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EXPRESS LETTER

Rotation of the Philippine Sea plate inferred from paleomagnetism of oriented cores taken with an ROV-based coring apparatus

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Abstract

Reconstructing the history of Philippine Sea (PHS) plate motion is important for better understanding of the tectonics of the surrounding plates. It is generally considered that the PHS plate migrated northward since Eocene, but its rotation has not been constrained well; some reconstructions incorporated a large clockwise rotation but others did not. This is mainly because the difficulty of collecting oriented rocks from the mostly submerged PHS plate hindered establishing an apparent polar wander path. In this study, we conducted a paleomagnetic study of oriented cores taken using an ROV-based coring apparatus from the Hyuga Seamount on the northern part of the Kyushu-Palau Ridge, a remnant arc in the stable interior of the PHS plate. Stepwise thermal and alternating-field demagnetizations were applied to specimens taken successively from two ~ 30 cm long limestone cores of middle to late Oligocene age, and characteristic remanent magnetization directions could be isolated. Declination and inclination of $D = 51.5°$ and $I = 39.8°$, respectively, were obtained as the mean of the two cores. The easterly-deflected declination means ~ 50° clockwise rotation of the PHS plate since middle to late Oligocene. In addition, ~ 5° latitudinal change of the site is estimated from the mean inclination. The result implies that the Kyushu-Palau Ridge was located to the southwest of the present position in middle to late Oligocene, and that PHS plate rotation as well as the Shikoku and Parece Vela Basin spreading contributed to the eastward migration of the Izu-Ogasawara (Bonin) Arc to the current position.

Keywords: Philippine Sea plate, Kyushu-Palau ridge, Paleomagnetism

Introduction

The Philippine Sea (PHS) plate has interacted with the surrounding plates since its birth, and thus reconstructing its development is important for better understanding the related tectonics, for example, Pacific plate subduction initiation in Eocene and subsequent backarc spreadings (Ishizuka et al. 2011, 2018; Lallemand 2016), and the development of the Southwest Japan arc (e.g. Kimura et al. 2005,2014; Mahony et al. 2011). Studies on PHS plate motion reconstruction have a long history for about 40 years since Seno and Maruyama (1984). Based mainly on paleomagnetic inclination data of cores drilled from the PHS plate seafloor by the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) (Louden 1977; Kinoshita 1980; Keating and Herrero 1980; Keating 1980; Bleil 1982; Haston et al. 1992; Koyama et al. 1992; Richter and Ali 2015), it is generally considered that the PHS plate was located near the equator in Eocene, and migrated northward since then with expanding its area by backarc spreading of the West Philippine basin from ~ 50 to 35 Ma and Parece Vela and Shikoku basins from ~ 30 to 15 Ma (Hall et al. 1995; Deschamps and Lallemand 2002; Yamazaki et al. 2010). However, its rotation has not been constrained well. Some reconstructions incorporated a large clockwise rotation (Hall et al. 1995; Deschamps

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and Lallemand 2002; Sdrolias et al. 2004), whereas others did not (Xu et al. 2014; Zahirovic et al. 2014). A recent study that took account of already subducted slabs deduced from seismic tomography presented two alternative reconstructions with and without rotation (Wu et al. 2016). If the Pacific plate has subducted underneath the PHS plate continuously since ~ 50 Ma, a large clockwise rotation of the PHS plate requires a large roll back of the Pacific plate, which is not consistent with the amount of Pacific slab materials inferred from seismic tomography (Zahirovic et al. 2014; Wu et al. 2016). This is the main reason for that the model of Zahirovic et al. (2014) and the model 2 of Wu et al. (2016) did not adopt a large clockwise PHS plate rotation. The model 1 of Wu et al. (2016) (their preferred model), which incorporated a large clockwise PHS plate rotation, introduced an already subducted plate between the PHS and Pacific plates, which reconciles with the constraint from seismic tomography.

An established method for a plate motion reconstruction is to construct an apparent polar wander path based on paleomagnetism. However, it was difficult to obtain oriented samples for paleomagnetic measurements from the stable interior of the PHS plate, because it is a mostly submerged oceanic plate. Some paleomagnetic studies showed easterly deflected declinations using rocks from the margins of the plate, Izu–Ogasawara (Bonin) and Mariana forearc (Kodama et al. 1983; Haston and Fuller 1991) and Indonesia (Hall et al. 1995), but they were not conclusive, because the studied areas are tectonically active and the paleomagnetic directions obtained may have been influenced by local block rotations. An analysis of marine magnetic anomaly skewness also suggested a clockwise rotation (Shih 1980). However, an increased amount of data since then resulted in revisions of anomaly chron identification and seafloor spreading directions (Deschamps and Lallemand 2002; Taylor and Goodliffe 2004; Sasaki et al. 2014). Because skewness analyses strongly depend on seafloor spreading directions, the result of Shih (1980) is rather outdated now.

In this paper, we present a paleomagnetic direction of Oligocene age from the Kyushu-Palau ridge in the PHS plate (Fig. 1), and discuss its rotation. The Kyushu-Palau ridge is a remnant arc, which was active from ~ 48 to 25 Ma before the opening of the Shikoku and Parece-Vela basins (Ishizuka et al. 2011). This is the first paleomagnetic direction data based on fully oriented cores collected from the stable interior of the PHS plate. We utilized an ROV-based coring apparatus introduced below for taking oriented cores. Collecting oriented rocks from the seafloor was attempted before by measuring strikes and dips (Hurst et al. 1994), but the technique was not used widely.

