

A Method for Core Reorientation Based on Rock Remanent Magnetization: Application to Hemipelagic Sedimentary Soft Rock^{*1}

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Abstract

The in-situ orientation of drilled core samples provides valuable information for a broad range of geological and geophysical studies, such as the determination of in-situ principal stress directions or analyses of geological structure. However, the in-situ orientation of core samples is not available in many cases. In this paper, we present a method for restoring the in-situ orientation of drilled whole-round core samples and its application to hemipelagic sedimentary rocks. The method is based on the natural remanent magnetization (NRM) of rocks. As a case study, we apply this method to 15 oceanic sedimentary soft rock samples recovered from the toe of the Nankai Trough off Cape Muroto, SW Japan, during International Ocean Discovery Program Expedition 370.

We developed a new sample-preparation procedure that enables more data

31 acquisition and evaluated the NRM measurement results. Some samples could not be
32 reoriented owing to magnetic overprints associated with the drilling operations. To
33 evaluate the magnetic overprints caused by drilling and assess the data quality of the
34 core reorientation by this method, we propose an evaluation system with three ranks
35 defined for different levels by which NRM results are affected by drilling. This
36 evaluation system is also useful for assessing the data quality of core reorientation by
37 the NRM method in other similar applications.

38
39 *Keywords:* Paleomagnetism, Core reorientation, Natural remanent magnetization
40 (NRM), Hemipelagic sedimentary rock, Drilled rock core sample

1. Introduction

The safe and effective exploitation of the crust requires a wide range of information regarding its physical properties, in-situ stress, and underground structure. One way to obtain this information is to analyze drilled rock core samples (referred to as core samples). The use of core samples offers the following advantages: i) real materials in the crust can be measured directly, and ii) experiments can be conducted under a range of laboratory conditions. The in-situ orientation of a core sample is crucial to extract its full range of information, including principal stress directions, anisotropy of permeability, and geological structures such as orientations of faults. However, core samples are rotated during conventional drilling and the in-situ orientation is lost. Several methods have been reported to restore the in-situ orientation of a core sample, referred to as “core sample reorientation”^{1–3)}.

The natural remanent magnetization (NRM) of a core sample has been successfully used for core reorientation^{4–7)} with some variations according to differences in the sample preparation. The most common method uses a small cylindrical specimen drilled from a core sample, and the specimen NRM is measured. However, this method cannot determine measurement errors. To address this problem, we propose a new method of preparing nine small specimens from a single core sample and measuring the NRM of eight of the specimens to obtain a statistical evaluation of the measurement error. While some previous studies have performed NRM measurements on several specimens from a single rock sample⁸⁾, those studies did not undertake core reorientation.

In this article, we first present the principle of core reorientation based on NRM, followed by a detailed explanation of specimen preparation from a core sample. We then discuss the results of an application of this method to hemipelagic sedimentary soft rock collected from an ocean drilling borehole off Cape Muroto during Expedition 370 conducted by the International Ocean Discovery Program (IODP). We also discuss the effects of secondary remanent magnetization owing to drilling process on core reorientation and propose a data quality assessment criterion.

2. Theoretical basis for reorientation

2.1 Core sample reorientation based on rock NRM

Rocks generally contain magnetic minerals, such as magnetite and pyrrhotite, and hence can be magnetized. When a rock forms, it usually acquires a remanent magnetization parallel to the Earth's magnetic field at that time: referred to as the primary NRM⁹⁾. The method used in this study reorientates a core sample based on the assumption that the primary NRM points to the present geographic north. This assumption is reasonable for areas that have experienced small degrees of regional tectonic rotation.

2.2 Demagnetization of secondary NRM

After a rock forms, it can acquire secondary remanent magnetizations owing to changes in the external environment, such as an artificial magnetic field caused by drilling. This type of remanent magnetization is called secondary NRM. The resultant NRM of a core sample immediately after drilling is a vector sum of primary and secondary NRMs (Fig. 1). To reorientate a core sample based on the primary NRM, it is necessary to eliminate the secondary NRM. This process is called demagnetization (Fig. 1).

