Ocean Sci. J. (2018) 53(2):369–380
http://dx.doi.org/10.1007/s12601-018-0024-0

Available online at http://link.springer.com

Article

pISSN 1738-5261
eISSN 2005-7172

Rock Magnetic Approaches Used on Deep-sea Sediments in the Northeastern Equatorial Pacific

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Received 2 July 2017; Revised 21 September 2017; Accepted 9 February 2018

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Abstract – Rock magnetic properties of unconsolidated sediments from the Korea Deep Ocean Study area of the northeastern equatorial Pacific were analyzed to trace the time-dependent variations of sedimentary environments. For upper Pleistocene sediments, light-brown sediments predominate, whereas the lower sediments deposited in the late Pliocene are dark brown. Rock magnetic properties also clearly differ among the two distinct color environments. Values of anhysteretic remanent magnetization and low-field magnetic susceptibility are highly responsive to changes in the color of the sediment. For example, comparatively low values denote a dominance of coarse-grained magnetic minerals as observed in the lower dark-brown layers. With respect to the content of magnetic minerals, coarse magnetic grains are highly concentrated in the darker-colored sediment layers. However, both the magnetic mineral dependent parameter (S ratio) and results of the scanning electron microscope observation indicate that magnetic mineral changes did not occur along the core depth, which means that there was no apparent source change. Without distinctive source changes, the variations in the rock magnetic properties likely reflect a process by which the magnetic grains were primarily transported by enhanced wind and bottom currents and affected by diagenetic dissolution as a function of both the time from burial and the extremely low sedimentation rates after deposition.

Keywords – rock magnetic properties, paleoenvironment, polymetallic nodules, northeastern equatorial Pacific, KODOS area

1. Introduction

Development of eco-friendly deep seabed mineral resources is an issue that is generating much interest, debate and contention in the field of deep-sea mining in the 21st-century as it becomes a new domain in the marine industry. Deep-sea mining intrinsically produces environmental impact characteristics of various types. As the effects of deep-sea mining may change the sea floor environment, detailed data on past and present marine geological characteristics need to be assessed in order to restore the environment and minimize the impacts of deep-sea mining. For this purpose, acquiring and understanding the baseline data of as many geological phenomena as possible related to the deep seabed should be the first study aim when considering deep-sea mining programs.

The Clarion-Clipperton Fracture Zone (C-C Zone), known as the polymetallic nodule belt of the northeastern equatorial Pacific (NEP) region, is bounded by the Hawaiian and Line Island ridges to the west and the Central American continent to the east. The KOrea Deep Ocean Study (KODOS) area is located in the southern part of the C-C Zone. Since 1990, the Korea Institute of Ocean Science and Technology (KIOST) has performed a number of investigations on the potential for the C-C Zone to become a promising area to conduct a national long-term R&D program. With respect to evaluating the commercial value of polymetallic nodules and development potential of deep-sea mining technology, sedimentological approaches to study the sea floor and seabed are indispensable tools for understanding the formation mechanisms and distribution trends of mineral deposits.

Among various sedimentary methods, magnetism of sediments has played a key role in reconstructing paleoceanographic and paleoclimatic conditions associated with deep-sea resource evaluation models. Because magnetic minerals in sediments have primarily undergone the same sedimentary processes as non-magnetic particles, the magnetic components recorded in sediment cores could be used as an index to infer changes in the paleoclimate and depositional environment (Tarduno 1994; Verosub and Roberts 1995; Sminov and Tarduno 2000; Sagnotti

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*Corresponding author. E-mail: ckpark@kiost.ac.kr et al. 2001; Deng et al. 2006). In particular, rock magnetism has provided indications to help understand the origin of primary magnetic materials and aeolian fluxes associated with glacial/interglacial cycles (Korff et al. 2016). In the north and west Pacific, the fluctuation in the rock magnetic signal with core depth is caused by the change in input of aeolian dust transported from the Asian continent (Yamazaki and Ioka 1997). Yamazaki (2009) showed that the inter-parametric ratio of rock magnetic components could be used to estimate the relative abundances of biogenic and terrigenous materials in western Pacific sediments. Studies have actively used rock magnetic and environmental magnetic approaches to investigate Pacific sediments. These approaches have also been applied to the study of both paleoceanography and paleoclimatology (Janecek et al. 1983; Doh et al. 1988; Doh 1989; Yamazaki and Ioka 1997; Tarduno et al. 1998; Yamazaki 2009; Park et al. 2012).

However, most studies using rock magnetic approaches in the Pacific have mainly focused on the relatively high latitudes of the western, central, and northern Pacific areas. In the NEP sediments, the temporal and spatial variation in rock magnetic properties are not yet well documented and defined. The sedimentary environment of the NEP is generally characterized by deep water depths, low primary production, extremely low sedimentation rates, oxic conditions, and a distinct latitudinal zonation of sedimentary facies. The paleoenvironment of the KODOS area is difficult to understand because of the complex distribution of sediments from various sources and the prolonged geochemical processes occurring after deposition. One of the most useful methods used in this area involves the interpretation of paleoceanographic changes using rock magnetic properties maintained in the sediment column.

Several prior studies regarding the anisotropy of magnetic susceptibility (AMS) and paleomagnetism have been conducted based on the core samples used in this study (Park et al. 2000, 2004). Park et al. (2000) showed that anomalous magnetic fabric (magnetic lineation) is mainly observed at the boundary where sediment color changes and outlined its relation to input changes of intensified bottom currents. Park et al. (2004) carried out a paleomagnetic study of the studied sediments from the KODOS area and discussed the relation between paleomagnetic properties. According to Park et al. (2004), the geologic timeframe contained within 4 m long cores corresponds to the period from the Pleistocene and Late Pliocene, and the boundaries between these periods in cores KPC02 and KPC09 are located at 196.2 and 193.7 cm, respectively. They suggested that the down-core variations in sediment magnetism of KODOS sediments were affected by dissolution processes in an oxic depositional regime. However, despite the significant results obtained from the study of sediment magnetism, it remains debatable whether the changes in magnetic properties with depth were caused by changes in magnetic minerals or by geochemical changes minerals after deposition. In the present study, we obtained a sequential variation record of rock magnetic properties from sediment cores collected in the abyssal plain of the NEP. The factors controlling sedimentation and their potential connection to climate change can be inferred by studying the sedimentary rock magnetic variation along with biogeochemical and isotopic parameters.