Apparatus for obtaining oriented cores from the seafloor

An ROV-based coring apparatus recently developed by KOKEN BORING MACHINE CO. LED. was used for taking oriented cores from the seafloor (Fig. 2a). The maximum penetration length is 37 cm, which enables to drill target rocks covered with relatively thick manganese (Mn) crust. The core diameter is 3 cm. The drilling rod consists of an inner pipe and an outer pipe with a drill bit (Fig. 2b). The inner pipe does not rotate, which enables coring of soft rocks such as limestone. The inside of the inner pipe is not straight but slightly inclined at a certain point of the pipe to snap off a core from bedrock. The inner pipe has a hard chip at its entrance to mark an orientation line to a core (Fig. 2d). The direction and inclination of the orientation line are measured with a sensor unit (a magnetic compass and inclinometer) placed on the frame of the corer. Using this technique, we can obtain fully oriented cores such as those used for onshore paleomagnetic research. Refer Tajima et al. (2020) for more information of the coring apparatus.

Samples

Dive 2092 of the ROV Hyper-dolphin, owned and operated by Japan Agency for Marine-Earth Science and Technology, was conducted during the KS-19-8 cruise of R/V Shinsei-maru in 2019. Five cores with orientation lines were drilled on the northern flank (1929 m in water depth) of the Hyuga seamount in the northern part of the Kyushu-Palau ridge at 27°59.36’N, 134°45.13’E (Figs. 1 and 2c). The drilling site is covered with Mn crust (Fig. 2a). The distance between Cores 1 and 2 are a few meters or less, and the locations of Cores 3 and 4 are several meters apart from Cores 1 and 2. The lengths of Cores 1 and 2 are 28.5 and 31.5 cm, respectively, excluding surface Mn crust of a few centimeters. Cores 3 and 4 are 15 and 12 cm long, respectively, and have thicker Mn crust of ~ 10 cm. These cores consist of silty or sandy limestone. Only Mn crust was recovered for Core 5. The age of the recovered limestone is estimated to be middle to late Oligocene from calcareous nannofossil: NP23–25 (32.0–24.4 Ma according to the timescale of Expedition 320/321 Scientists 2010) for Core 2 at ~ 25 cm in depth and NP25 (26.8–24.4 Ma) for Core 3 at ~ 12 cm (Additional file 1: Table S1). These ages are close to the timing of the final phase volcanism on the Kyushu-Palau ridge and an $^{40}Ar/^{39}Ar$ age (29.25 ± 0.22 Ma) of a volcanic rock from the Hyuga seamount (Ishizuka et al. 2011). This indicates that the deposition of the limestone occurred soon after the formation of the seamount.

The cores were sliced at about 2 cm intervals with a diamond saw, and two rectangular specimens for paleomagnetic measurements were cut from each slice; the

