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High-resolution magnetic analysis of sediment cores: Strengths, limitations and strategies for maximizing the value of long-core magnetic data

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Abstract

Narrow-access long-core cryogenic magnetometers enable measurement of a range of magnetic parameters at a speed and resolution that cannot be matched by other techniques. Despite the revolutionary impact that these instruments have had on paleomagnetic and environmental magnetic investigations, some fundamental constraints limit their usefulness. First, the pick-up coils have different response functions for the transverse and axial measurement axes. Transverse coils typically have regions of negative response on either side of the main response peak, whereas the axial coil usually lacks the negative response lobes. Zones of negative response affect the measured remanence intensity, for which corrections can be made by normalizing the measured magnetic moment by the area under each respective response curve. This correction works adequately for homogeneously magnetized cores. Second, in cores with significant changes in remanence intensity, the ratio of axial to transverse moment varies with intensity change, which can introduce spurious artefacts into the paleomagnetic directional record. Deconvolution is required to remove such effects. Third, measurements of non-centred samples with irregular cross-section (e.g., split core measurements), cause geometric effects that can introduce small but paleomagnetically important artefacts. Corrections for such effects are only possible if spatial variability of the magnetometer response is known throughout the entire measurement volume rather than solely along the centre-line of the magnetometer. Fourth, analysis of cores deposited at rates >10 cm/ky is desirable to minimize the effects of measurement smoothing. Finally, measurements of magnetic susceptibility should be conducted using loop sensors with a similar response function as a u-channel magnetometer to ensure comparability of data. Routine adoption of these five strategies should help to maximize the value of long-core magnetic measurements.

Keywords: Paleomagnetism; Magnetometer; U-channel; Susceptibility; Ocean Drilling Program

1. Introduction

Low-field magnetic susceptibility is routinely one of the first physical parameters measured after recovery of sediment cores. This is because variations in susceptibility are often controlled by fluctuations in terrigenous mineral input into the depositional environment, with varying dilution by biogenic sedimentary components (e.g. Verosub and Roberts, 1995; Maher and Thompson, 1999; Evans and Heller, 2003). Susceptibility variations are enormously useful for core correlation, and, because susceptibility can be measured

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inexpensively and rapidly, it is often used to provide near-real-time information that can be used to guide further coring.

Measurement of the remanent magnetization of a sediment core is much more complex, and requires sophisticated magnetometers that are so costly that field-based measurements are rare. One notable exception is the Ocean Drilling Program (ODP), where paleomagnetic parameters are routinely measured on sediment cores shortly after core recovery onboard the *JOIDES Resolution*. The relatively large diameter of ODP cores (6.6 cm) limits the resolution of paleomagnetic measurements on the wide-bore shipboard magnetometer system. Furthermore, severe time limitations resulting from high rates of core recovery mean that shipboard measurements are usually restricted to reconnaisance analyses that are aimed at assessing the stability of the magnetization and determining whether more detailed shore-based efforts are worthwhile. Nevertheless, some outstanding shipboard magnetostratigraphic records have been obtained from hydraulic piston cores over the years, as summarized up to ODP Leg 133 by Clement et al. (1996), which demonstrates the great value of shipboard paleomagnetic measurements. Many other high quality records have also been obtained since Leg 133.

High-resolution paleomagnetic measurements are now routinely conducted on small, continuous subsamples that are taken from the centre of split cores, in u-shaped plastic liners known as u-channels (Tauxe et al., 1983; Weeks et al., 1993; Nagy and Valet, 1993). High-resolution u-channel magnetometers make it possible to measure a wide range of magnetic parameters at a speed and resolution that cannot be matched by other existing techniques (e.g. Weeks et al., 1993; Verosub, 1998). This technical development has already revolutionized paleomagnetic research because it enables execution of an entirely new scale of study. For example, not only is it possible to conduct classical studies of magnetic reversal stratigraphy of hundreds of metres of cored sequences with unprecedented resolution (e.g. Acton et al., 2002a; Channell et al., 2003; Roberts et al., 2003; Florindo and Roberts, 2005), but such studies can also provide detailed records of geomagnetic field behaviour (e.g. Channell and Lehman, 1997; Verosub et al., 2001) and have played a crucial role in the development of detailed relative paleointensity time series that have revolutionized our understanding of geomagnetic field behaviour (e.g. Tric et al., 1992; Meynadier et al., 1992; Valet and Meynadier, 1993; Weeks et al., 1995; Lehman et al., 1996; Roberts et al., 1997; Guyodo and Valet, 1999; Channell et al., 2000; Laj et al., 2000; Stoner et al., 2002). U-channel measurements have been fundamental to this explosion of studies of geomagnetic field behaviour. Discovery that variations in the Earth's magnetic field intensity are globally coherent and synchronous has led to the development of geomagnetic timescales that provide far better resolving power than conventional magnetic polarity stratigraphy (Guyodo and Valet, 1999). Age models developed using geomagnetic paleointensities are now widely used in studies of paleoclimatology and paleoceanography (e.g. Laj et al., 2000; Channell et al., 2000; Kiefer et al., 2001; Stoner et al., 2002). Paleointensity-based age models have a major advantage over standard paleoceanographic proxies (e.g. $\delta^{18}O$) that are used for dating sediment cores because relative paleointensity is a geophysical property that is independent of ocean water chemistry and can therefore help to provide independent dating of leads and lags in the ocean–atmosphere–cryosphere system. Furthermore, the geomagnetic field varies on far more rapid timescales than typical glacial/interglacial cycles, so resolution approaching millennial scales (and sometimes better) is possible (e.g. Laj et al., 2000; Channell et al., 2000; Stoner et al., 2002).

In addition to analysis of geomagnetic phenomena, Weeks et al. (1993) predicted that the u-channel technique would be highly useful for paleoceanographic and paleoenvironmental studies because of the range of problems that could be rapidly addressed with high-resolution magnetic analysis of sediment cores. This prediction has subsequently been validated by completion of a wide range of studies, including, for example, investigations of climate change and catchment processes in lakes (Williamson et al., 1998), studies of rapid climate change recorded by marine sediments (Kissel et al., 1999, 2003), investigations of variations in ocean basin-scale ventilation of bottom waters (Larrasoaña et al., 2003a), orbital forcing of the African Monsoon and of outbreaks of dust from the Sahara (Larrasoaña et al., 2003b), and studies of storage diagenesis in sediment cores (Richter et al., 1999). There is no reason to suppose that the current range of high-resolution paleomagnetic and environmental magnetic investigations of sediment cores will abate. On the contrary, it is probable that the range of exciting research prospects in this field will continue to attract new researchers. The purpose of the present paper is therefore to provide a tutorial to new workers on how long-core magnetometers work, including some of the limitations of continuous paleomagnetic measurements of sediment cores and strategies for maximizing the value of such data.

