ABSTRACT

This paper presents a nearly complete magnetostratigraphic record for a 38-m long piston core. The core MD97-2143, collected at the water depth of 2989 meters on the Benham Rise of the western Philippine Sea, is mainly composed of olive-brown, hemi-pelagic calcareous oozes and intercalated with volcanic ash layers in 1-15 cm thickness. Analysis of magnetic mineralogy and granulometry reveals that the main magnetic carrier of sediments is magnetite with grain sizes within the range of pseudo-single domain. Detailed magnetic measurements on 1661 discrete samples of the whole sequence further indicate that the volcanic ash layers usually have high values of low-field magnetic susceptibility and intensity of natural remanent magnetization. After alternating field demagnetization was carried out on 383 selected samples, the directions of characteristic remanent magnetization can be isolated and show a clear record of geomagnetic polarities of the sequence from the recent down to the early Matuyama age. According to the nanofossil datum levels of Wei et al. (1998), three prominent normal-polarity zones can be easily recognized as the Brunhes, Jaramillo and Olduvai for the intervals of 0-1560 cm, 1823-1905 cm and 2738-2937 cm, respectively. Using the boundary ages of three magnetic zones, the sedimentation rate of the sequence is estimated to be about $1.15 \pm 0.15$ cm/kyr for the age interval of 0.78-1.95 Ma and then increases to 2.0 cm/kyr since 0.78 Ma. In addition, four short normal-polarity events, occurring at the levels of 1728-1735 cm, 2031-2044 cm, 3231-3270 cm and 3295-3305 cm, have been detected within the reversed Matuyama. Correlation of these short events with the geomagnetic polarity time scale suggests that the first two younger events should be the Santa Rosa and Cobb Mountain, respectively. For the older two events, they are considered to be linked with the Réunions (II and I) although the record of Réunion I is not
complete due probably to a hiatus within a reworked foram sand layer (3291-3395 cm).

Key words: magnetostratigraphy, Brunhes, Matuyama, geomagnetic events

INTRODUCTION

The core, MD97-2143, is a 38-m long piston core that was raised from the Benham Rise of the western Philippine Sea during IMAGES III-IPHIS cruise of the R/V Marion Dufresne in 1997 (Fig. 1). The position of the coring site is $15^\circ52.262'N$, $124^\circ38.96'E$ at the water depth of 2989 m, which is on the route of the Kuroshio Current and very close to Site 292 ($15^\circ49.11'N$, $124^\circ39.05'E$, 2937 m) of DSDP Leg 31 in 1973. Because the Kuroshio Current is a major western boundary current of the Pacific Ocean and plays an important role in regulating the global transports of heat and water vapor, the primary objective of this core is to decipher its history since late Cenozoic. In order to establish a precise geochronological framework for our knowledge of the Kuroshio Current history, magnetostratigraphic study was therefore carried out on this well-recovered (75.6%) core.

![Location map](image)

Figure 1. Location map of IMAGES core MD97-2143 (solid circle) and Site 292 of DSDP Leg 31 (solid asterisk). Both are located on the Benham Rise of the western Philippine Sea. Numbers associated with contour lines indicate the water depth in meter.
In this paper, I demonstrate that the sediment sequence has a nearly complete magnetostratigraphic record from the recent down to the early Matuyama age. In addition to three prominent normal-polarity zones, namely, the Brunhes, Jaramillo and Olduvai, four short normal events in the reversed Matuyama chron have been detected as well. Because the magnetic polarity record is so complete that it can be used as a reference for correlating sedimentary sequences.

CORE DESCRIPTION AND BIOSTRATIGRAPHY

After retrieval, the core was labeled and cut into 26 sections of the standard 1.5-m length or less, starting at the top. Physical properties of the sediments, including magnetic susceptibility, bulk density, P-wave velocity and reflectance, were then measured on board, by passing each section through a multi-sensor track (MST) system. After this routine measurement, the core sections were split in half lengthwise for description and sampling for preliminary bio-chronological study. The MST device, the physical properties and the core description of MD97-2143 can be found in Wei et al. (1998) and the scientific report of the cruise.

