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ORIGINAL

Evolution of the Dok Do seamounts, Ulleung Basin, East Sea: constraints based on the reconstruction of virtual geomagnetic poles using paleomagnetic data

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Abstract In the Ulleung Basin, East Sea, the Dok Do seamount group comprises Dok Do (Dok Island), consisting of very small islets/rocks and a large submerged volcanic edifice, and two voluminous tablemounts, Simheungtaek and Isabu. We attempted to reconstruct the evolution of these seamounts, using virtual geomagnetic poles (VGPs) determined by the least-squares and the seminorm magnetization methods, with 1,500 m upward continued magnetic anomalies. The VGPs of Dok Do with normal dipole anomaly, and of Simheungtaek with normal dipole anomaly are located near the present magnetic pole. The VGP of Isabu with normal dipole anomaly is located at low latitude, presumably due to overprints of reversals in the Tertiary, and the distortion of magnetization and structures associated with volcanism after its formation. In contrast to the tablemounts, magnetic anomalies over Dok Do are a combination of both normal polarity and reversed polarity dipoles in the northern hemisphere, indicating that Dok Do has had at least two major eruptions, one during normal and another during reversed polarity intervals. From these results, and information on the ages of the seamounts (either published radiometric ages of subaerial volcanic rocks, or ages reconstructed in terms of reported elastic thickness incorporated into an existing cooling plate model), we tentatively propose that (1) Isabu formed first, during a normal polarity interval after the opening of the East Sea had ceased; (2) this was followed by an initial and subsequent large eruption of Dok Do during a normal polarity and a reversed polarity interval after about 5 Ma; and (3) the formation of Simheungtaek occurred in between that of Isabu and Dok Do in a normal polarity interval. The pattern of normal/reversed magnetization is not inconsistent with the geomagnetic polarity timescale for at least the last 5 Ma. Nevertheless, precise ages of formation would need verification by additional geophysical/geochemical constraints. Evaluating various possible models explaining the successive formation of the Dok Do seamounts, we currently favor fracturing and volcanism related to compression-induced weakening of the extensional field from the late Miocene to Pliocene after the opening of the East Sea.

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Introduction

The East Sea (Sea of Japan) is a back-arc basin consisting of three deep basins—the Ulleung, Japan, and Yamato basins—surrounded by Korea, Japan, and Russia (Fig. 1) in a complex junction between the Eurasian, Pacific, and Philippine plates (Uyeda and Miyashiro 1974). When the East Sea formed in response to the subduction of the Philippine and Pacific plates, the Japan islands moved away from the Eurasian margin (Hilde and Wageman 1973; Uyeda and Miyashiro 1974). It is generally accepted that

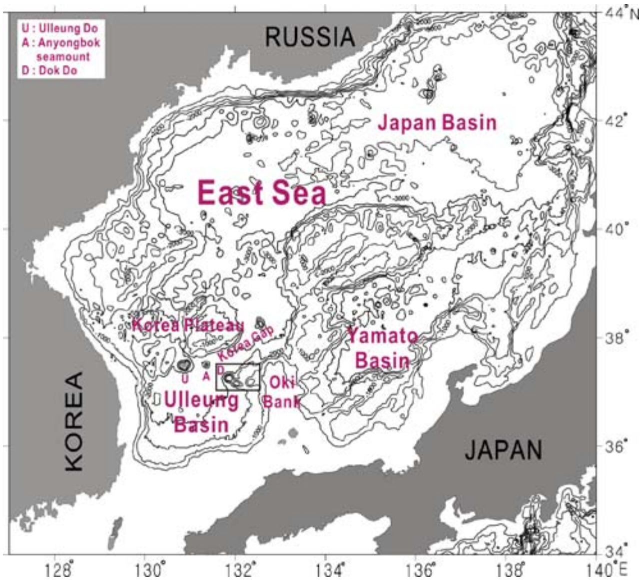

Fig. 1 Bathymetry of the East Sea, showing the three deep basins, enclosed by Korea, Japan, and Russia (contours in meters). The *rectangle* represents the study area in the vicinity of the Dok Do seamounts

the opening of the East Sea commenced in the early Miocene, and terminated at about 15–12 Ma (Lee et al. 1999; Itoh 2001), and that the Ulleung Basin was formed after the other two basins during the final stage of opening (Lallemand and Jolivet 1986; Tatsumi et al. 1989). From the estimated age of the syn-rift sediments, Yun et al. (2007) suggested that the age of initial rifting of the Ulleung Basin might be Oligocene or earlier.

Of the three basins, the Japan Basin may contain the only true oceanic crust in the East Sea (Hirata et al. 1989; Jolivet and Tamaki 1992). Seismic refraction surveys have shown that its crust is typically oceanic, and 6–7 km thick (Isezaki and Uyeda 1973; Jolivet and Tamaki 1992; Hirata et al. 1992). By contrast, the crust of the Yamato Basin is about twice as thick, although its crustal velocity structure is oceanic (Hirata et al. 1989; Jolivet and Tamaki 1992; Tamaki et al. 1992). Likewise, the Ulleung Basin has a velocity structure typical of oceanic crust, although its thickness is about twice that of normal oceanic crust (Park 1998; Lee et al. 1999; Kim et al. 2003). Thus, the crust of these two basins is disputably oceanic or continental. Many scientists have proposed that the Ulleung Basin is characterized by a thick oceanic crust possibly representing a spreading center, based on interpretations of ocean bottom seismometry, gravity, magnetic, and other geophysical data (Jolivet et al. 1991; Kim et al. 1994; Park 1998; Lee et al. 1999). Chough and Lee (1992) suggested that its acoustic basement comprises largely volcanic materials interlayered with sedimentary sequences, forming an anomalously thick layer; the volcanism was probably initiated in the early Miocene, and was time-transgressive northward, associated with the possible southward drift of the Japanese islands.

