Paleomagnetic investigation of seamounts in the vicinity of Ogasawara Fracture Zone northwest of the Marshall Islands, western Pacific

Tae-Gook Lee[1,2], Sang-Mook Lee[1], Jae-Woon Moon[1], and Kiehwa Lee[2]

[1]*Marine Resources Laboratory, Korea Ocean Research and Development Institute, P.O. Box 29, Seoul 425-600, Korea*
[2]*School of Earth and Environmental Sciences, Seoul National University, Seoul 151-742, Korea*

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Nine seamounts located northwest of the Marshall Islands near the Ogasawara Fracture Zone were inverted for their uniform magnetization using total field magnetic anomaly and detailed bathymetric data. The paleomagnetic poles of most of the seamounts in our study area generally cluster around the Pacific Apparent Polar Wander Path (APWP). However, those that deviate significantly from the APWP are located south of the fracture zone. The seamounts in our study area can also be divided into two groups on the basis of complexity of the observed magnetic field anomaly. In general, simple conical seamounts exhibit a dipole-like field anomaly pattern with a paired anomaly low and high, and can be explained to a large extent by a uniformly magnetized source. On the other hand, those with complex morphology are larger in size, show multiple magnetic lows and highs and lie very close to or within the fracture zones, suggesting that they were formed by multi-stage volcanism.
Key words: Seamount paleomagnetism, Apparent Polar Wander Path (APWP), Cretaceous seamounts, magnetic field inversion.

1. Introduction

Paleomagnetic investigations of seamounts in the past three decades have provided important constraints on the location of plates with respect to the Earth's rotation axis (e.g., Sager, 1992 and references therein). An important advantage of seamount paleomagnetism is that, once total field magnetic anomaly and bathymetric data are collected during a routine marine geophysical survey, the analysis can be done readily by assuming that the seamount body is uniformly magnetized or that the deviation from uniform magnetization is small. One of the areas where seamount magnetism has been particularly successful is the western Pacific where numerous seamounts were produced during the Cretaceous Normal Superchron when the polarity of the Earth's field did not change for a long period (118–83 Ma). Paleomagnetic analyses of these seamounts have also led to discovery of important clues regarding the spatial and temporal distribution of volcanism in the Pacific (Menard, 1984; Duncan and Clague, 1985; Sager, 1992).

While many Cretaceous seamounts can be explained by uniform magnetization (that is, in both intensity and direction), some exhibit complex magnetic anomalies and thus indicate nonhomogeneous magnetization. The exact cause of the inhomogeneity is unclear and may well differ among seamounts (see Sager *et al.*, 1993 for detailed discussion). Some possible explanations include multi-stage volcanism in which magmatic sources of different magnetic properties erupted and formed the different parts of seamount (e.g., Gee *et al.*, 1988, 1989), volcanic rejuvenation long after the formation of the seamount, tectonic deformation of underlying basement on which the seamount was forming, and modification of the original seamount magnetization by processes such as mass wasting, weathering and alterations. If the coverage of magnetic field measurement is sufficiently dense and additional sets of information such as high-resolution bathymetry, seismic profiles and age dating from relatively fresh dredge rock samples are available, one may get some insight into the possible cause of magnetization inhomogeneity by carefully comparing these data with the magnetic results.

This paper examines the paleomagnetic properties of nine seamounts that lie northwest of Marshall Islands in the western Pacific in the vicinity of old structural discontinuities in the crust known as the Ogasawara Fracture Zone. Using the total field magnetic anomaly and detailed bathymetric information, we calculated the average magnetization of the seamounts and compared their paleomagnetic poles against the Apparent Polar Wander Path (APWP) of the Pacific to see if any additional information can be gained about the origin of the seamounts and magmatism in this region. Also because, some of the seamounts in this study are located near the fracture zone and thus could be affected by the crustal discontinuity, it is worthwhile to examine how they compare with those further away from the fracture zone.

