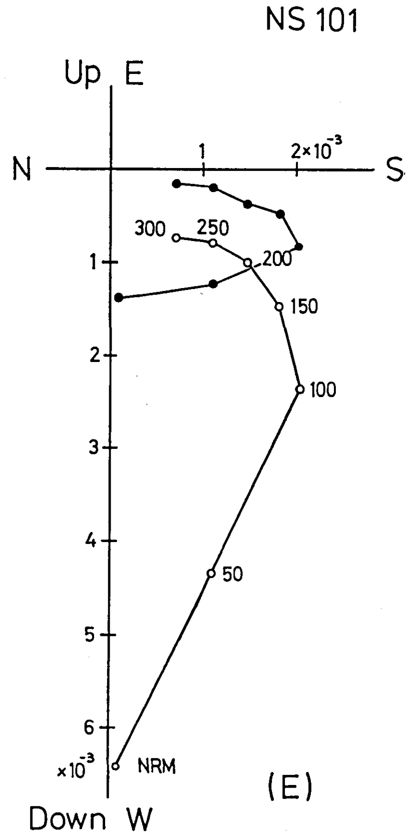


Fig. 3. Orthogonal projections of the successive endpoints of the magnetization vector during progressive AF demagnetization. Numbers are intensities of peak fields in oersted. Solid circles represent projections on the horizontal plane, and open circles those on the north-south vertical plane. Unit in emu. A, B; boninitic pillows at site MU-1 (Muko-jima) and KM (Chichi-jima). C, D, E; andesitic lavas at sites MY, NK and NS (Haha-jima).

The optimum demagnetization field was defined as that above which systematic change in direction ceased. However, as shown later, no systematic directional change was shown during stepwise AF demagnetization in most cases, especially in pillow lavas, so that the remaining specimens were cleaned by fields determined arbitrarily, say 100 Oe. In addition to AF demagnetization, five specimens were selected from separate sites in order to test the thermal stability of the remanence. The specimens were



heated and cooled in nitrogen gas and in an ambient field of less than 100 nT. Thermomagnetic analysis was performed on three specimens, two from Chichi-jima and one from Haha-jima, in vacuum ($\sim 10^{-5}$Torr) and in a strong magnetic field of about 4000 Oe.



5. Magnetic behaviors

The representative behavior of some pilot specimens during AF demagnetization are shown in Fig. 3 by projecting successive endpoints of magnetization vectors. AF demagnetization was made stepwise until the intensity was reduced to one third to one tenth of the initial NRM intensity. The results show no systematic directional change except the specimen from site NS on Haha-jima which seems to carry a large amount of secondary components. Almost all of the pilot specimens from pillow lavas were found to be fairly stable during AF demagnetization up to 700∼800 Oe. Such being the case, the remaining specimens were cleaned only by 100 Oe for obtaining paleomagnetic data. Thermal demagnetization, as well as AF demagnetization, revealed stable directional behavior up to 550°C for several selected samples as shown in Fig. 4. The change of relative intensities during demagnetization steps indicates high blocking temperatures over 300°C. The magnetic and thermal stabilities of the remanence thus obtained show that almost all the samples carry stable primary magnetization (TRM) acquired when they cooled. Fig. 5 shows the thermomagnetic analysis of the boninitic pillow and andesitic dike on Chichi-jima, and one of andesitic lava on Haha-jima. The J_s versus T curves are irreversible; cooling curves being always higher than heating curves. The results indicate the presence of titanomaghemite produced by low temperature oxidation of titanomagnetite in a subaqueous environment (OZIMA and LARSON, 1970). Heating curves of the two examples (Fig. 5-A, 5-B) clearly demonstrate two substantial phases, whereas cooling curves show a single phase. The phase with a