The Ulleung Basin is located in the southwestern part of the East Sea, and is separated from the Japan and Yamato basins by the Korea Plateau and the Oki Bank, respectively (Fig. 1). It has an uneven seabed morphology above 2,200 m b.s.l. (below sea level), but its floor is fairly smooth and gradually deepens northeastward from about 1,000 m b.s.l. at the basin margin, to about 2,300 m b.s.l. near the Korea Gap (Ulleung Interplain Gap; Fig. 1). The volcanic islands and seamounts of Ulleung Do, Anyongbok, Dok Do, Simheungtaek, and Isabu form a roughly W-E-oriented string in the northern part of the basin (Figs. 1 and 2), the formation history of which is as yet still only partly known. Based on the difference in topography between subaerially exposed Dok Do, and the Simheungtaek and Isabu tablemounts (cf. below), Song et al. (2000) argued that Dok Do is younger. More recently, Song et al. (2006) proposed that the main formation stage of Ulleung Do occurred after 2.7 Ma, when that of Dok Do had been completed. In combination, this suggests a successive westward formation for the group.

Our study area comprises Dok Do (Dok Island), consisting of a small group of volcanic rocks and two main islets, associated with a large submerged volcanic edifice, as well as the two tablemounts Simheungtaek and Isabu (Fig. 1). For ease of reference, these are collectively called the Dok Do seamounts in the present study.

The subaerial parts of Dok Do are composed of volcanic rocks such as alkali basalts, trachytes, and trachyandesites (Won and Lee 1984; Sohn and Park 1994). Subaerial rock samples have been dated at 4.6±0.4 Ma (early Pliocene) to

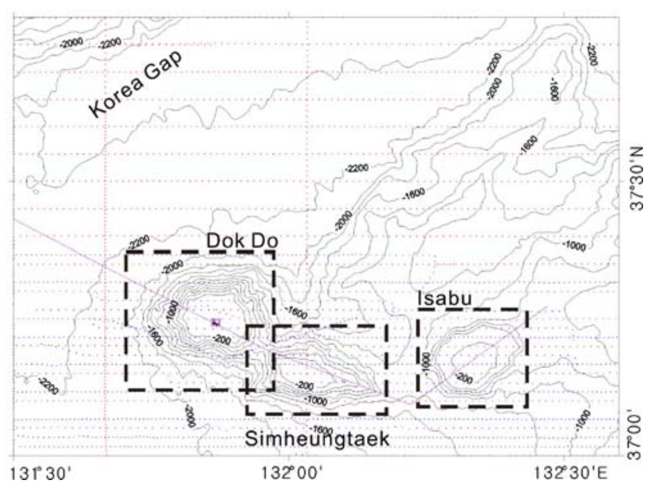

Fig. 2 Detailed bathymetry of the study area (contour interval 200 m). The *red dots* are the survey tracks of the National Oceanographic Research Institute of Korea, the *blue dots* of the Korea Institute of Geoscience and Mineral Resources, and the *purple dots* of the Korea Ocean Research and Development Institute. The *rectangles* (dashed lines) represent the VGP modeling areas

2.7±0.1 Ma (late Pliocene) by Sohn and Park (1994), whereas Kim (2000) and Song et al. (2006) reported ages of 2.42±0.05 to 2.28±0.11 Ma, and 3.67±0.4 to 1.89±0.29 Ma, respectively. This data scatter can at least partly be explained by site-specific weathering effects. This confounding aspect can be circumvented by examining the submerged parts of the Dok Do seamounts. However, the difficult access makes coring operations practically impossible, at least over Dok Do itself. Paleomagnetism is a technique that can be applied to estimate the mean direction and intensity of the magnetization of a seamount's rocks, using its shape and magnetic anomaly. These sea-surface magnetic data can serve to date the seamount if the volcanism is continuous, as has been done by Maia et al. (2005) for the Foundation hotspot off the Pacific-Antarctic Ridge. As for any other paleomagnetic datum, it is possible to determine the distance and azimuth of the volcano from the geomagnetic pole at the time when the seamount was formed. This technique is particularly useful in the study of oceanic plates and underwater igneous edifices, such as the Pacific Plate, and the Hawaiian and Line islands seamounts, from which oriented paleomagnetic samples are difficult to obtain (Sager and Keating 1984; Sager et al. 2005).

The Ulleung Basin is known to have very poor magnetic lineations, which may be attributed to an anomalously thick crust (cf. above), or high heat flow (Isezaki and Uyeda 1973; Kurashimo et al. 1996). Nevertheless, it was expected that this disadvantage would be sufficiently reduced by increasing the number of magnetometer profiles run in the study area.

Within the context outlined above, we applied the virtual geomagnetic pole (VGP) method using magnetic and bathymetric data to enable indirect paleomagnetic estimation for the submerged parts of the Dok Do seamounts. Together with information on the ages of the seamounts, either published radiometric ages, or reconstructed in terms of reported elastic thickness incorporated into an existing cooling plate model, our aim was to better understand the evolution of these seamounts in the Ulleung Basin in the East Sea.

Materials and methods

We used magnetic and bathymetric data obtained by magnetometer and multibeam echo sounder measurements made in the study area by the Korea Ocean Research and Development Institute in 1999 and 2000, the National Oceanographic Research Institute of Korea in 1997, and the Korea Institute of Geoscience and Mineral Resources in 1997. The magnetic data had been acquired during several cruises (Fig. 2) using different equipment over a study period of ca. 3 years, making it difficult to merge these datasets. Notably, the magnetic field undergoes temporal variations that lead to mismatches of data at track intersections. To overcome this difficulty, the data were corrected to a common version of the International Geomagnetic Reference Field 1995 (Barton 1997). Where the offset between tracks was consistent, a constant value correction was made using the average offset value (Sager et al. 2005).

