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FULL PAPER

An initial case study to deconvolve natural remanent magnetization of a continuous paleomagnetic sample using the software UDECON

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Abstract

Previous studies have compiled relative paleointensity data for the last 2–3 Ma from individual paleomagnetic records obtained from marine sediment cores. These records have mostly been obtained by pass-through measurements, which are known to smooth and alter magnetic signals. Among many efforts, a standalone open-use graphical software UDECON has been developed to deconvolve pass-through measurement data. As an initial case study to assess the applicability of the software to deconvolve natural remanent magnetization (NRM) of a continuous paleomagnetic sample, we chose 40 discrete samples from a piston core recovered in the northeast Pacific. We measured NRMs after alternating field demagnetization at 20 mT for both discrete samples and a simulated continuous sample, made by connecting the discrete samples. The discrete samples show centimeter-scale variations in NRM. Such variations are smoothed out and mostly disappear in the results of the simulated continuous sample. However, after using the software to deconvolve the data, the variations are almost completely restored. Good agreement between the discrete sample data and the deconvolved data indicates that the deconvolution by the software is very successful. We observe detailed features of a directional reversal in the data from the discrete samples and in the deconvolved data but not in the data from the simulated continuous sample. This emphasizes that the deconvolution analysis by the software is a powerful tool to extract detailed features from continuous paleomagnetic records obtained by pass-through measurements.

Keywords: Superconducting rock magnetometer, Deconvolution, Reversal

Introduction

Recent progress in paleomagnetism has resulted in relative paleointensity stacks for the last 2–3 Ma. These include the PISO-1500 record for the last 1.5 Ma (Channell et al. 2009), the Sint-2000 record (Valet et al. 2005) and the PADM2M model for the last 2 Ma (Ziegler et al. 2011), and the EPAPIS-3Ma record for the last 0.8–3 Ma (Yamazaki and Oda 2005). All of these stacks have been compiled from individual paleomagnetic records obtained from marine sediment cores, which were mostly measured by a pass-through superconducting rock magnetometer (SRM). Pass-through measurements are known to be a very efficient way to obtain paleomagnetic records from long sediment cores, but the convolution effects due to the sensor response of SRM inevitably smooth and alter the magnetic signals.

Researchers have made efforts to deconvolve pass-through measurement data (e.g., Dodson et al. 1974; Constable and Parker 1991; Oda and Shibuya 1994), and Oda and Shibuya (1996) were the first to incorporate the effects of cross terms among x, y, and z magnetization components on the sensor response of SRM. Oda et al. (2000) carried out an indirect comparison between deconvolved pass-through measurement data and corresponding discrete measurement data. They reported

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downcore variations of natural remanent magnetization (NRM) after alternating field demagnetization (AFD) by 20 mT for Ocean Drilling Program (ODP) Holes 767B, 769A, and 769B. Reasonable matches were shown between pass-through measurement data from archive-half cores deconvolved using the technique of Oda and Shibuya (1996, 1998) and the measurement data directly obtained from discrete samples. The discrete samples were taken from working half cores with 5 cm spacing for the 1-m interval for Hole 767B, 3-m interval for Hole 769A, and 1-m interval for Hole 769B.

Guyodo et al. (2002) made a more direct comparison on a natural sample. They conducted NRM measurements on the two u-channel samples from ODP Site 1090 after AFD of 100 mT with a resolution of 1 cm using an SRM (2G-Enterprises 760R u-channel magnetometer at the University of Florida). They subsequently cut 1-cm-thick slices of the sediment from the u-channel samples and measured the NRMs of the slices using a three-axis discrete magnetometer. It was recognized that the moderate-to-large amplitude features observed in the NRM results of the slices, including directional excursions in inclination records, were mostly lost in those of the u-channel samples. These features were restored to a reasonable standard when the deconvolution scheme of Oda and Shibuya (1996) was applied to the NRM results of the u-channel samples. Jackson et al. (2010) also made a similar comparison on a natural lake sediment core from Deming Lake, but this was done after applying a pulsed isothermal remanent magnetization rather than NRM.