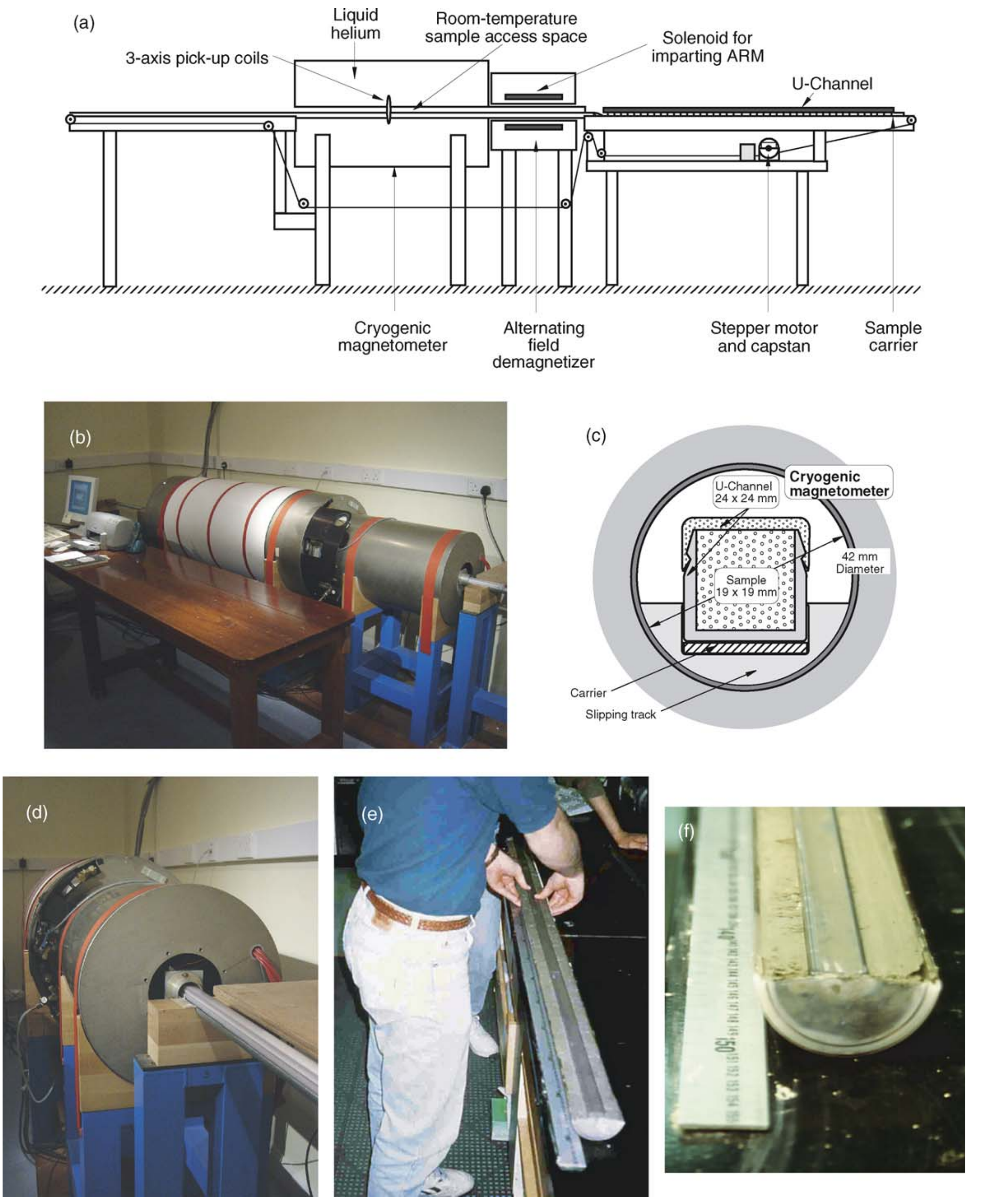

Fig. 1. (a) Schematic cross-sectional view through a narrow-access high-resolution long-core cryogenic magnetometer, with illustration of the sample handling system and in-line AF demagnetization unit (and solenoid for ARM acquisition). (b) Photograph of the u-channel magnetometer system in the author's laboratory at the National Oceanography Centre (NOC). (c) Cross-section through a u-channel sample showing how it fits within a typical 42-mm internal diameter of a narrow-access magnetometer. Note the sharp tips at the ends of the u-channel, which helps it to cut cleanly into the sediment during sampling, and the snugly fitting u-channel cap. Parts (a) and (c) have been modified after Weeks et al. (1993). (d) Photograph of a u-channel as it enters the in-line AF demagnetization coil of the long-core magnetometer system housed in the NOC laboratory. (e, f) Photographs of u-channel sampling, as described in the text.

2. Long-core superconducting rock magnetometers

2.1. How they work

Superconducting rock magnetometers make use of superconducting quantum interference device (SQUID) sensors. These magnetometers are often referred to as cryogenic magnetometers because the SQUID sensors are immersed in liquid helium (∼4 K). Samples are introduced into the centre of the SQUID sensors through a room-temperature access space. The weak magnetization of a paleomagnetic sample will induce a small persistent dc supercurrent into the SQUID pick-up coils, where the current is proportional to the magnetization of the sample. Measurement using three mutually orthogonal pick-up coils enables unique determination of the magnetization vector within the sample. High sensitivity and speed of measurement have made superconducting magnetometers the workhorses of most modern paleomagnetic laboratories. Early cryogenic rock magnetometers employed radio frequency (RF) SQUID sensors, which make use of a resonant circuit that is driven by an RF current. New generation magnetometers use dc SQUID sensors, which take advantage of advanced thin film technology, and which are generally more sensitive and less prone to problems associated with RF interference. Readers are referred to the excellent review articles of Goree and Fuller (1976) and Clarke (1994) for details concerning the operation of SQUID magnetometers. This paper focuses on paleomagnetic applications of SQUID magnetometers, particularly in relation to analysis of sediment cores, which follow on from the pioneering efforts by Dodson et al. (1974) who were the first to document attempts to analyse long cores using SQUID magnetometers.

Long-core magnetometers almost exclusively have automatic sample handling systems that are operated through a computer-controlled interface. Cores or u-channel samples are typically loaded onto a sample holder in a loading area located in front of the magnetometer access space (Fig. 1a). The sample holder is moved into the magnetometer and demagnetizing system using a stepper motor, with a pulley system connected through capstans to allow forward and reverse motion of the sample holder (Fig. 1a). Computer controlled micro-switches are placed at each end of the sample track and the sample is moved to specified positions through the demagnetizing coils or to the measurement position by counting a specified number of steps on the stepper motor. Typical stepper motors enable extremely precise positional control to within tens of microns (i.e., 400–500 steps per cm). Use of string made from non-stretching compounds in the sample handling system results in precise sample movement, so that multiple types of measurements can be made with confidence on precisely the same positions of a core. Precise positional control is crucial for assessing the stability of the remanence to progressive stepwise demagnetization treatment and for calculating various inter-parametric ratios that are widely used in paleomagnetism and environmental magnetism (e.g. NRM/ARM, ARM/IRM, etc.).

High-resolution long-core cryogenic magnetometers (Fig. 1b) have narrow-access apertures that are just large enough to fit u-channel samples (Fig. 1c,d). A u-channel is a u-shaped 2 cm × 2 cm square-cross-section plastic liner with sharp tips (Fig. 1c) that can be pushed into a sediment core (Fig. 1e, f). The plastic is transparent, which makes it easy to see when the u-channel has been pushed in far enough (Fig. 1e, f). When the u-channel has been pushed into the sediment, a nylon fishing line can be passed under the u-channel to free it from the surrounding sediment. When the u-channel has been extracted from the core and the sides have been cleaned, the cap can be fitted (Fig. 1c) and the ends can be sealed with laboratory film to prevent the sediment from drying. The concept of u-channel samples was first suggested by Tauxe et al. (1983), while the u-channel design currently used globally by the ODP and many other groups, as shown in Fig. 1c, was developed by the paleomagnetic group at Gif-sur-Yvette, France, as described by Weeks et al. (1993). 2-G Enterprises are currently the only manufacturer of long-core cryogenic magnetometers used by paleomagnetic groups around the world.