Short wavelength noise components, assumed to result from small magnetization heterogeneities, or reversals in the uppermost layers of the volcanoes, were filtered out by upward continuation at a height of 1,500 m a.s.l. (above sea level). Advantages of this approach are that it has a simple physical interpretation, and that the estimate of the intensity of the magnetization vector remains valid (Sager 1984). We used the least-squares and the seminorm magnetization methods with upward continued magnetic anomalies to compare the VGPs and complement reliability (Plouff 1976; Hildebrand and Parker 1987; Parker et al. 1987).

Generally, the goodness-of-fit ratio (GFR) is used to assess the fit between calculated and observed magnetic anomalies in least-squares statistics, this being the mean of observed anomaly values divided by the mean of residuals (Richards et al. 1967). A GFR greater than 2.0 is considered to indicate an acceptable fit (Sager 1984; Sager and Koppers 2000). However, the GFR is meaningless in the seminorm model, because the model can fit the observed anomaly to arbitrary closeness using non-uniform magnetization components (Sager et al. 2005). In such cases, typically the root mean square (RMS) residual is reduced to some reasonable value, such as about 30 nT, justified on the basis of random noise in the anomaly data (Hildebrand and Parker 1987). If the least-squares model has a small residual misfit to the observation, and the uniform magnetization is much larger than the non-uniform intensity in the seminorm model, then the least-squares pole falls within the 95% confidence ellipse of the seminorm pole for the modeled seamounts, implying that the two poles are not significantly different (Hildebrand and Parker 1987).

Results

The detailed bathymetry of the study area (Fig. 2) shows the contour line of 2,000 m b.s.l. forming the boundary between the basin floor and the Dok Do seamounts. Dok Do and the Simheungtaek Tablemount are more centrally situated, whereas the Isabu Tablemount merges with the western slope of the Oki Bank in the east (Figs. 1 and 2). The summits of Simheungtaek and Isabu are typical for guyots, flat and gently sloping at about 200 m b.s.l.; their flanks are steep. The NE-SW-trending Korea Gap lies west of Dok Do, at a maximum of about 2,500 m b.s.l.

Magnetic anomalies over the even seafloor of the Korea Gap show a subtle rise and fall from about–100 to 100 nT (Fig. 3a). Magnetic anomalies over the seamounts are much more complex, particularly over Dok Do (Fig. 3a). Simheungtaek has an E-W-trending linear anomaly pattern, with lows to the north and highs to the south, whereas only small-amplitude magnetic anomalies occur over Isabu. Indeed, selected magnetic anomaly profiles indicate that the magnetic anomaly amplitude of Isabu is much smaller than that of Dok Do (Fig. 3b). Despite the close proximity of the seamounts (~50 km), the more complex anomaly pattern and higher magnitude recorded over Dok Do suggest that the volcano erupted several times during its formation, or later than the other seamounts.

Dipole anomalies with a high over the south and a low over the north (generally normal polarity patterns in the northern hemisphere; Nettleton 1962) occur over Simheungtaek and Isabu in the upward continued anomalies (Fig. 4). By contrast, the magnetic anomalies over Dok Do have a high, a low, and a high sequentially from north to south. This anomaly pattern is the combination of dipoles of normal polarity and of reversed polarity in the northern hemisphere, indicating that Dok Do had at least two main eruptions—one during a normal, and another during a reversed polarity interval.

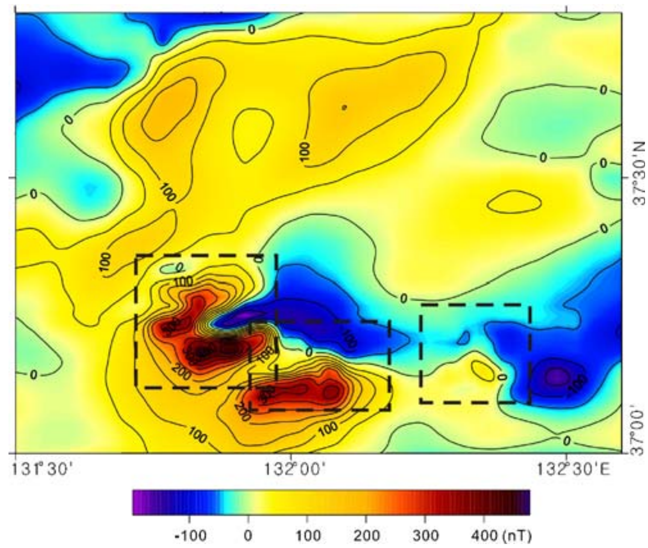

Fig. 4 Upward continued anomaly map at 1,500 m a.s.l. (contour interval 50 nT). The *rectangles* (dashed lines) represent the VGP modeling areas

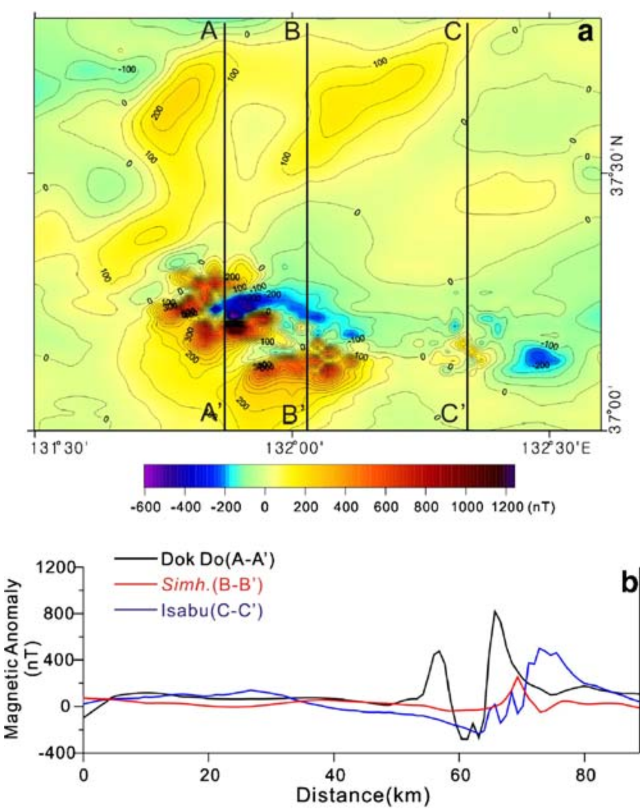

Fig. 3 **a** Magnetic anomaly map of the study area (contour interval 50 nT). **b** Selected magnetic anomaly profiles for Dok Do, Simheungtaek (*Simh.*) Tablemount, and Isabu Tablemount (see a for locations of profiles)