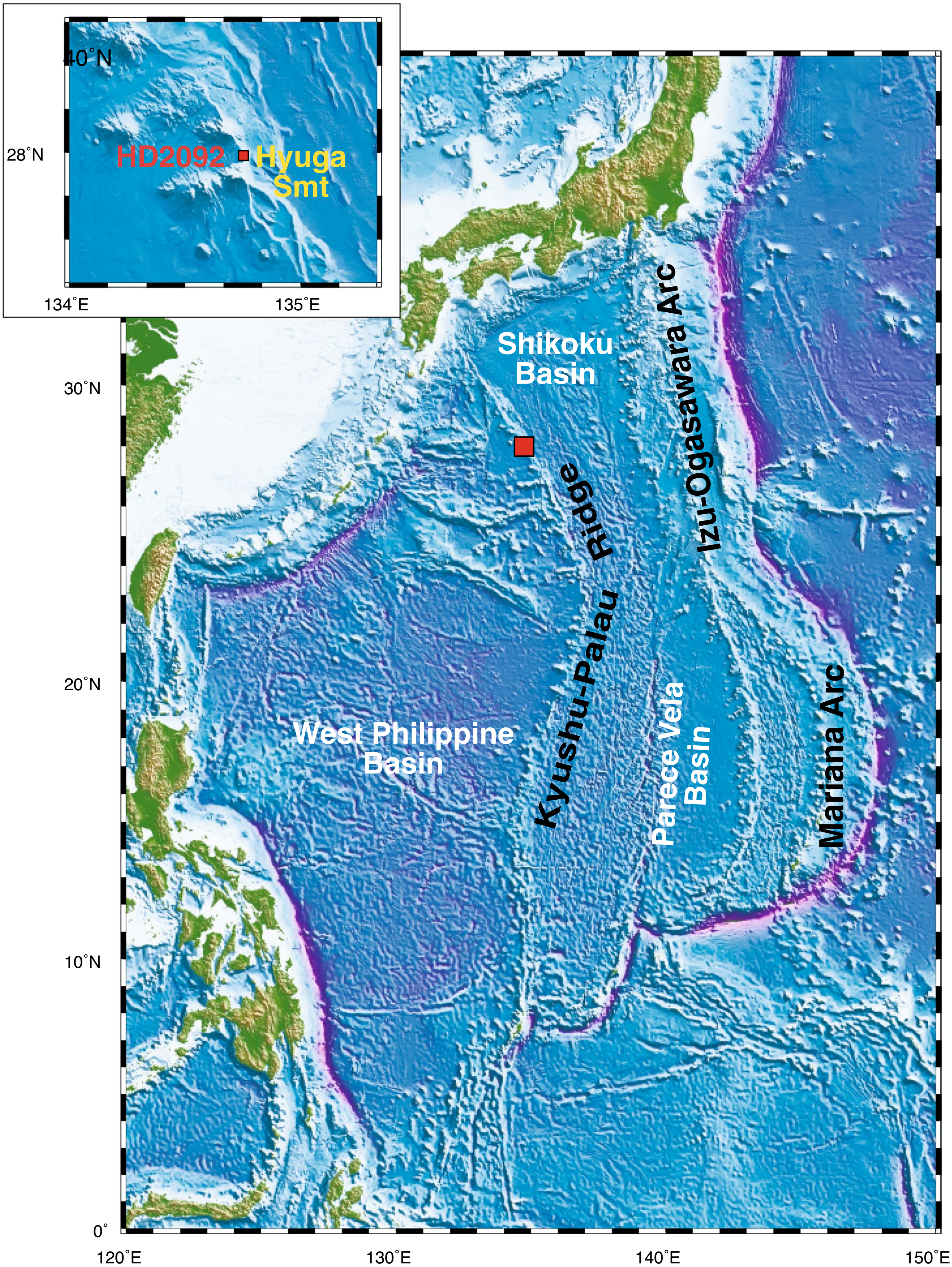

Fig. 1 Shaded relief map of the Philippine Sea plate and the location of the sampling site (red square). Around the Hyuga seamount is enlarged in the inset

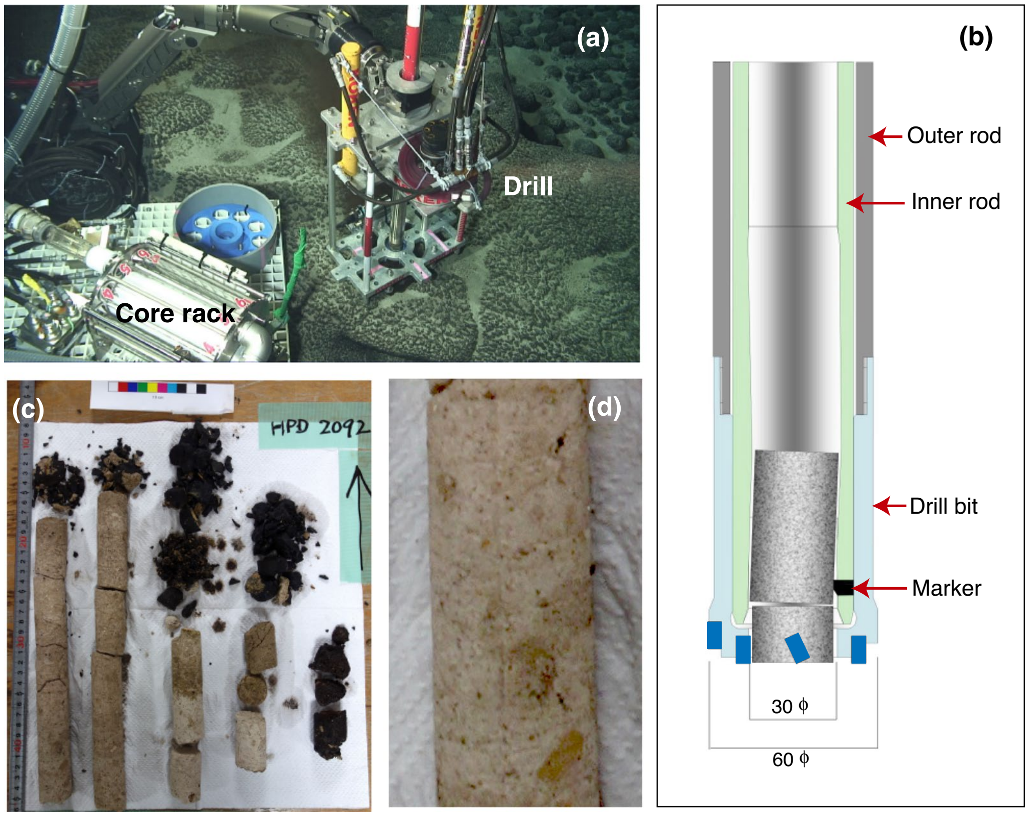

Fig. 2 Coring apparatus and drilled cores. **a** The coring apparatus drilling the seafloor covered with manganese crust and a core rack installed on the ROV Hyper-dolphin, **b** cross section of the drilling rod, **c** photo of the cores collected during the Dive 2092 of the ROV Hyper-dolphin, and **d** orientation line along a core marked during drilling

size of each specimen is approximately 2 cm in length, 1 cm in width, and 2 cm in height. One specimen from each horizon was devoted to thermal demagnetization and the other to alternating-field (AF) demagnetization. An exception is at 4 cm in depth of Core 1, where only one specimen was cut and only AF demagnetization was applied.

Paleomagnetic measurements and results

Paleomagnetic measurements were conducted at the Center for Advanced Marine Core Research, Kochi University, using a cryogenic magnetometer (2G Enterprises model 755), a thermal demagnetization oven (Natsuhara-Giken TDS-1), and an AF demagnetizer (Natsuhara-Giken DEM-95). Stepwise thermal demagnetization was carried out at 30° to 35 °C intervals up to 600 °C, and AF demagnetization was carried out at an interval of 5 mT from 5 to 40 mT then an interval of 10 mT up to 80 mT. For Cores 1 and 2, characteristic remanent magnetization (ChRM) was resolved in both AF and thermal demagnetizations after removal of a soft secondary component in the first few demagnetization steps (Fig. 3). ChRM directions were determined using principal component analysis (Kirschvink 1980). Maximum angular dispersion (MAD) ranges from 5° to 22° (Fig. 4). For Cores 3 and 4, stepwise thermal and AF demagnetizations showed unstable magnetization, and ChRM was not resolved (Additional file 1: Fig. S1). Cores 3 and 4 are less stiff and more fragile compared with Cores 1 and 2. This suggests that Cores 3 and 4 may have suffered from weathering, which might be a cause of the unstable magnetization.