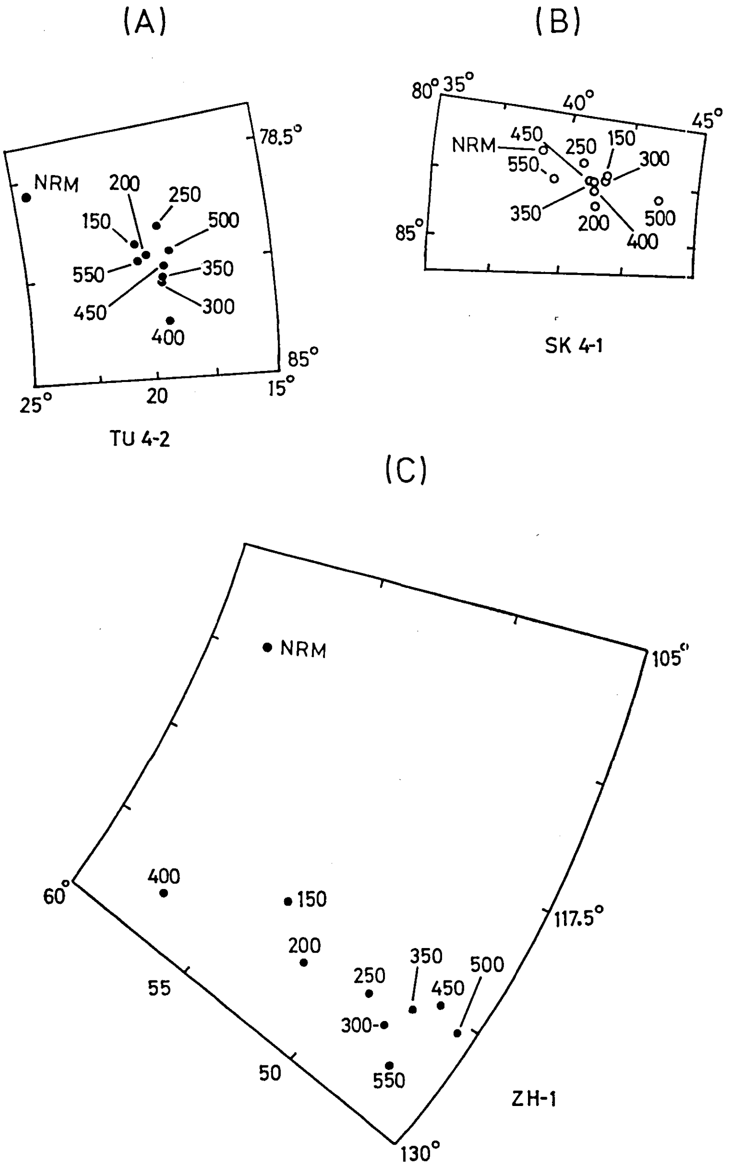
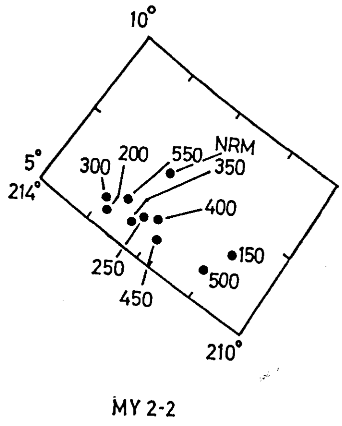
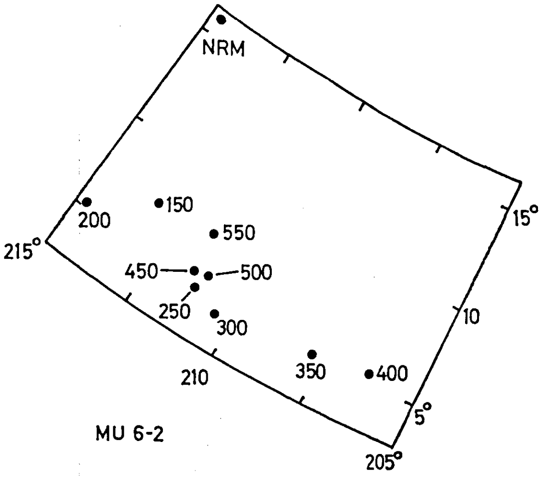


