Improvements in long-core measurement techniques: applications in palaeomagnetism and palaeoceanography

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SUMMARY

We report on new developments in the long-core measurement techniques using *u* channels in connection with new small-access cryogenic magnetometers. With these new instruments, *u*-channel samples allow us to measure a wide range of magnetic parameters along entire-core length with a spatial resolution and accuracy virtually equivalent to that obtained using discrete cubic samples. An additional advantage is that the sediment disturbance when sampling is significantly less when using *u* channels.

We present comparisons of results from both continuous and discrete measurements and examine the effectiveness of minimal deconvolution using various techniques. Examples of continuous measurements of low-field susceptibility, NRM, ARM, IRM, Hrc from North Atlantic deep-sea cores show that it is possible to generate logs of combination of parameters related to rock-magnetic characteristics of the sediments useful in palaeoceanography. In particular, the continuous method allows us to rapidly detect core regions with fast changing magnetic parameters useful for correlation between cores and also for understanding changes in palaeo-environmental conditions.

The fast scan also allows us to detect regions of the core where the rock magnetic parameters are suitable (or not suitable) for palaeomagnetic studies related to changes in the geomagnetic field such as the relative changes in palaeointensity.

Key words: palaeomagnetism, palaeoceanography, rock magnetism, *u* channels.

1 INTRODUCTION

One of the initial motivations for development of the SQUID (Super Conducting Quantum Interference Device) magnetometer for palaeomagnetism was the eventual possibility of long-core measurement (Goree & Fuller 1976). Not only did the SQUID magnetometer promise to bring substantial improvement in sensitivity to palaeomagnetic observations, but the nature of the measurement by the SQUID opened the possibility of new applications, not readily carried out with the spinner magnetometers commonly used in the late 1960's and early 1970's. The SQUID measurement gives a measure of the flux change brought about by the introduction of a magnetized sample into the pick-up coil array. SQUID electronics work at radio and high audio frequencies, so the measurement is very rapid as well as highly sensitive. These factors suggest that a continuous measurement of the magnetization could be obtained if a long core was passed through the system. However, the SQUID sense coil array was designed for single-sample measurements which required homogeneity of response over the volume of standard cylinders of 1″ height and diameter. The result was that the resolution of the long-core measurement was considerably lower than that of standard 1″ cylinders. In some applications this was not important, but ultimately better resolution became desirable.

Resolution of long-core measurements can be improved by deconvolution in the frequency domain. In the initial study by Dodson, Fuller & Pilant (1974), measurements were made only for the axial component, with satisfactory

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results, so that with deconvolution, the resolution was increased by more than a factor of 2. With the availability, at Pittsburgh of a new magnetometer which had three coils and SQUID sensors, so that all three components could be measured at the same time, the long-core measurements became more feasible (Dodson *et al.* 1974). However, as attempts to increase the resolution were made, severe ringing was encountered at the wavelength corresponding to the axial length of the coils. Moreover, despite application of standard techniques to mitigate the problem, the three component measurements did not reach the resolution of the earlier axial component measurements. The problem was studied by Constable & Parker (1991) who used an improved method of deconvolution in the time domain. However, these authors noted that the only sound way to make major improvements in resolution was to do a better experiment. The availability of small cross-sectional area subsamples of cores, called *u* channels, following the suggestion of Tauxe *et al.* (1983), has brought about the development of new magnetometers with smaller apertures that are specifically designed for high-resolution long-core measurements.

This paper outlines developments in the use of these new magnetometers for long-core measurements using *u*-channels. A further development has been the recognition that standard rock magnetic characterization can also be done with these instruments.

2 SAMPLING AND EQUIPMENT

2.1 Sampling for the smaller access SQUID magnetometers

One of the newer developments in the continuous measurement of sediment cores involves the use of '*u* channels' (Tauxe *et al.* 1983). In this sampling method, a long subsample, of about 4 cm^2 square cross-sectional area, is taken from the core half using open-sided, *u*-shaped, non-magnetic, stiff PVC plastic tubing. The *u* channels are cut into sections which are the same length as the core sections (usually 1.5 m). These smaller samples can be passed through small diameter access magnetometers such as that at Gif-sur-Yvette (Fig. 1a) (described below). This sampling method produces less sediment disturbance than sampling with conventional cubic samples since the surface area to volume ratio is much less. Cubic samples, which have drag on four sides when they are pushed into the sediment, have been shown, in some cases, to introduce a susceptibility anisotropy parallel to the direction of push (Hailwood, Stump & Zukin 1989). The *u* channels developed at Gif are made of transparent plastic, so recovery of sediment can be visually controlled. An airtight cover, made of the same plastic, clips over the *u* channel to hold the sediment in place and to prevent it from drying.