(See figure on next page.)

Fig. 3 Examples of stepwise thermal (left) and alternating-field (AF) (right) demagnetizations of samples from HD2092 Cores 1 and 2. Open (solid) circles are projection of vector endpoints on the vertical (horizontal) plane. Data points of temperature or AF steps adopted for calculation of characteristic remanent magnetization direction are colored, and those not used are in gray. Numbers attached to the data points are the peak temperature (°C) or peak AF (mT)

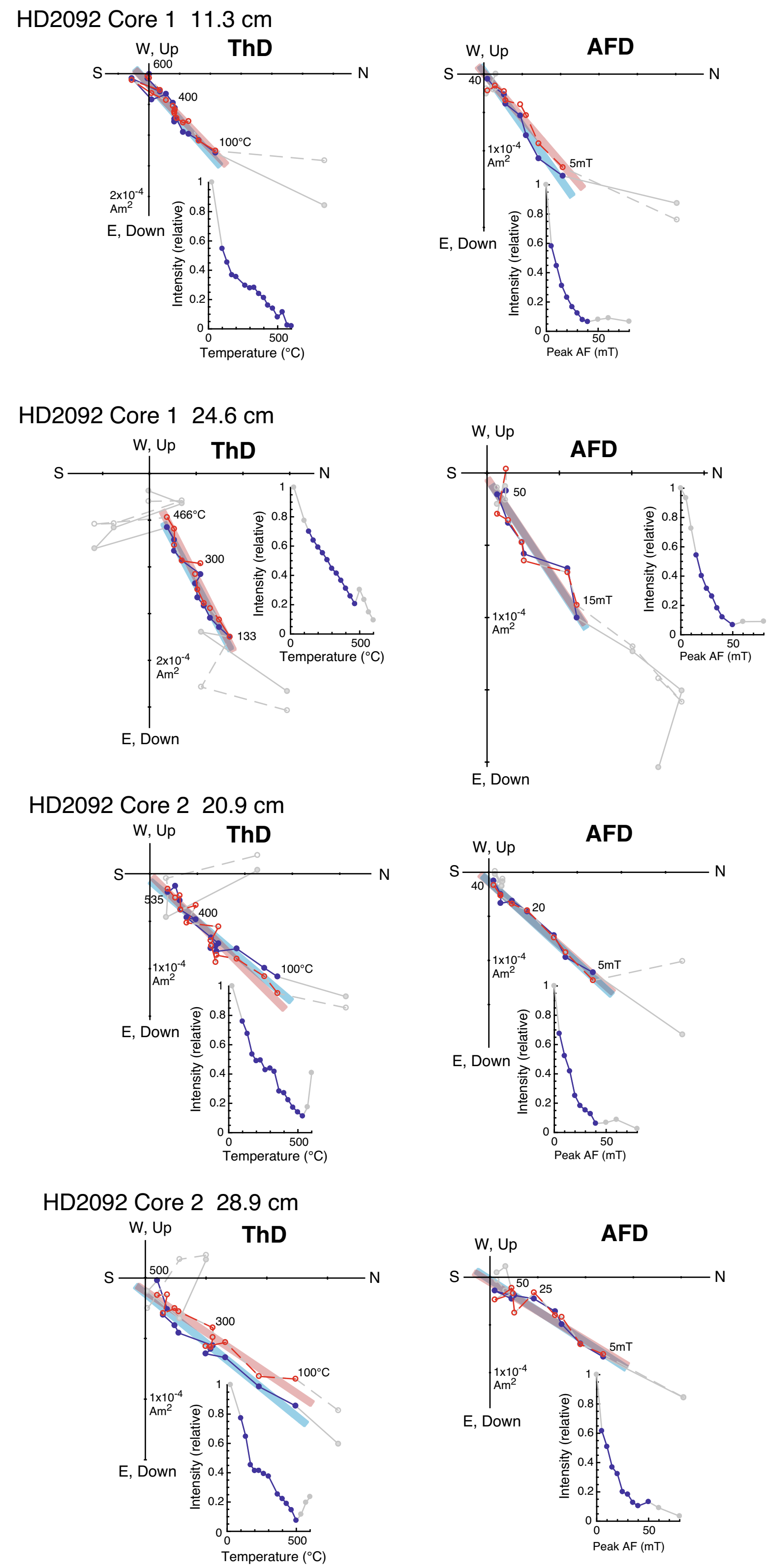

Fig. 3 (See legend on previous page.)

The ChRM declinations and inclinations obtained from thermal and AF demagnetizations agree with each other within the uncertainties represented by MAD (Fig. 4a and b). Easterly deflected declinations were observed commonly in the both cores. No depth-dependent directional variations are recognized except for a declination jump of about 180° at 23 cm in depth of Core 2. The ~ 180° declination jump appears only for two specimens from a single horizon and does not accompany any inclination change. A geomagnetic polarity reversal or excursion recorded in sediments usually accompany a remanent magnetization intensity decrease, which is caused by the filtering effect inherent to depositional remanent magnetization acquisition (e.g. Løvlie 1976; Hyodo 1984) in addition to an actual geomagnetic intensity decrease during a reversal. However, no remanent intensity drop occurs at or near the declination jump (Fig. 4a and b). Hence we consider that this is likely caused by miss-orientation of the specimens at cutting rather than a geomagnetic reversal or excursion. We excluded these two specimens from the calculation of the average paleomagnetic direction.