2. Geological Settings

Our study area lies on Jurassic seafloor, which is the oldest part of the Pacific plate. The area is marked by a numerous seamounts that formed by active volcanism during the Cretaceous (Menard, 1984; Duncan and Clague, 1985). Another important geological feature in this area is the Ogasawara Fracture Zone (OFZ), which is thought to have formed during the Middle to Late Jurassic (Nakanishi *et al.*, 1989) pre-

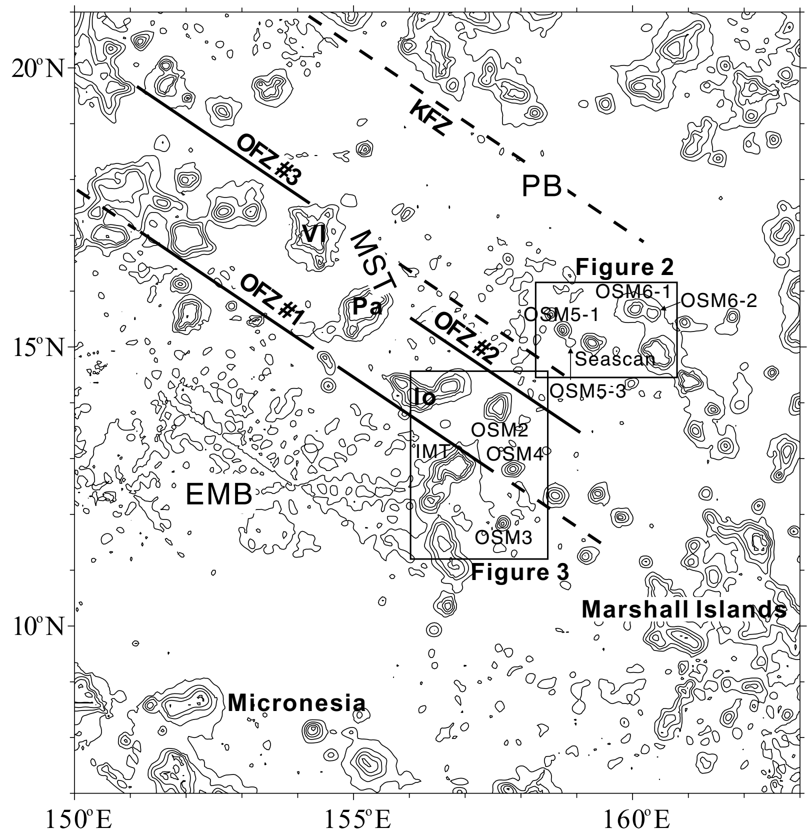

Fig. 1. (a) Our study area in the western Pacific, which is divided into two sectors and delineated by boxes. The detailed bathymetry of seamounts in these boxes is shown in Figs. 2 and 3. OFZ and KFZ denote Ogasawara and Kashima Fracture Zones, respectively. Ita Mai Tai and Magellan seamount trail are abbreviated as IMT and MST, respectively. EMB and PB are East Mariana Basin and Pigafetta Basin. The former consists of three smaller fracture zones (#1–3). Vlinder is abbreviated as Vl, Pako as Pa, and Ioah as Io, and these Magellan seamounts were dated by Koppers *et al.* (1998) as 95.1, 91.3 and 87.1 Ma, respectively.

sumably by the spreading ridge between the Izanagi and Pacific plates (Fig. 1). OFZ roughly divides this area in the west Pacific into the East Mariana Basin (EMB) and Pigafetta Basin (PB). According to multichannel seismic profiles by Abrams *et al.* (1992), the OFZ represents a 150-km-wide rift zone with sharp bounding walls that cuts perpendicularly the surrounding magnetic lineations. Koppers *et al.* (1998) further divided the OFZ into three separate fracture zones and numbered them (Fig. 1).

Our study area is divided into two sectors, and the existing seismic profiles (Abrams *et al.*, 1992) show that there are important differences in the structure of sedimentary sequence and crust between the two sectors (Fig. 1). The northeastern sector is located some distance away from major fracture zones and lies on relatively flat basement. On the other hand, in the southeastern sector, there are evidences of fracture zone transecting the region and the basement is complicated by Aptian sills and flows that overlie the oceanic crust.