Xuan and Oda (2015) recently developed a standalone graphical software UDECON, which is capable of directly reading data files of pass-through measurements obtained by an SRM and conducting deconvolution using the algorithm developed by Oda and Xuan (2014). This algorithm optimizes Akaike's Bayesian information criterion (ABIC) not only for smoothness of the signal but also for realistic error in sample length and shift in measurement position introduced during sampling and measurement in the laboratory (Xuan and Oda 2015). As an initial case study to assess the applicability of the UDECON to deconvolve NRM of a continuous paleomagnetic sample, we first measured NRMs of both discrete samples and a simulated continuous sample, which was made by connecting the discrete samples. We then made a direct comparison between deconvolved pass-through measurement data using the UDECON and the corresponding discrete measurement data. This approach avoids one of the sources of error which occurred in similar studies conducted before (Guyodo et al. 2002; Jackson et al. 2010). In previous studies, measurements were first made on a continuous sediment core, which was then sliced into discrete samples and remeasured. In such an approach, the degree of disturbance produced by the subsampling is unknown and the differences between the deconvolved record and the discrete measurements may be due in part to such a disturbance. In the current study also, such a disturbance may be present, but it is the same for both discrete and continuous measurements.

Methods

Samples

A piston core KR0310-PC6 of 15.3 m long was taken from the northeast Pacific, in an area to the South of Aleutian Islands (48°40.10′N, 161°29.97′W), during the R/V Kairei KR03-10 cruise in September 2003. The water depth of the coring site is 5080 m. The sediments consist of siliceous clay of moderate yellowish to a dusky yellowish-brown color, which frequently intercalates tephra and ice-rafted pebbles.

About 600 paleomagnetic samples were continuously taken from split sections of the core KR03-10-PC6 using discrete plastic cubic capsules of 7 cm^3. Preliminary paleomagnetic measurements were carried out for the interval of 3.5–15.2 m (Fig. 1), revealing that a possible Brunhes-Matuyama transition is recorded at a depth of ~ 7.4 m; this was particularly evident as a sharp change in inclination and a prominent low in NRM intensity. We chose 40 cubic samples from the depth interval 6.94–7.85 m for the measurements in this study (hereafter called the discrete samples, Fig. 2a). To simulate a continuous u-channel sample, we prepared a special case to connect the discrete samples (Fig. 2b). Using the case, the discrete samples can be measured as a simulated u-channel sample of ~ 90 cm length (hereafter called the u-channel sample, Fig. 2c, d).

Measurements

Natural remanent magnetizations (NRMs) of the discrete samples and the u-channel sample were measured after AFD at 20 mT. The measurements and the AFD were conducted using a pass-through SRM with an inline static alternating field demagnetizer (2G Enterprises Model 755R) at the Center for Advanced Marine Core Research (Kochi Core Center), Kochi University, Japan. For the u-channel sample, the measurements were carried out at 1-cm intervals, not only for the sample length (0–90 cm) but also for the leader (− 10 to 0 cm), and the trailer (90–100 cm) intervals.

Deconvolution analysis

The software UDECON (Xuan and Oda 2015) was used to deconvolve the measurement data of the u-channel sample. Data of the sensor response of the SRM were necessary for the deconvolution. The main three diagonal terms ("XX," "YY," and "ZZ") were determined and