The mean declination and inclination of Core 1 are 56.4° and 40.6°, respectively, with the 95% confidence angle (α_{95}) of 12.6°. Those of Core 2 are 46.8° and 38.8° with α_{95} of 12.5°. The paleomagnetic directions of Cores 1 and 2 coincide within the uncertainties (Fig. 4c). $D = 51.5°$ and $I = 39.8°$ were obtained as the mean of Cores 1 and 2. The inclination corresponds to the paleolatitude of 22.6°.

Discussion

We have successfully obtained oriented cores of limestone from the seafloor using the ROV-based coring apparatus. Oriented cores are crucial for research on paleomagnetism, and also demanded for studies on structural geology. The coring apparatus can be used widely for such studies on the seafloor. This is also useful for obtaining rocks underneath a thick Mn crust cover, which is often the case for rocks of older ages.

The paleomagnetic directions of the two cores from the Hyuga seamount showed easterly deflected declinations, the mean of 51.5°. This is the first paleomagnetic direction data based on fully oriented cores from the seafloor in the stable interior of the PHS plate. The declination indicates that the PHS plate rotated ~ 50° clockwise since middle to late Oligocene. This generally agrees with the estimation from previous declination data obtained from the PHS plate margins (Fig. 5b), which suggests that the influence of local tectonics on the paleomagnetic data from the plate margins may be small. This supports the PHS plate reconstructions incorporating a large clockwise rotation (Hall et al. 1995; Deschamps and Lallemand 2002; Sdrolias et al. 2004). There are two different views regarding the timing of the rotation and the paleopositions of the Kyushu-Palau ridge and Izu–Ogasawara (Bonin) arc. In one view, the rotation of the PHS plate had almost been completed by the initiation of the Shikoku and Parece Vela basin rifting at ~ 30 Ma, and the Kyushu-Palau ridge (proto-Izu–Ogasawara arc) was located near the present position south of Kyushu island (Maruyama et al. 1997; Kimura et al. 2005). According to this model, the Izu–Ogasawara (Bonin) arc moved eastward with the spreading of the Shikoku and Parece Vela basins, and reached in the vicinity of the current position at the completion of the spreading at ~ 15 Ma. This model is concordant with the idea that the bending of the Median Tectonic Line in the eastern part of the Southwest Japan arc, called the Kanto syntax, started around 15 Ma by a collision with the Izu–Ogasawara (Bonin) arc associated with the opening of the Japan Sea (Takahashi and Saito 1997; Otofuji et al. 1999). Alternatively, the Kyushu-Palau ridge was located to the southwest of the current position at the onset of the Shikoku and Parece Vela basin spreading (Fig. 5c), and the PHS plate rotation and eastward movement of the Kyushu-Palau ridge continued successively (Hall et al. 1995; Sdrolias et al. 2004; Mahony et al. 2011; Kimura et al. 2014). This model is consistent with the result of a sediment provenance study that middle Miocene sediments of the Nankai Trough were partly derived from the North China Craton (Clift et al. 2013). According to this model, the eastward motion of the Izu–Ogasawara (Bonin) arc may have continued even after the cessation of the Shikoku and Parece Vela basin spreading. Our paleomagnetic result supports the latter reconstruction.

The paleolatitude of 22.6° obtained from the two cores is consistent with the previous estimation (19.9°) from a nearby core on the Hyuga Seamount (Yamazaki et al. 2010). Compared with the present latitude of the coring site (~ 28°N), ~ 5° latitudinal shift since middle to late Oligocene is estimated. Our estimation overlaps with the previously reported latitudinal changes (Fig. 4a), but it is near the smallest end of the data distribution. In some previous PHS plate reconstructions (Hall 2002; Sdrolias et al. 2004), the present northern part of the Kyushu-Palau ridge was estimated to be located at ~ 15°N at that time. The paleolatitudes of the Hyuga seamount in this study and Yamazaki et al. (2010) suggest that the paleoposition of the northern part of the Kyushu-Palau ridge in the previous reconstructions may be too far south.