Because the water depth of the coring site is above the carbonate compensation depth, the sediments consist of hemi-pelagic calcareous ooze with olive-brown color. Volcanic ash layers in 1-15 cm thickness are intercalated, which generally reveal high values of magnetic susceptibility due to a relatively large amount of magnetic particles. In addition to these features, three points should be noted here. First, the core is void between the sub-bottom depths of 0-12 cm. Second, cracks occur at the levels of 78-87 cm. Third, reworked white foraminifera sands predominate in sediments between the interval of 3291-3395 cm (Section 23).

Wei et al. (1998) regarded that the age of the lowermost part of the core (3396-3800 cm) is older than 2.59 Ma but younger than 2.78 Ma, as bracketed by the two last appearance datum (LAD) levels of Discoaster surculus and D. tamalis. Moreover, they also recognized four age-diagnostic datum levels: (1) the first appearance datum (FAD) of Emiliania huxleyi (0.27 Ma) at 365 cm, (2) LAD of Pseudoemiliania lacunosa (0.46 Ma) at 1105 cm, (3) LAD of Calcisiscus macintyrei (1.59 Ma) at 2510 cm, and (4) LAD of D. brouweri (1.95 Ma) at 2970 cm.

EXPERIMENTAL METHODS

Discrete samples for paleomagnetic measurements were obtained by pressing 7-cm³ plastic cubes into the sediments. An arrow cast on the plastic cube helps for orientation. A total of 1661 samples were collected sequentially from the 26 working-half sections, with gaps between the plastic cubes being minimized. Occasionally, some void space exists in the cube at the last sample of each section because sediments cannot be filled in thoroughly. Discrete specimens were tightly sealed to prevent dehydration. Non-oriented samples at different levels were also taken for the study of magnetic mineralogy and hysteresis properties (i.e., saturation magnetization (Ms), saturation remanence (Mn), coercivity (Bc) and coercivity of remanence (Bcr)).

Low-field magnetic susceptibility (κ) and natural remanent magnetization (NRM) of discrete samples were measured with a Bartington MS2 system and a 2G Enterprises superconducting rock magnetometer, respectively. To examine the stability of the remanent magnetization, stepwise alternating field (AF) demagnetization of NRM was then carried
out on 383 selected samples using an in-line tri-axial demagnetizer linked with the rock magnetometer. The spacing between samples is usually about 12-cm but set to the minimum near magnetic reversals. Thirteen demagnetization steps from 0 (NRM) to 80 mT were performed, with a 5-10 mT increment of each step.

In order to understand the dominant magnetic carrier in sediments, four non-oriented samples at the levels of 852, 1614, 2122 and 2656 cm were used for magnetic extraction. They were dispersed completely in water with an ultrasonic bath. Magnetic particles were then extracted with a 'magnetic finger' and identified with a Philips X-ray diffractometer (XRD) with CuKα radiation. Because the ratios of Mrs/Ms and Bcr/Bc can provide useful information of magnetic granulometry (Day et al., 1977), a small amount of the sediments were loaded on a Princeton alternating gradient force magnetometer to measure Ms, Mrs, Bc and Bcr.

RESULTS

X-ray analysis on the four magnetic extracts indicates that the main magnetic carrier in sediments is magnetite (Fig. 2). Based on Day plot (i.e., Bcr/Bc vs. Mrs/Ms), it further reveals that the grain sizes of magnetite particles are within the field of pseudo-single domain (Fig. 3). All of these suggest that variations in magnetic mineralogy and magnetic granulometry may be small throughout the sediment sequence.

Figure 2. X-ray diffractogram of magnetic extract from the level of 2122 cm (sample: 15-14), indicating that magnetite (M) is the main magnetic carrier of sediments. Magnetite was also identified at the levels of 852 cm, 1614 cm and 2656 cm.
The low-field magnetic susceptibility (κ) of 1661 discrete samples ranges from 14 to 472 x10⁻⁴ (SI), with an average of 127 x10⁻⁴ (SI) (Fig. 4a). The variations in κ are very consistent with the results measured by MST system on board, except that some bottom samples of each section exhibit abnormal values due to the void space. The wide range of κ implies that the concentration of magnetite particles is highly variable. As mentioned above and shown in Figure 4a, the volcanic ash horizons, which generally have high concentration of such magnetic particles, yield high values of κ. The occurrence of volcanic ash layers is mainly clustered in two groups. The younger group between 500 and 1200 cm usually has lower values of κ than the older one between 2200 and 3400 cm. However, below the level of 2200 cm, other non-ash horizons usually have lower values than the average and the 1-m thick reworked foraminiferal sand layer has the lowest ones. Same as the magnetic susceptibility, the intensity of NRM (Jo) also shows a wide range from 1 to 390 mA/m, with an average of 40 mA/m (Fig. 4b), and some volcanic ash layers yield high values of Jo as well. It is noted that above the level around 1560 cm, the values of Jo are generally higher than the average.