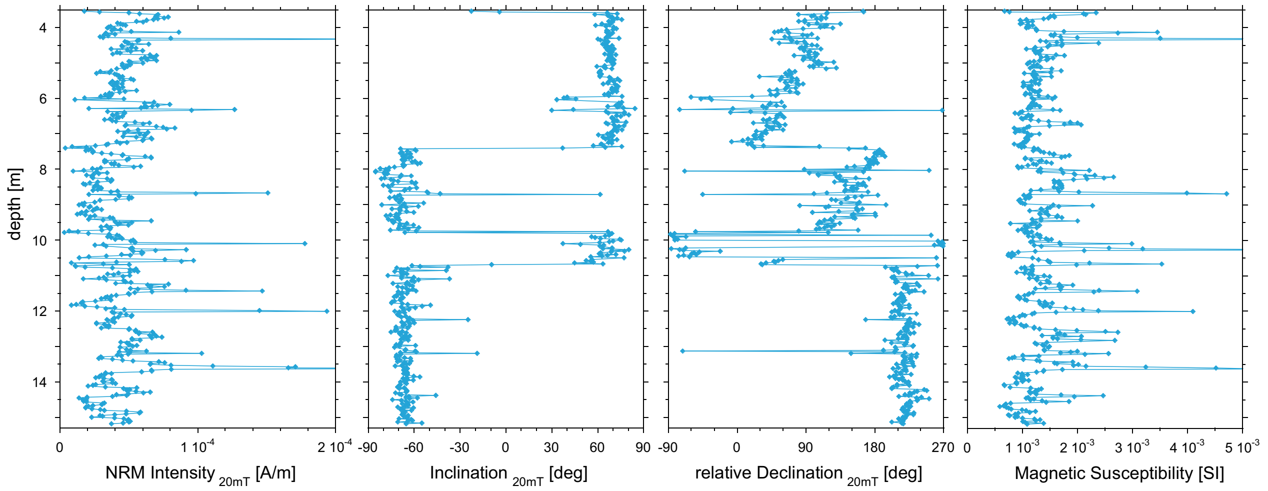


Fig. 1 Downcore variations of NRM and magnetic susceptibility from the preliminary paleomagnetic measurements. The variations are shown for a whole interval of the core except for the topmost 3.5 m. As for NRM, data points indicated are the results of intensity, inclination, and relative declination after AFD of 20 mT