The VGP of Dok Do (all magnetic anomalies combined) is located at low latitude. Furthermore, there is a large difference between the VGPs calculated by the least-squares magnetization method and the seminorm magnetization method (Fig. 5a, Table 1). Both these findings, and the low GFR are attributed to the combined dipole anomalies over Dok Do. For Simheungtaek, the least-squares VGP overlaps with the confidence ellipse of the seminorm VGP, and both are located near the present magnetic pole (McElhinny 1973) in the northern hemisphere (Fig. 5a). The GFR value is high, and the uniform magnetization intensity is much larger than the non-uniform. The VGPs of Isabu are also at low latitude. This can be explained by overprints of reversals in the Tertiary, and the distortion of magnetizations and structures associated with post-volcanism after the formation of Isabu (Bryan and Cherkis 1995; Sager and Koppers 2000). Nevertheless, the Isabu VGP data do not have high reliability, because the uniform magnetization intensity is very small (Table 1; cf. Sager et al. 1993).

We estimated the corresponding VGPs for the normal dipole anomaly (a high over the south, and a low over the north), and for the reversed dipole anomaly (a low over the south, and a high over the north) recorded for Dok Do (cf. above). The Dok Do VGP with normal dipole anomaly shifts to near the Simheungtaek VGP, and the GFR value increases slightly (Fig. 5b, c, and Table 1). Also, the intensity of uniform magnetization increases above that of the Dok Do VGP based on all magnetic anomalies combined. The Dok Do VGP with reversed dipole anomaly is located at low latitude in the southern hemisphere. This

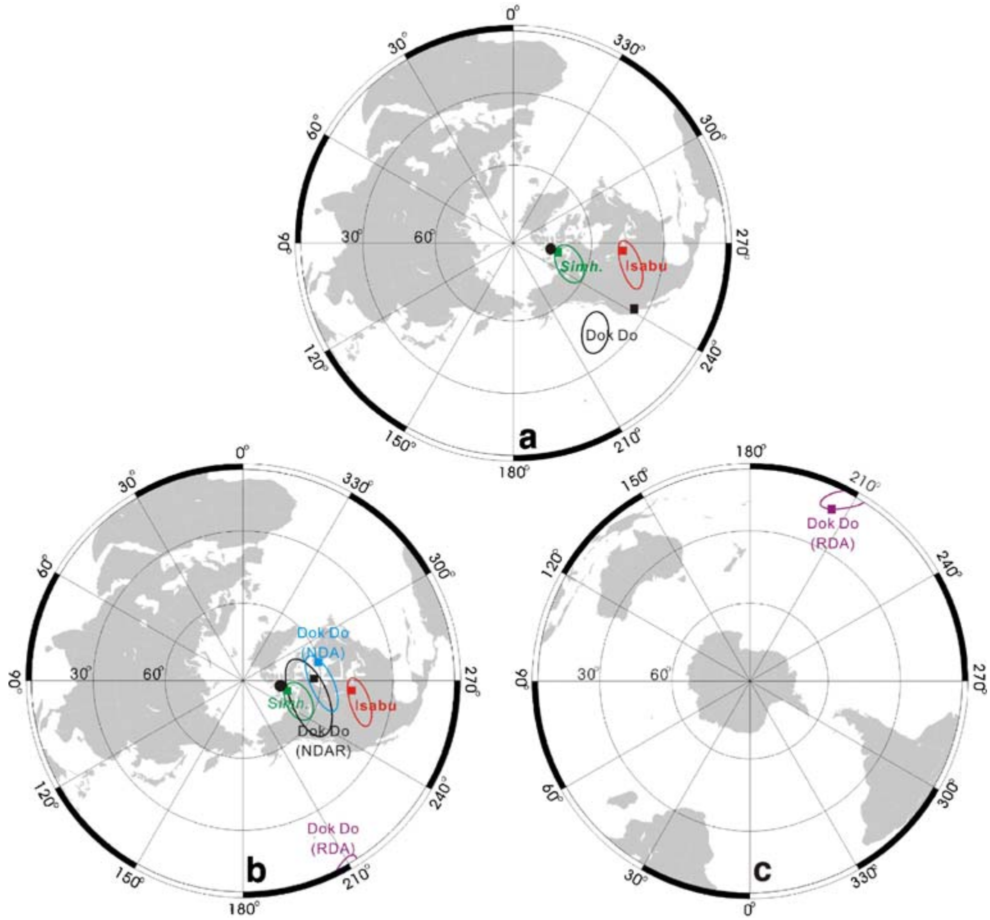

Fig. 5 Virtual geomagnetic poles (VGPs) estimated in this study based on Lambert azimuthal projection. The *circle* denotes the present magnetic pole (McElhinny 1973). The *squares* denote the VGPs from the least-squares method, and the *ellipses* the 95% confidence limits from the seminorm method. **a** *Black square and ellipse* for Dok Do, *green square and ellipse* for the Simheungtaek (*Simh.*) Tablemount, and *red square and ellipse* for the Isabu Tablemount in the northern hemisphere. **b** *Green and red* are the same as in a. *Blue square and ellipse* for Dok Do with normal dipole anomaly (*NDA*), *black square and ellipse* for Dok Do with normal dipole anomaly after removal of the uppermost 500 m (*NDAR*), *purple ellipse* for Dok Do with reversed dipole anomaly (*RDA*). **c** *Purple square and ellipse* for Dok Do with reversed dipole anomaly (*RDA*) in the southern hemisphere (also see Table 1)

can largely be explained by distortion due to the normal dipole anomaly and later volcanic intrusions.