There are two main demagnetization techniques: i) thermal demagnetization (ThD), which demagnetizes secondary NRM by heating a sample in a zero magnetic field; or ii) alternating field demagnetization (AFD), which demagnetizes secondary NRM by applying an alternating magnetic field to a sample in a zero magnetic field. In this study, we used the AFD technique, which can effectively demagnetize multiple samples simultaneously. The demagnetization process is usually plotted on a Zijderveld diagram¹⁰⁾, as shown in Fig. 2.

Two important hypotheses are as follows: i) the measured NRM is the vector sum of primary and secondary NRMs; and ii) demagnetization of primary NRM begins after the secondary NRM is completely demagnetized. Then projections of the vector end points of the primary NRM during the demagnetization process form a line that

passes through the origin on the Zijderveld diagram. Previous studies have used this fact to distinguish primary NRM from secondary NRM and we also adopt this approach.

2.3 Assessment of reorientation results

This section describes the quality assessment of reorientation results, with particular attention given to quantifying the influence of drilling. Reorientation results were classified into three ranks indicating good (A), fair (B), and poor (C) quality according to the following procedures.

Step 1 Determination of rank C

This classification was based on the demagnetization results of specimen 1 (Fig. 3b), which was located at the center of the disc-shaped sample and thought to be less influenced by drilling than the other specimens. Rank C is defined if a demagnetized component that does not linearly decay to the origin on the Zijderveld diagram and thus primary NRM is not recognized. Consequently, the core sample cannot be reoriented by NRM analysis. If the line can be confirmed, further analysis is conducted in Step 2.

Step 2 Classification of the remaining results into ranks A or B

If the result is not classified into rank C, that is, primary NRM can be determined in specimen 1, the 95% confidence limit of the mean angle (α_{95}) of the primary NRM¹⁰⁾ is calculated using the demagnetization results from the eight specimens from the same core sample including specimen 1. A result of $\alpha_{95} \leq 5^\circ$ is classified as rank A and $\alpha_{95} > 5^\circ$ as rank B. Rank A results can be used for reorientations without problems. On the other hand, we suggest that the use of rank B results depends on the number of core samples and/or the importance of the location where the sample is retrieved.

3. Materials and methods

3.1 Experimental procedure

A detailed explanation of the procedure used to prepare eight specimens from a core sample is given below.

First, a disc-shaped sample with a thickness of about 2 cm was cut from the upper or lower end of the core sample (Fig. 3a) using a diamond saw. The thickness was determined by the maximum specimen height measured by the NRM-measuring instrument because larger specimen volumes may increase data quality. The disc-shaped sample was then cut into nine specimens, as shown in Fig. 3b. The reasons for separating the sample are 1) limited sample size by the measuring equipment, 2) the remaining core sample can be used for other measurements, 3) the quality of the results can be determined statistically.

When cutting a sample, an isothermal remanent magnetization (IRM) can be added owing to the artificial magnetic field around the diamond saw. However, this mainly affects the specimen surface, which is small compared with the total volume ($\sim 8 \text{ cm}^3$). In the case that the influence cannot be ignored, the IRM formed from the saw is also considered as a part of the secondary NRM. An assessment of the influence of cutting therefore requires consideration based on the final result. To prevent drying, specimens were wrapped in parafilm (Fig. 3c). Because the number of specimens that can be simultaneously measured is eight according to the equipment specifications, eight specimens including specimen 1 were selected from nine specimens. Specimens with sufficient volume were selected.

In this study, NRM demagnetization and measurement were conducted using a pass-through superconducting rock magnetometer manufactured by 2-G Enterprise (Model 760R) at Kochi University, Japan. Progressive AFD was performed by applying an alternating magnetic field to specimens, typically in 24 steps between 0 and 80 mT. NRM vector end points at each demagnetization step were plotted on a Zijderveld diagram and the primary NRM was extracted as the line passing through the origin ^{11, 12)} (Fig. 2).