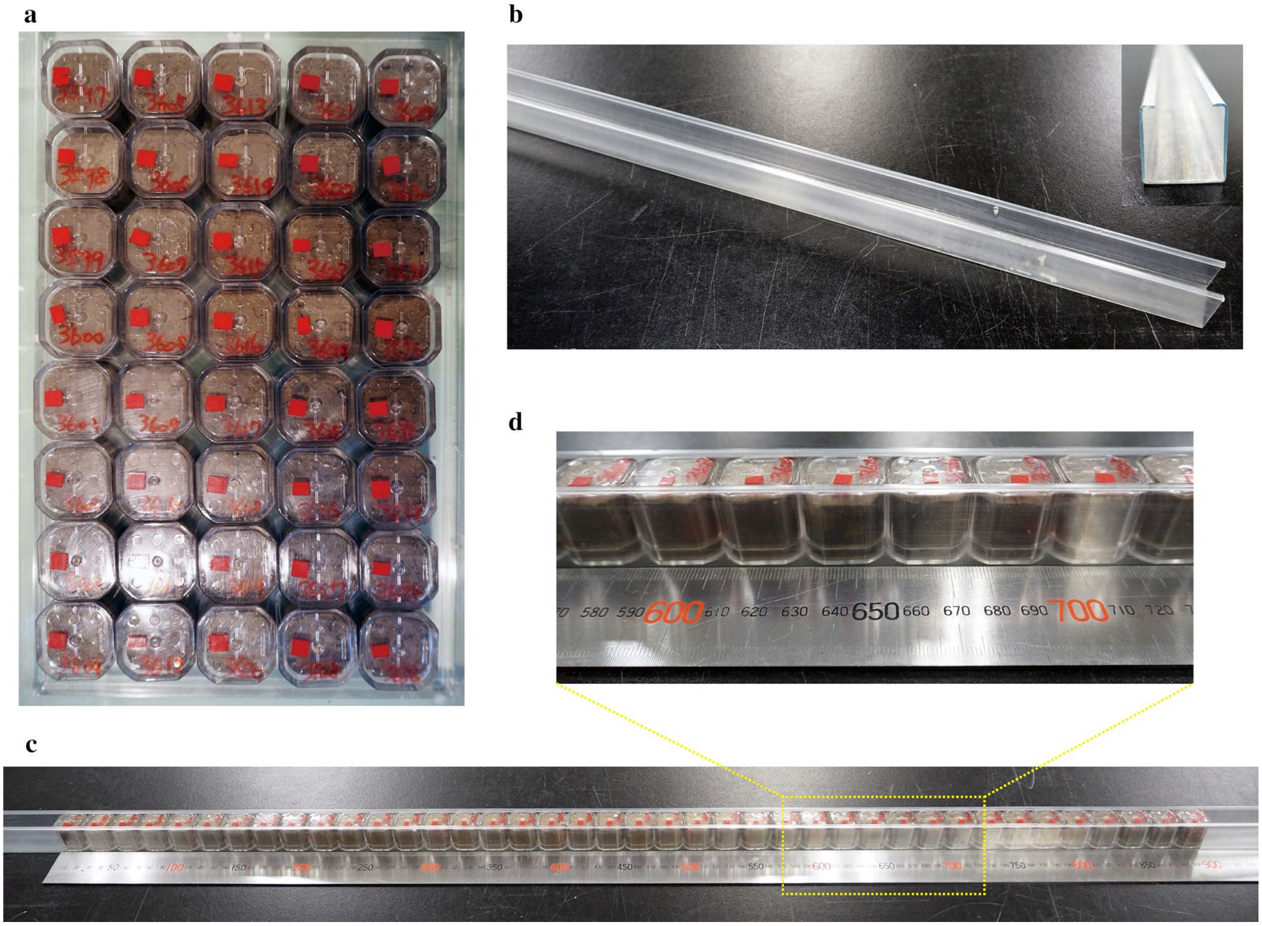


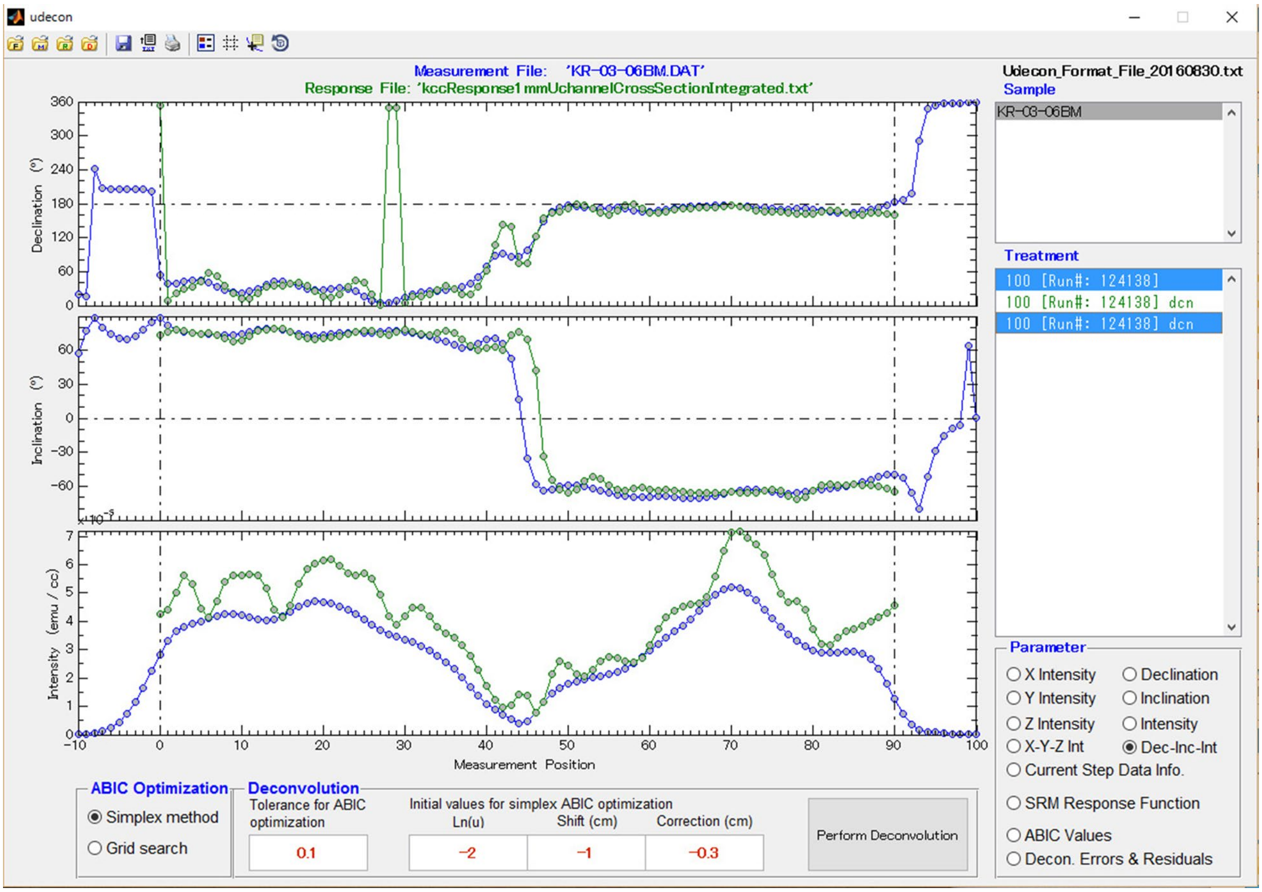
Fig. 2 Photographs showing the samples. **a** The discrete samples; **b** a special case used to connect the discrete samples in order to simulate a continuous u-channel sample; **c** simulated u-channel sample with a length of ~ 90 cm constructed by connecting the discrete samples; **d** close-up of a part of the simulated u-channel sample

reported in Oda et al. (2016). They are characterized by single peaks with full widths at half maxima of 46 mm (XX and YY) and 54 mm (ZZ) (Figure 2 in Oda et al. 2016). The measurement data were analyzed firstly by the "ABIC Optimization: Grid search." After an initial optimization, this analysis yielded a deconvolved result with three parameter values: ln(u) (smoothness), position shift, and length correction. The measurement data were subsequently analyzed by the "ABIC Optimization: Simplex method," using the three parameter values as initial input values for a further optimization (Fig. 3). The deconvolved result obtained after this optimization is hereafter referred to as the deconvolved data.

Results and discussion

The deconvolved data were obtained with the optimal values of ln(u) as − 1.42, position shift as − 1.48 cm, and length correction as 0.39 cm. Depth variations of the three components (X, Y, and Z) of NRM intensity after 20 mT AFD for the discrete samples (blue), the u-channel sample (red), and the deconvolved data (green) are shown in Fig. 4. Depth variations of NRM intensity, inclination, and relative declination after 20 mT AFD are also shown in Fig. 5. In the figures, depths are indicated as relative depths from the topmost cubic sample chosen for the present study (6.94 m below the sea floor). NRM intensities of the u-channel sample and the deconvolved data were scaled to those of the discrete samples in order to have the same average values (factors of 1.36 and 1.04 were, respectively, multiplied).