Existing evidence of a successive westward formation of the Dok Do seamount group (cf. Introduction), and the east normal dipole and west reversed dipole anomalies recorded for Dok Do imply that the major eruption of the volcano in the normal polarity interval preceded that in the reversed polarity interval. Therefore, the lavas of the former might be accumulated underneath those of the latter interval. Accordingly, we estimated the Dok Do VGP with the normal dipole anomaly after removal of the uppermost 500 m, indicating the upper volcanic body of reversed polarity interval (cf. Harrison 1971; Brusilovsky et al. 1995). This results in the Dok Do VGP being located closer to the Simheungtaek VGP, and near the present magnetic pole; also, the GFR value increases (Fig. 5b, Table 1). These findings are consistent with the interpretations that Dok Do had at least two main eruptions, and that the eruption in the normal polarity interval is older.

A flexure model is frequently applied to enable the interpretation of isostatic compensation and indirect age estimation for volcanic edifices on oceanic crust in the deep sea (Watts 1978; Watts et al. 1980; Harris and Chapman 1994; Kruse et al. 1997). The response of the lithosphere to volcanic loads depends on its rigidity—elastic thickness—hence, on its age and thermal history (McNutt 1984; Watts 2001). A smaller elastic thickness indicates a younger lithosphere. Elastic thicknesses associated with seamounts approximately follow 200~400°C isotherms in the cooling plate model of Parsons and Sclater (1977; Wessel 1992). Based on gravity data, Kim et al. (2005) suggested elastic thicknesses of about 5, 3, and 2 km for Dok Do, Simheungtaek, and Isabu, respectively. In Fig. 6, we have incorporated these data into the cooling plate model of elastic thickness versus age of seafloor at time of loading, together with independent assessments of radiometric ages for subaerial rock samples from Dok Do extracted from Sohn and Park (1994), and Song et al. (2006; cf. Introduction). This shows that the range of values for the Dok Do seamounts is consistent with model predictions, and similar with those recorded for the Easter Seamount Chain, and seamounts in the southeastern Gulf of Alaska (Parsons and Sclater 1977; Harris and Chapman 1994; Kruse et al. 1997). Thus, lithosphere age at the time of loading of Isabu would be younger than that of Dok Do—i.e., Isabu would be measurably older than Dok Do.

Table 1 Magnetization parameters for the Dok Do seamounts[a]

	Location		VGP		Inclination (+downward)	Declination (+east)	Uniform intensity	Non-uniform intensity	GFR	Residual error
	Long. (E) (°)	Lat. (N) (°)	Long. (E) (°)	Lat. (N) (°)	(°)	(°)	(A/m)			(nT)
Simheungtaek Tablemount										
LS	132.04	37.15	256.2	72.5	44.5	16.1	2.6		3.5	
Semi	132.04	37.15	250.1	67.05	42	22.2	2.7	0.4		30.9
Isabu Tablemount										
LS	132.34	37.19	322.1	59.4	13.7	−5.0	0.4		1.5	
Semi	132.34	37.19	301.1	50.3	−3.8	7.1	0.3	0.2		6.0
Dok Do										
LS	131.87	37.25	240.8	34.9	15.2	51.5	2.3		2.0	
Semi	131.87	37.25	222.6	42.3	41.0	53.8	2.5	1.8		0.4
NDA, LS	131.87	37.25	278.7	56.0	14.5	18.0	3.1		2.1	
NDA, semi	131.87	37.25	253.2	56.3	29.7	29.5	3.0	1.3		29.4
NDAR, LS	131.87	37.25	269.9	61.2	26.8	19.4	3.5		2.3	
NDAR, semi	131.87	37.25	257.3	63.9	35.8	22.4	3.1	1.4		39.5
RDA, LS	131.87	37.25	205.6	−12.2	10.4	109.6	3.2		2.1	
RDA, semi	131.87	37.25	207.1	−4.6	17.3	102.7	3.0	0.9		25.4

[a] VGP, virtual geomagnetic pole; LS, least-squares magnetization method; semi, seminorm magnetization method; NDA, normal dipole magnetic anomaly; NDAR, normal dipole anomaly after removal of the uppermost 500 m; RDA, reversed dipole magnetic anomaly; GFR, goodness-of-fit ratio

Combined, the results presented above suggest that the Isabu Tablemount formed first, followed successively by the formation of the Simheungtaek Tablemount and Dok Do.

Discussion and conclusions

The latitudes of mean paleomagnetic poles of various areas in Northeast Asia range from about 85 to 88° for the Neogene (Zheng et al. 1991; Lee et al. 1997). Butler (1992) proposed that the dispersion of VGPs was well constrained to the range 10~20° during the past 5 Ma, and that the amplitude of VGP dispersion for the interval 5–45 Ma was slightly greater than for 0–5 Ma. The VGPs for Simheungtaek and the first large eruption of Dok Do in the normal polarity intervals are consistent with this proposal, although there are some differences between the mean paleomagnetic pole at the formation time of the Dok Do seamounts and the VGPs in this study. Furthermore, the pattern of normal/reversed magnetization is not inconsistent with the geomagnetic polarity timescale (Cande and Kent 1995) for at least the last 5 Ma (Fig. 7). Therefore, for the three Dok Do seamounts, we tentatively propose that (1) the Isabu Tablemount formed first, during a normal polarity interval occurring after the opening of the East Sea had ceased; (2) this was followed by an initial and subsequent large eruption of Dok Do in a normal polarity interval and a reversal, after about 5 Ma; and (3) the formation of the Simheungtaek Tablemount occurred in between that of Isabu and Dok Do in a normal polarity interval. Considering the available constraints, this interpretation needs verification based on additional