2. Materials and Methods

Prior to sediment core sampling, bathymetric surveys were performed using a multi-beam echosounder. The sea floor of the studied area has depths between 4500 m and 5300 m. A rectangular area represented by black dashes in Fig. 1 was selected to explain the morphological features in the study area. As shown in the figure, the morphology generally comprises flat-topped abyssal hills and adjacent troughs, both of which are developed parallel in a northwest—southeast direction. The mean slope gradient in this area was 2.8°, ranging from 0.1° to 17.1°, which is typical of abyssal plains. The trend in morphology appears to be roughly perpendicular to the trend of the Clarion and Clipperton Fracture.

Corliss and Hollister (1979) found that the spatial distribution pattern of northeastern Pacific sediments could be divided into three sediment facies. First, between 20°N and 40°N, the sediments contain a large detrital component along with some authigenic minerals, which is attributed to the increased input of terrestrial materials from intensified atmospheric circulation. Second, between 10°N and 20°N, the C-C zone sediments are mainly composed of authigenic minerals with siliceous clay. In particular, they include calcareous compensation depths (CCD) presently located at ~ 4600 ± 100 m (Bostock et al. 2011). Because the sediments obtained from the research area are far below the CCD, core sediments mainly comprise radiolarian-bearing siliceous sediments (Park et al. 2000). These sediments contain a large amount of authigenic minerals that are important ingredients of polymetallic nodules and smectites (Horn et al. 1973; Greenslate et al. 1973; Bischoff et al. 1979). Third, near the equator, the sediments are

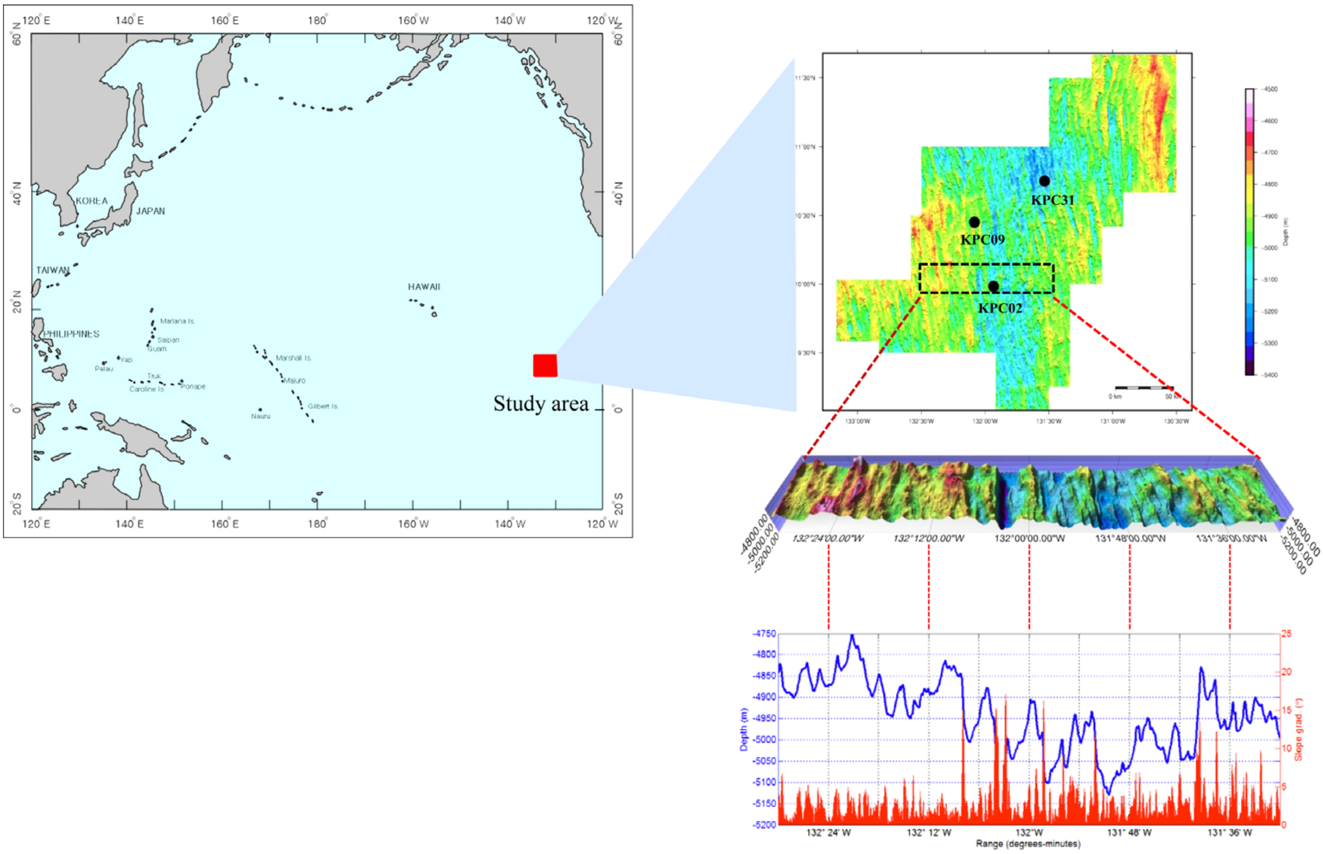

Fig. 1. Topographic map of the study area

dominantly composed of calcaresous ooze. The sedimentary regime of the study area belongs to a transitional zone between a non-fossiliferous, pelagic clay-dominated zone and a calcareous sediment-dominated zone. The observed latitudinal zonation of sedimentary facies has resulted from both the accumulation of biogenic materials associated with the equatorial current and the movement of the Pacific plate toward the north or northwest (Corliss and Hollister 1979).