The seamounts in our study area have not been mapped in detail before and are not named except for two. They were referred to as open-sea seamount (OSM) and denoted sequentially from southwest to northeast as number 1, 2, 3, 4, 5-1, 5-2, 5-3, 6-1, and 6-2 during our survey (Figs. 2 and 3). OSM1 and OSM5-2 corresponds to previously studied seamount Ita Mai Tai and Seascan, respectively (Sager, 1983; Koppers *et al.*, 1998). Geographically, Ita Mai Tai lies in line with a group of seamounts that extends northwest, referred to as the Magellan seamounts or Magellan seamount trail (MST). However, its age does not appear to follow the linear progression of hotspot seamount trail as the two rock samples recovered on the northeast slope of Ita Mai Tai were dated as 118 Ma (Koppers *et al.*, 1998).

3. Data and Method

The total field magnetic and multibeam bathymetric data used in this study were obtained in 2000 and 2001 during a reconnaissance survey of seamounts for manganese crusts in this area by KORDI onboard R/V *Onnuri*. The total magnetic field was measured using a proton precession magnetometer which was towed 200 m behind the ship near the sea surface. Figures 2 and 3 are magnetic anomaly maps of the two sections of our study area that were produced after removing the long-wavelength component of Earth's field according to the International Geomagnetic Reference Field (IGRF, 2000) together with bathymetric contours.

The most of the seamounts in our study area show a charactertistic pattern where magnetic anomaly high appears north of the seamount and low near the summit (Figs. 2 and 3), which is typical for Cretaceous seamounts in this area. This pattern can be seen quite clearly for OSM4, Seascan, OSM6-1 and OSM6-2, and although it is less obvious, it is there for OSM5-1 and OSM5-2 as well. For OSM2 and Ita Mai Tai, the overall anomaly pattern is quite complex. The only true exception appears to be OSM3 where a magnetic