2.2 Small access SQUID magnetometers

Two 2*G* horizontal pass-through magnetometers are now installed at the CFR palaeomagnetic laboratory at Gif-sur-Yvette. The first is a 'conventional' 4.2 cm access, 2*G* model 755-R operated horizontally. It has a set of SQUID sensing coils with high homogeneity (HH set) of

sensitivity over a volume which is large compared to the size of standard palaeomagnetic samples. The second, specifically developed at the demand of this palaeomagnetic laboratory, is a modified 4.2 cm access 755-R with six SQUIDS. This magnetometer has two sets of sensing coils offering different resolutions. It was designed to give improved long-core measurements where one three-axis set of coils (identical to the HH set of the 755-R magnetometer) is used for high homogeneity measurements (i.e. discrete sample) and the second set, called the high resolution or HR set, is for improved spatial resolution along the long-core axis. Previously, the conventional long-core measurement was made by passing whole cores, or half cores, through a larger access magnetometer. The small access magnetometers give better sensitivity and spatial resolution upon measurement of *u* channels than previously obtained on whole core halves: that is, they resolve changes in magnetization over much smaller lengths along the core.

The basic features of the new magnetometer are schematically shown in Fig. 1(b). In the long-core measurement, a core section, or long *u*-channel subsample from a core section, is stepped through the pick-up coil system and readings are taken every centimetre or so. The measurement time is controlled by the speed of acquisition of data and the measurement spacing required. Two modes of acquisition are possible. Translation of the *u* channel can be continuous, with measurements made at the maximum rate possible for the electronic system. Continuous translation produces the faster but not necessarily the most accurate measurements. We use stop measurements because of the rather slow read time of the 2*G* electronics. The Gif system, from which the 2*G* system is derived, uses a stepper motor drive with measurements taken while stopped at 1 mm or longer intervals.