Conventional cryogenic magnetometers have a large-diameter access space and are fitted with high homogeneity SQUID sensors (e.g. Fig. 2a). These pick-up coils have a relatively flat peak in which the response to a point magnetic dipole source will be uniform even if the source is moved over a distance of ∼5 cm. A result of this high homogeneity is that precise sample location is not crucial as long as the sample is located underneath the main peak of the response curve. This geometry is ideal for analysis of discrete paleomagnetic samples, and the majority of cryogenic rock magnetometers in the world have similar coil geometries. This geometry is less ideal for pass-through analysis of sediment cores because the width of the response curve is rather broad. The spatial (stratigraphic) resolution of such magnetometer systems is typically estimated (e.g. Weeks et al., 1993) from the width of the response curve at half the maximum height (referred to hereafter as the half-power width). As shown by the horizontal line in Fig. 2a, the half-power width for a typical magne-

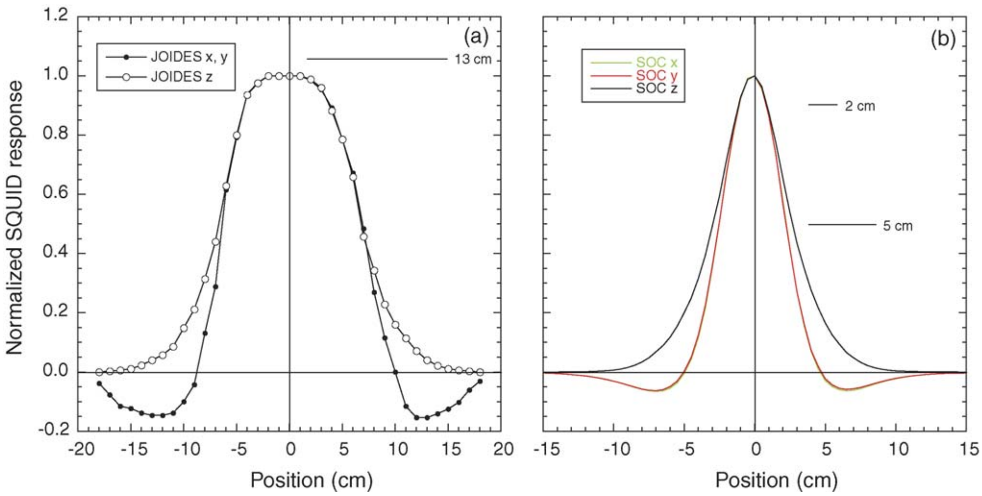

Fig. 2. Illustration of the response curves for a dipole point source sample as it is moved through the SQUID pick-up coils for: (a) the high homogeneity SQUIDs in the whole-core magnetometer system that operated onboard the *JOIDES Resolution* until 1996 and which has since been operated at Texas A&M University, College Station, Texas; (b) the high-resolution SQUIDS in the narrow-access u-channel magnetometer system housed in the NOC paleomagnetic laboratory. The half-power width (see text) is ∼13 cm in (a) and ∼5 cm in (b) and provides a measure of the degree of spatial (and therefore temporal) smoothing of the magnetic signal.

tometer with high homogeneity coils, in this case the system that until 1996 was installed onboard the *JOIDES Resolution* and that is now housed at Texas A&M University, College Station, Texas, is ∼13 cm. This means that the magnetic signal carried by a sediment core will be smoothed by a ∼13-cm moving window when long-core measurements are made with this magnetometer. An additional feature that is worth noting, and that will be discussed in more detail below, is the fact that the different pick-up coils do not have identical response curves. The transverse coils (x and y axes) have similar to almost identical response, with negative lobes on either side of the main peak, whereas the axial (z axis) coil has a more simple response curve that lacks the negative lobes. The negative lobes for the transverse axes result from the fact that the coil first detects the back-field of the dipole point source while it is some distance away from the coil. It then detects the main positive field when the dipole lies in the centre of the pick-up coil (Weeks et al., 1993).

High-resolution cryogenic magnetometers are fitted with high-resolution SQUID sensors. These pick-up coils have a much sharper peak (Fig. 2b) than the high-homogeneity coils (Fig. 2a). The advantage of these coils is that the half-power width is much reduced to ∼5 cm, as indicated by the scale bar on Fig. 2b. This coil geometry gives substantially better spatial (and therefore temporal) resolution, with much reduced smoothing. A negative result of the sharply peaked nature of the response curve, however, is that it makes analysis of discrete paleomagnetic samples more challenging. Precise sample location becomes crucial because a typical 2-cm sample must be precisely centred on the peak of the response curve to enable accurate paleomagnetic analysis of discrete samples. As stated above, however, the position of samples can be precisely controlled by the combined use of micro-switches, non-stretching string and fine-control stepper motors. High-resolution pick-up coils (e.g., Fig. 2b) are a compromise design that still allow paleomagnetic analysis of discrete samples, while substantially improving resolution for long-core analyses. In principle, higher-resolution coils could be developed, but this would require reduction of the diameter of the sample, which has attendant adverse side-effects such as decreased signal/noise ratio as a result of decreased sample size and as a result of increased sample disturbance due to increased surface area/volume ratio for a smaller u-channel sample. The coil geometry that gives rise to the response curves shown in Fig. 2b has therefore become standard for u-channel analysis and nearly 20 such high-resolution magnetometers are now installed in paleomagnetic laboratories around the world.

2.2. Alternating field demagnetization

Alternating field (AF) demagnetization of discrete samples involves application of a linearly decaying AF

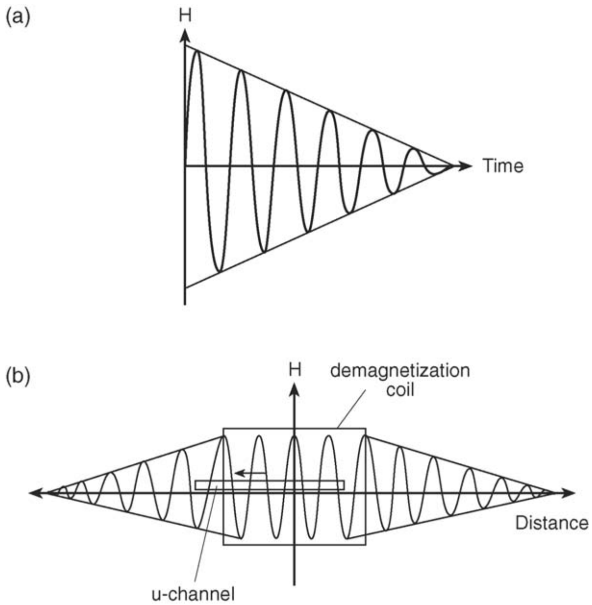

Fig. 3. Illustration of (a) conventional AF demagnetization where the applied field undergoes linear decay with time (see text). In contrast, u-channels are demagnetized (b) through linear decay of the field in space as the sample (shown with arbitrary length) is moved at constant velocity through a demagnetization coil that maintains a fixed peak field for the duration of the sample's movement (not to scale).

(Fig. 3). In conventional static AF demagnetization, the sample sits within the field while it is ramped up to the peak field and then while it decays linearly to zero (Fig. 3a). During each half cycle, the magnetic moments of grains with coercivities less than that of the peak field in the previous half cycle and greater than that of the peak field in the succeeding half cycle will be oriented along the direction of the AF that last exceeded the coercivity of the grain. For a distribution of grains, AF treatment will cause a similar number of moments to be oriented in a downward direction as would be oriented in an upward direction. The magnetic moments with coercivities less than the peak applied field will therefore be cancelled by this procedure.

AF demagnetization using a set of three mutually orthogonal demagnetization coils that are in-line with the long-core magnetometer sample track (Fig. 1a, b and d) is achieved by a modification of the above process. In this case, a field is ramped up until the desired peak field is reached within the demagnetization coil. The u-channel sample is passed through the coil while the field "tracks" at a constant peak value. The linear field decay required for effective demagnetization is achieved by moving the sample through the coil at a constant speed. The u-channel therefore moves through an AF that decays in space rather than in time (Fig. 3b). Once the u-channel has moved far enough through the coil so that it is demagnetized at the required peak field, the field is ramped down to zero and the desired field is ramped up in the next demagnetization coil and the sample is passed through again. This procedure is then repeated for the third coil to produce a 3 axis AF demagnetization. Once this 3 axis treatment is complete, the remaining remanence of the sample can be measured. A sequence of demagnetization steps with accompanying remanence measurements can then be achieved through an automated procedure.

The effectiveness of a conventional demagnetization treatment depends on the decay rate of the field, which, in the case of the long-core analysis, is equivalent to the speed of sample movement. Brachfeld et al. (2004) demonstrated this empirically and showed that rapid u-channel translation speeds can adversely affect the efficiency of AF demagnetization treatments. They recommend use of a 1 cm/s translation speed. The author has also conducted extensive experiments during the process of setting up a new instrument in his laboratory at the National Oceanography Centre (NOC), U.K., in 2001 and his findings are consistent with those reported by Brachfeld et al. (2004). A translation speed of 1 cm/s is routinely used for all sample movements in the NOC laboratory and this speed is recommended for routine use.