In Figs. 4 and 5, the discrete samples show centimeter-scale variations (blue) in NRM intensity, inclination, and relative declination. Such variations smoothen and mostly disappear in the results of the u-channel sample (red). However, the variations are almost completely restored in the data deconvolved by the analysis (green). A good agreement between the discrete sample data and the deconvolved data indicates that the deconvolution is very successful. A small shift of ~ 1 cm is observed for the u-channel sample data relative to the discrete sample



Measurement File: 'KR-03-06BM.DAT'

Response File: 'kccResponse1mmUchannelCrossSectionIntegrated.txt'

Udecon_Format_File_20160830.txt

Sample: KR-03-06BM

Treatment:
100 [Run#: 124138]
100 [Run#: 124138] dcn
100 [Run#: 124138] dcn

Parameter: ● Dec-Inc-Int

ABIC Optimization: ● Simplex method ○ Grid search

Deconvolution

Tolerance for ABIC optimization: 0.1

Initial values for simplex ABIC optimization: Ln(u) −2; Shift (cm) −1; Correction (cm) −0.3

Fig. 3 Screen shot of results obtained by the software UDECON. Data points connected by blue lines are from the u-channel sample, and those connected by green lines are deconvolved data. The deconvolved data were obtained by using the three parameter values in the lowermost panel as initial input values

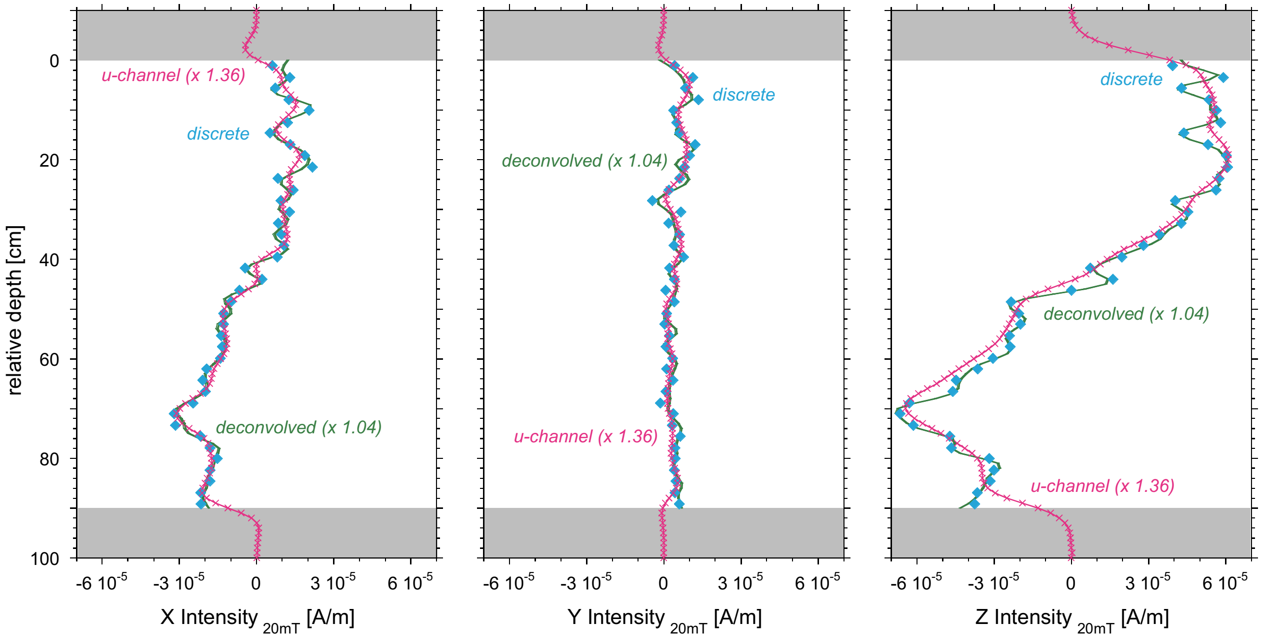


Fig. 4 Depth variations of the three components (*X*, *Y*, and *Z*) of NRM intensity after 20 mT AFD. Data are indicated for the discrete samples (blue), the u-channel sample (red), and the deconvolved data (green). For the deconvolved data, error limits are shown as thin green lines. The leader (− 10 to 0 cm) and the trailer (90–100 cm) intervals are indicated by the area shaded gray