2.3 In-line AF demagnetization

An important step, that increases the efficiency of the pass-through measurement technique, is the inclusion of 'in-line' (along the magnetometer access track) AF demagnetization coils. *U* channels are demagnetized and measured with a minimum of movements along the same track. In the set up at Gif-sur-Yvette, a series of three coils are arranged to demagnetize on the three perpendicular axes and the *u*-channel sample demagnetized by passing it through the coils at constant AF values of up to 120 mT. Because of space restrictions, the three coils are closely spaced, so that they interact. Therefore, it is not possible to demagnetize in a single pass, each axis requires a separate pass. The region of AF decay is well shielded as the sample moves away from the coils so that demagnetization is in as close to zero DC field as possible. The in-line arrangement allows the procedure to be easily automated. At Gif, computer control of the demagnetization coils, the *u*-channel translation system and data acquisition, allows the entire demagnetization and measurement of a *u* channel to be made automatically. A 1.5 m *u* channel can thus be entirely studied with eight steps of demagnetization and measurements taken every centimetre in half a day, i.e. the complete declination and inclination record for a 15 m core can be obtained in one week.
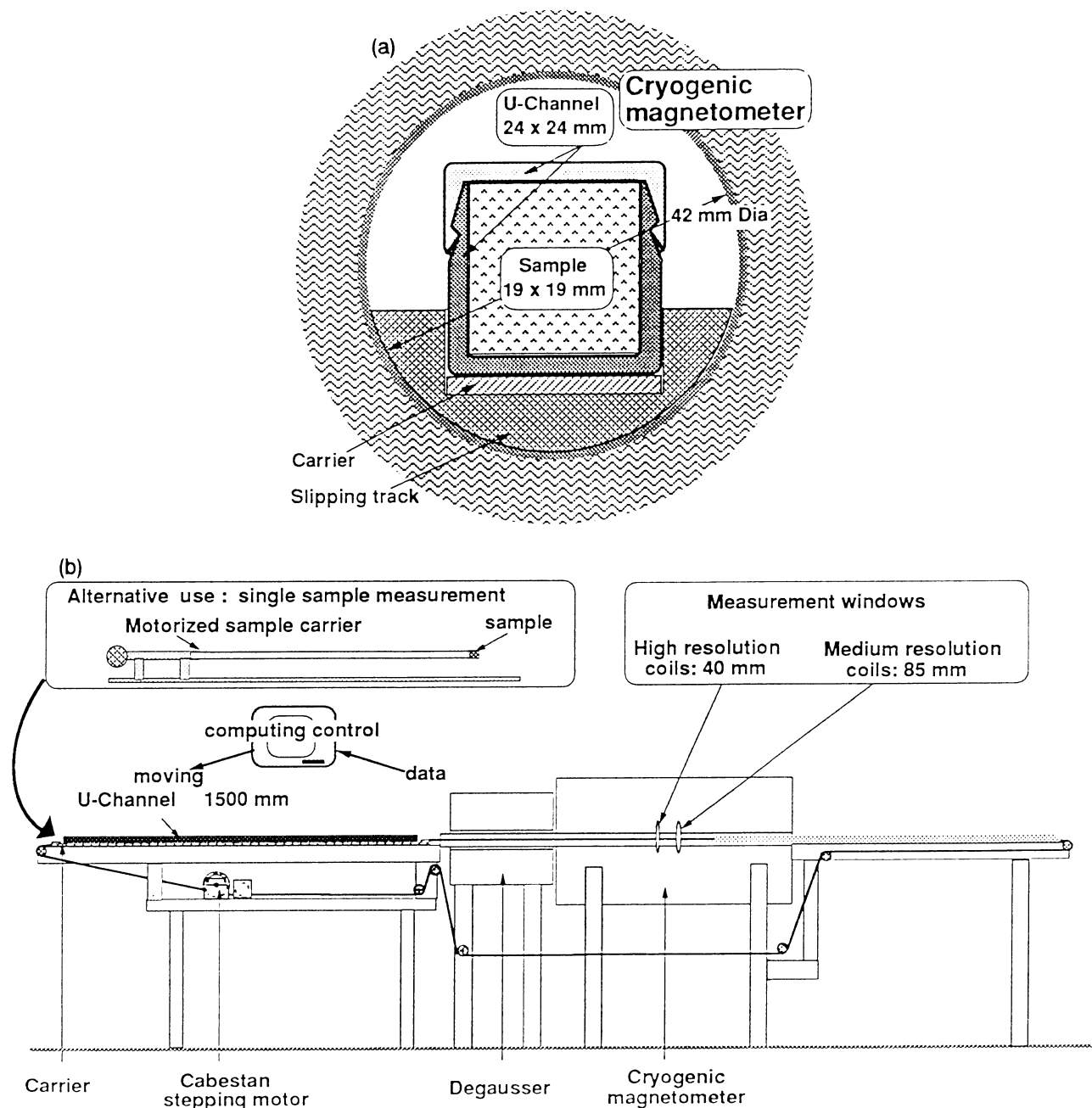
Figure 1. (a) Cross-section of a *u*-channel subsample within the internal tube of the small-access pass-through magnetometer. (b) Schematic view of this new 2*G* magnetometer with two sets of three sensors giving differing resolutions of long-core measurement. The in-line AF demagnetizer and the translation system are also shown.

2.4   Low-field susceptibility measurements

Low-field susceptibility coils, and indeed other types of rock magnetic instrumentation, could be installed in-line with the AF demagnetization coils along the magnetometer access track. However, space restrictions at Gif-sur-Yvette have dictated that an independent vertical set-up be designed which is made of rigid plastic. A Bartington sensing coil, of 4 cm internal diameter, is displaced vertically relative to the fixed *u*-channel section. Measurements are made continuously by controlling the speed of translation of the coil so that, given the rate of data acquisition,

measurements are obtained with the required sampling interval (usually 1 cm). The response width of the Bartington coils yields about a 2 cm resolution.

3   THE MEASUREMENT AND ITS ANALYSIS

The discussion above clearly shows that measurements can be much faster with continuous *u* channels than with conventional cubic samples. The question of accuracy of the results must now be discussed before this technique can be considered reliable and routinely used. In this section we

address this topic and discuss the bearing of the geometry of the sensors on the recovered signal. We also briefly describe the mathematical methods which can be used to improve the resolution and correct for some minor spurious effects.