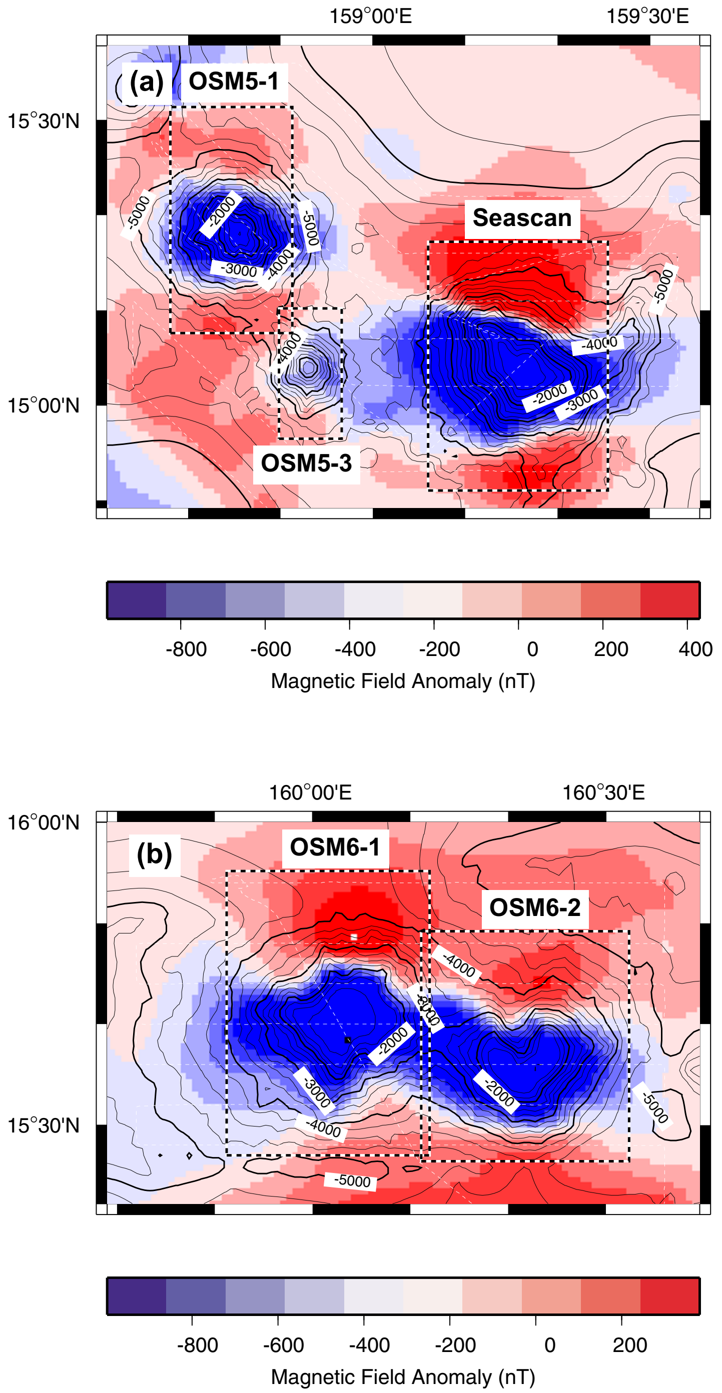

Fig. 2. Bathymetry and magnetic anomaly maps of five seamounts the northeastern sector (Fig. 1). (a) OSM5-1, OSM5-3 and Seascan, and (b) OSM6-1 and OSM6-2. Thin white dashed lines are ship tracks. Bathymetry contours are shown at 250-m interval. The rectangles outlined by black dashed line represent areas where magnetic anomalies were used for semi-norm minimization inversion.

anomaly high appears to the west of the summit (Fig. 3(c)).

To calculate magnetization parameters, we employed semi-norm minimization inversion scheme of Parker *et al.* (1987). The semi-norm minimization inversion divides the seamount magnetization into uniform and non-uniform parts and calculates the magnetization that minimizes the latter part. The method assumes that the heterogeneities in the seamount magnetization produce short-wavelength anomalies, and therefore if large magnetization nonuniformities exist, it fails to give reliable results. Semi-norm minimization method provides a little more versatility than least-squares methods, such as Plouff (1976), because of its ability to treat small inhomogeneities in magnetization. In general, magnetic investigation of seamount assumes that the magnetization that produces the anomaly is entirely remanent and that the average Earth's field can be represented as axial geocentric dipole field.

In this study, we used root mean squares (rms) misfit error of 30 nT as the cut-off criterion for matching the modeled to the observed field in the inversion. The results of inversion can be checked using goodness of fit ratio (GFR), which is defined as the sum of observed magnetic anomaly divided by