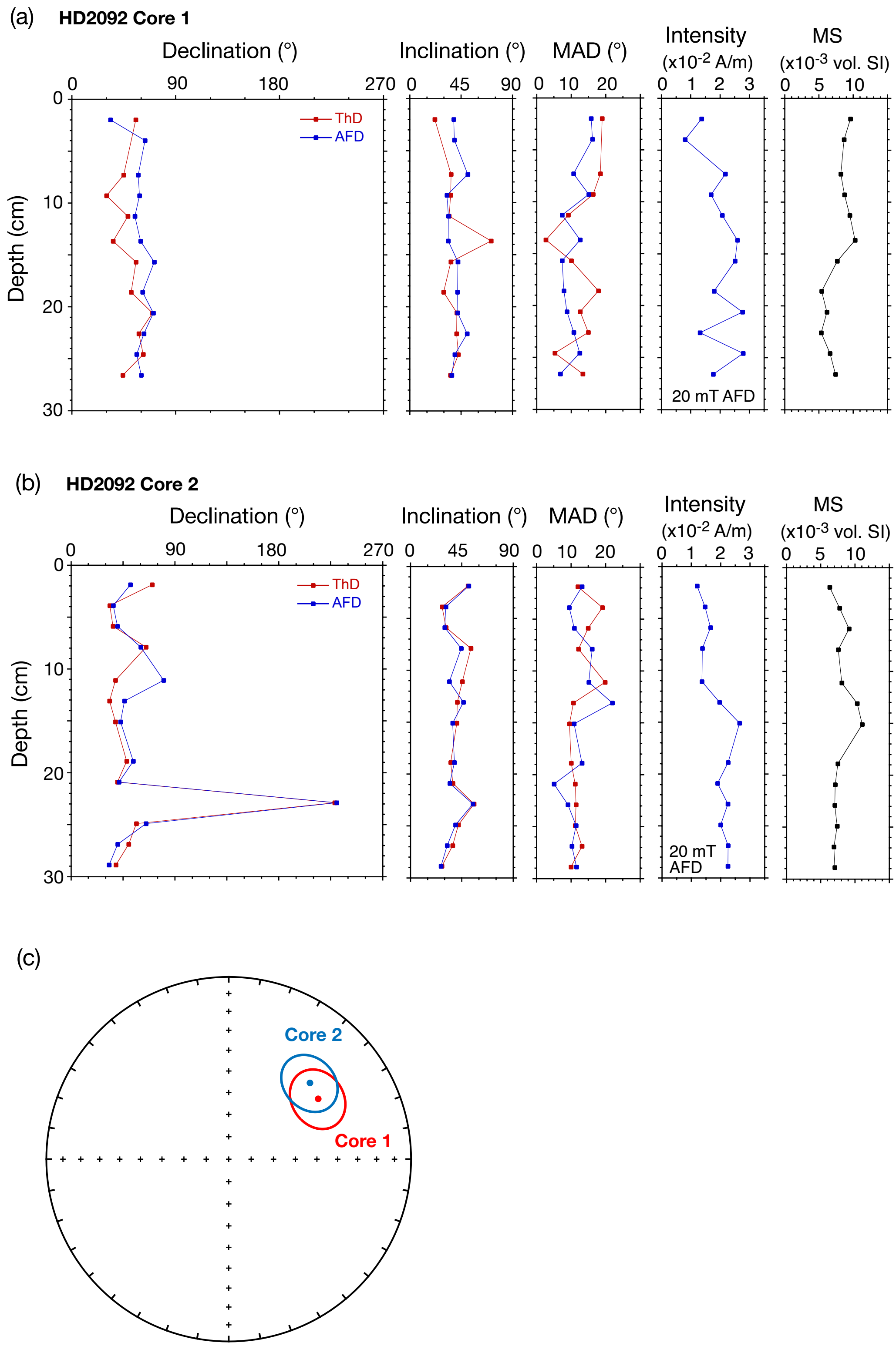

Fig. 4 Results of paleomagnetic measurements. From left to right, declination, inclination, maximum angular dispersion (MAD), intensity of natural remanent magnetization before demagnetization, and magnetic susceptibility (MS) with depth of Core 1 (**a**) and Core 2 (**b**) collected during the Dive 2092 of the ROV Hyper-dolphin after stepwise thermal (red) and AF (blue) demagnetization. **c** The mean paleomagnetic directions and the 95% confidences of Cores 1 (red) and 2 (blue)