3.1 Coil design and response in SQUID magnetometers

Spatial resolution in a long-core measurement is important since, in a sediment core of a particular sedimentation rate, spatial resolution translates to resolution in time. The question of resolution arises because the pick-up coils respond to a volume region along the access track. Thus, in the long-core measurement, the output is a smoothed version of the magnetization of the core. The primary controls on the spatial resolution and sensitivity of the magnetometer are the placement, size and design of the superconducting pick-up coils. Small access magnetometers allow smaller pick-up coils to be placed closer to the sample. This increases both resolution and sensitivity of the measurement.

The response function of the pick-up coils is generally measured by passing a dipole point source through the instrument and measuring the output with distance as the dipole approaches and passes through the sense coils. An important factor is that the response functions of the transverse axes are somewhat different, in both area and geometry, from that of the axial axis. This difference is necessarily true because of the geometry of the measurement: as a dipole approaches the coil region on the transverse axes, the coil first gives a negative response, corresponding to the back field of the dipole at a distance and then gives the main central positive response. The axial response functions are always more simple and do not have regions of negative response (Fig. 2). The size of the negative lobes varies with coil and instrument design. Examples of the response curves from two different
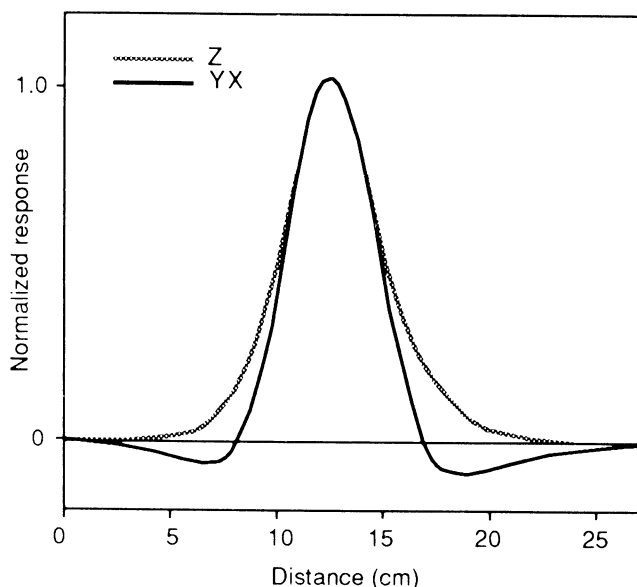

Figure 2. Comparison of transverse and axial responses for the high-resolution sensors at Gif-sur-Yvette. The transverse responses have negative lobes which are not present on the axial response.
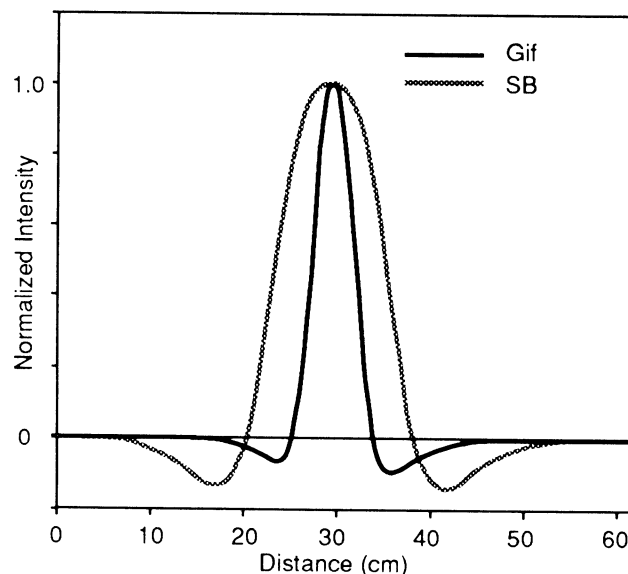

Figure 3. Comparison of the transverse response functions of the large access system at Santa Barbara and the high-resolution system at Gif-sur-Yvette. These curves are obtained by passing a dipole point source through the sensor region. The half-power width of the Santa Barbara instrument is about 15 cm while that at Gif is about 5 cm.

instruments (a 7.6 cm access 2*G* magnetometer at Santa Barbara and the 4.2 cm access magnetometer at Gif-sur-Yvette) are shown in Fig. 3. Usually the half-power width of the response curve is taken as a measure of the maximum resolution of the pick-up coils. The large access magnetometer at the University of California, Santa Barbara, has about a 15 cm resolution while the small access magnetometer at Gif-sur-Yvette has either 8 or 4 cm resolution depending on the coil sets used.