Two angles are usually used to represent the NRM orientation, namely, inclination and declination (Fig. 4). In this study, declination is defined as the angle between an arbitrary determined reference line (Fig. 4) and the horizontal NRM component, although it generally refers to the angle between the latter and true north. Inclination is defined as the angle between the horizontal plane and NRM vector. It is known that the Earth's magnetic field varies over time and the two angles of primary NRM usually correspond to the averaged direction of the field over time for formation of a rock. If a rock formed over a few thousand years, the geocentric axial dipole hypothesis¹⁰⁾ allows the declination of the primary NRM to be regarded as corresponding to the present geographic north. These two angles were calculated by linear regression analysis on components that linearly decay to the origin on a Zijderveld diagram¹²⁾.

3.2 Core samples

The core samples used in the case study were retrieved from borehole C0023A during the IODP Expedition 370. C0023A is a vertical borehole located at the toe of the subduction zone of the Nankai Trough about 120 km southeast of Muroto, Kochi ($32^{\circ} 22.00' \text{ N}$, $134^{\circ} 57.98' \text{ E}$, 4,776 m water depth)¹³⁾. The core samples are composed of Miocene to Quaternary soft sedimentary rocks (Table 1) (430–1123 m below seafloor) with porosities of 25%–45%¹³⁾. Fifteen core samples were used and nine specimens were cut from each sample, as described in section 3.1.

4. Results

Fig. 5 shows the Zijderveld diagram with the demagnetization results of specimen 1 from sample core-1 in each demagnetization step. Black solid circles represent projections of the end points of the NRM vectors in each demagnetization step onto the horizontal plane, and black open circles are those onto a vertical plane oriented north-south. Gray circles (both solid and open) show the secondary components of the NRM vector. The vector length represents the magnetization magnitude. The two black

dashed lines in the figure are regression lines fitted to the primary NRM. To extract the primary NRM, a straight line is fitted to a component that linearly decays to the origin. The inclination and declination can be determined from the angles between the lines and the x -axis. Table 1 lists the inclinations and declinations obtained from each core sample. Some inclinations show negative values, which are due to magnetization recorded in the reversed polarity chron¹⁰.

Following the geocentric axial dipole hypothesis, the inclination at each latitude of Earth's surface can be calculated as follows¹⁰:

$$I = \tan^{-1}(2 \tan \lambda), \quad (1)$$

where I represents inclination and λ is the latitude of the drilling site. Substituting the latitude of the drilling site into Eq. (1), the calculated inclination is $\sim 52^\circ$. Although it is seemingly possible to assess the quality of the reorientation based on this theoretical value, the actual inclination value has been reported to potentially differ substantially from theory owing to the consolidation or rotation of the formation¹⁰. An evaluation of the data quality is therefore difficult using only this value.

5. Assessment of drilling influence

The most unique feature of the reorientation method proposed in this study is that it can statistically assess the influence of secondary NRM caused by drilling. In this section, we show the results of three samples (Core-1, Core-6, and Core-4) selected from each of the three ranks defined in section 2.3 and discuss the influence of drilling on the reorientation results.

Fig. 6 shows the Zijderveld diagrams of each specimen from the three core samples. Numbers 1–9 in the figure correspond to the numbers of specimens in Fig. 3b. Fig. 7 shows equal area projections of the primary components of the normalized NRM vectors for each specimen. Black solid and open circles indicate lower and upper hemisphere projections, respectively. Gray circles (solid and open) indicate specimens that were not used for averaging. Triangles show the averaged direction using the results from specimens, except for those marked by gray circles. Dotted ellipses show the 95%

confidence areas.

5.1 Rank A

Fig. 6a and Fig. 7a show the results of Core-1, which is rank A. The results show no significant difference between the specimen in the center (specimen 1) and the others. We consider that this type of sample was not affected by drilling and reorientation was accomplished. However, Core-15, which is also rank A, has an inclination of $\sim 80^\circ$ (Table 1), which indicates a vertical downward NRM and requires further consideration with regards to the influence of drilling.

5.2 Rank B

Fig. 6b and Fig. 7b show the results of Core-6, which is rank B. α_{95} of Core-6 is 13.7° . For this type of result, the primary NRM component of specimen 1 was able to be extracted. However, specimens cut from the periphery (4, 5, 6) were affected by drilling and have secondary NRMs with inclinations of $\sim 90^\circ$. It is therefore difficult to extract the primary NRM component from these specimens.