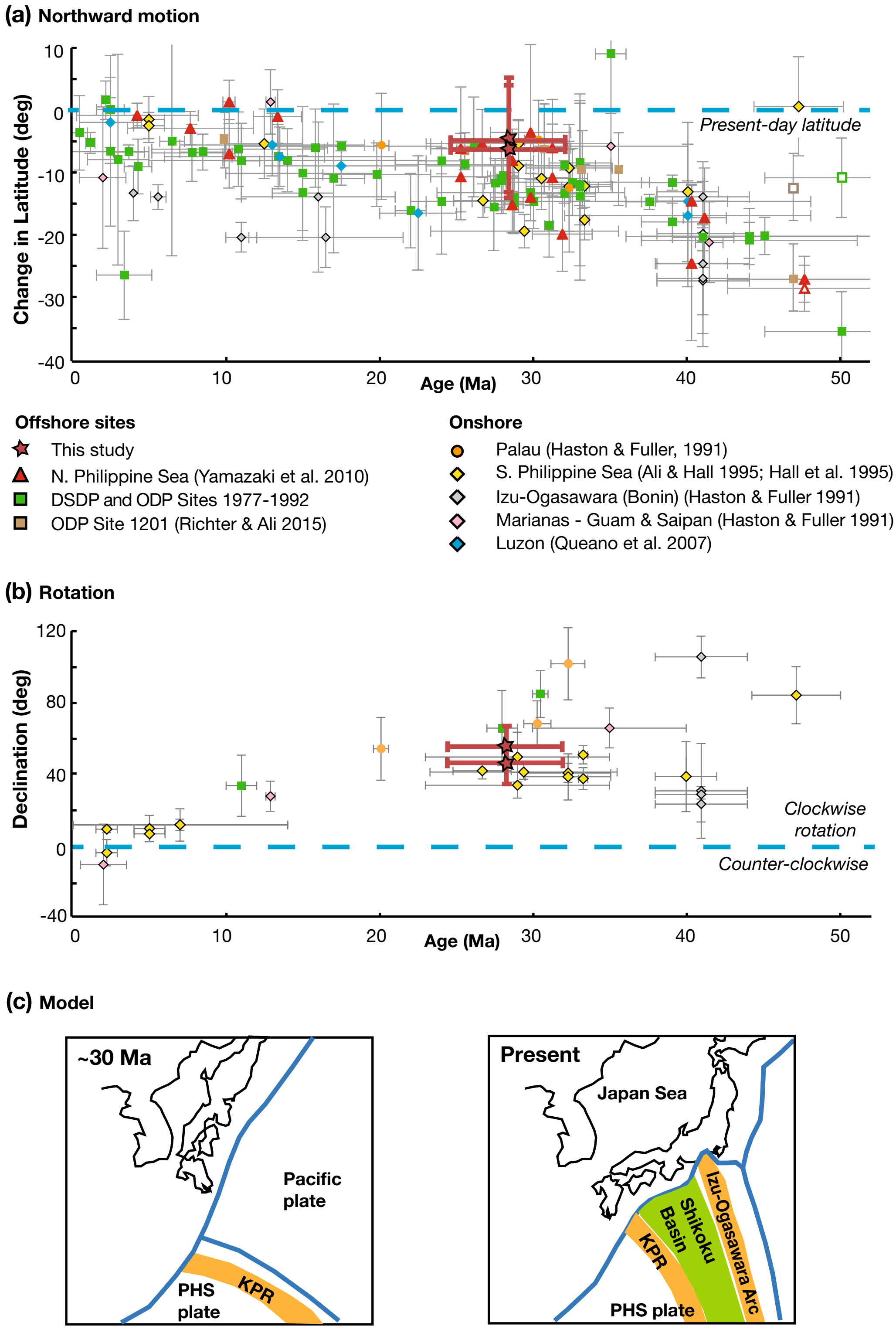

Fig. 5 Latitudinal change (**a**) and rotation (**b**) of the Philippine Sea plate with age compiled from published studies (Wu et al. 2016, Fig. 3) and the present study (red star). References for DSDP and ODP Sites in 1977–1992 are Louden (1977), Kinoshita (1980), Keating and Herrero (1980), Keating (1980), Bleil (1982), Haston et al. (1992), and Koyama et al. (1992). **c** Schematic model of the Kyushu-Palau ridge (KPR) location at ~ 30 Ma (left) and the present positions of KPR and Izu-Ogasawara (Bonin) arc (right)

Conclusions

We successfully obtained oriented cores from the Hyuga seamount on the Kyushu-Palau ridge in the stable interior of the PHS plate using an ROV-based coring apparatus. Paleomagnetic declinations from two limestone cores showed that the PHS plate rotated ~ 50° clockwise since middle to late Oligocene. Inclinations suggest ~ 5° latitudinal change of the Hyuga seamount. It is estimated that the Kyushu-Palau ridge was located to the southwest of the present position in middle to late Oligocene, and moved eastward subsequently to the present position with the PHS plate rotation. It is estimated that the PHS plate rotation as well as the Shikoku and Parece Vela basin spreading contributed to the eastward shift of the Izu–Ogasawara (Bonin) arc to the present position.

Abbreviations

AF: Alternating field; MAD: Maximum angular dispersion; PHS: Philippine Sea; ROV: Remotely operated vehicle.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40623-021-01490-5.

Additional file 1: **Table S1**. Occurrence of calcareous nannofossils in HD2092 cores and estimated ages. **Fig. S1**. Examples of stepwise thermal and alternating-field demagnetizations of samples from HD2092 Cores 3 and 4.

Additional file 2: Data file of paleomagnetic directions shown in Fig. 4.

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Authors' contributions

TY designed the project, conducted the paleomagnetic measurements, and wrote the manuscript. SC conducted nannofossil analysis, OI partly designed the project and provided information on the PHS plate, FT, NU, and ST developed and operated the coring apparatus. All authors read and approved the manuscript.

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Availability of data and materials

The data presented in Fig. 4 are included in Additional file 2.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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References

Ali JR, Hall R (1995) Evolution of the boundary between the Philippine Sea plate and Australia: palaeomagnetic evidence from eastern Indonesia. Tectonophysics 251:251–275. https://doi.org/10.1016/0040-1951(95)00029-1

Bleil U (1982) Paleomagnetism of Deep Sea Drilling Project Leg 60 sediments and igneous rocks from the Mariana region. Init Rept DSDP 60:855–873

Clift PD, Carter A, Nicholson U, Masago H (2013) Zircon and apatite thermochronology of the Nankai Trough accretionary prism and trench, Japan: sediment transport in an active and collisional margin setting. Tectonics 32:377–395

Deschamps A, Lallemand S (2002) The West Philippine Basin: an Eocene to early Oligocene back arc basin opened between two opposed subduction zones. J Geophys Res 107:2322. https://doi.org/10.1029/2001JB001706

Expedition 320/321 Scientists (2010) Methods. In: Pälike H, Lyle M, Nishi H, Raffi I, Gamage K, Klaus A, the Expedition 320/321 Scientists (eds) Proceedings of IODP, vol. 332/321, Integrated Ocean Drilling Program Manage Int Inc, Tokyo. https://doi.org/10.2204/iodp.proc.320321.102.2010

Hall R, Ali JR, Anderson CD (1995) Cenozoic motion of the Philippine Sea Plate: paleomagnetic evidence from eastern Indonesia. Tectonics 14:1117–1132

Hall R (2002) Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations. J Asian Earth Sci 20:353–431

Haston RB, Fuller M (1991) Paleomagnetic data from the Philippine Sea plate and their tectonic significance. J Geophys Res 96:6073–6098

Haston RB, Stokking LB, Ali J (1992) Paleomagnetic data from Holes 782A, 784A, and 786A, Leg 125. Proc ODP Sci Results 125:535–545

Hurst SD, Karson JA, Verosub KL (1994) Paleomagnetism of tilted dikes in fast spread oceanic crust exposed in the Hess Deep rift: Implications for spreading and rift propagation. Tectonics 13:789–802

Hyodo M (1984) Possibility of reconstruction of the past geomagnetic field from homogeneous sediments. J Geomag Geoelecter 36:45–62

Ishizuka O, Taylor RN, Yuasa M, Ohara Y (2011) Making and breaking an island arc: a new perspective from the Oligocene Kyushu-Palau arc, Philippine Sea. Geochem Geophys Geosyst 12:Q05005. https://doi.org/10.1029/2010GC003440

Ishizuka O, Hickey-Vargas R, Arculus RJ, Yogodzinski GM, Savov IP, Kusano K, McCarthy A, Brandl PA, Sudo S (2018) Age of Izu-Bonin-Mariana arc basement. Earth Planet Sci Lett 481:80–90