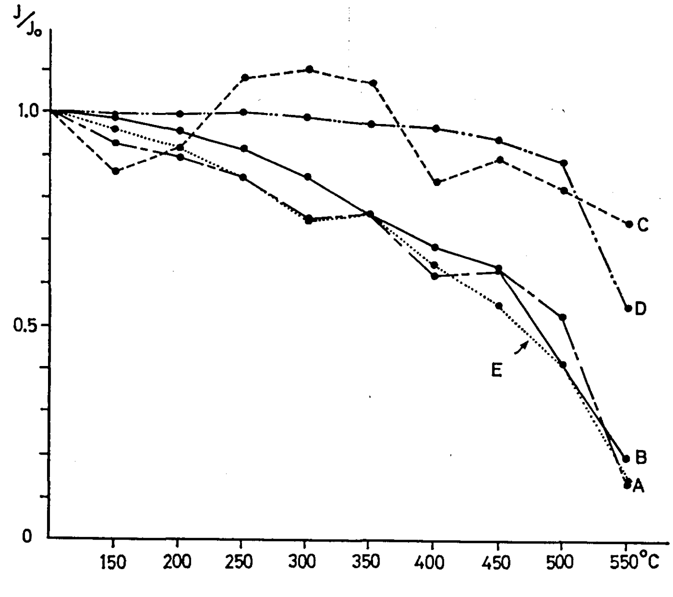
Fig. 4. Equal-area projections of directions of magnetization through the progressive thermal demagnetization (A-E). Numbers indicate demagnetization temperatures. Solid (open) circles represent projections on the lower (upper) hemisphere. Fig. (F) shows the change of relative intensities during thermal demagnetization. A, B, E; boninitic pillows at site TU and SK on Chichi-jima, and site MU-2 on Muko-jima. C; andesitic dike at site ZH on Chichi-jima. D; andesitic lava at site MY on Haha-jima.

(D)


10°
5°
214°
300
200
550
NRM
350
400
250
450
150
500
210°
MY 2-2

(E)


NRM
200
150
550
215°
450
500
250
300
350
400
210
15°
10
5°
205°
MU 6-2


J/J₀
1.0
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(F)

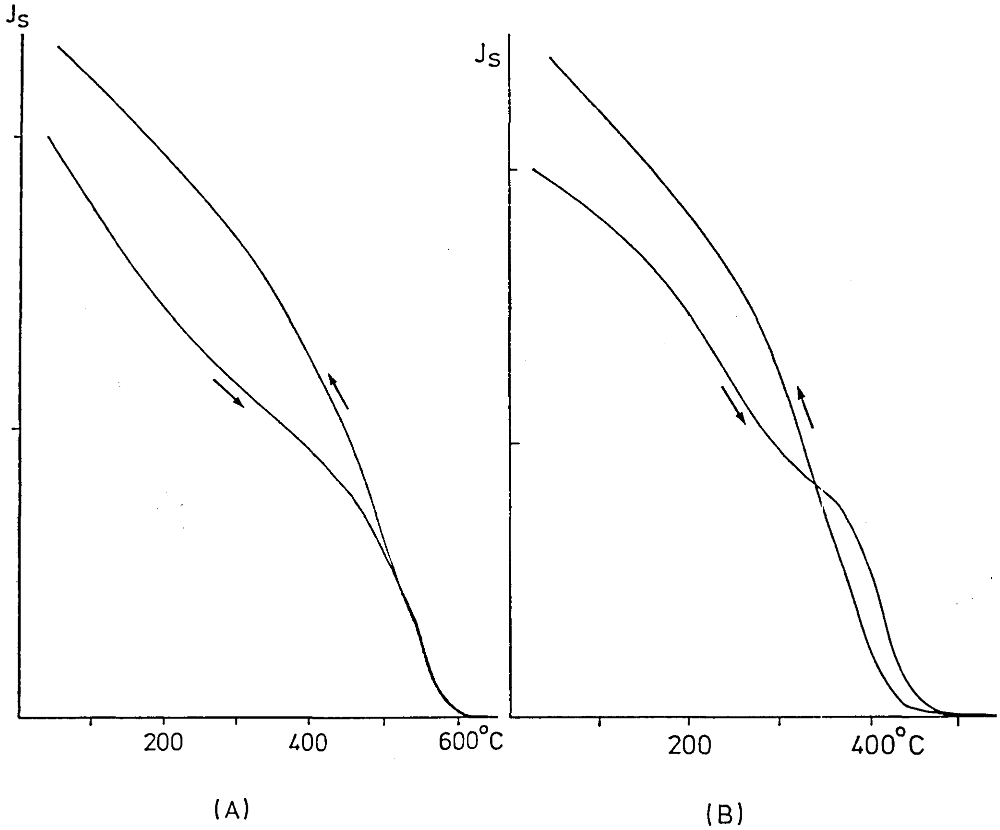

Fig. 5. Thermomagnetic curves of boninitic pillow (A) at site KM (Chichi-jima), andesitic lava (B) at site MY (Haha-jima) and andesitic dike (C) at site ZH (Chichi-jima). Vertical axis is the relative intensity of saturation magnetization.

lower Curie point shown in the heating curve may be considered as a thermally unstable titanomaghemite which decomposes to Ti-poor titanomagnetite and Ti-rich phase during heating. The amount of titanomaghemite, however, would be small compared to that of titanomagnetite as suggested by the relatively small difference in J_s between the heating and cooling paths.