Three piston cores were recovered from the research area (Table 1). Cores KPC02 and KPC09 were obtained during the KODOS cruise on the Korea R/V Onnuri in 1995 from neighboring stations that differed in location by less than 30′ in latitude and longitude. Cores KPC02 and KPC09 are 306 and 345 cm long and were recovered from water depths of 4976 and 4788 m, respectively. The site of core KPC31 is situated in the northern part of the research area. Core KPC31 was also obtained during the KODOS cruise on the R/V Onnuri in 1994. The 306 cm long core KPC31 was recovered from a water depth of 5050 m. Prior to collecting subsamples, the cores were examined in detail for both lithological features and color change with core depth using a soil color chart (Munsell 1975).

Table 1. Summary of Cores collected in the Research area

Core	Sampling location		Water depth (m)
	Latitude (N)	Longitude (W)	
KPC02	10°00'	131°56'	4,976
KPC09	10°27'	132°05'	4,788
KPC31	10°45'	131°30'	5,050

A total of 341 subsamples were obtained from the cores using 8 cm^3 non-magnetic cubes, and rock magnetic measurements were performed. The number of collected subsamples used for the analyses was 129, 139, and 73 cubic samples obtained from cores KPC02, KPC09, and KPC31, respectively. After weighing, all samples were subjected to various magnetic experiments and measurements including low-field magnetic susceptibility (X_{LF}), anhysteretic remanent magnetization (ARM), and saturation isothermal remanent magnetization (SIRM). X_{LF} was measured using a magnetic susceptibility meter (Bartington Instruments MS1B) at a frequency of 0.47 kHz. Following measurements of natural remanent magnetization, several pilot samples were selected based on lithological characteristics, such as variations in sediment color and facies. The ARM measurements were conducted using a Molspin alternating field (AF) demagnetizer with an ARM attachment at a peak of 90 mT, superimposed with a steady 0.05 mT direct current (DC) field. Isothermal remanent magnetization (IRM) acquisition was performed using an ASC Scientific IM-10-30 impulse magnetizer. For convenience, an IRM of 2.5 T imparted on a sample is regarded here as SIRM. A DC field of 0.3 T was applied at saturation in the opposite direction ($IRM_{-0.3T}$). All the remanence measurements were performed using a Molspin spinner magnetometer. The measurements were used to obtain the typical magnetic parameters and inter-parametric ratios related to magnetic concentrations (X_{LF}, ARM and SIRM), grain - size (ARM/X_{LF}), and the relative ease of swapping the coercivity polarities ($HIRM = (SIRM/2)(1 + IRM_{-0.3T} / SIRM$; S ratio ($S_{-0.3T}$) = $-IRM_{-0.3T}/SIRM$). Sediment samples for microscopic observation were prepared from core KPC31. Magnetic grains were extracted using a circulated suspension method driven by a peristaltic pump similar to Channell et al. (2013). Surface pattern of magnetic extracts were observed with the scanning electron microscope (SEM, Philips SEM515) in conjunction with an energy dispersive x-ray microanalyser (EDX) after coating the surface with gold.

3. Results

As observed in Fig. 2, core KPC02 displays alternating sections of lightly gray (10YR 6/1), lightly yellowish brown (10YR 6/4), brown (10YR 3/4), grayish brown (10YR5/2) and dark brown (10YR 3/2) layers. The upper (0–20 cm) and middle parts (110–140 cm) of the core are intensively bioturbated and characterized by numerous planolites, solid open burrows, some zoophycos, and horizontal and vertical burrows. Core KPC09 shows alternating intervals of grayish brown (10YR 6/1), yellowish brown (10YR 6/4), grayish brown (10YR5/2), pale brown (10YR 6/3), brown (10YR 5/3), and very dark grayish brown (7.5YR 3/2) layers. The hues of the lower part are darker than the upper part with a light yellowish brown shade. These features may be related to the content ratio of microfossils and sediments. Core KPC31 comprises brown (10YR 3/4), dark yellowish brown (10YR 5/3), and very dark grayish brown (10YR 3/2) sediment layers (Fig. 2). The burrowing traces in the dark brown sediment layers are relatively simple