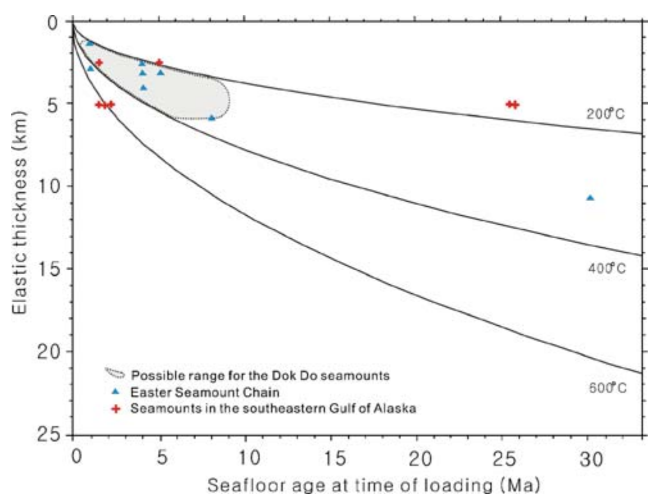

Fig. 6 Elastic thickness versus age of seafloor at time of loading. Curves are isotherms (°C) for the cooling plate model (extracted from Parsons and Sclater 1977; Harris and Chapman 1994; Kruse et al. 1997; Kim et al. 2005). Possible seafloor age at time of loading for Dok Do was estimated based on elastic thickness (about 5 km), and on the dating of rock samples (Sohn and Park 1994; Kim et al. 2005; Song et al. 2006). Possible seafloor ages at time of loading for the Simheungtaek and Isabu tablemounts are based on elastic thicknesses (about 3 and 2 km, respectively; Kim et al. 2005)

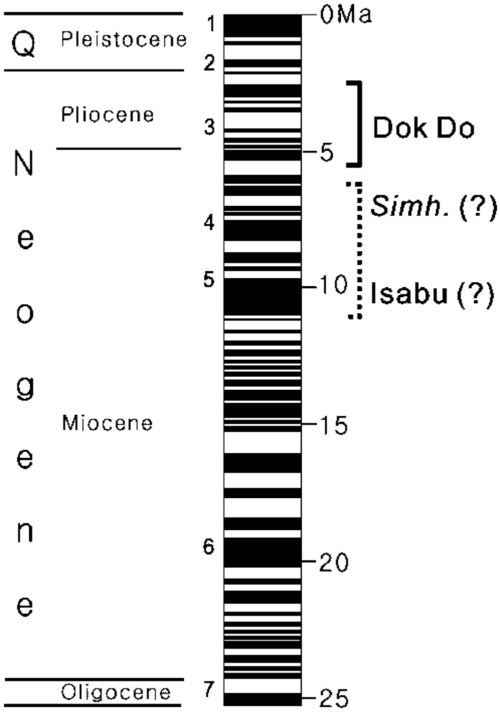

Fig. 7 Geomagnetic polarity timescale from 0 to ca. 25 Ma (cf. Cande and Kent 1995; *black* normal polarity, *white* reversed polarity). Geologic time divisions are shown to the *left* of the polarity column, as are magnetic values (polarity chron numbers). Age (in Ma) is shown to the *right* of the polarity column, including possible age ranges for the formation of the seamount group: Dok Do, Simheungtaek (*Simh.*) Tablemount, and Isabu Tablemount (ages extracted from Sohn and Park 1994; Kim et al. 2005; Song et al. 2006)

geophysical/geochemical assessments. Nevertheless, this successive formation from east to west is in good agreement with the low-amplitude magnetic anomalies recorded over Isabu, plausibly explained by an extended period of secondary changes of magnetic minerals after formation, and the increase in magnetization from Isabu to Dok Do (e.g., Brusilovsky et al. 1995).

The Dok Do seamounts are linearly aligned from east to west. The origins of such linear volcanic chains have been explained in terms of various processes (e.g., Watts et al. 1980; Sager and Keating 1984; Molnar and Stock 1987; Bryan and Cherkis 1995; Tarduno and Cottrell 1997; Koppers et al. 2008). In the New England Seamounts, for example, subsequent activation of faulting occurred from west to east, and so these seamounts must be older in the west (Brusilovsky et al. 1995). In the northern Ulleung Basin, Song et al. (2006) proposed that the igneous activity of Ulleung Do, west of the Dok Do seamounts, started as early as 8.07±0.39 Ma, but that the main volcano building stage of Ulleung Do was initiated after 2.7 Ma. By this time, the formation of Dok Do would have been largely completed, indicating sequential generation by volcanic activity. However, from 3D gravity modeling of the Anyongbok seamount situated between Ulleung Do and Dok Do, Kang et al. (2007) argued that the Anyongbok seamount might not be related to ridge volcanism associated with other seamounts and islands, because of the significant crustal thickness (ca. 20 km) under this seamount, compared to that of others in the northern part of the Ulleung Basin.

Other scientists have suggested that Dok Do originated from a hotspot process (W.O. Song et al. 2000; Y.S. Song et al. 2006). However, it is difficult to conceive a moving plate above a hotspot in the Ulleung Basin, because the moving Pacific and Philippine plates subducted against the relatively stable Eurasian Plate after the end of the opening of the East Sea (Jolivet and Tamaki 1992; Tamaki et al. 1992).