6. Paleomagnetic results and discussions

The mean remanence directions of the rocks at 15 sites after AF demagnetization are summarized in Table 1 and Fig. 6. The results clearly show that the mean directions of Chichi-jima and the other islands are significantly different, especially in the declination. That is, apart from the less reliable data of Yome-jima (k$\sim$7), the mean directions of Haha-

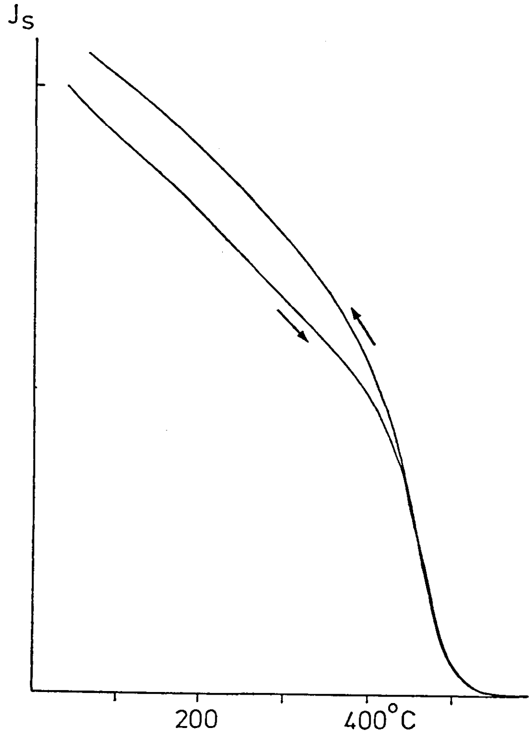

Fig. 5. (C)

Table 1. Paleomagnetic data from the Bonin Islands.

Site	N	ODF	Inc.	Dec.	k	α_{95}
			Chichi-jima			
LP	13	150	−53.7°	87.9°	71	5.1°
ZH	5	100	47.9	125.8	149	6.3
KM-1	7	100	−7.2	88.2	310	3.6
KM-2	7	100	−15.2	90.6	43	9.2
MK	6	250	31.0	75.4	53	9.2
TU	7	250	27.4	90.4	138	5.1
SD	5	150	−41.5	261.8	243	5.1
SK	9	250	−32.5	266.5	13	14.8
			Haha-jima			
NK	12	100	−10.2	210.7	77	5.1
KK	6	150	22.1	234.9	24	13.8
NS	13	250	8.4	190.7	23	8.9
MY	11	100	−2.2	209.7	67	5.7
			Muko-jima			
MU-1	8	100	−25.0	203.7	32	9.9
MU-2	5	100	14.1	209.2	663	2.6
			Yome-jima			
YM	4	100	−27.0	233.0	7	37.4

N; Number of specimens, ODF; Optimum demagnetization field in oersted, k; Fisher's statistical parameter, α_{95}; radius of 95% confidence level.