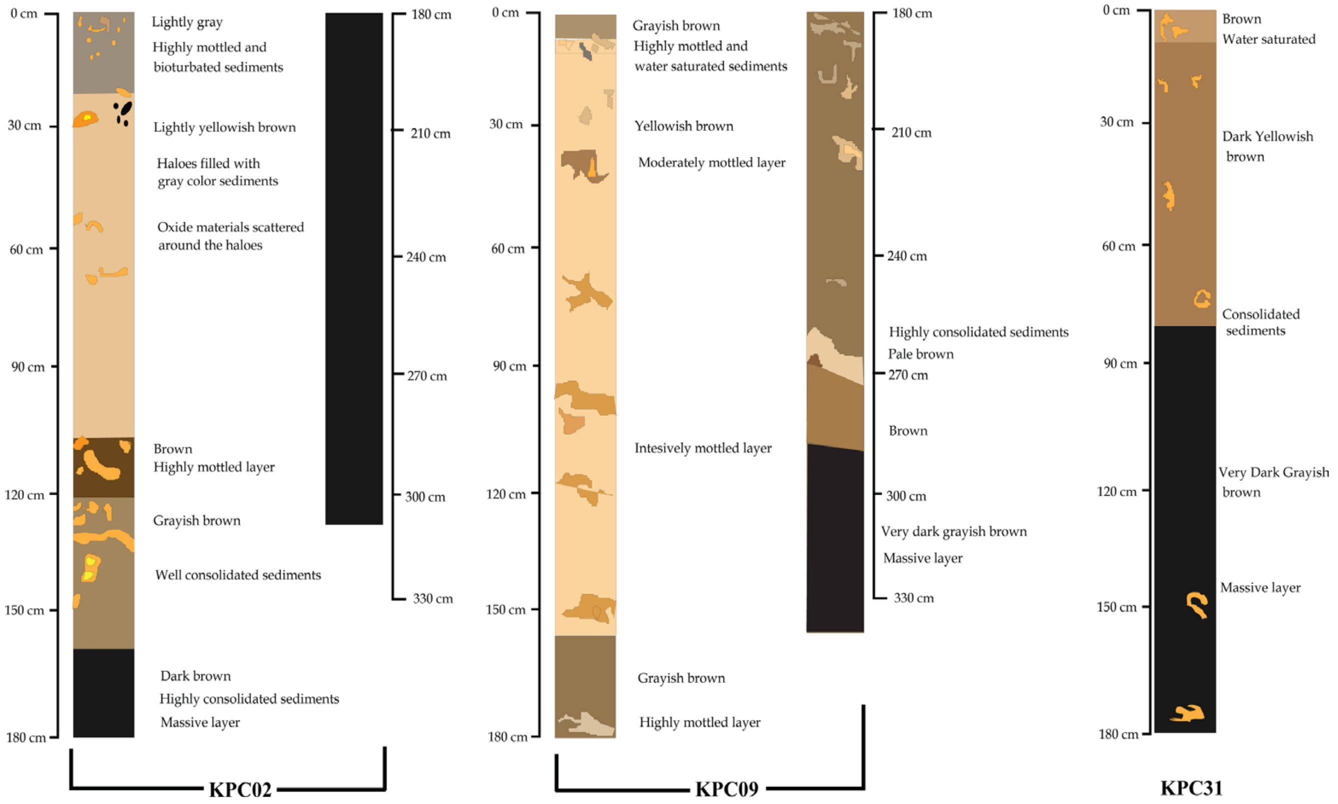

Fig. 2. Visual descriptions of archived sediments including distinctive sedimentary layers, bioturbation, and color. Color was determined from the Munsell (1975)

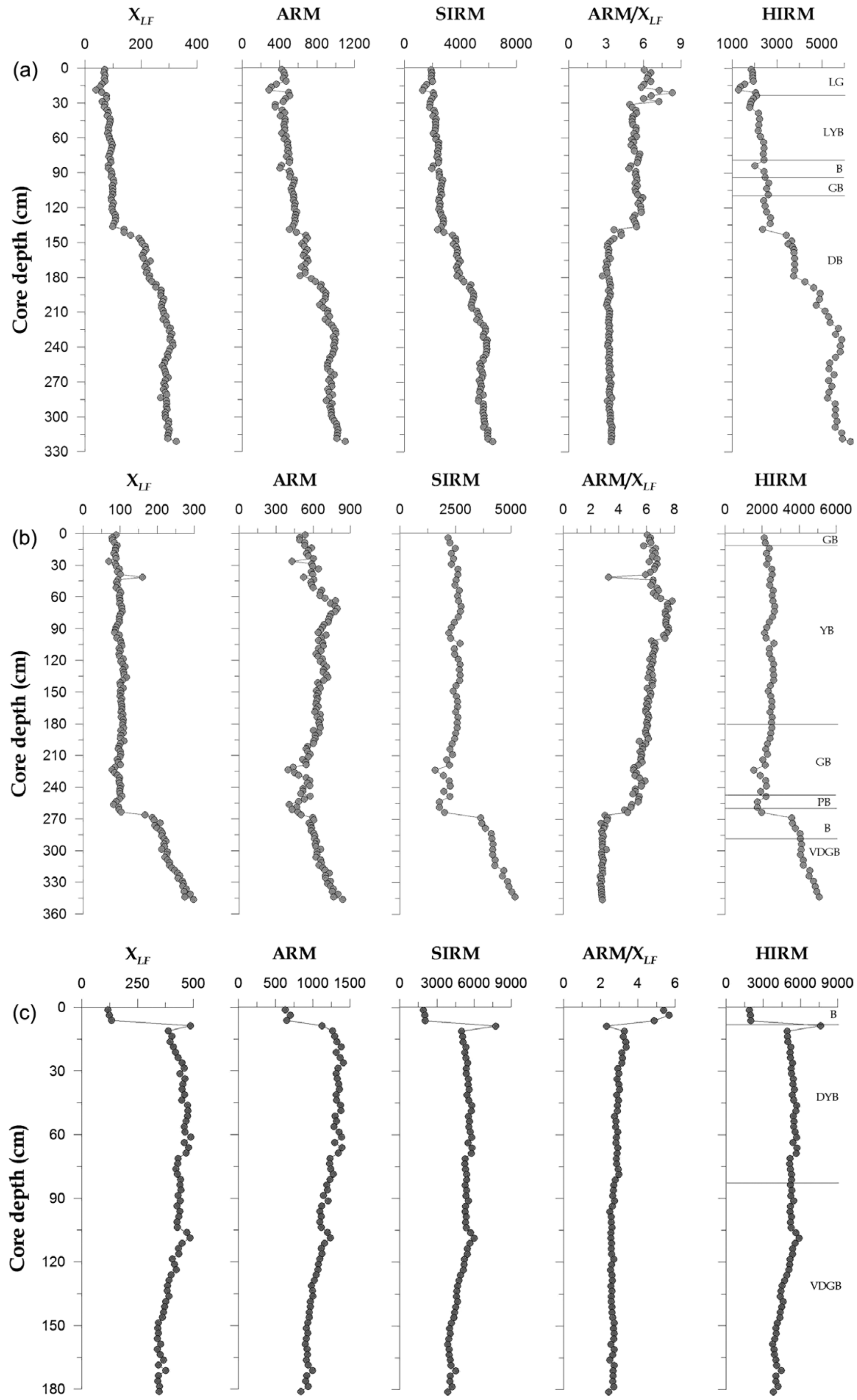

Fig. 3. Vertical profiles of rock-magnetic parameters in a) KPC02; b) KPC09; c) KPC31, including magnetic concentration dependent parameters (X_{LF}, ARM, SIRM), grain-size dependent parameters (ARM/X_{LF}), and relative abundance of high- and low-coercivity minerals (HIRM)

and less mottled compared with the brown sediments.