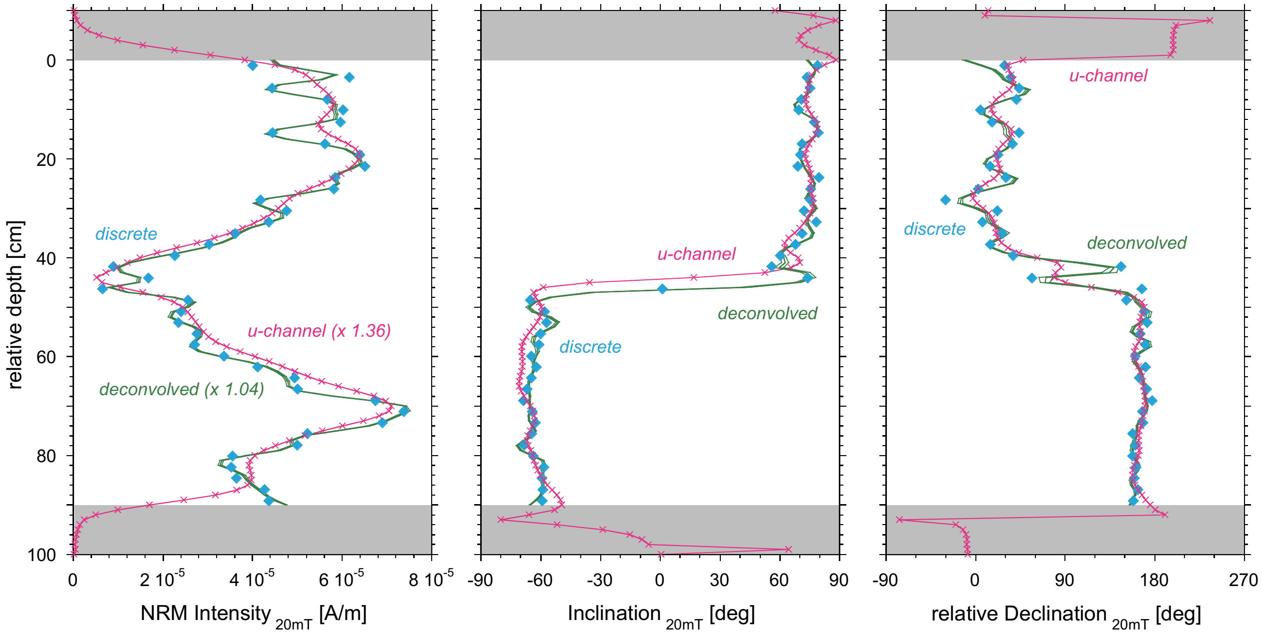


Fig. 5 Depth variations of NRM intensity, inclination, and relative declination after 20 mT AFD. Data are indicated for the discrete samples (blue), the u-channel sample (red), and the deconvolved data (green). For the deconvolved data, error limits are shown as thin green lines. The leader (− 10 to 0 cm) and the trailer (90–100 cm) intervals are indicated by the area shaded gray

data as well as the deconvolved data. This is most evident in a minimum value of the Z component at a depth of ~ 70 cm (Fig. 4). It is thought that the shift can be reasonably accounted by the optimal values of the position shift (− 1.48 cm) and the length correction (0.39 cm).

A directional reversal is observed at the relative depth interval 40–50 cm in Fig. 5: Inclination and relative declination goes from approximately − 65° to + 65° and 175° to 30°, respectively. Although the relative declination showed an incomplete flipping (did not reach ~ 0°), it probably originated from the twisting of the core during coring, which is suggestive from a systematic upward increase in the relative declination for the upper part of the piston core (Fig. 1). The reversal is associated with a significant reduction in NRM intensity compared with the other intervals, as is typical of a paleomagnetic reversal (e.g., Yamazaki and Oda 2001). In the other intervals, strong intensity variations are observed; however, they are not considered to be greatly affected by the sediment material properties because the susceptibility does not show a large change for those intervals (6.94–7.32 m and 7.44–7.85 m; Fig. 1). Detailed features such as rebounds in NRM intensity and relative declination are observed in the discrete sample data and the deconvolved data, but not in the u-channel sample data. This emphasizes that the deconvolution is very powerful and successful in order to recover reversal features from a continuous sample.