5.3 Rank C

Fig. 6c and Fig. 7c show the results of Core-4, which is rank C. For this type of sample, almost all the specimens, including the central one, were affected by ferromagnetic materials (such as steel pipes) while drilling, and the primary NRM itself was also disturbed. There are no specimens from which the linear component decays to the origin on a Zijderveld diagram can be extracted, and the method proposed in this paper cannot be applied. Three different results can therefore be obtained from the same drilling owing to the different degrees of magnetization of the drilling bit and coercive forces of the sample itself.

6. Conclusions

We applied a reorientation method using the NRM of rock to hemipelagic sedimentary soft rocks from the Nankai Trough and discuss the magnetic influence of drilling on the reorientation results. The primary NRM recorded in the central specimen must be extracted to reorientate a core sample. Because rocks can acquire secondary NRM after formation, secondary NRM must be demagnetized. When applying the reorientation method based on rock NRM, it is important to evaluate the influence of drilling on the reorientation results. In this study, this assessment was conducted by comparing the demagnetization results of the central specimen, which is considered to be less affected by drilling, with those of surrounding specimens, which are more likely to be affected by drilling. Reorientations were achieved in cases where the components decaying linearly to the origin on the Zijderveld diagrams were identified. Statistical analyses then allow for further data assessment: rank A (good) is defined by a concentrated distribution of the primary NRM orientation ($\alpha_{95} \leq 5^\circ$) (e.g. Core-1), whereas rank B (fair) is defined by a relatively scattered distribution ($\alpha_{95} > 5^\circ$) (e.g. Core-6).

One of the remaining problems is the approach by which to weigh the results of each specimen by calculating the average direction of each specimen. The result of the central specimen is generally considered to be more reliable than those of other specimens. A means to incorporate this information into the average calculation is the subject of a future study. The method of sample preparation and data quality assessment proposed here offers important guidelines, especially for valuable core samples such as those retrieved from the deep drilling of the IODP.

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272

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Caption List

Table 1 Results of core reorientation based on the Natural Remanent Magnetization Measurements.

Fig. 1 Schematic graph showing demagnetization steps. Two-dot chain lines show primary natural remanent magnetization (NRM). One-dot chain lines show secondary NRM on each demagnetization steps, which are demagnetized in order to extract primary NRM. Black solid lines show sums of primary NRM and secondary NRM (resultant NRM) on each demagnetization steps. Broken lines show demagnetized secondary NRMs. Resultant NRMs are measured on each step and plotted on Zijderveld diagram.

Fig. 2 (a) Projections of NRM onto the horizontal and vertical planes. (b) Schematic diagram of a Zijderveld projection. The numbers in the figures show the number of steps in demagnetization process. Solid black circles are projections of the end points of the NRM vector onto the horizontal plane and open circles are those onto a vertical plane oriented north-south¹⁰⁾.

Fig. 3 Pictures of sample preparation. (a) A whole round core sample. Strain gages attached to the sample were used for another measurement. (b) A disc-shaped sample cut from a whole round core sample. The numbers show those of specimens used in Fig. 6. (c) Specimens wrapped by parafilms. White allow show the direction of the reference line of the whole-round core sample.

Fig. 4 The definitions of inclination and declination. Inclination is the angle from the horizontal plane and declination is the angle from an arbitrary determined reference line.

Fig. 5 The Zijderveld diagram of the result of specimen Core-1-1. Black solid circles are projections of the end points of the NRM vector onto the horizontal plane and black open circles are those onto a vertical plane oriented north-south. Gray circles (open and

solid) are the secondary components of the NRM vector.

Fig. 6 Zijderveld diagrams of NRM obtained from (a) Core-1, (b) Core-6, (c) Core-4. The numbers show those of the specimens (see Fig. 3 (b)).