Because it is desirable to measure at the maximum resolution possible, it is tempting to imagine that resolution can be increased by designing smaller and smaller pick-up coils geometries. However, there are trade-offs; the smaller coils have better resolution for cores and higher dipole moment sensitivity, but reduced homogeneity for discrete samples. This is especially important in the measurement of single palaeomagnetic samples. Because a sample may have a non-homogeneous magnetization, the response of the coils must be homogeneous within a few per cent over the entire sample to avoid a biased measurement. The region of homogeneous response is equivalent to the length of the 'flat' region at the top of the response curves and the homogeneity of the response depends on just how 'flat' this region is.

The differences in system-response geometry have consequences for the long-core measurement. It is important to consider two aspects. The first is the linearity of the response curve with magnetization intensity. It is well established that the heights of the curves vary linearly with magnetization, so that the measurement of discrete samples is a linear one. However, this is not to say that the area under the curve does not change with intensity. Responses for different dipole moments are shown in Fig. 4 for the Santa Barbara instrument. The zero crossings for the transverse response curves are, as one would expect,
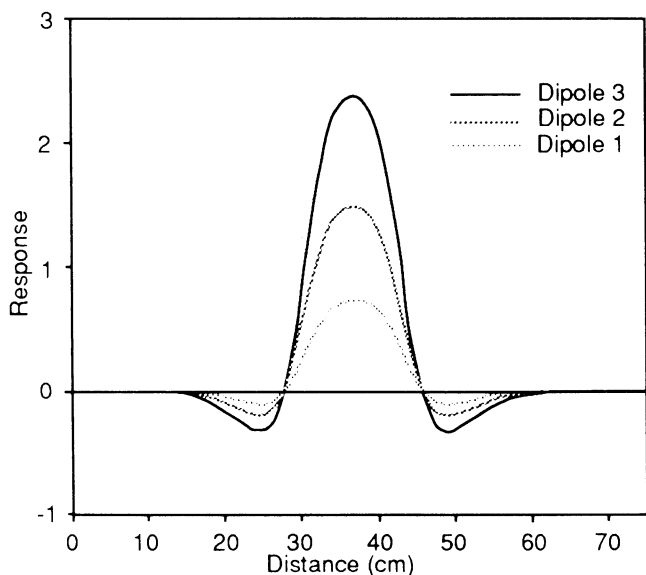
Figure 4. The transverse response on the large access Santa Barbara instrument at different values of dipole moment. The geometry of the curves does not vary but the response is earlier at larger dipole moments, amounting to a 1 per cent non-linearity with every order of magnitude change in moment.

entirely controlled by geometry and are not displaced with intensity. However, a minor effect, revealed by large changes in intensity, is that the negative region of the response curve for larger dipole moments departs from the noise level earlier (i.e. it is detected farther away from the coils). For two orders of magnitude increase in dipole moment, the departure from linearity of response by this effect is only about 2 per cent and, in principle, a correction could easily be applied. It appears, therefore, that intensity change is accurately recorded in the long-core measurement. To achieve the correct intensity the measurements on each axis are normalized by the area under the response curve. The negative lobes of the transverse axes are treated as negative areas. This correction has been introduced in the computer software.

A second important consequence of the form of the response curves results from the difference between the transverse and axial responses. Assuming that a vertical sediment core is being measured, this difference will primarily affect the measured inclination of magnetization, which will differ from the true inclination. In a homogeneously magnetized core, it is the difference in net positive area of the curves which steepens the inclination measured with respect to the true magnetization and, just as described above for the intensity, normalization by the area in the software automatically corrects the measurement.