2.3. Laboratory-induced magnetizations

2.3.1. Anhysteretic remanent magnetization (ARM)

An anhysteretic remanent magnetization (ARM) can be imparted on modern u-channel magnetometers through use of an in-line solenoid that sits within the axial demagnetization coil (z axis). A dc bias field can be applied through the solenoid during AF demagnetization in order to impart an ARM. This procedure was suggested as a future development by Weeks et al. (1993) and is far superior to the early experiments that they conducted by placing an AF demagnetization coil inside a large set of Rubens coils with a steady dc bias field. While this experiment demonstrated for the first time that an ARM could be effectively imparted to u-channel samples, the manual handling of the u-channel through the demagnetization coil meant that translation speed could not be monitored. Brachfeld et al. (2004) showed, unsurprisingly, that translation speed affects ARM acquisition in the same way that it affects efficiency of AF demagnetization because rapid velocities decrease the number of AF half cycles experienced by the sample. Again, translation speeds of 1 cm/s are recommended by Brachfeld et al. (2004), which is consistent with the findings of independent tests in the NOC laboratory.

2.3.2. Isothermal remanent magnetization (IRM)

An isothermal remanent magnetization (IRM) can be imparted to u-channel samples through use of a pulse magnetizer in the form of a long (1.6-m) solenoid that is capable of inductions of up to about 0.9 T. Some laboratories have such solenoids arranged in-line with the sample track, so that an IRM can be imparted as part of a series of measurements to be successively made on the single u-channel sample. U-channel magnetometer systems are usually housed inside magnetostatically shielded laboratories, and, in these cases, the track usually passes through the wall of the shielded laboratory with the pulse magnetizer being placed outside the shielded space. This arrangement has a speed advantage, but a severe disadvantage is that the sample holder invariably becomes strongly magnetized as a result of exposure to large pulsed fields. This means that it becomes desirable to use a different sample holder when measuring samples with weaker natural remanent magnetizations (which defeats the initial objective of speed). To avoid this problem, the pulse magnetizer is arranged in an off-line mode in many laboratories, including the NOC laboratory. In such cases, the pulse magnetizer is manually operated. Regardless of the mode of control, the experience of workers in many laboratories is that application of a single pulsed field does not efficiently magnetize the sample. We have found that application of two pulsed fields is required to correctly impart the desired IRM (and application of a third pulse (or more) will usually only increase the magnetization by a matter of $\sim$1%). This procedure is also recommended by Brachfeld et al. (2004).

2.3.3. Demagnetization of laboratory-induced magnetizations

Laboratory-induced magnetizations can be subjected to AF demagnetization following the procedures described above, but complexities arise for dc demagnetization. Determination of the coercivity of remanence (B_{cr}) is highly problematical because different values are systematically obtained for the same samples when the induction is imparted with a pulse magnetizer compared to an electromagnet. This problem has resulted in some authors abandoning efforts to experimentally determine B_{cr} (e.g. Fabian and von Dobeneck, 1997; Tauxe et al., 2002). This problem is exacerbated when attempting to determine B_{cr} using the pulse magnetizers used for u-channel samples, because control of the applied field is imprecise at low field settings. Determination of B_{cr} is therefore not recommended for u-channel samples.

3. Limitations of long-core paleomagnetic measurements

3.1. Correction for the area under the SQUID response curves

When using a cryogenic magnetometer to analyse discrete samples, paleomagnetic declinations, inclinations and remanence intensities can be immediately interpreted (unless corrections are required for field orientation of samples or for bedding attitude of the sampled outcrop). In contrast, additional corrections often need to be made to long-core data. The reason for this can be seen when inspecting typical response functions for the SQUID pick-up coils of either a high-homogeneity (Fig. 2a) or a high-resolution (Fig. 2b) 3 axis SQUID configuration. In contrast to the axial SQUID, the response functions of transverse SQUIDs have negative lobes to the sides of the main positive peak. The breadth of these response functions means that a significant volume of sediment will contribute to the measured magnetization at any point along the core, so that the measured magnetization represents a convolution of the magnetometer response function with the true magnetization of the core (e.g. Constable and Parker, 1991; Weeks et al., 1993). The negative lobes on the sides of the main response peak for the transverse coils have important implications for which correction needs to be made. This correction is made by normalizing the magnetic signal recorded by each pick-up coil by the area under the respective response curve (Weeks et al., 1993). The effect of not making this correction is shown in Fig. 4 for Oligocene sediments from ODP Hole 744A (61°34.66′S latitude) from the southern Kerguelen Plateau in the Southern Ocean (see Roberts et al., 2003). At this latitude, a geocentric axial dipole (GAD) field has an inclination of $\pm 75°$. Notably, however, the data prior to correction (dark line) lie almost exclusively at steeper inclinations (Fig. 4). Adding the area of the negative lobes to the area of the positive main response for the transverse pick-up coils gives a smaller area for the transverse coils compared to the axial coil. Dividing the total measured magnetization for each axis by the area under the respective response curve will therefore give rise to a relative increase in values for the x and y axes compared to the z axis. This will cause an increase in the recalculated total magnetization for the sample (where intensity $= \sqrt{x^2 + y^2 + z^2}$). The paleomagnetic

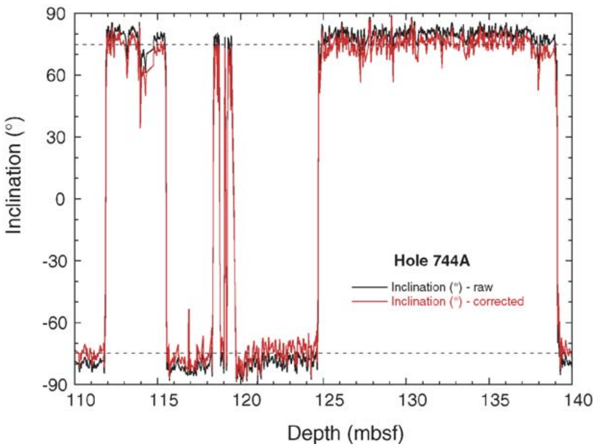

Fig. 4. Illustration of the effects on the paleomagnetic inclination of correction for the area under the response curves of the magnetometer SQUID sensors. This correction for the effects of the negative regions on the edges of the response functions for the transverse axes (Fig. 2) causes a change in the proportion of the remanence along the x, y, and z sample axes, which will have a variable effect on the paleomagnetic direction (and intensity) depending on the relative magnetic moment along each axis (which will vary, for example, with latitude). The data shown are for the Oligocene portion of Hole 744A from the southern Kerguelen Plateau (Roberts et al., 2003). The dashed lines represent the expected inclination (±75°) for a geocentric axial dipole field at the site latitude.

inclination is given by:

$$\text{inclination} = \sin^{-1}\left(\frac{z}{\sqrt{x^2+y^2+z^2}}\right).$$

The effect of increasing the total magnetization is that $z/\sqrt{x^2+y^2+z^2}$ becomes smaller, thereby producing a shallower inclination. As shown in Fig. 4, recalculation of the inclinations after applying this correction results in shallower inclinations that are consistent with a GAD field at the site latitude (Roberts et al., 2003). Omission of this correction is probably responsible for occasionally reported paleomagnetic inclinations from marine sediment cores that are slightly steeper than expected (e.g. Dinarès-Turell et al., 2002). Histograms of characteristic remanent magnetization (ChRM) directions for u-channel-derived magnetostratigraphic data from thick sedimentary sequences (Fig. 5) reveal that AF demagnetization can effectively remove the overprints that often plague paleomagnetic studies of ODP cores (e.g. Roberts et al., 1996; Fuller et al., 1998; Acton et al., 2002b) and that correction for the area under the SQUID response curves can yield inclinations that are consistent with that expected for a GAD field (e.g. Roberts et al., 2003; Florindo and Roberts, 2005).