Fig. 7 Equal-area projections of the NRM directions for 8 specimens from one whole round core sample. Black solid circles show lower hemisphere projection and open circles show upper hemisphere projection. Gray circles (solid and open) show the specimens which are not used for averaging. Triangles show the averaged direction using the results from specimens except for gray ones. Dotted circles show the 95 % confidential area. (a) The result of Core-1 (rank A), (b) the result of Core-6 (rank B), (c) the result of Core-4 (rank C).

Table 1 Results of core reorientation based on the Natural Remanent Magnetization Measurements.

Sample ID	IODP core sample source	Core top depth (mbsf)	Inclination (degree)	Declination (degree)	α_{95} (degree)	Rank
Core-1	C0023A-18R-1-WR 101.0-121.0 cm	429.01	54.4	286.7	3.8	A
Core-2	C0023A-23R-1-WR 98.0-109.0 cm	475.98	55.6	137.8	3.3	A
Core-3	C0023A-24R-7-WR 25.0-45.0 cm	491.17	45.5	317.1	2.2	A
Core-4	C0023A-33R-7-WR 70.0-85.0 cm	567.13	-52.0	214.5	7.8	C
Core-5	C0023A-43R-5-WR 60.0-81.0 cm	654.87	63.5	215.2	1.8	A
Core-6	C0023A-54R-2-WR 20.0-37.0 cm	713.80	-37.1	36.7	13.7	B
Core-7	C0023A-55R-1-WR 112.0-131.0 cm	718.62	63.4	180.5	4.1	A
Core-8	C0023A-61R-2-WR 0.0-19.0 cm	748.34	56.9	102.2	1.9	A
Core-9	C0023A-67R-1-WR 108.0-121.0 cm	776.08	-16.7	188.5	4.7	A
Core-10	C0023A-77R-2-WR 127.0-146.5 cm	822.02	-17.9	18.2	2.7	A
Core-11	C0023A-81R-4-WR 15.0-35.0 cm	846.48	56.4	290.7	2.4	A
Core-12	C0023A-86R-3-WR 131.0-151.0 cm	892.99	-54.4	117.5	3.8	A
Core-13	C0023A-92R-3-WR 70.0-96.0 cm	950.11	-73.8	156.6	18.4	C
Core-14	C0023A-99R-3-WR 20.0-40.0 cm	1023.11	71.9	116.7	5.3	C
Core-15	C0023A-110R-2-WR 46.0-65.0 cm	1122.74	80.2	71.5	2.5	A

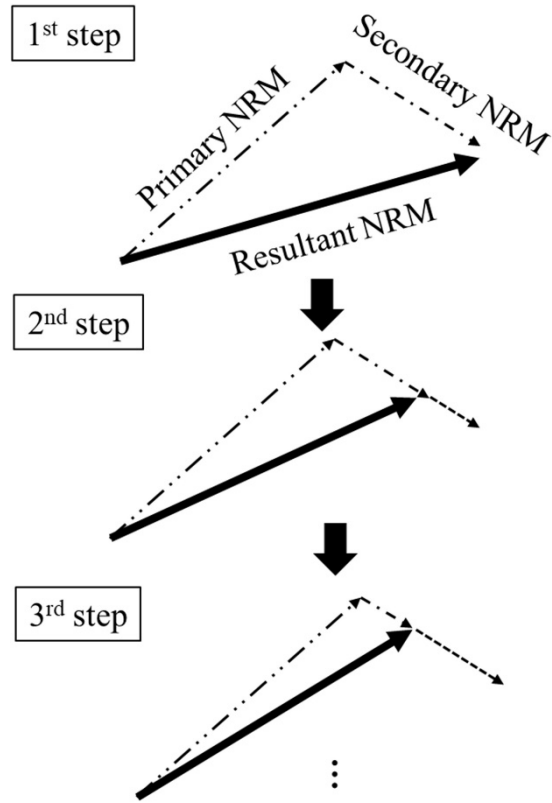


Fig. 1 Schematic graph showing progressive demagnetization steps. Two-dot chain lines show primary natural remanent magnetization (NRM). One-dot chain lines show secondary NRM on each demagnetization steps, which are demagnetized in order to extract primary NRM. Black solid lines show sums of primary NRM and secondary NRM (resultant NRM) on each demagnetization steps. Broken lines show demagnetized secondary NRMs. Resultant NRMs are measured on each step and plotted on a Zijderveld diagram.