We calculated the latitudes of the virtual geomagnetic pole (VGP) for the three datasets (the discrete samples, the u-channel sample, and the deconvolved data), by setting the mean of relative declinations to be 90° for each dataset. Figure 6 illustrates the variations of the VGP latitudes with depth for the three datasets. It is recognized that the deconvolved data almost completely recover the rebound in the VGP latitude during the reversal, which was originally observed in the discrete samples at a depth of ~ 42 cm. The rebound does not appear in the u-channel sample data and a smooth change in the VGP latitude during the reversal could be inferred. Although three values of the deconvolved data appear to diverge from the discrete data at a depth of ~ 54 cm, which probably originate from local misfits between the two data for X and Y intensities (Fig. 4), these results again emphasize that the deconvolution analysis is a powerful tool to extract detailed features from continuous paleomagnetic records obtained by pass-through measurements of SRM.

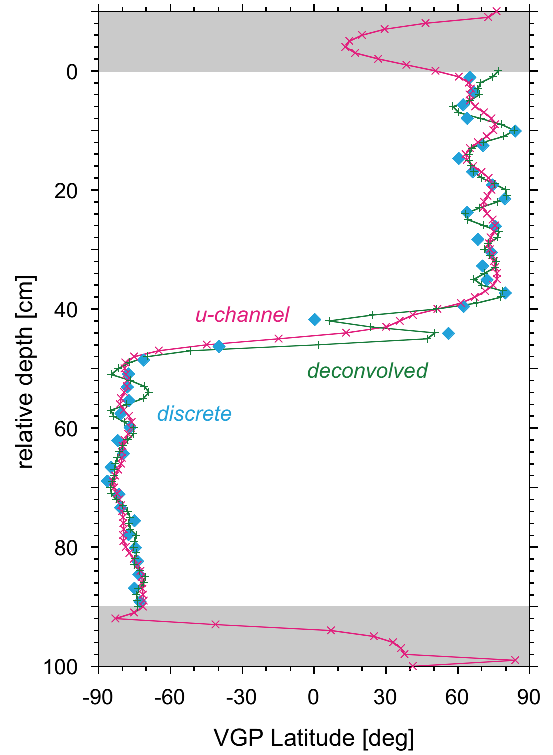


Fig. 6 Depth variations of the VGP latitudes. Data are indicated for the discrete samples (blue), the u-channel sample (red), and the deconvolved data (green). The leader (− 10 to 0 cm) and the trailer (90–100 cm) intervals are indicated by the area shaded gray

Conclusions

Deconvolution of the data from the 90-cm-long simulated u-channel sample by the software UDECON was very successful in restoring the centimeter-scale variations in NRM, which were recognized in the 40 discrete samples. Reversal features such as rebounds in NRM intensity and relative declination were observed in the data from discrete samples and in the deconvolved data, but not in the simulated u-channel sample data.

Abbreviations

ABIC: Akaike's Bayesian information criterion; AFD: alternating field demagnetization; NRM: natural remanent magnetization; ODP: Ocean Drilling Program; SRM: superconducting rock magnetometer; VGP: virtual geomagnetic pole.

Authors' contributions

TY and TK planned and conducted the cruise, and collected the samples. All authors carried out the paleomagnetic measurements. YY analyzed the measurement data and wrote the manuscript. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

Availability of data and materials
The data and materials used in this study are available on request from the corresponding author, Yuhji Yamamoto (y.yamamoto@kochi-u.ac.jp).

Consent for publication
Not applicable.

Ethics approval and consent to participate
Not applicable.

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