However, in a core with significant magnetization intensity and/or directional changes the effect is more complicated. To illustrate these effects we have modelled measurements of a synthetic magnetization signal where there is an abrupt two-fold increase in intensity on all axes (i.e. a change in intensity without change in direction). This signal was then convolved with the appropriate (Gif-sur-Yvette) response functions to produce the synthetic
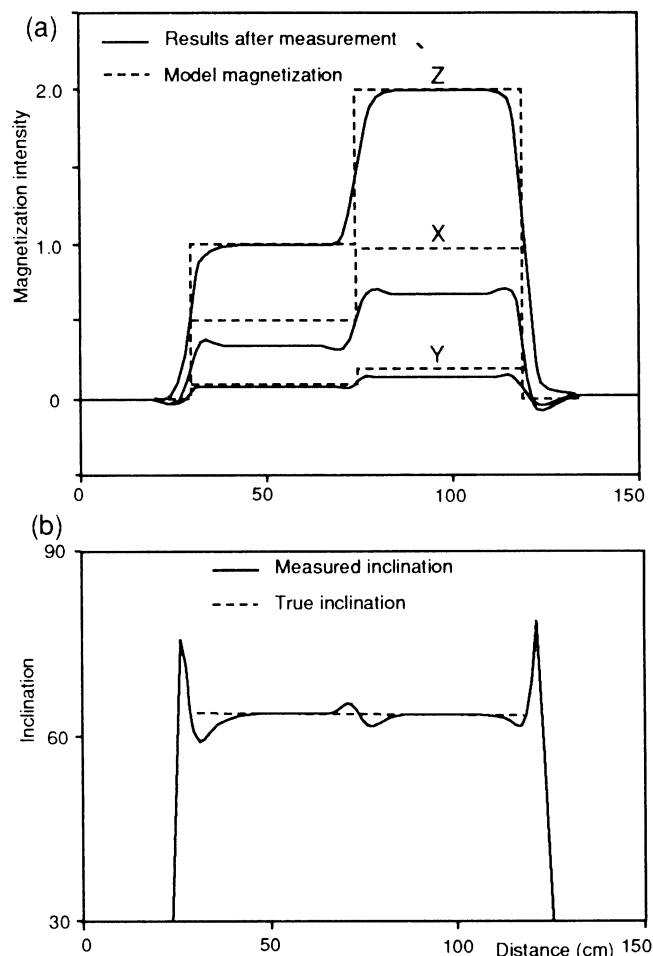

Figure 5. Synthetic continuous pass-through measurements of a two-fold change in intensity without change in direction (a). Normalization for the differing area of the axial and transverse response functions is required to produce the correct mean inclination. The different geometry of axial and transverse responses produces the spurious signal in the inclination at about 75 cm (b).

measurement (Fig. 5a). After normalization by the areas, the true inclination is recovered in regions with no change in intensity (Fig. 5b). This is not the case, however, at the abrupt two-fold increase in intensity at 75 cm (and also of course at the two extremities of the *u* channel). Indeed, because of the negative regions on the transverse axes, which are not present on the axial axis, at or near any significant rapid change in magnetization, the ratio of axial to transverse moment will vary and consequently a signal is produced in the inclination that was not present in the original magnetization. The effect is spread beyond the half-power-width distance.

There is no spurious effect, due to geometry, on declination since the response functions for the two transverse axes are nearly identical. It is therefore the relative complexity of the transverse, with respect to the axial-response curves, which is important. Fortunately, it is not difficult to remove these geometrical effects, as discussed below.

3.2 Deconvolution

The simple experiments described above presented the system with rather drastic magnetization variation and hence represent the extreme possible spurious effects of the respone function geometry. They suggest, however, that cores having recorded fast changes in direction and in intensity of the magnetic field, such as geomagnetic reversals, events or excursions, may require that the analysis of the output signal be performed with high accuracy. The goal of the mathematical treatment described below is to explore how such accuracy can be reached. Applications to palaeointensity determination, recovery of accurate palaeo-directions and use of these measurements for correlation techniques will then be discussed.

Although the primary effect of the response function is to smooth the magnetization signal, the process is obviously more complicated and it is more correct to think of the measurement as being the convolution of the response function $[H(x)]$ with the true magnetization of the u channel sample $[M(x)]$. The measurement $[s(x)]$ can be expressed as a convolution integral:

$$s(x) = \int_0^1 M(x_0)H(x - x_0)\,dx_0 = M(x) \cdot H(x)$$

where l is the length of the u channel.

Deconvolution is the mathematical procedure for recovery of the true magnetization $M(x)$ from the measurement $s(x)$. This procedure can be done as an inverse problem in the temporal, or spatial domain, by convolving the signal with the appropriate inverse filter. It can also be done in the frequency domain, as a division of the Fourier transforms of the signal and response functions.