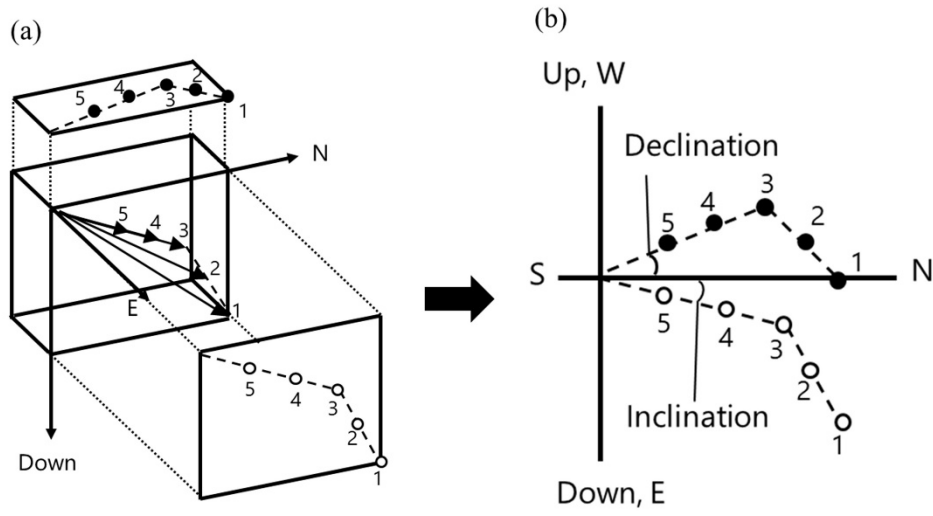


Fig. 2 (a) Projections of NRM onto the horizontal and vertical planes. (b) Schematic diagram of a Zijderveld diagram. The numbers in the figures show the number of steps in demagnetization process. Solid black circles are projections of the end points of the NRM vector onto the horizontal plane and open circles are those onto a vertical plane oriented north-south¹⁰⁾.

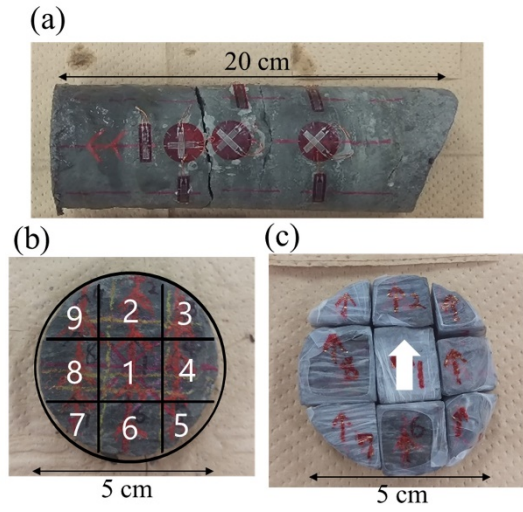
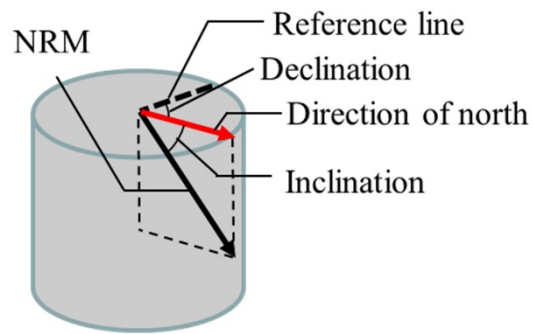


Fig. 3 Pictures of sample preparation. (a) A whole round core sample. Strain gages attached to the sample were used for another measurement. (b) A disc-shaped sample cut from a whole round core sample. The numbers show those of specimens used in Fig. 6. (c) Specimens wrapped by parafilms. White allow show the direction of the reference line of the whole-round core sample.



Whole round core sample

Fig. 4 The definitions of inclination and declination. Inclination is the angle from the horizontal plane and declination is the angle from an arbitrary determined reference line.