Rather, we suggest that the successive formation of the Dok Do seamounts is related to fracturing with volcanism associated with the evolution of the East Sea, in analogy with, for example, the New England Seamounts (Brusilovsky et al. 1995). Many scientists have argued that the extension with seafloor spreading of the East Sea occurred from the early to middle Miocene (Chough and Barg 1987; Tamaki 1988; Jolivet and Tamaki 1992; Tamaki et al. 1992). After the cessation of the opening of the East Sea, horizontal compressive stresses became active from the late Miocene to 1.8 Ma (Jolivet et al. 1991; Jolivet and Tamaki 1992). The compressive force resulting from the Pacific and Philippine plates moving against the Eurasian Plate has caused a weakening of the extensional field in the East Sea (Kaneoka et al. 1990). Such a weak extensional regime would be more prone to create small fractures than regional spreading, thereby facilitating magma eruption. Based on the arguments presented above, we propose that the Dok Do seamounts could have originated following fracturing and successive volcanism related to compression-induced weakening of the extensional field from the late Miocene to Pliocene after the opening of the East Sea. Nevertheless, more detailed lithologic characterization, age dating of submerged rocks, and additional geophysical/geochemical constraints (e.g., seismic surveys) are evidently needed to more precisely identify the origin and age of volcanism, and the tectonic environments prevailing during the formation of the Dok Do seamount group in the Ulleung Basin.

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References

Barton CE (1997) International Geomagnetic Reference Field: the seventh generation. J Geomag Geoelectr 49:123–148

Brusilovsky YV, Gorodnitsky AM, Ivanenko AM (1995) Geomagnetic study of seamounts. In: Gorodnitsky AM (ed) Anomalous magnetic field of the world ocean. CRC Press, Moscow, pp 171–222

Bryan PC, Cherkis NZ (1995) The Bahia Seamounts: test of a hotspot model and a preliminary South American Late Cretaceous to Tertiary apparent polar wander path. Tectonophysics 241:317–340

Butler RF (1992) Geochronological applications. In: Butler RF (ed) Paleomagnetism: magnetic domains to geologic terranes. Blackwell, Boston, MA, pp 157–223

Cande SC, Kent DV (1995) Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. J Geophys Res 100(B4):6093–6095

Chough SK, Barg E (1987) Tectonic history of Ulleung Basin margin, East Sea (Sea of Japan). Geology 15:45–48

Chough SK, Lee KE (1992) Multi-stage volcanism in the Ulleung Back-arc Basin, East Sea (Sea of Japan). Island Arc 1:32–39

Harris RN, Chapman DS (1994) A comparison of mechanical thickness estimates from trough and seamount loading in the southeastern Gulf of Alaska. J Geophys Res 99(B5):9297–9317

Harrison CGA (1971) A seamount with a nonmagnetic top. Geophysics 36:349–357

Hilde TWC, Wageman JM (1973) Structure and origin of the Japan Sea. In: Coleman PJ (ed) The western Pacific: island arcs, marginal seas, geochemistry. University of Western Australia Press, Perth, pp 415–434

Hildebrand JA, Parker RL (1987) Paleomagnetism of Cretaceous Pacific seamounts revisited. J Geophys Res 92(B12):12695–12712

Hirata N, Tokuyama H, Chung TW (1989) An anomalously thick layering of the crust of the Yamato Basin, southeastern Sea of Japan: the final stage of back-arc spreading. Tectonophysics 165:303–314

Hirata N, Karp BY, Yamaguchi T, Kanazawa T, Suyehiro K, Kasahara J, Shiobara H, Shinohara M, Kinoshita H (1992) Oceanic crust in the Japan Basin of the Japan Sea by the 1990 Japan-USSR Expedition. Geophys Res Lett 19:2027–2030

Isezaki N, Uyeda S (1973) Geomagnetic anomaly pattern of the Japan Sea. Mar Geophys Res 2:51–59

Itoh Y (2001) A Miocene pull-apart deformation zone at the western margin of the Japan Sea back-arc basin: implication for the back-arc opening mode. Tectonophysics 334:235–244

Jolivet L, Tamaki K (1992) Neogene kinematics in the Japan Sea region and volcanic activity of the northeast Japan Arc. Proc Ocean Drilling Program Sci Results 127/128 2:1311–1331

Jolivet L, Huchon P, Lepichon X, Chamot-Rooke N, Thomas JC (1991) Arc deformation and marginal basin opening: Japan Sea as a case study. J Geophys Res 96(B3):4367–4384

Kaneoka I, Notsu K, Takigami Y, Fujioka K, Sakai H (1990) Constraints on the evolution of the Japan Sea based on 40Ar-39Ar ages and Sr isotopic ratios for volcanic rocks of the Yamato Seamount Chain in the Japan Sea. Earth Planet Sci Lett 97:211–225

Kang MH, Han, HC, Yun, HS, Kong GS, Kim, KO, Lee, YS (2007) 3D gravity modelling for Anyongbok Seamount in the East Sea. Mar Geophys Res 28:257–269

Kim KH (2000) K-Ar ages and Nd-Sr isotopes of Dokdo alkali volcanic rocks in the East Sea, South Korea (in Korean with English abstract). J Geol Soc Korea 36:313–324

Kim HJ, Park CH, Hong JK, Jou HT, Chung TW, Zhigulef V, Anosov GI (1994) A seismic experiment in the Ulleung Basin (Tsushima Basin), southwestern Japan Sea (East Sea of Korea). Geophys Res Lett 21:1975–1978

Kim HJ, Jou HT, Cho HM, Bijwaard H, Sato T, Hong JK, Yoo HS, Baag CE (2003) Crustal structure of the continental margin of Korea in the East Sea (Japan Sea) from deep seismic sounding data: evidence for rifting affected by the hotter than normal mantle. Tectonophysics 364:25–42

Kim CH, Park CH, Yoo SH, Min KD, Shim JS (2005) The study of Dok seamounts in the northeastern part of the Ulleung Basin using gravity data (in Korean with English abstract). J Geol Soc Korea 41:523–531

Koppers AAP, Russell JA, Jackson MG, Konter J, Staudigel H, Hart SR (2008) Samoa reinstated as a primary hotspot trail. Geology 36:435–438

Kruse SE, Liu ZJ, Naar DR, Duncan RA (1997) Effective elastic thickness of the lithosphere along the Easter Seamount Chain. J Geophys Res 102(B12):27305–27317