Before AF demagnetization, declinations and inclinations of NRM have already shown an outline of magnetozones of the sediment sequence (Fig. 4c-d). For instance, the interval between 0-1560 cm can be readily assigned to the Brunhes normal-polarity chron because most samples have positive inclinations, although negative inclinations occur at some bottom levels of each section. Below this, the interval of 1560-3800 cm is then expected to be the Matuyama reversed chron because it is dominated by negative inclinations and punctuated by several zones with positive inclinations. According to this recognition, the magnetic polarities with positive inclinations within the Matuyama should belong to short normal magnetic zones, such as the Jaramillo, Olduvai, etc. Corresponding to the changes in inclination, the declination also shifts about 180° during magnetic reversals.
Figure 4. A composite plot of (a) low-field magnetic susceptibility, (b) intensity of NRM, (c) declination of NRM, (d) inclination of NRM and (e) section, for Core MD97-2143 versus sub-bottom depth. Asterisks denote prominent volcanic ash layers. Magnetic susceptibility data measured with MST and MS2 systems are both shown. The dash lines indicate the averages for the values of low-field magnetic susceptibility and intensity of NRM. Core sections are numbered 1-26.
Although the directions of NRM have already provided a simple framework of magnetostratigraphy, the polarity at some levels is still ambiguous. For instance, at the levels of 2332, 2650 and 3115 cm, the polarities based on declination are inconsistent with those expected by inclination (Fig. 4c-d). In addition, both declinations and inclinations between the interval of 3300-3800 cm are highly variable. These discrepancies could be resulted from overprints of secondary remanent magnetization, geomagnetic excursions or physical disturbance of sediments. After AF demagnetization on 383 selected samples throughout the sequence, their stable characteristic directions can be isolated and therefore provide a more solid magnetozones. Figure 5 presents the orthogonal-vector diagrams that illustrate individual sample behavior during demagnetization. For most of the samples between the interval of 0-1500 cm, NRMs usually reveal univectorial decay toward the origin and their characteristic remanent magnetizations (ChRM) can be easily defined. However, for the samples in the deeper part, they may show either one or two vector components, depending on the overprints of secondary remanent magnetization. In spite of this, ChRMs of most samples were isolated when the AF demagnetization was above 10-15 mT. Because continuous samples near the magnetic reversals were demagnetized, the polarity boundaries were clearly defined. Figure 6 shows the recognized magnetozone based on the directions of ChRM and their correlation with the geomagnetic polarity time scale (GPTS).

It is clear from Figure 6 that the declinations of ChRM change progressively in the whole sequence. This may indicate that the sediments have been twisted during core recovery. On the other hand, the variations in inclination are relatively small for the interval above 3230 cm. The average inclinations in the normal and reversed sections are 29.1° and -31.6°, respectively, whose absolute values are not significantly different from the inclination of the axial dipole field at the site, which is 29.6°. However, below the depth of 3230 cm, the inclinations are highly variable. This could be due to the core nature that becomes stiff at depths, re-deposition of foraminiferal sands by slumping and possible disturbance during drilling process.