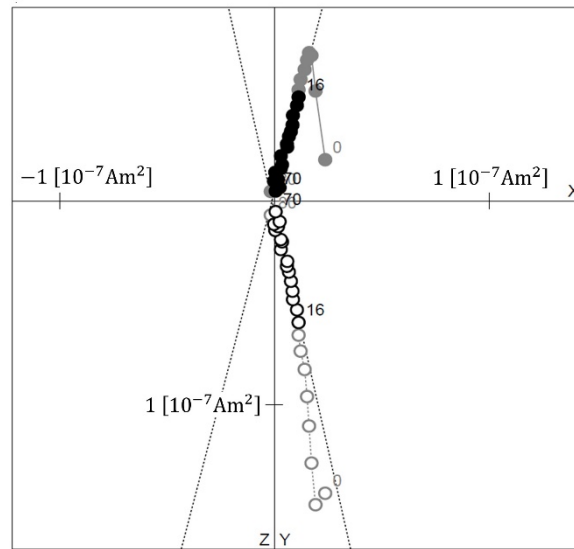


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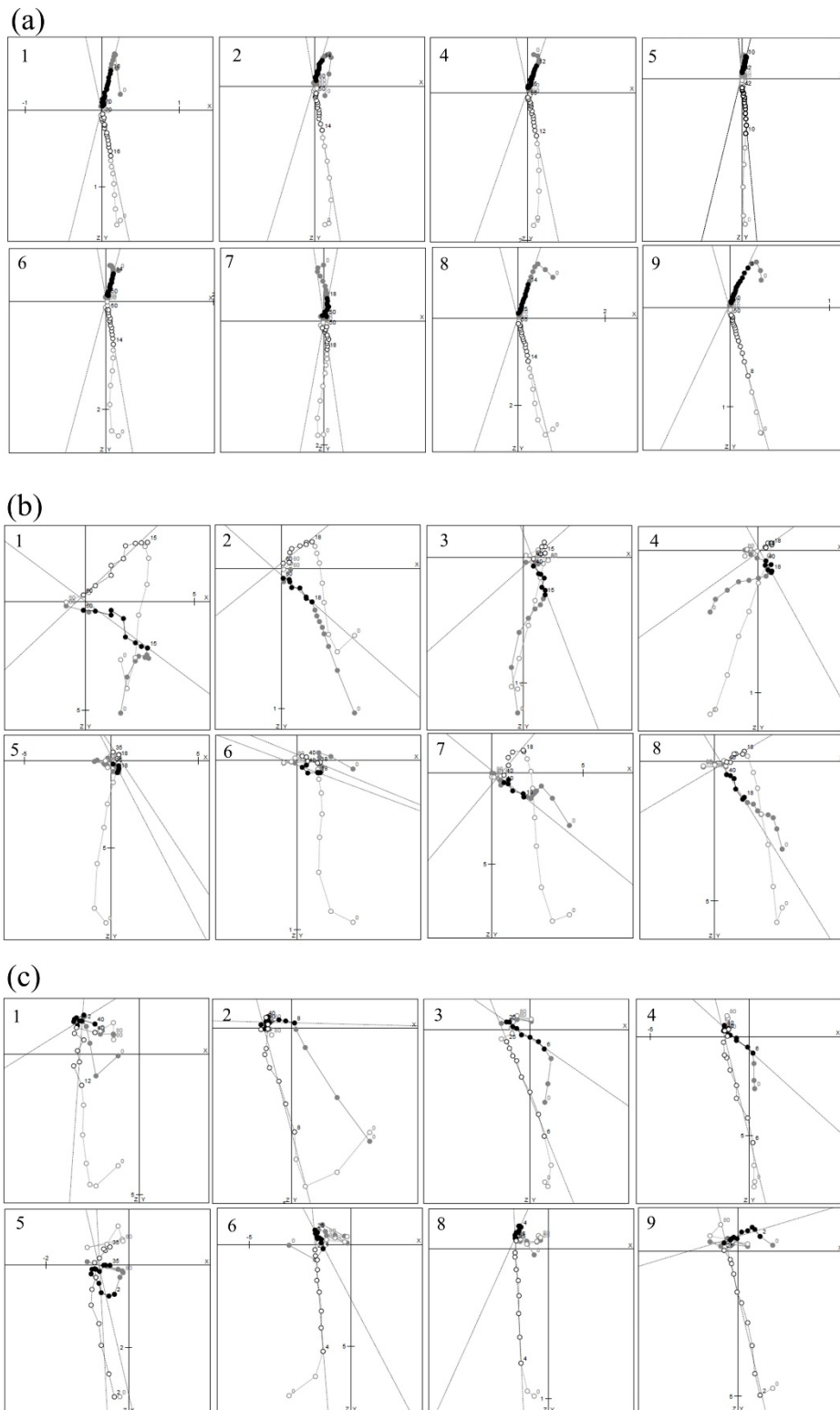