Figure 3a shows the vertical profiles of the concentration-dependent magnetic parameters (X_{LF}, ARM, and SIRM) and a grain-size proxy (ARM/X_{LF}) for core KPC02. The values of X_{LF}, ARM and SIRM are in the range of 39–326 × 10^{-8} m^3kg^{-1}, 286.5–1101.4 × 10^{-8} Am^2kg^{-1} and 1314.0–6307.4 × 10^{-5} Am^2kg^{-1}, respectively. The concentration-related magnetic parameters show coherent fluctuations within a core. The concentration-dependent parameters show a monotonous decrease from the lightly gray to the lightly yellowish brown layer and then gradually increasing trends toward the base of the cores. ARM/X_{LF} results show rather high values (4.6–5.9 × 10^{-8} A/m) in the upper part (0–133 cm in depth), whereas below the depth of 150 cm, lower values (2.6–4.9 × 10^{-8} A/m) than those of the upper part were observed. And these values did not change significantly with depth. The variation in ARM/X_{LF} results indicates an inverse correlation between the concentration-dependent parameters, indicating that coarser magnetic grains are found in the higher magnetic concentration intervals. The values of the S ratio increased from 0.96 to 1.0 with magnetite being the major contributor to the magnetic component (Fig. 4).

The variations in X_{LF}, SIRM, and HIRM for core KPC09 are distinct at the color boundary between the grayish brown and dark grayish brown layers (Fig. 3b). The above concentration parameters show relatively uniform values in the upper section (0–270 cm in depth) and increase dramatically at the color boundary. For instance, moderate X_{LF} values ranging from 78.1 × 10^{-8} to 160.2 × 10^{-8} m^3kg^{-1} are maintained until the depth of 270 cm and then increased abruptly to 298.4 × 10^{-8} m^3kg^{-1} at the depth of ~340 cm, where the very dark grayish brown sediment interval begins. The ARM profiles show increasing trends (490.6–777.6 × 10^{-8} Am^2kg^{-1}) to the depth of 70 cm, gradually decrease (438.0–793.8 × 10^{-8} Am^2kg^{-1}) to the depth of 235 cm, and increase (405.5–839.4 × 10^{-8} Am^2kg^{-1}) toward the base of the core. The ARM/X_{LF} ratio shows a decreasing trend toward the base of the core. In particular, below the depth of 270 cm, the values of ARM/X_{LF} show a drastic decreasing trend. The ARM/X_{LF} profiles are highly responsive to changes in the color of the sediment. The high magnetic concentration and coarse magnetic grains found at the depth of lithologic change (below the depth of 270 cm) appear to result from either a change in deposition of magnetic materials or by geochemical processes. The increase of the S ratio values ranged from 0.90 to 1.0, indicating that the main magnetic mineral is a low coercivity magnetic mineral (Fig. 4).

In core KPC31, an abrupt increase in magnetic concentration-

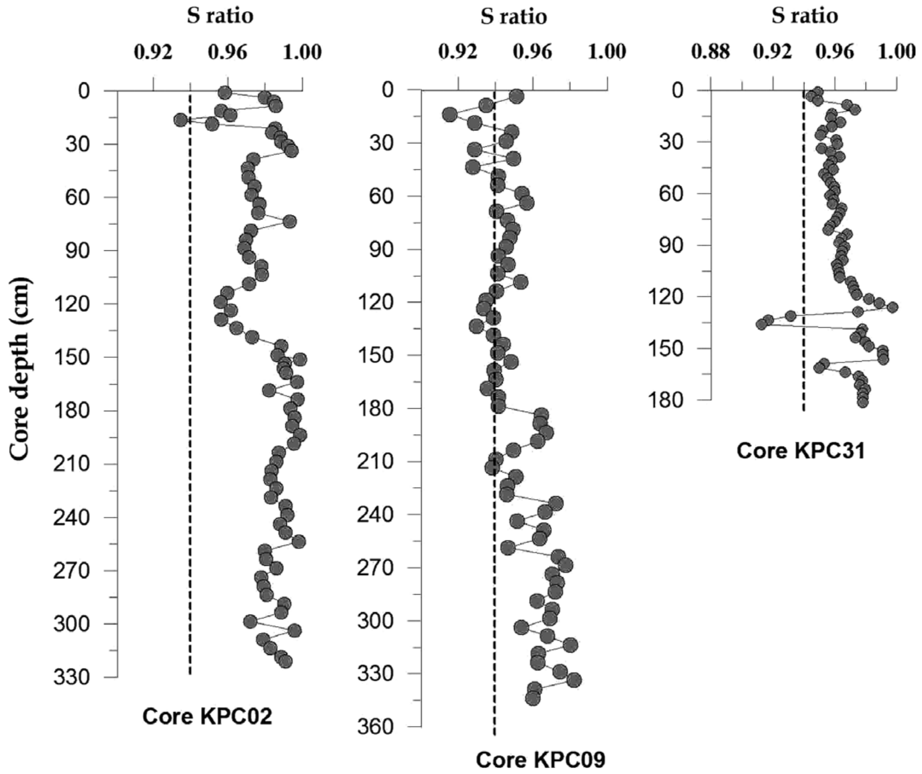

Fig. 4. Vertical fluctuations of S ratio in each sediment cores

dependent parameters (X_{LF}, ARM, and SIRM) was observed at the boundary between the brown and dark-brown layers (10 cm in depth) (Fig. 3c). In the dark-brown layer, the value of the concentration-dependent parameters is more than twice as high as that of the upper brown layer. ARM/X_{LF} in the brown layer shows relatively high values that indicate fine magnetic grains, whereas ARM/X_{LF} in the lower dark layer shows low values that indicate coarse magnetic grains. A minimum value of ARM/X_{LF} occurred on the boundary between the brown and dark-brown layers. Below the color boundary, the ARM/X_{LF} profile shows a relatively low value ($2.3–3.4 \times 10^{-8}$ A/m) that slightly decreases toward the base. The down-core variations of grain-size- and concentration-dependent parameters in the dark-brown sediments indicate that the magnetic materials in the lower dark sediments reflect coarser magnetic grains and higher magnetic concentrations than those in the upper brown sediments. The S ratio value ranged from 0.91 to nearly 1.0, indicating that the magnetic minerals are low-coercivity magnetic minerals (Fig. 4). The evaluation results of the entire cores imply that the coarser magnetic grains are highly concentrated in the darker - sedimentary layers (i.e., those corresponding to the apices of X_{LF}, ARM, and SIRM, and the lower values of ARM/X_{LF}).