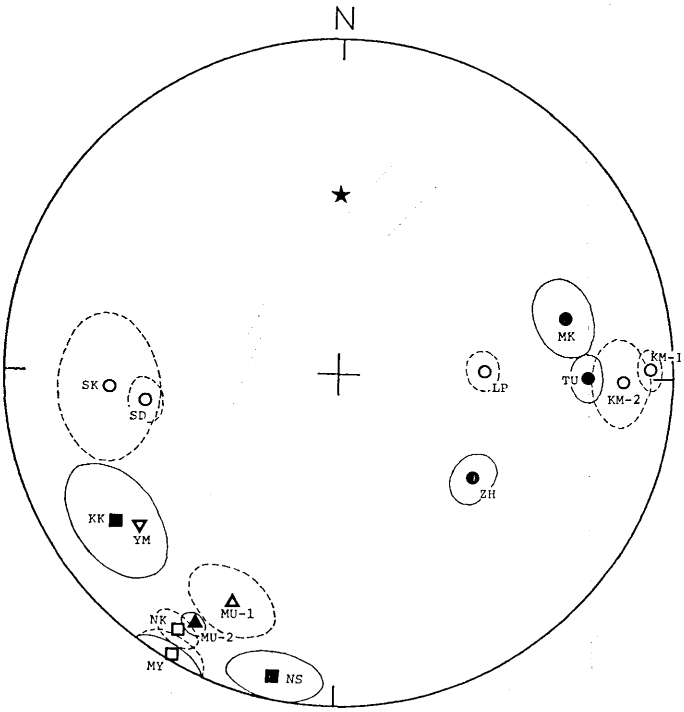

Fig. 6. All of the mean magnetic directions of the Bonin Islands and their cones of 95% confidence level (equal-area projection). Solid (open) symbols are projections on the lower (upper) hemisphere. ●; Chichi-jima, ■; Haha-jima, ▲; Muko-jima, ▼; Yome-jima. Star represents the direction of axial dipole field expected at the present latitude of the Bonin Islands.

jima and Muko-jima fall into one group having the between-site mean direction of I=3°, D=207° with a 95% confidence radius of 18°, while the mean directions of Chichi-jima are not grouped as a whole but rather seem to be separated into two distinct groups. In spite of the marked dispersion between sites and the insufficient number of sites on Chichi-jima, the two groups are apparently opposite in polarities. Since the two groups on Chichi-jima, as well as sites on the other islands, show a large deflection from the present geomagnetic direction, it is unlikely that they have acquired marked magnetic overprint such as chemical remanent magnetization due possibly to titanomaghemitization in the recent past. If two directions in Chichi-jima are inverted through the origin, we obtain the mean direction for all sites as I=15°, D=90°, α_{95}=27°. Although the poor grouping between sites may be attributed to the geomagnetic secular variation or unresolvable structural disturbances or both, the deflected declinations of the data from Chichi-jima lead us to suspect that the island had been affected by a significant amount of tectonic rotation around the vertical axis. On the other hand, the remanence directions of the other two islands seem to be grouped well into a reversed direction deflected a little to the west of the south (Fig. 6). Therefore it is suspected that these offset declinations could be explained, more or less, by a clockwise tectonic rotation also. Another characteristic of the present paleomagnetic data is that inclinations are definitely shallower than that expected at the present latitude of the Bonin Islands (I=46° at 27°N). These shallow inclinations (15°±27° for Chichi-jima and 3°±18° for the other islands) may indicate a northward drift of the islands. Considering the reconstruction of the Philippine Sea such as proposed by KARIG (1975), these tectonic interpretations (clockwise rotation and northward migration) are quite attractive. Paleomagnetic studies (KOBAYASHI, 1972; LARSON *et al.*, 1975) indicated a significant amount of clockwise rotation for the island of Guam also. However, at the present preliminary stage of investigation, it is uncertain whether the limited paleomagnetic observation can assure such tectonic movements, because it seems also possible that some anomalous geomagnetic behavior in Early Tertiary could have caused the deflected remanent directions. In any case, much more detailed paleomagnetic and geological investigations are essential to delineate the tectonic development of the Bonin Islands.

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17. 小笠原諸島の古地磁気学的予察

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小笠原諸島（北緯27度，東経142度）の火山岩に関する古地磁気学的研究を行なった．総計15ヶ所（父島8ヶ所，母島4ヶ所，婿島2ヶ所，嫁島1ヶ所）から岩石試料を採取した．それらの残留磁化の方向は，現在の地球磁場の方向から著しくずれるばかりでなく，父島とその他の島々の間でも大きな相違のあることが分った．すなわち，父島の8ヶ所の平均残留磁化方向が，伏角15度，偏角90度，誤差半径（95% 信頼度）27度であるのに対し，その他の島々の平均は伏角3度，偏角207度，誤差半径18度である．このようにずれた偏角と浅い伏角は，現段階では一時的な地球磁場の異常でも説明できるが，小笠原諸島の第三紀早期以来の時計回りの回転と北方への移動という構造運動によって説明することもできる．