Routine correction for the area under the response curves of the magnetometer can now be made within the operating software provided by 2-G Enterprises with their long-core magnetometer systems (this was not the case with earlier software versions). Correction for the volume of sediment that is detected by the SQUID sensors is made by entering the cross-sectional area of the sample, which, in the case of u-channels, is 2 cm × 2 cm = 4 cm^2. This area is multiplied by the cross-sectional area of the respective magnetometer response curves, which is referred to as an "effective sensor length" (in order to obtain volume units, i.e., area × length = volume in cm^3). In the case of the u-channel magnetometer housed in the author's laboratory at the NOC, the effective sensor lengths are approximately 4.27 cm for the x and y axes and 6.48 cm for the z axis. The effective sensor lengths for the 2-G Enterprises magnetometers on board the *JOIDES Resolution* before and after 1996, respectively, are 11.17, 9.49, and 14.26 cm for the x, y and z axes, respectively, and 6.07, 6.21, and 9.92 cm (Wilson et al., 2003). Use of the effective sensor length option in the 2-G Enterprises control software is recommended for long-core paleomagnetic measurements. Nevertheless, corrections can also be made after the measurements are made, as demonstrated in Fig. 4.

3.2. Geometric effects resulting from non-centred samples and magnetometer mis-calibration

In many cases, such as onboard the *JOIDES Resolution*, cores are split in half and the archive halves of cores are measured in a long-core magnetometer. The cross-section of the split core is irregular, therefore such measurements, by definition, do not correspond to the ideal case for which a long-core magnetometer is designed (i.e. homogeneous magnetizations within samples with uniform (ideally circular) cross-section measured along the centre-line of the magnetometer access space). Parker (2000) demonstrated that directional artefacts can be produced as a result of measurement of geometrically irregular or imperfectly centred cores. Similar effects can occur if the magnetometer is not perfectly aligned, which could easily go undetected if, for example, there was a difference in alignment between the centre of the access space and the centre of the magnetometer pick-up coils. This has been documented to be the case for the shipboard magnetometer on the *JOIDES Resolution* (Parker and Gee, 2002), so this is more than a purely theoretical problem. Parker and Gee (2002) argued that directional distortions will be a universal feature of all pass-through magnetometers. It should be remembered, however, as is evident from the range of contributions in this volume, that long-core magne-

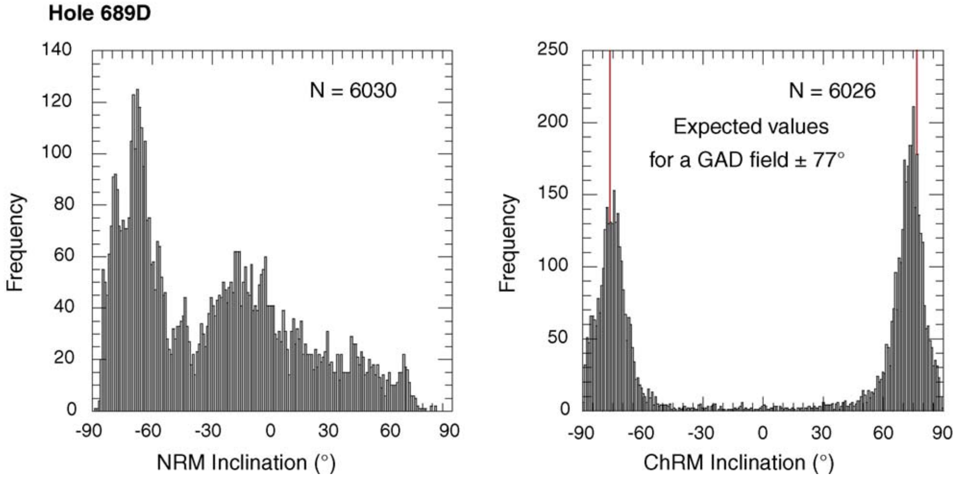

Fig. 5. Representative histograms of paleomagnetic inclinations (left) for the undemagnetized natural remanent magnetization (NRM) and for the stable ChRM (right) determined after stepwise AF demagnetization for the late Eocene and Oligocene portion of Hole 689D, from Maud Rise, Weddell Sea (from Florindo and Roberts, 2005). These data demonstrate the strong effect of coring-induced and other magnetic overprints (left; see Fuller et al., 1998; Acton et al., 2002a) as well as demonstrating that in many cases these overprints can be successfully removed to provide excellent records of geomagnetic field behaviour with inclinations that are consistent with those expected for a geocentric axial dipole (GAD) at the site latitude (marked by vertical lines at $\pm 77°$). The large number of ChRM values obtained from u-channel studies such as those by Acton et al. (2002b; >13,000), Channell et al. (2003; ∼16,000), Roberts et al. (2003; >11,000) and Florindo and Roberts (2005; >16,000) compared to those of conventional magnetostratigraphic studies (typically up to a few hundred ChRM directions are obtained) demonstrates a major advantage of the u-channel measurement technique. As was shown by Roberts et al. (2003), measurement at 1-cm intervals allows assessment of subtle variations in the strength of overprinting, which can be complex and less easy to unravel at more typical coarse measurement intervals.

tometers have provided outstandingly useful data for a wide range of paleomagnetic applications. The distortions discussed by Parker (2000) and Parker and Gee (2002) are generally small (of the order of a few degrees); nevertheless, some observed asymmetries in the measured signals can lead to a completely spurious picture of high-resolution field behaviour with respect to details of great interest to paleomagnetists. Mercifully, some of these geometrical problems can be substantially reduced in the case of u-channel measurements because the u-channel has a regular cross-section (although it is not ideally circular) and is easier to centre within the measurement region of the magnetometer. Misalignment of the centre-lines of the access space of the magnetometer and of the pick-up coils is, however, a potential problem that could easily go undetected if detailed tests are not made on any given magnetometer. The potential for directional distortion should serve as a caution to paleomagnetists (and other users of long-core magnetometer data) about interpretation of fine-scale features in a long-core paleomagnetic record. There is often no substitute for measurement of continuous discrete samples when seeking to elucidate details of geomagnetic field behaviour (e.g. secular variation, excursions, polarity transitions).

3.3. *Paleomagnetic artefacts produced by large changes in remanence intensity*

If the above-described correction for area of the SQUID response curves is made, and a magnetometer is perfectly aligned and a symmetrical sample is measured exactly in the centre of the magnetometer access space, there are still additional pitfalls that can compromise the usefulness of long-core paleomagnetic data. Long-core magnetometers are explicitly designed for measurement of homogeneously magnetized materials. Most sediments of interest for paleomagnetic studies are not homogeneously magnetized and design limitations of long-core magnetometers can therefore affect the usefulness of results. Weeks et al. (1993), Roberts et al. (1996) and Parker and Gee (2002) have all recognized spurious results from cores in which there were significant changes in remanence intensity. Convolution of the magnetometer response functions with an idealized signal represented by an unchanging direction of magnetization in a core containing a large increase in remanence intensity will produce spurious paleomagnetic directions at the region of major intensity change (Fig. 6). In the case shown, the modelled magnetization increases by a factor of only 2.5 in the central part of the