4. Discussion

Rock magnetic parameters are commonly applied as indices to define changes in both the paleoclimate and the depositional environment based on the concentration, grain-size, and mineralogy of the magnetic minerals in sediment cores (Verosub and Roberts 1995; Sagnotti et al. 2001; Deng et al. 2006). Of the various parameters, ARM is sensitive to fine grains (< 1 μm), whereas X_{LF} and SIRM are applicable to the various sizes of magnetic minerals (e.g., Maher 1988; Evans and Heller 2003). Hence, ARM/X_{LF} is widely used as a grain-size proxy, wherein higher values of ARM/X_{LF} indicate a finer average grain-size in the sample. For the magnetic mineralogy deduced from coercivities, HIRM and S ratios are effective in determining the relative abundance of high-coercivity magnetic minerals (hematite and/or goethite) over low-coercivity magnetic minerals (magnetite), respectively. For instance, magnetite-dominant samples have low HIRM and high S ratios.

According to Park et al. (2004), the geologic timeframe contained within 4 m long cores corresponds to the period from the Pleistocene and Late Pliocene, and the boundaries between these periods in cores KPC02 and KPC09 are located at 196.2 and 193.7 cm, respectively. In paleoceanography, the sedimentary environment during the Pliocene and Pleistocene is summarized by the onset of the northern hemisphere glaciation and subsequent climatic deterioration resulting in an increase in global aridity and the intensification of atmospheric circulation (Janecek and Rea 1983). During these periods, large amounts of aeolian materials were transported to the deep-sea floor by strong winds or active bottom currents (Corliss and Hollister 1979; Janecek and Rea 1983). Previous results from measurements made on these core samples showed that terrestrial minerals dominate in the surface sediment layers (Park et al. 2000). However, in the lower dark-brown sediments that are just below the surface, the brown sediments mainly comprise authigenic smectite with small amounts of terrestrial minerals. The high content of terrestrial minerals resulted from increased aeolian input derived from the American continent (Janecek and Rea 1983) from the Late Pliocene to Pleistocene eras (Jacob and Hayer 1972; Janecek and Rea 1983). Authigenic smectite is an iron (Fe-)-rich montmorillonite that typically forms by the chemical reaction between Fe-oxyhyroxides and silicas dissolved from siliceous fossils under oxic conditions (Aoki et al. 1979; Hein et al. 1979).

These variations in mineralogical patterns with depth or color can be interpreted in two ways: 1) differences of aeolian input rates and 2) diagenesis of terrestrial materials. Detrital magnetic minerals are also subject to the same depositional processes as the non-magnetic components of aeolian materials (Doh et al. 1988). The result of rock magnetic measurements of the north Pacific sediments revealed that the relative grain-size variations of magnetic materials are parallel to those of the total aeolian component within the magnetically stable sediments (Doh et al. 1988). Yamazaki and Katsura (1990) proposed that an intensified global atmospheric circulation was responsible for the increase in the aeolian magnetic grain size. These results indicate that the variation in magnetic grain size is closely related to the change in aeolian input rates. The ARM/X_{LF} profiles show an inverse correlation to down-core variations in the concentration-dependent parameters, indicating that the magnetic grain size in the high magnetic concentration levels is relatively coarser than that in the low concentration levels (Fig. 3a, b, and c). The fine magnetic grains and low magnetic concentrations in the upper brown sediment layers imply that the influence of aeolian inputs in the upper part is relatively weaker than that of the aeolian inputs in the lower part. Aforementioned results are commonly explained through the change in aeolian flux associated with climate change. However, aeolian inputs have been continuously existed in the north Pacific since the Pliocene. The results of variation in the magnetic grain size and concentration within the sediment column from the cores in this study indicate that there should be additional factors other than climate change to show such variations.

Another possible explanation for the down-core variation in the magnetic grain size and concentration is the dissolution process, as shown in the diagenetically altered sediments of the northwest Pacific region (Karlin 1990). Karlin and Levi (1985) suggested that the decrease in the magnetic stability with depth is associated with the dissolution of magnetic material from marine sediments, indicated by the change in sediment color from brown (oxidizing condition) to greenish gray (anoxidizing condition). The variation in magnetic properties is attributed to the change in the magnetic gran size in diagenetically altered sediments (Karlin 1990; Yamazaki and Katsura 1990). It has been reported that authigenesis of both magnetic minerals and manganese oxyhydroxides is the dominant process occurring in pelagic clay from the north Pacific (Henshaw and Merill 1980; Prince et al. 1980). Diagenetic and authigenic magnetic materials significantly contribute to the bulk magnetic properties in suboxic or anoxic sediments (Leslie et al. 1990). In the north Pacific seabed, diagenesis and authigenesis are dominant during intervals of low sedimentation rates, and the natural remanence behavior deteriorates in this type of sediment (Prince et al. 1980). The sediments, distributed in the KODOS seabed, are known to be oxic (Jung 1998). In an oxic sedimentary environment, the diffusion of oxygen by porewater in the sediments exceeds the consumption of oxygen by bacteria during the degradation of organic matter because of extremely slow sedimentation rates (less than 2 mm/kyr). Thus, the sediments remain oxic throughout the length of the sediment column. The upper, lighter brownish sediments show a stable remanence and mainly comprise detrital mineral assemblages. The lower, darker brownish sediments show less stable magnetic behavior and mostly comprise amorphous Fe- oxides and authigenic materials. Sufficient formation of authigenic oxides (very-fine-grained manganese nodules) can be caused by the micro-reducing conditions to remobilize metal oxides within the oxic sediments in NEP (Jung 1998). Yamazaki et al. (1991) concluded that the higher clay content of no-fossil-bearing sediments would cause corrosion of magnetite, resulting in a larger amount of viscous superparamagnetic grains under oxidizing conditions. These results imply that the variation in magnetic behaviors with depth can be produced by the difference in the size distribution of magnetic particles in oxidizing sedimentary environments. This effect can also account for the dissolution of the fine-grained magnetic fractions and the partial dissolution of coarser magnetic grains. An increase in magnetic grain size is related to a reduced concentration of fine, single domain or pseudo single domain magnetic grains resulting from the dissolution process.