From Figure 6, it is also obvious to assign the uppermost normal-polarity section (0-1560 cm) to the Brunhes chron and the two prominent normal magnetozone (1823-1905 cm and 2738-2937), that are typically seen within the Matuyama, to the Jaramillo and Olduvai subchrons, respectively. The four nannofossil datum levels proposed by Wei et al. (1998) support this correlation because LADs of Ca. macintyrei and D. brouweri are in the vicinity of the Olduvai and LAD of P. lacunosa and FAD of E. huxleyi are within the Brunhes (Berggren et al., 1995). In addition to these three easily recognized magnetic zones, Figure 6 also shows four short normal-polarity intervals in the Matuyama. The first one (1728-1735 cm) is between the Brunhes and Jaramillo, the second (2031-2044 cm) is below the Jaramillo and the third (3231-3270 cm) and the fourth (3295-3305 cm) are all below the Olduvai. Their correlation with GPTS is discussed below.
Figure 5 Representative vector end-point diagrams of stepwise AF demagnetization of NRM of samples from Core MD97-2143. Solid (open) circles are projections of remanent vector end-point on horizontal (vertical) plane. Characteristic remanent magnetizations were generally isolated above 10-15 mT. The magnetic polarities for the samples 2-60, 6-16, 12-40, 13-33, 14-44, 20-33, 22-45 and 23-06 are normal and the rest are reversed.
Figure 6. (a-b) Declination and inclination of the characteristic remanent magnetization (ChRM) versus sub-bottom core depth. (c) Magnetostratigraphy of Core MD97-2143 and its correlation with the geomagnetic polarity time scale (d). Four nannofossil datum levels proposed by Wei et al. (1998) and the sub-bottom depths of polarity boundaries are shown. The dash lines indicate the inclination (±29.6°) of the axial dipole field at the site. The ages of the geomagnetic polarity time scale are after Berggren et al. (1995 and references therein) and Singer et al. (1999). Ka: Kamikatsura; SR: Santa Rosa; J: Jaramillo; Pu: Punaruu; CM: Cobb Mountain; O: Olduvai; RII: Réunion II; RI: Réunion I. Uncertain ages of the short normal events are shown by gray areas.
DISCUSSION

Correlation of sediment magnetozones to the well-dated GPTS allows determining relatively precise sedimentation rates. In the past decade, the age of the Brunhes/Matuyama boundary and the upper and lower limit ages of the Jaramillo and Olduvai have been improved in precision and accuracy by \(^{40}\text{Ar}/^{39}\text{Ar}\) dating technique and astronomical tuning method (Shackleton et al., 1990; Hilgen, 1991; Baski et al., 1992; Spell and McDougall, 1992; Izett and Obradovich, 1994; Bassinot et al., 1994). According to the GPTS of Berggren et al. (1995) and Cande and Kent (1995), the currently accepted ages of these boundaries are 0.78, 0.99, 1.07, 1.77 and 1.95 Ma, respectively. However, there is still some discrepancy among the dating ages for short events in the Mayuyama, such as the Cobb Mountain (Mankinen et al., 1978; Turrin et al., 1994) and Réunions (McDougall and Watkins, 1973; McDougall et al., 1992; Baski et al., 1993; Kidane et al., 1999). In this study, we adopt the above five ages as time controls for the determination of sedimentation rates and attempt to correlate the four short normal magnetozones to GPTS in Figure 6.

Figure 7 displays a plot of the sub-bottom depths of the five reversal boundaries with respect to their ages. The slope of the line drawn through the points is a measure of the sedimentation rate for each given interval. It is quite clear that sedimentation rates are almost constant, about 1.15 ± 0.15 cm/kyr, between the ages of 0.78-1.95 Ma and then increase to 2.0 cm/kyr since 0.78 Ma. Unfortunately, no precise age control can be used to determine the sedimentation rate below the base of the Olduvai.

Based on \(^{40}\text{Ar}/^{39}\text{Ar}\) dating ages and paleomagnetic data of basaltic lava, Singer et al. (1999) recently found that there are higher frequency reversals near the Jaramillo subchron. In addition to the well-known Kamikatsuura and Cobb Mountain magnetozones, they further identified two short normal events, called the Santa Rosa and Punaruu (Fig. 6). Their \(^{40}\text{Ar}/^{39}\text{Ar}\) dating ages for the Kamikatsuura, Santa Rosa, Punaruu and Cobb Mountain are 0.886 Ma, 0.92 Ma, 1.105 Ma and 1.181 Ma, respectively. It is evident that the complicate magnetic reversal pattern proposed by Singer et al. (1999) has caused some difficulties in the assignment of our own two short normal magnetozones (i.e., 1728-1735 cm and 2031-2044 cm) to GPTS. To solve this problem, I estimated their ages using the sedimentation rates and the sub-bottom depths and then correlated them to GPTS (see Figs. 6 and 7). According to this graphic method (Fig. 7), the age of these two short normal magnetozones is about 0.914-0.920 Ma and 1.176-1.187 Ma, respectively. Evidently, they are correlated well with the Santa Rosa and Cobb Mountain of Singer et al. (1999). This complete record of the Santa Rosa and Cobb Mountain of the sediment sequence may further provide a good estimation of the duration of each magnetzone. Based on the above boundary ages, the time spans for the Santa Rosa and Cobb Mountain events are about 6 kyr and 11 kyr. The two normal magnetozones at the intervals of 3231-3270 cm and 3295-3305 cm are considered to be linked with the Réunion events (II and I, respectively) because they occurred after the Gauss chron and before the Olduvai subchron (Fig. 6). It is worthy to note that the record of Réunion I is not complete as it is truncated by a hiatus marked by the reworked foramin sand layer (Wei et al., 1998).