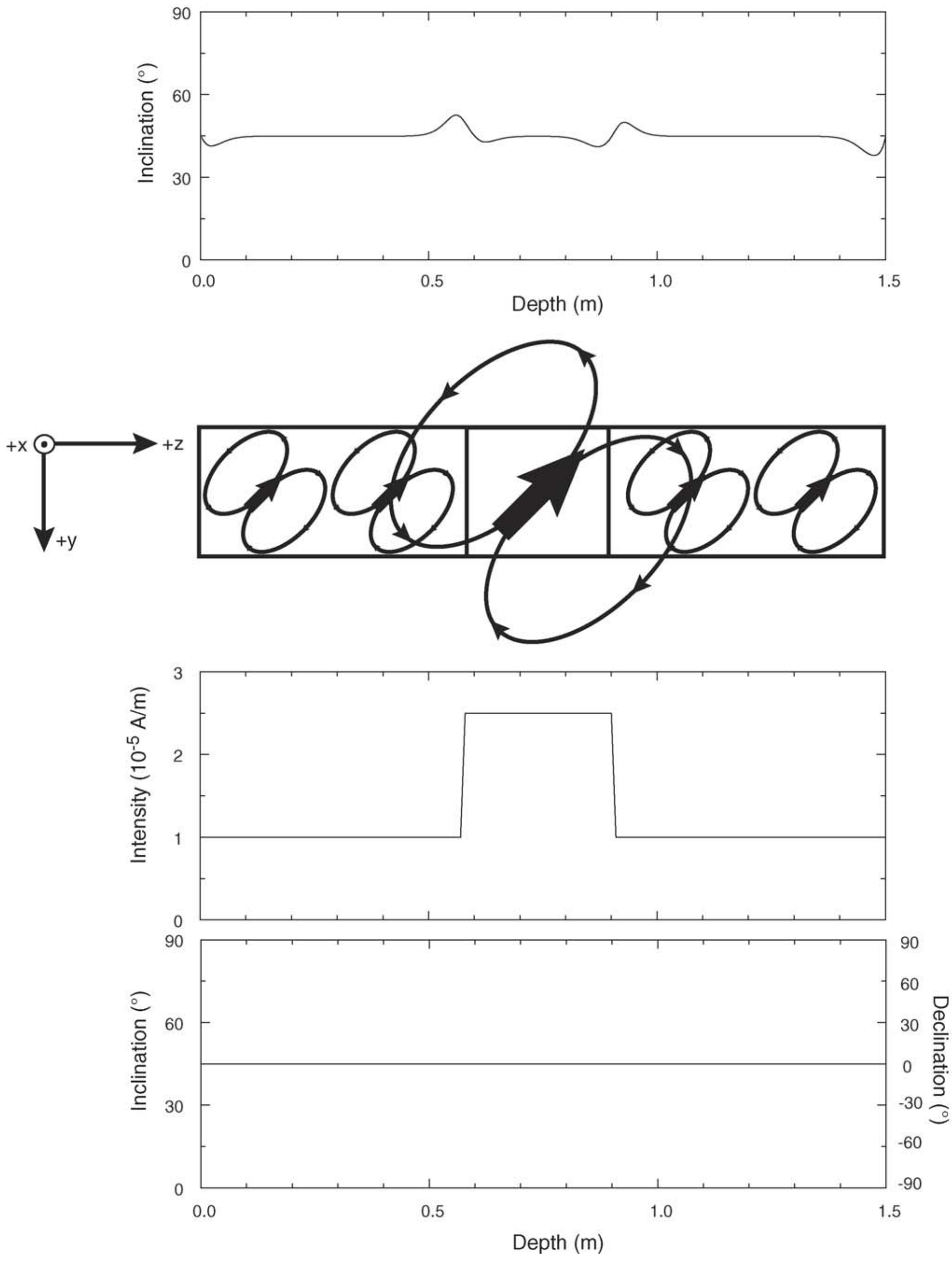

Fig. 6. Simulated effect on the paleomagnetic direction of a major change in remanence intensity (increase by a factor of 2.5) in a core subjected to continuous u-channel measurements. This simulation illustrates how spurious artefacts are introduced into the paleomagnetic directional record as a result of convolution of the magnetometer response functions with a straightforward paleomagnetic signal. The complications arise from the fact that the transverse axes detect the large back-fields produced by the bed with strong remanence intensities. Deconvolution (or analysis of discrete samples) is necessary to remove (or avoid) this problem.

1.5-m core section, which produces inclination artefacts with a total amplitude of 10° at the lower and upper boundaries of the interval with higher magnetizations. Larger contrasts in magnetization will produce larger anomalies. The anomalous directions can be attributed to variations in the ratio of the axial to transverse moment (due to variable effects of the negative lobes for the transverse axes) in the region where the remanence intensity changes. Complexities caused by strong variations in remanence intensity and the relationship between the response curves for the transverse and axial SQUIDs demonstrate that care must be taken when interpreting detailed features in long-core measurements. Some of the results of Roberts et al. (1996) are reproduced here to further demonstrate the effects of intensity changes on measured magnetic signals.

Roberts et al. (1996) placed a number of discrete cubic samples, with known remanence directions and intensities, back-to-back in a "cube-train" to determine the effect of convolution of the magnetic signal with the SQUID response functions shown in Fig. 2a when measured in long-core mode. They included one minor change in declination, one large inclination "excursion" and two large changes in remanence intensity (by a factor of almost 100), as well as several smaller step changes (black symbols in Fig. 7). As expected, the long-core magnetometer was able to accurately track the small change in declination, but it substantially smoothed the record of the large inclination excursion as well as the large intensity changes (white symbols in Fig. 7). Alarmingly, a spurious declination "excursion" is produced in the vicinity of one of the major changes in remanence intensity. The axial component of magnetization is dominant in this experiment (i.e., inclinations are relatively steep; 60–80°), so it is easier to produce spurious declinations rather than inclinations by varying the remanence intensity. If the magnetization had greater contributions from the transverse components, it would have been easier to produce spurious inclinations, as was observed by Weeks et al. (1993). It is clear from these examples that significant, but entirely spurious, changes in declination and inclination can accompany major changes in remanence intensity and that care should be taken when interpreting long-core paleomagnetic results in the vicinity of such non-homogeneous magnetizations. The best way to avoid such pitfalls is to analyse discrete samples for intervals where large changes in remanence intensity are expected. This includes, by definition, core intervals that record geomagnetic polarity transitions and excursions. Alternatively, as discussed below, numerical deconvolution can help to remove such spurious effects.

3.4. New parameters that avoid measurement limitations

One of the limitations of cryogenic magnetometer systems is that it is usually difficult to measure the magnetization of samples with intensities exceeding ~1 A/m. This remains problematical even with the expanded dynamic range of the latest systems with dc SQUIDs. It is therefore often difficult to consistently measure the IRM imparted at the maximum field of about 0.9 T for samples with high concentrations of magnetic minerals without causing the magnetometer to undergo a dreaded "flux jump". Flux jumps occur when the SQUID electronics cannot count the large magnetic flux from strongly magnetized samples fast enough and a non-reversible jump in magnetization occurs. Such flux jumps usually render useless the data for the measurement sequence affected by the jump. Repeating measurements to avoid flux jumps near this intensity threshold (the exact level of which varies from magnetometer to magnetometer) can be frustrating and often fruitless. If IRM data are required, it is often better to take sub-samples and to

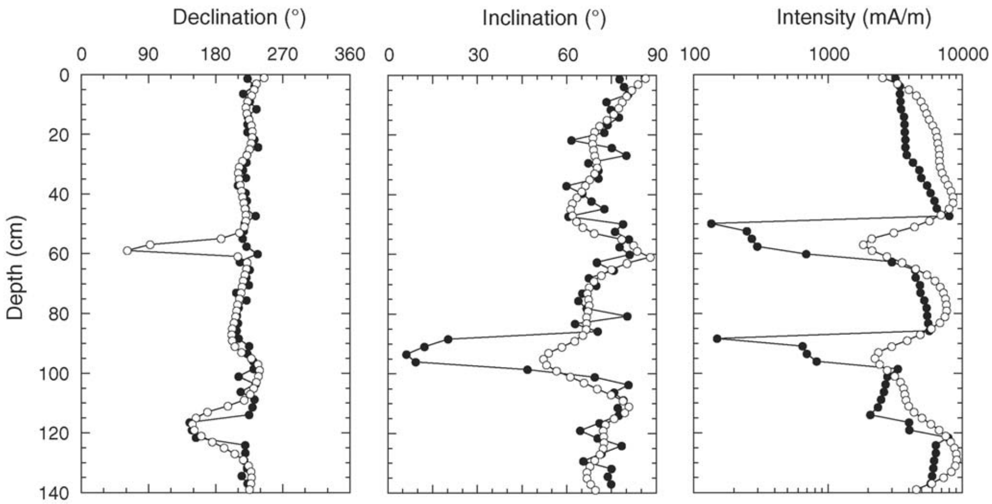

Fig. 7. Results of a "cube-train" experiment aimed at demonstrating the effects of large changes in remanence intensity on long-core paleomagnetic measurements. Solid circles represent results from individually measured discrete samples, which were placed back-to-back and measured in continuous long-core mode at 2-cm intervals (open symbols). See text for explanation (after Roberts et al., 1996).