Kurashimo E, Shinohara M, Suyehiro K, Kasahara J, Hirata N (1996) Seismic evidence for stretched continental crust in the Japan Sea. Geophys Res Lett 23:3067–3070

Lallemand S, Jolivet L (1986) Japan Sea: a pull-apart basin? Earth Planet Sci Lett 76:375–389

Lee YS, Nishimura S, Min KD (1997) Paleomagnetotectonics of East Asia in the Proto-Tethys Ocean. Tectonophysics 270:157–166

Lee GH, Kim HJ, Suh MC, Hong JK (1999) Crustal structure, volcanism and opening mode of the Ulleung Basin, East Sea(Sea of Japan). Tectonophysics 308:503–525

Maia M, Dyment J, Jouannetaud D (2005) Constraints on age and construction process of the Foundation chain submarine volcanoes from magnetic modeling. Earth Planet Sci Lett 235:183–199

McElhinny MW (1973) Paleomagnetism and plate tectonics. Cambridge University Press, Cambridge

McNutt MK (1984) Lithospheric flexure and thermal anomalies. J Geophys Res 89(B13):11180–11194

Molnar P, Stock J (1987) Relative motions of hotspots in the Pacific, Atlantic and Indian oceans since late Cretaceous time. Nature 327:587–591

Nettletton LL (1962) Gravity and magnetics for geologists and geophysicists. Bull Am Assoc Petrol Geol 48:1815–1838

Park CH (1998) Crustal structure and evolution of the Ulleung Basin in the East Sea of Korea (the Japan Sea) by deep penetrating seismic refraction, reflection, and potential field data. PhD Thesis, Chiba University, Chiba

Parker RL, Shure L, Hildebrand JA (1987) The application of inverse theory to seamount magnetism. Rev Geophys 25:17–40

Parsons B, Sclater JG (1977) An analysis of ocean floor bathymetry and heat flow with age. J Geophys Res 82:803–827

Plouff D (1976) Gravity and magnetic fields of polygonal prisms and application to magnetic terrain corrections. Geophysics 41:727–741

Richards MC, Vacquier V, Van Voorhis GD (1967) Calculation of the magnetization of uplifts from combining topographic and magnetic surveys. Geophysics 32:678–707

Sager WW (1984) Paleomagnetism of Abbott Seamount and implication for the latitudinal shift of the Hawaiian hot spot. J Geophys Res 89(B7):6271–6284

Sager WW, Keating BH (1984) Paleomagnetism of Line Islands Seamounts: evidence for Late Cretaceous and Early Tertiary volcanism. J Geophys Res 89(B13):11135–11151

Sager WW, Koppers AAP (2000) Late Cretaceous polar wander of the Pacific Plate: evidence of a true polar wander event. Science 287:455–459

Sager WW, Duncan RA, Handschumacher DW (1993) Paleomagnetism of the Japanese and Marcus-Wake Seamounts, western Pacific Ocean. In: Pringle MS, Sager WW, Sliter WV, Stein S (eds) The Mesozoic Pacific: geology, tectonics, and volcanism. American Geophysical Union, Washington, DC, pp 401–435

Sager WW, Lamarche AJ, Kopp C (2005) Paleomagnetic modeling of seamounts near the Hawaiian-Emperor bend. Tectonophysics 405:317–329

Sohn YK, Park KH (1994) Geology and evolution of Tok Island. J Geol Soc Korea 30:242–261

Song WO, Kwon MS, Kim ES, Myung JG, Park CH et al (2000) The study of on land and marine environments and ecosystems of Dokdo (in Korean). Korea Ocean Research and Development Institute, Seoul, pp 385–600

Song YS, Park ME, Park KH (2006) Ages and evolutions of the volcanic rocks from Ulleung-do and Dok-do (in Korean with English abstract). J Petrol Soc Korea 15:72–80

Tamaki K (1988) Geological structure of the Japan Sea and its tectonic implications. Bull Geol Surv Japan 39:269–365

Tamaki K, Suyehiro K, Allan J, Ingle JC, Pisciotto KA (1992) Tectonic synthesis and implications of Japan Sea ODP drilling. Proc Ocean Drilling Program Sci Results 127/128 2:1333–1348

Tarduno JA, Cottrell RD (1997) Paleomagnetic evidence for motion of the Hawaiian hotspot during formation of the Emperor Seamounts. Earth Planet Sci Lett 153:171–180

Tatsumi Y, Otofuji Y, Matsuda T, Nohba S (1989) Opening of the Sea of Japan back-arc basin by asthenospheric injection. Tectonophysics 166:317–329

Uyeda S, Miyashiro A (1974) Plate tectonics and the Japanese island: a synthesis. Geol Soc Am Bull 85:1159–1170

Watts AB (1978) An analysis of isostasy in the world's ocean 1. Hawaiian-Emperor Seamount chain. J Geophys Res 83 (B12):5989–6004

Watts AB (2001) Isostasy and flexure of the lithosphere. Cambridge University Press, Cambridge

Watts AB, Bodine JH, Ribe NM (1980) Observation of flexure and the geological evolution of the Pacific Ocean basin. Nature 283:532–537

Wessel P (1992) Thermal stress and the bimodal distribution of elastic thickness estimates of the oceanic lithosphere. J Geophys Res 97 (B10):14177–14193

Won JK, Lee MW (1984) The volcanism and petrology of alkali volcanic rocks, Ulrung Island (in Korean with English abstract). J Geol Soc Korea 20:296–305

Yun HS, Yi SS, Oh JY, Byun HS, Shin KS (2007) Micropaleontological and seismic observations for early developmental stage of the southwestern Ulleung Basin, East Sea (Japan Sea). Island Arc 16:262–275

Zheng Z, Kono M, Tsunakawa H, Kimura G, Wei Q, Zhu X, Hao T (1991) The apparent polar wander path for the North China block since the Jurassic. Geophys J Int 104:29–40