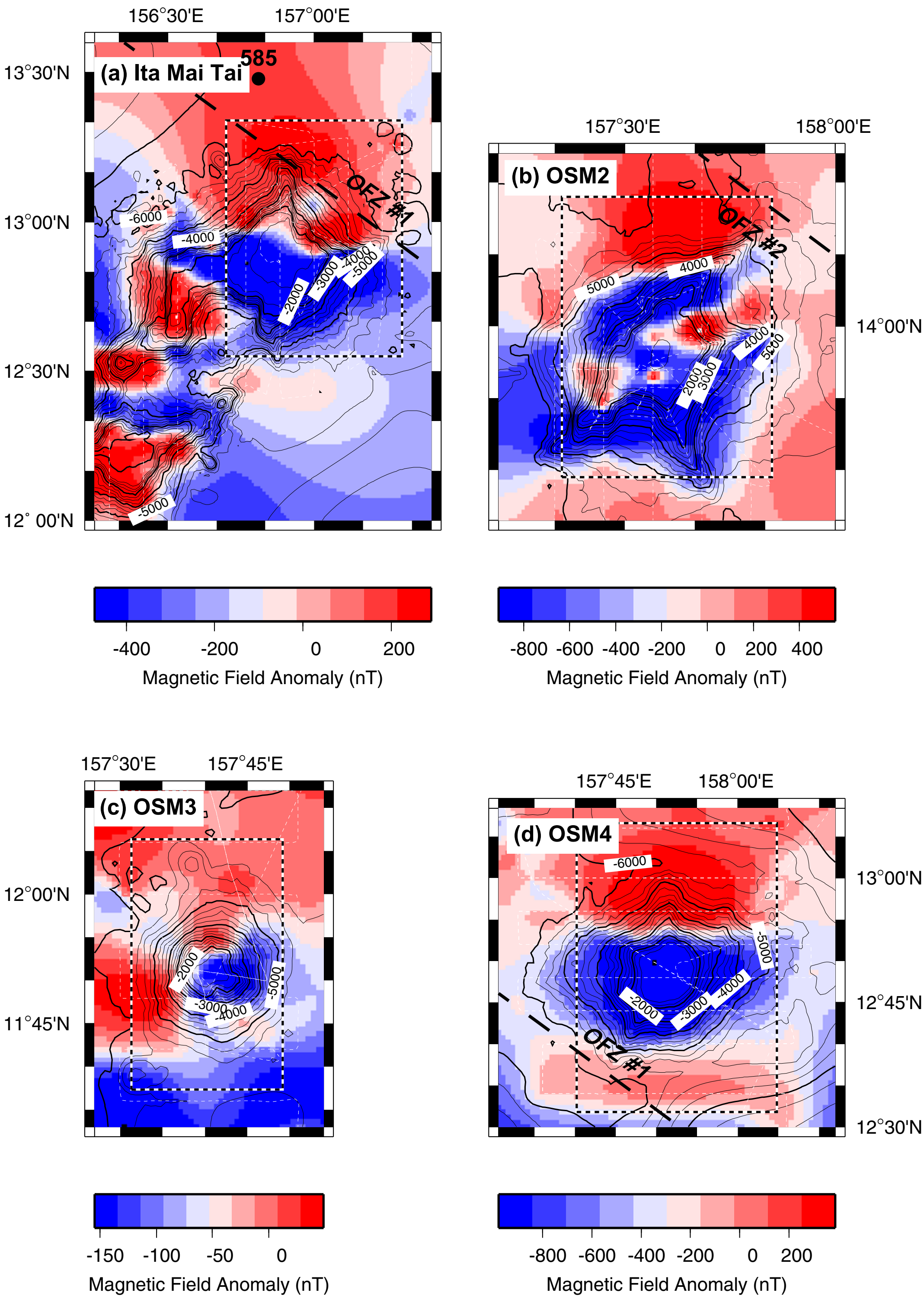

Fig. 3. Bathymetry and magnetic anomaly maps of four seamounts in the southwestern sector (Fig. 1). (a) Ita Mai Tai, (b) OSM2, (c) OSM3 and (d) OSM4. Thin white dashed lines are ship tracks. Bathymetry contours are shown at 250-m interval. The location of DSDP Site 585 is shown in (a), OFZ #1 in (a) and (d), and OFZ #2 in (b). The rectangles outlined by black dashed line represent areas where magnetic anomalies were used for semi-norm minimization inversion.

the sum of misfit between the calculated and observed magnetic anomaly. The background crustal fields such as those due to nearby magnetic lineations were not taken into account because our seamounts lie within so-called the Jurassic Quiet Zone where the amplitude of crustal magnetic anomalies is low.

4. Results

The results of our magnetization inversions are summarized in Table 1. The seamounts that were studied are all normally magnetized and have uniform magnetization intensities that range from 0.2 to 8.2 A/m with an average of 4.2 A/m. The GFR of Ita Mai Tai, OSM2 and OSM3 are significantly lower than that of other seamounts. OSM4, OSM5-1