use an alternative treatment procedure. In cases where we have been interested in determining the so-called "hard" IRM (where HIRM = $IRM_{0.9\,T} - IRM_{-0.3\,T}/2$), it has often been impossible to obtain accurate measurements of the two key components of this parameter ($IRM_{0.9\,T}$ and $IRM_{-0.3\,T}$). The HIRM parameter provides a measure of the concentration of high coercivity minerals (e.g. hematite and goethite) within a sample. Quantification of the high coercivity component can be done in an alternative way that avoids the problem with the dynamic range of the magnetometer. Instead of trying to measure $IRM_{0.9\,T}$, we have immediately subjected the $IRM_{0.9\,T}$ to AF demagnetization at 120 mT. This will demagnetize the contribution from magnetite or other low coercivity minerals and should only leave a signal that is carried by the high coercivity minerals. This new parameter (which we call $IRM_{0.9\,T}$ @ $AF_{120\,mT}$) is easily measurable because the unwanted magnetite component no longer causes the undesired flux jumps. Larrasoaña et al. (2003b) showed that this parameter is quantitatively similar to the HIRM parameter; they used it to obtain a continuous 3-million-year record of orbital modulation of Saharan dust fluxes into the eastern Mediterranean Sea. The $IRM_{0.9\,T}$ @ $AF_{120\,mT}$ parameter is only one example of a new parameter. There is considerable scope for development of new parameters using standard hardware installed with modern long-core magnetometer systems.

4. Other issues that affect the resolution of long-core measurements

4.1. Deconvolution

One of the obvious questions raised by the above discussion of measurement artefacts is whether it is possible to recover the original magnetization record, as well as to improve the resolution of the measured record, using numerical deconvolution techniques. Numerous attempts to develop effective deconvolution schemes for long-core measurements have been made since the first efforts of Dodson et al. (1974). These authors used Fourier transforms in the frequency domain, but noted that practical difficulties affected the results, with any noise in the measured remanence record being greatly amplified by the deconvolution procedure. Constable and Parker (1991) worked in the time domain and attempted to deal with the inherent instability associated with amplification of noise associated with the most attenuated small-scale features by imposing maximum smoothness on the unknown magnetization. This was done by comparison of model residuals and observational errors. Their procedure resulted in a three-fold improvement in resolution, which proved to be comparable to a parallel record obtained from discrete samples. Weeks et al. (1993) used the Constable and Parker (1991) approach and noted that it was remarkably successful in retrieving details of the directional record, but that it was less successful in retrieving the intensity. They noted a two-fold increase in resolution, which was again verified by a parallel discrete sample record. Oda and Shibuya (1996) agreed that the Constable and Parker (1991) method works for a well-defined noise level, but found that it tends to be unstable when the noise level is unknown. They modelled the magnetization vector as a smoothly changing function by minimizing Akaike's Bayesian Information Criterion and obtained a spatial resolution of ~2 cm. Guyodo et al. (2002) used the Oda and Shibuya (1996) method to test whether it is possible to retrieve information about short-duration geomagnetic features such as polarity transitions and excursions. In a significant advance, they did not use simple magnetometer response functions of the type shown in Fig. 2b. Instead, they recognized the problem of variable response depending on location within the measurement region, as pointed out by Parker and Gee (2002), and measured the response for each pick-up coil along a 9-node square grid over the volume represented by a u-channel within the magnetometer. The response functions over this area were integrated to reflect the average response of the sensors in the volume occupied by the u-channel during measurement (to avoid possible non-homogeneous response). They reported a significant increase in resolution upon deconvolution compared to u-channel data, with a resultant resolution equivalent to continuous discrete sampling.

Overall, it appears that deconvolution methods are improving to the point where their routine use is increasingly justified. An additional important advantage of deconvolution is that, even if it is applied in a minimalistic manner so that spatial resolution is not improved (which avoids the attendant danger of amplifying noise), it can remove the spurious directional artefacts produced by convolution of the magnetometer response functions with large-scale changes in remanence intensity (Weeks et al., 1993; Roberts et al., 1996). On the other hand, a point that is rarely made in discussions aimed at improving the resolution of long-core paleomagnetic measurements is that some level of smoothing is desirable since paleomagnetic data from discrete samples can contain noise (resulting from errors introduced by sampling, including deformation, or measurement) that authors often seek to remove by numerical filtering. Application of deconvolution methods that use smoothness criteria therefore provides a sensible approach to the noise amplification problem inherent to deconvolution and recognizes that smoothness will be present because of the nature of remanence acquisition in sediments.

4.2. Measurement smoothing and the likelihood of recording short-duration features

If a sediment acquires a remanence through a post-depositional remanent magnetization (PDRM) lock-in mechanism, geomagnetic field variability recorded by that sediment will be smoothed by the lock-in process. It is therefore worth comparing whether smoothing caused by the response function of a high-resolution u-channel magnetometer will combine with the effects of PDRM smoothing to cause non-recovery of important geomagnetic information. Roberts and Winklhofer (2004) developed a PDRM lock-in model in which they calculated the likelihood of recording short-duration features, such as geomagnetic excursions, under ideal recording conditions where most (95%) of the PDRM is locked in within 5 cm of the sediment–water interface (with 100% of PDRM locked in at 10 cm depth). Their results for many model calculations are presented in the nomograms shown in Fig. 8, where the PDRM success rate (percentage of excursions recorded) is plotted with respect to variation in sedimentation rate and excursion length. A reasonable criterion is imposed whereby three consecutive measurements (at 1 cm spacing) are required to identify a geomagnetic excursion. The nomogram in Fig. 8a indicates that, for shallow lock-in, if excursions have relatively short durations of ∼1 ky, sedimentation rates of >7 cm/ky are required to ensure that they will be recorded. On the other hand, if excursions have lengths of 2–3 ky, minimum sedimentation rates of 2–3 cm/ky are required to ensure their detection. For deeper lock-in, where 95% of the remanence is locked ∼10 cm below the sediment-water interface (and 100% locked in at 20 cm depth), substantially higher sedimentation rates are required to ensure detection of excursions (Fig. 8b). These model results provide some practical guidelines on the likely recording fidelity with respect to sedimentation rate for u-channel studies of sediments where PDRM lock-in is efficient.

4.3. Comparing measurement smoothing and sedimentary lock-in smoothing

It is also worth comparing whether it is possible to constrain the relative effects of PDRM smoothing and smoothing caused by the u-channel measurement. This can be attempted by comparing a u-channel record with a detailed discrete sample record for a short-duration feature such as a geomagnetic excursion. A detailed record of the ∼188 ka Iceland Basin excursion (cf. Channell, 1999) from ODP Hole 884D in the North Pacific Ocean is shown in Fig. 9. Continuous (8 cm^3) discrete samples were taken (open circles in Fig. 9) to test whether the excursion record documented from u-channel results (from Roberts et al. (1997); solid circles in Fig. 9) was robust. This test was conducted because of the possibility that spurious directional "excursions" can be produced as a result of substantial remanence intensity variations, as discussed above. The average sedimentation rate for