The magnetic minerals of surface brown sediments show stable behavior, finer magnetic grain size, and low magnetic concentration. These results seldom appear to be influenced by climatic change. In contrast, previous studies proposed that the large amounts of terrestrials found in surface sediments result from metal removal by diagenetic processes rather than an increased accumulation of terrigenous sediments (Marchig and Gundlach 1979; Fostner and Stoffer 1981; Piper 1988; Jung et al. 1998). The magnetic materials in the lower, dark sediments show relatively coarser grain size, less stable behavior, and high magnetic concentration (Fig. 3a, b, and c). The deterioration of magnetic stability within the lower dark-brown layer may be ascribed to the dissolution of stable single domain (SD) grains (Park et al. 2004). Moreover, the increasing HIRM in the dark-brown sediment layer indicates the presence of high-coercivity magnetic materials such as hematite/goethite. However, Fe-magnetic minerals dominate the overall magnetic properties of the sediments. Hematite is much more chemically stable in oxic sediments and commonly occurs as early authigenic mineral (Tarling and Hrouda 1983). As a detrital magnetic mineral, hematite can be associated with partially oxidized ilmenite, magnetite, and other Fe-bearing minerals (Tarling and Hrouda 1983). In this study, the increasing HIRM has been influenced by authigenic oxides or oxyhydroxides distributed in the dark-brown sediments because these sediments contain abundant manganese micronodules. The morphology of magnetic grains is caused by authigenic formation or diagenetic dissolution processes (Fig. 5). The occurrence pattern of siliceous microfossils with depth also shows a decrease in the abundance and deterioration of the quality of revealed microfossils (Fig. 6). The majority of radiolarians are corroded, fragmented, and evenly barren below the boundary of color change.

Figure 7 denotes a plot of ARM versus X_{LF} for the studied cores. Changes in the slope are attributed to changes in relative grain size. Higher slopes indicate smaller magnetic

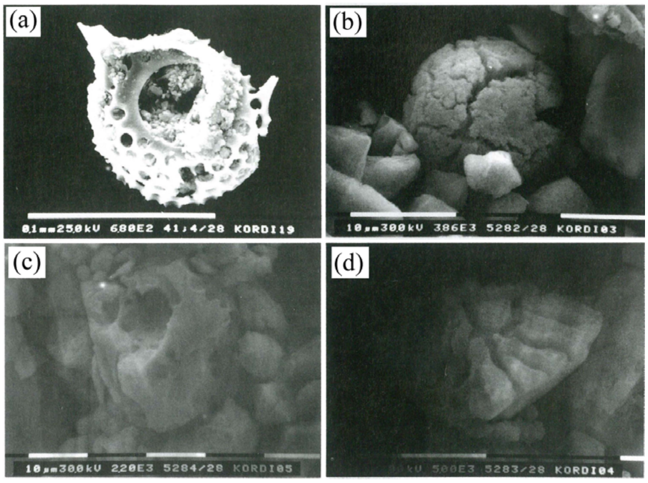

Fig. 5. Scanning electron microscope of magnetic separates from core KPC31. Dimensions in microns are the widths of the scale bar. a) Typically detrital and authigenic magnetic grains within siliceous micro fossil in brown color layer, b), c) and d) dissolution features of detrital magnetite in lower dark brown layer (136.2 cm in core depth)

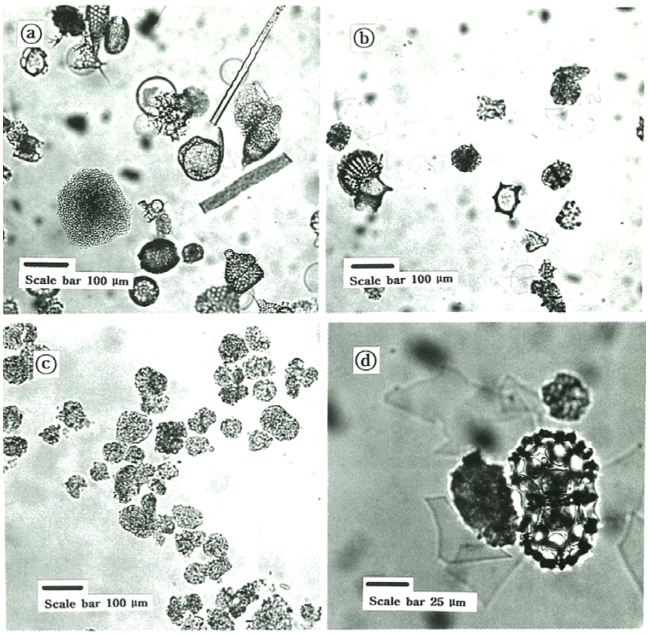

Fig. 6. The occurrence of intensively corroded siliceous fossils with measuring depth in core KPC31: a) the topmost part; b) 16 cm; c) 60 cm

grain size; lower slopes indicate larger magnetic grain size. The data points closer to the origin imply gradually decreasing magnetic concentration. Distinct features differentiating ARM from X_{LF} include the bimodal distributions of magnetic mineral grain sizes as found in cores KPC02, KPC09, and KPC31. The finer magnetic grains occur in the brown layer.