Keating B (1980) Paleomagnetic study of sediments from Deep Sea Drilling Project Leg 59. Init Rept DSDP 59:523–532

Keating B, Herrero E (1980) Paleomagnetic studies of basalts and andesites from Deep Sea Drilling Project Leg 59. Init Rept DSDP 59:533–543

Kimura J-I, Stern RJ, Yoshida T (2005) Reinitiation of subduction and magmatic responses in SW Japan during Neogene time. Geol Soc Am Bull 117:969–986

Kimura G, Hashimoto Y, Kitamura Y, Yamaguchi A, Koge H (2014) Middle Miocene swift migration of the TTT triple junction and rapid crustal growth in southwest Japan: A review. Tectonics 33:1219–1238. https://doi.org/10.1002/2014TC003531

Kinoshita H (1980) Paleomagnetism of sediment cores from Deep Sea Drilling Project Leg 58, Philippine Sea. Init Rep DSDP 58:765–768
Kirschvink JL (1980) The least-squares line and plane and the analysis of paleomagnetic data. Geophys J R Astron Soc 62:699–718
Kodama K, Keating BH, Helsley CE (1983) Paleomagnetism of the Bonin Islands and its tectonic significance. Tectonophysics 95:25–42
Koyama M, Cisowski SM, Pezard P (1992) Paleomagnetic evidence for northward drift and clockwise rotation of the Izu-Bonin forearc since the early Oligocene. Proc ODP Sci Results 126:353–370
Lallemand S (2016) Philippine Sea Plate inception, evolution, and consumption with special emphasis on the early stages of Izu-Bonin-Mariana subduction. Prog Earth Planet Sci 3:15. https://doi.org/10.1186/s40645-016-0085-6
Louden KE (1977) Paleomagnetism of DSDP sediments, phase shifting of magnetic anomalies, and rotations of the West Philippine Basin. J Geophys Res 82:2989–3002
Løvlie R (1976) The intensity pattern of post-depositional remanence acquired in some marine sediments deposited during a reversal of the external magnetic field. Earth Planet Sci Lett 30:209–214
Mahony SH, Wallace LM, Miyoshi M, Villamor P, Sparks RSJ, Hasenaka T (2011) Volcano-tectonic interactions during rapid plate-boundary evolution in the Kyushu region, SW Japan. Geol Soc Am Bull 123:2201–2223
Maruyama S, Isozaki Y, Kimura G, Terabayashi M (1997) Paleogeographic maps of the Japanese Islands: Plate tectonic synthesis from 750 Ma to the present. Island Arc 6:121–142
Otofuji Y-I, Enami R, Yokoyama M, Kamiya K, Kuma S, Saito H (1999) Miocene clockwise rotation of southwest Japan and formation of curvature of the Median Tectonic Line: Paleomagnetic implications. J Geophys Res 104:12895–12907
Queano KL, Ali JR, Milsom J, Airchison JC, Pubellier M (2007) North Luzon and the Philippine Sea Plate motion model: Insights following paleomagnetic, structural, and age-dating investigations. J Geophys Res 112:B05101. https://doi.org/10.1029/2006JB004506
Richter C, Ali JR (2015) Philippine Sea Plate motion history: Eocene-Recent record from ODP Site 1201, central West Philippine Basin. Earth Planet Sci Lett 410:165–173. https://doi.org/10.1016/j.epsl.2014.11.032
Sasaki T, Yamazaki T, Ishizuka O (2014) A revised spreading model of the West Philippine Basin. Earth Planets Space 66:83. https://doi.org/10.1186/1880-5981-66-83
Sdrolias M, Roest WR, Müller DR (2004) An expression of Philippine Sea plate rotation: the Parece Vela and Shikoku Basins. Tectonophysics 394:69–86
Seno T, Maruyama S (1984) Paleogeographic reconstruction and origin of the Philippine Sea. Tectonophysics 102:53–84
Shih TC (1980) Marine magnetic anomalies from the western Philippine Sea: implications from the evolution of marginal basins, tectonic and geologic evolution of southeast Asia seas and islands. AGU Geophys Monogr 23:49–75
Tajima F, Uto N, Takagawa S (2020) Surveying cobalt crust: ROV-based coring machine supports deep-sea mining. Sea Technol 61(9):10–12
Takahashi M, Saito K (1997) Miocene intra-arc bending at an arc-arc collision zone, central Japan. Island Arc 6:168–182
Taylor B, Goodliffe AM (2004) The West Philippine Basin and the initiation of subduction, revisited. Geophys Res Lett 31:L12602. https://doi.org/10.1029/2004GL020136
Wu J, Suppe J, Liu R, Kanda R (2016) Philippine Sea and East Asian plate tectonics since 52 Ma constrained by new subducted slab reconstruction methods. J Geophys Res Solid Earth 121:4670–4741. https://doi.org/10.1002/2016JB012923
Xu J, Ben-Avraham Z, Kelty T, Yu H-S (2014) Origin of marginal basins of the NWPacific and their plate tectonic reconstructions. Earth-Sci Rev 130:154–196
Yamazaki T, Takahashi M, Iryu Y, Sato T, Oda M, Takayanagi H, Chiyonobu S, Nishimura A, Nakazawa T, Ooka T (2010) Philippine Sea Plate motion since the Eocene estimated from paleomagnetism of seafloor drill cores and gravity cores. Earth Planets Space 62:495–502
Zahirovic S, Seton M, Müller RD (2014) The Cretaceous and Cenozoic tectonic evolution of Southeast Asia. Solid Earth 5:227–273

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