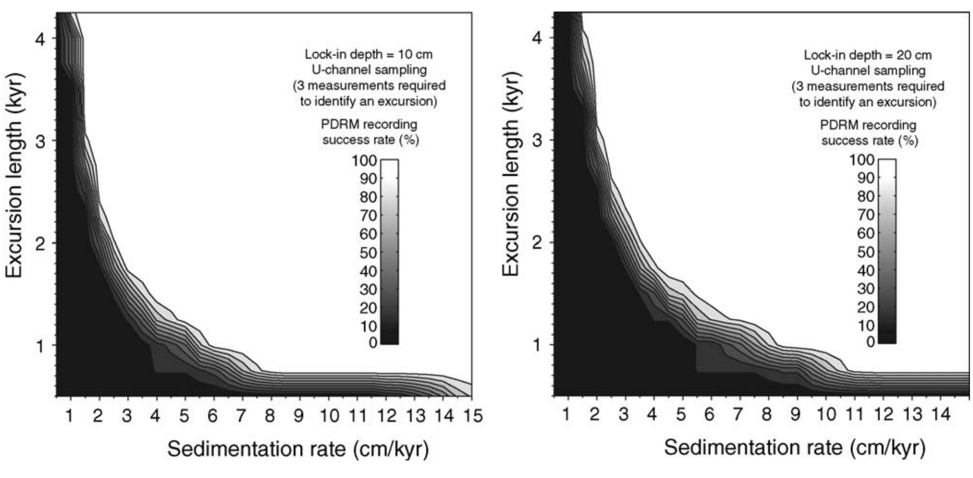

Fig. 8. Nomograms of expected PDRM recording success rate for detection of excursions in sediments where 95% of the PDRM is locked 5 cm below the sediment-water interface (left; with 100% lock-in at 10 cm depth) and for complete lock-in at 20 cm depth (right). A detection criterion of three continuous measurements within a u-channel is imposed. See text for explanation (after Roberts and Winklhofer, 2004).

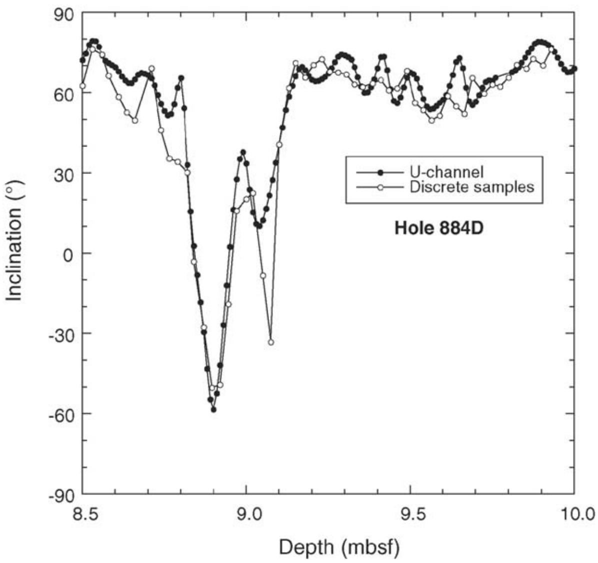

Fig. 9. Illustration of the relative effects of u-channel measurement smoothing and PDRM smoothing for a record of the Iceland Basin excursion from ODP Hole 884D, North Pacific Ocean. The u-channel results are from Roberts et al. (1997). See text for discussion.

this core over the last 200 ky was 5 cm/ky (Roberts et al., 1997). However, the excursion shown in Fig. 9 is ∼30-cm thick, and, based on an estimate of 3 ky for its duration (Channell, 1999), local sedimentation rates for this part of Hole 884D were probably around 10 cm/ky. The fact that a 3-ky excursion is recorded at these sedimentation rates is consistent with the nomograms shown in Fig. 8.

It is immediately clear that the results from discrete samples for this record of the Iceland Basin excursion generally provide verification of the validity of the u-channel results (Fig. 9). The discrete samples were measured using the high-resolution pick-up coils shown in Fig. 2b, which also verifies that such strongly peaked response curves can be successfully used for paleomagnetic measurements of discrete samples. The excursion waveform has two peaks with negative inclinations. The lower peak is substantially attenuated by the u-channel measurement, whereas the upper peak is faithfully reproduced in detail. This is probably due to the fact that the upper inclination feature is relatively thick (10–15 cm). In this case, the stratigraphic rate of change of the geomagnetic feature is small compared to the resolution of the magnetometer pick-up coils. On the other hand, the lower inclination feature is < 10 cm thick, and is strongly peaked, so it has been substantially smoothed in the u-channel record compared to the discrete sample record. The u-channel and discrete sample records match each other reasonably well except in places where discrete samples indicate short-period changes. While it is often assumed that such differences between u-channel and discrete sample records result from smoothing of u-channel records, it is also possible that the discrete samples are affected by a range of effects (e.g. sediment deformation, decreased signal/noise ratio).

Close agreement between the u-channel and discrete sample records probably suggests that the remanence acquisition process caused smoothing at a similar, although probably slightly lower level, compared to the smoothing caused by the u-channel measurement. This might suggest that at sedimentation rates > 10 cm/ky, the effects of smoothing due to u-channel measurements and PDRM recording will become less important and that higher-frequency geomagnetic features will be more easy to resolve. This conclusion, of course, will be affected by variations in PDRM recording efficiency. Also, as pointed out by Roberts and Winklhofer (2004), localized reductions in sedimentation rate, which usually go unrecognized because of the relatively low resolution of age models (see Guyodo and Channell, 2002), will impair recording fidelity (Fig. 8). Regardless, sediments deposited at rates in excess of 10 cm/ky would seem to be ideal for minimizing the effects of measurement and PDRM smoothing for u-channel studies of geomagnetic field behaviour.

5. Continuous magnetic susceptibility measurements of sediment cores

Continuous measurement of the low-field magnetic susceptibility of cores and u-channels provides an important additional parameter for a wide range of paleomagnetic and environmental magnetic studies. Lack of space here prevents more detailed discussion, and such a treatment is being prepared for publication elsewhere. The most important conclusions of this detailed analysis are simply mentioned here without further justification. It is recommended to use loop sensors with a similar response function and therefore a similar spatial resolution as a u-channel magnetometer to ensure comparability of data. Calibration of loop sensors using independent high-precision susceptibility meters, such as Kappabridge meters (see Sagnotti et al. (2003) for a brief treatment of the calibration problem), is also strongly recommended.

6. Conclusions

Long-core paleomagnetic measurements made onboard the *JOIDES Resolution* have provided many superb magnetic polarity stratigraphies that have laid a chronological foundation for understanding the tectonic and paleoceanographic development of the world's ocean basins. High-resolution studies of u-channel samples have also provided a wide range of important new insights into geomagnetic field behaviour, geochronology, and environmental change. Despite the fact that long-core magnetic measurements have provided a foundation for major recent developments in the Earth sciences, many aspects of such measurements can be compromised and knowledge of these technical limitations is needed to avoid over-interpretation of data. These aspects have been described in the present paper, and are as follows. (1) It is necessary to correct for the zones of negative response on the transverse pick-up coils of a magnetometer to avoid substantial distortions of the paleomagnetic direction and intensity. (2) It is necessary to measure samples with geometrically uniform cross-section along the centre-line of the magnetometer. If this cannot be achieved, as is routinely the case with shipboard measurements of split-cores, it is necessary to know how the magnetometer response functions vary spatially throughout the measurement volume, although corrections for such cases will be complex. Knowledge of spatial variation of the response functions is also useful when applying deconvolution schemes to data from centred samples with uniform cross-section. (3) It is worth considering routine use of numerical deconvolution schemes (without increasing the spatial resolution of the results) in order to remove directional artefacts caused by large variations in remanence intensity. Recent attempts to use deconvolution for increasing the spatial resolution of long-core measurements appear to be successful in avoiding the amplification of noise that has plagued such attempts in the past. Routine use of deconvolution for this purpose is therefore worth consideration. (4) Smoothing as a result of PDRM acquisition in one studied case with estimated local sedimentation rates of ~10 cm/ky appears to have a similar effect to smoothing caused by the u-channel measurement. Thus, paleomagnetic analysis of sediments deposited at rates exceeding 10 cm/ky appears to be a reasonable strategy for minimizing the effects of smoothing associated with u-channel measurements (notwithstanding the issues discussed above). (5) Magnetic susceptibility loop sensors with a similar response function as a u-channel magnetometer are recommended to ensure comparability of the two types of data. Calibration of loop sensors using independent high-precision susceptibility meters is also strongly recommended. Routine adoption of these five strategies should help to maximize the value of long-core measurements.

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