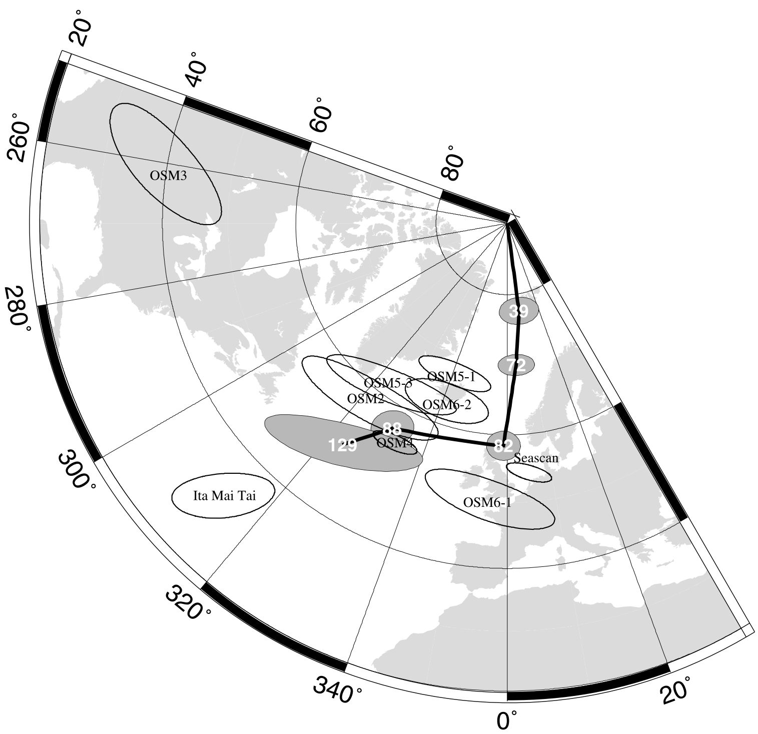

Fig. 4. Comparison of seamount paleopoles determined in this study and Apparent Polar Wander Path (APWP) of the Pacific plate. Shaded ellipses with numbers represent paleomagnetic poles for the Pacific APWP and associated uncertainties (Sager and Pringle, 1988; Tarduno and Sager, 1995), and unshaded ellipses are the mean paleopoles of seamounts and their uncertainties.

Table 1. Summary of seamount morphology and paleomagnetic parameters.

	Location		Depth (m)		Summit plateau break depth (m)	Paleopole		Paleo-latitude (°S)	Inclination (°) (+Down)	Declination (°) (+East)	Uniform intensity (A/m)	Non-uniform intensity (A/m)	Semi-norm model GFR	RMS residual (nT)
	Longitude (°E)	Latitude (°N)	Crest	Base		Longitude (°E)	Latitude (°N)							
Ita Mai Tai	156.9	12.9	1350	5860	1650	313.9	32.5	39.6	−58.8	25.3	2.3	0.3	2.0	77.5
OSM2	157.6	13.9	1220	5750	1500	321.5	58.2	16.7	−31.0	8.8	6.2	4.0	4.3	81.3
OSM3	157.7	11.8	1260	5900	1550	259.8	38.8	1.8	−3.6	49.7	0.2	0.1	2.2	24.5
OSM4	157.9	12.8	1270	6000	1500	339.4	53.1	24.1	−41.9	−1.0	5.9	2.0	24.2	21.2
OSM5-1	158.8	15.3	1205	5500	—	340.7	67.5	7.4	−14.6	−0.6	3.4	1.4	22.2	13.3
Seascan	159.3	15.1	1150	5500	1300	5.0	54.4	16.8	−31.2	−15.6	8.2	1.9	13.4	26.9
OSM5-3	158.9	15.1	2355	5450	—	324.4	61.7	12.4	−23.7	7.0	2.8	0.5	9.2	13.1
OSM6-1	160.0	15.7	1085	5300	1400	356.2	50.4	22.4	−39.6	−11.0	3.2	2.7	12.6	18.6
OSM6-2	160.4	15.6	1225	5300	1400	341.1	63.5	10.9	−21.1	−0.3	5.7	3.7	21.3	18.8

and OSM6-2, on the other hand, show high uniform magnetization intensity and GFR. In the case of Ita Mai Tai and OSM3, they also show declination and inclination that differ from the rest of seamounts. In particular, the declination of 49.7° for OSM3 is very much different from other seamounts in this area.

Using inclination and declination information, we determined the seamount paleomagnetic poles and compared them with the APWP of the Pacific plate (Fig. 4). Also the uncertainty level of paleomagnetic pole estimation was established on the basis of 95% confidence ellipse derived from statistical model of seamount nonuniformities (Parker *et al.*, 1987). In general, most of the poles appear to cluster along 129–72 Ma section of the Pacific APWP. For instance, the paleomagnetic poles of OSM2, OSM4, OSM5-1, OSM5-3 and OSM6-2 lie close to the path of 88–72 Ma, but with some deviation to the north. On the other hand, the paleomagnetic poles of Seascan and OSM6-1 lie slightly southwest to the 82-Ma pole. For Ita Mai Tai and OSM3, as expected because of large declination, the poles depart substantially from the Pacific APWP.