Fig. 6 Zijderveld diagrams of NRM obtained from (a) Core-1, (b) Core-6, (c) Core-4. The numbers show those of the specimens (see Fig. 3 (b)).

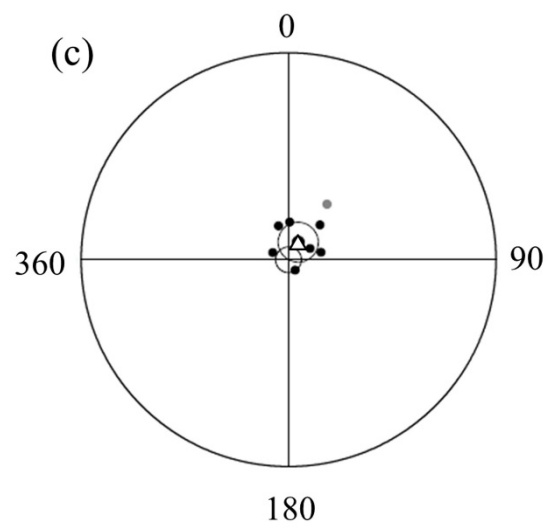
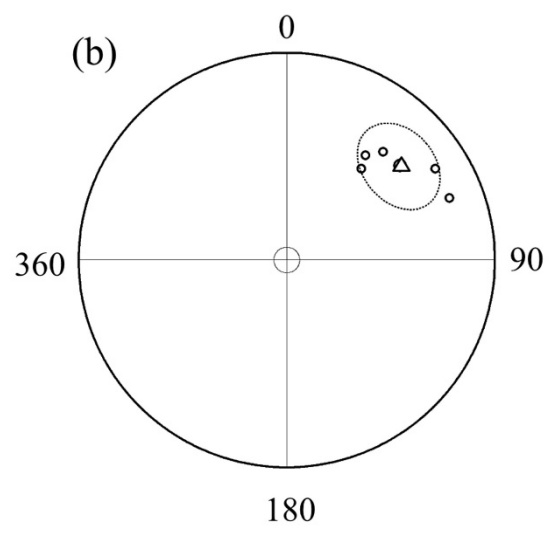
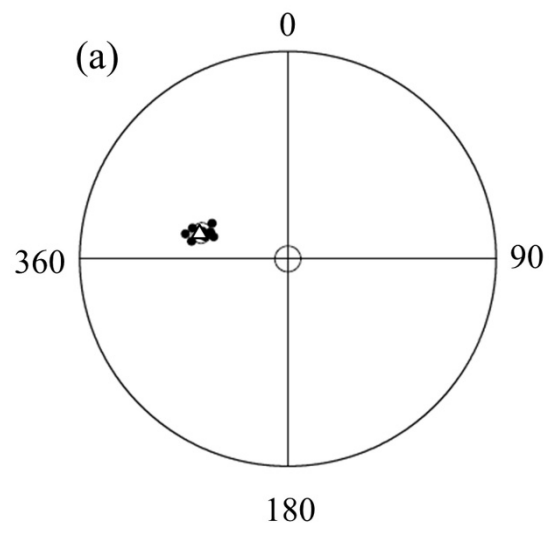


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354