Although recent studies have indicated that very brief geomagnetic excursions, such as the Laschamps (40-45 Ka), Blake (110-120 Ka), Jamaica (205-215 Ka) and La Palma (~600 Ka), occurred in the Brunhes chron (Champion et al., 1988; Langereis et al., 1997; Gudlall et al., 1999), our present data are not dense enough to detect them. To achieve this, more continuous samples in the Brunhes are needed in the future paleomagnetic study.
Figure 7. Age versus depth plot for Core MD97-2143. The slopes of lines (sedimentation rates) were determined by using the sub-bottom depths and the boundary ages of the Brunhes, Jaramillo and Olduvai. The two short normal-polarity zones near the Jaramillo are correlated with the Santa Rosa (SR) and Cobb Mountain (CM) events by projecting their depths onto the time axis.
CONCLUSION

Through AF demagnetization on the 383 selected samples, the core MD97-2143 has revealed a nearly complete magnetostratigraphic record since the early Matuyama age. In addition to the Brunhes, Jaramillo and Olduvai, four short normal events, the Santa Rosa, Cobb Mountain, Réunion I and II, have been identified in the Matuyama chron. The sedimentation rates of the sequence are about 1.15 ± 0.15 cm/kyr between the ages of 0.78-1.95 Ma and then increase to 2.0 cm/kyr since 0.78 Ma.

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位於西菲律賓海 Benham Rise 之上的 IMAGES 岩心
MD972143 其磁地層之記錄

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摘要

本文展示一根長三十八米之活塞岩心其近乎完整的磁地層記錄。這根岩心 MD97-2143 是取自西菲律賓海 Benham Rise 之上，水深 2989 米的地區。主要是由棕褐色、半深海相之鈣質軟泥所組成。其間並夾有多層厚約一至十五公分不等的火山灰層。由磁性礦物及磁學粒径之分析，顯示沉積物中的主要帶磁礦物為磁鐵礦，且粒徑屬於 pseudo-single domain 的範圍。經由 1661 個樣本詳細的磁性量測，顯示火山灰的層位通常有較高的磁感率值及自然殘磁強度。針對其中 383 個樣本從事交流磁場之去磁，可以解析出特性殘磁之方向進而得到一清晰的正反磁極序列，其年代自 Matuyama 的早期以迄今。根據魏國彥等人 (1998) 超微化石基準面之認定，此一序列中的三個明顯正向期很容易地被指認為 Brunhes、Jaramillo 与 Olduvai。其層位分別位在 0-1560 公分、1823-1905 公分及 2738-2937 公分。利用這三期的上下界年代，可以推求岩心的沉積速率在 1.95 至 0.78 百萬年前之間約為 1.15 ± 0.15 公分/千年；而在最近 0.78 百萬年間為 2.0 公分/千年。除上述三期正向外，另有四期較短的正向磁極出現在 Matuyama 的反向時段中。其層位分別位在 1728-1735 公分、2031-2044 公分、3231-3270 公分及 3295-3305 公分。經與磁極年表的比對，其中較年輕的兩期應分別為 Santa Rosa 及 Cobb Mountain 地磁事件。而較老的兩期則被認定為 Réunion 的第三及第一期事件。其中 Réunion 第一期的記錄並不完整，其原因可能是有一地層缺失存在於再積性有孔蟲砂質層內 (3291-3395 公分)。

關鍵詞：磁地層、Brunhes、Matuyama、地磁事件