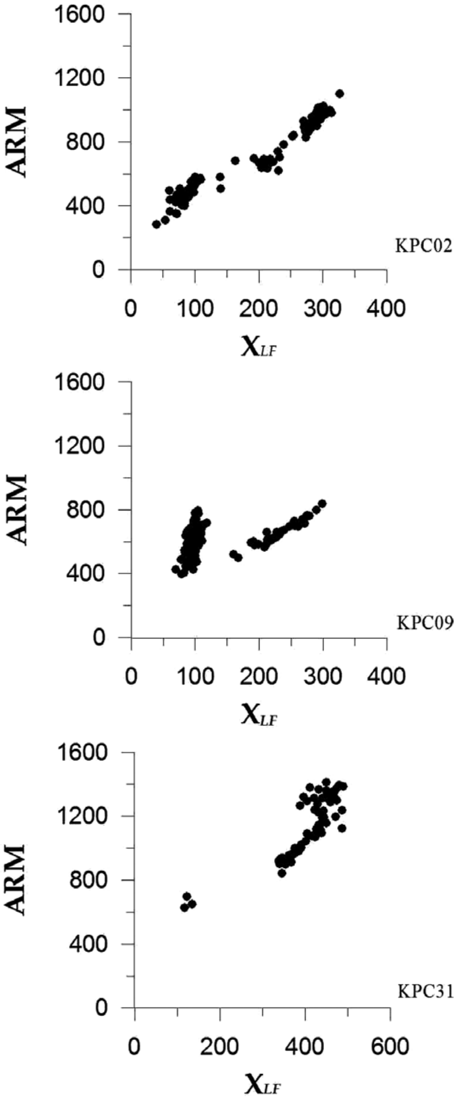

Fig. 7. A plot of ARM vs. X_{LF} for sediment cores from KPC02, KPC09 and KPC31

Below the brown layer, the magnetic grains are coarser and the magnetic concentration increases significantly. Bloemental et al. (1992) suggested that the bimodal distributions of magnetic grain sizes are caused by the post-depositional utilization of magnetic Fe oxides by bacteria for the oxidation of organic matter under suboxic conditions. However, this does not account for biogenic processes undertaken by magnetotatic bacteria in siliceous sediments as these bacteria are rare or nonexistent in siliceous sediments (Kirschvink and Chang 1984).

Differences in the magnetic mineralogy, changes of concentration, and variations in the grain sizes of the magnetic minerals may explain the observed rock magnetic

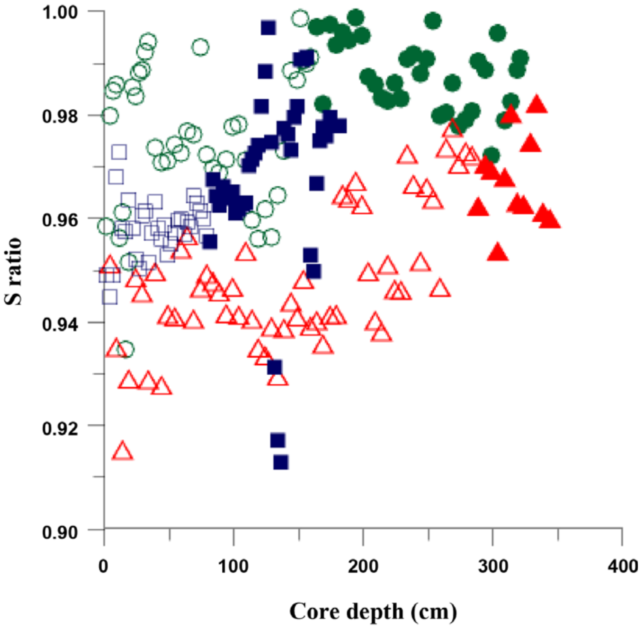

Fig. 8. Comparison of S ratio within the sediment cores (open and closed symbols denote S ratio in upper brown color layers (○denote S △: KPC09, and io in upp and lower dark brown layers (● and lower d KPC09, and ■ : KPC31), respectively)

variation within the sediment columns (Lovlie et al. 1971; Karlin and Levi 1985; Karlin 1990; Channell et al. 2013). Previous paleomagnetic studies suggested that the unstable magnetic components observed in pelagic sediments below the color change from yellowish brown to dark brown result from mineralogical changes after deposition (Henshaw and Merill 1980; Johnson et al. 1975; Kent and Lowrie 1974; Opdyke and Foster 1970). The high value of S ratio (0.9 <) in all samples reflects that magnetic minerals are mostly ferrimagnetic minerals. The variations in the S ratio values from the cores indicate that no magnetic mineral changes occurred with depth (Fig. 8). Based on SEM observation, magnetic extracts from core KPC31 at 136.2 cm in depth (the lower dark brown layer) also indicate that the major magnetic mineral is detrital magnetite (Fig. 5). The biogenic forms of magnetite can also contribute in significant proportion along the areas of low terrestrial input. However the SEM images show that a significant proportion of the relatively coarse-grained magnetic materials is detrital magnetite affixed to pure magnetite in the grain size range of 1–20 μm. The coarse magnetic grains have a subrounded shape and a pitted surface. The major source is considered to be atmospherically or oceanically transported detritus. Bottom currents may move eroded magnetic grains during the course of deposition. The result from the SEM observation is also in accord with rock magnetic properties showing the predominance of ferrimagnetic minerals. Although some values indicate a presence of high-coercivity minerals, the differences in magnetic mineralogy with depth can be ruled out as a controlling factor on the variation in rock magnetic properties.

5. Conclusion

As discussed above, if the magnetic mineral composition does not vary throughout the core section, the down-core behaviors of magnetic components will reflect the change in the magnetic concentration and grain size (or domain state) of the sediments. In the NEP area, rock magnetic results suggest that the stable magnetic materials in sediments would have been primarily transported to the deep-sea floor by either wind during intervals of arid climate in the source area or intensified bottom currents. Following deposition, diagenetic processes largely affect the sediments. Although the magnetic materials show detrital shape and have stable magnetic components, the results support the notion that the lower dark-brown sediments bear less stable magnetic components.

Acknowledgements

The authors thank reviewers for their critical comments and suggestions. The first author also would like to extend his gratitude to crew members of R/V Onnuri for their constant encouragement and assistance in the field. This research was performed with support from the fulfillment of obligations accruing from the contract with the ISA and capacity building for the commercial mining of polymetallic nodules (PM59940).

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