5. Discussion and Summary

The nine seamounts that were studied can be divided into two groups on the basis of inverted magnetization parameters and the pattern in observed magnetic field anomalies (Figs. 2 and 3). The seamounts that clearly exhibit a simple dipole-like anomaly pair with magnetic anomaly high to their north and low on their summit yield poles that lie close to the APWP like other Cretaceous seamounts in the western Pacific. These include all the seamounts in Fig. 2 and OSM2 and OSM4 in Figs. 3(b) and 3(d), respectively. On the other hand, Ita Mai Tai and OSM3 show paleomagnetic poles that differ substantially from the rest.

The seamounts can also be divided into two groups in terms of their complexity in morphology and magnetic anomaly pattern. Most of the seamounts in our study area are associated with a simple pair of magnetic low and high which can be readily identified. In the case of Ita Mai Tai and OSM2, however, the magnetic anomaly consists of multiple highs and lows (Figs. 3(a) and 3(b)). Such complexity in the magnetic anomaly appears to be related with similar complexity in morphology as Ita Mai Tai and OSM2 both show numerous limbs that extend from the seamount center. Vogt and Smoot (1984) proposed that seamounts and guyots generally start from a small conical feature on the seafloor and evolve to a larger and more complex stellate shape with increasing size and lateral development of rift zones. According to this development model, the Ita Mai Tai and OSM2 may have reached the mature stage, and the complexity in magnetization can be attributed in large part to the development of such rift zones.

Although there is no clear link between fracture zone and seamount magnetization, the two seamounts that exhibit complex morphology and anomaly, Ita Mai Tai and OSM2, lie very close to the fracture zone. Ita Mai Tai lies just south of OFZ #1, and OSM2 is located between OFZ #1 and #2 (Figs. 1 and 3). However, OSM4 located near OFZ #1 is an exception. It is unclear if the complexities in morphology and magnetic anomaly pattern are the result of growth of seamounts to a mature stage or related to the presence of the fracture zones in the region. If the latter is true, it is conceivable that fracturing of basement may have facilitated the distribution of magma which was supply to the crust from underlying source region, allowing the seamounts there to laterally build up quickly. This possibility may be tested in the future by exploring other seamounts near the fracture zones.

Our study area contains only a few examples to explore the relationship between the complexity of seamount morphology and its agreement with the APWP. In the case of OSM2, in spite of having a complex morphology, the paleomagnetic pole lies close to the APWP. This may be because OSM2 still as a whole exhibits dipolar pattern (Fig. 3(b)). In contrast, if the complexity is too severe such that it changes the overall magnetic anomaly pattern, as is the case of Ita Mai Tai (Fig. 3(a)), it may cause to the paleomagnetic pole to divert from the APWP.

As mentioned earlier, the dated rock samples from Ita Mai Tai do not match the predicted linear age progression of MST (Koppers *et al.*, 1998), which includes Ioah, Pako and Vlinder seamounts (Fig. 1). Our argument, which is similar to that of Koppers *et al.* (1998), is that Ita Mai Tai formed much earlier than those seamounts in MST and perhaps OSM3 as well. That Ita Mai Tai and OSM3 lie on an older oceanic basement and thus do not belong the same MST may also be demonstrated by the slight increase ($\sim$100–200 m) in the seafloor depth south of OFZ #1.

Unfortunately, none of the rocks recovered from the seamounts were dated except for two samples from Ita Mai Tai (Koppers *et al.*, 1998). Consequently, we cannot check the result of our inversion and determination of paleomagnetic poles. In the case of OSM2, however, the drilling by Deep Sea Drilling Project (DSDP) at Site 585 penetrated the nearby basement where volcanogenic turbidites and debris flows ranging from Aptian to Albian (98–120 Ma) were recovered. A careful examination of seismic stratigraphy (Abrams *et al.*, 1992) reveals that these deposits may have originated from OSM2. We checked if the paleomagnetic age of OSM2 is consistent with this age estimate. Our result shows that the paleomagnetic pole of OSM2 which lies close to 88-Ma stage pole (Fig. 4) is somewhat younger than that reported by DSDP. The cause of this age discrepancy is unclear at this stage. However, it is important to note that paleomagnetic pole estimation using sea surface magnetic anomaly can provide non-unique solution, and therefore a good practice may be to only trust ones that exhibit simple dipolar anomaly and morphology.

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T.-G. Lee, S.-M. Lee (e-mail: smlee@kordi.re.kr), J.-W. Moon, and K. Lee