In theory, knowing the response functions, it would be possible to completely recover $M(x)$ by going through the inverse, deconvolution procedure. However, the measurement of both the response functions and the magnetization is not perfect and contains a component of noise. This component is amplified by the deconvolution procedure. In effect, the deconvolution is usually used in an attempt to recover the higher frequencies which have been lost by the smoothing in the measurement (i.e. to increase the resolution of the measurement). Since the noise is also contained in the higher frequencies, it limits the recovery of the real signal. The obtainable increase in resolution is, therefore, limited by the amount of noise in the measurement. However, another, perhaps more important objective of deconvolution, is to remove the spurious effects of the system response geometry such as those discussed above, shown in Fig. 5. This removal can be achieved using a deconvolution procedure without attempting to significantly enhance the resolution of the measurement. In this case the effects of geometry are removed, leaving the effect of smoothing largely in the signal. Higher frequencies are not greatly enhanced and noise should not present a significant problem.

Deconvolution has been carried out by taking Fourier transforms and working in the frequency domain (Dodson *et al.* 1974) and in the time domain (Constable & Parker 1991; Shibuya & Oda 1991). The following experiment was devised in order to evaluate the success of the long-core measurement, coupled with particular deconvolution meth-

ods (a similar experiment, with cylindrical samples, has been independently used by Hailwood (1992) to test the resolution of a large access pass-through magnetometer).

A sequence of 66 discrete $2 \times 2 \times 2\,cm^3$ cubic samples taken from a North Atlantic piston core were measured individually with our second 2G magnetometer. These cubes were then stuck together to form a continuous chain of samples that was passed through the magnetometer and measured in the long-core mode. The results are illustrated in Fig. 6(a), where both the measurements of the individual samples, and the long-core measurement of the sample 'train' are illustrated. In this particular run, one of the samples (no. 52) was reversed with respect to the others. The dominant effect of the pass-through measurement is to smooth the individual sample results and we do not recover the reversed signal.

Deconvolutions, both in the frequency and time domains, were performed on the data and results are illustrated in Figs 6(b) and (c) respectively. Both methods appear to recover some of the true high-frequency variability and the sample results are more closely reproduced. However, the
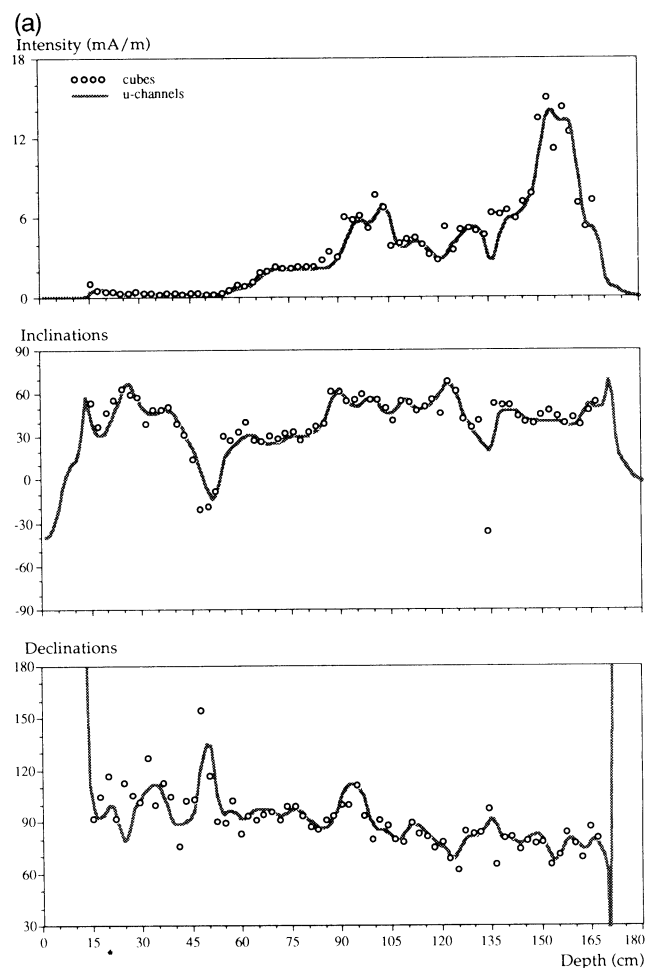

Figure 6. Comparison of discrete measurements of cubic samples (open circles) with the long-core measurement of the same samples joined to form a continuous 'chain' of samples (solid line). (a) The raw measurement. (b) Deconvolution in the frequency domain of the continuous measurement. (c) Deconvolution in the time domain of the continuous measurement (Constable & Parker 1991).
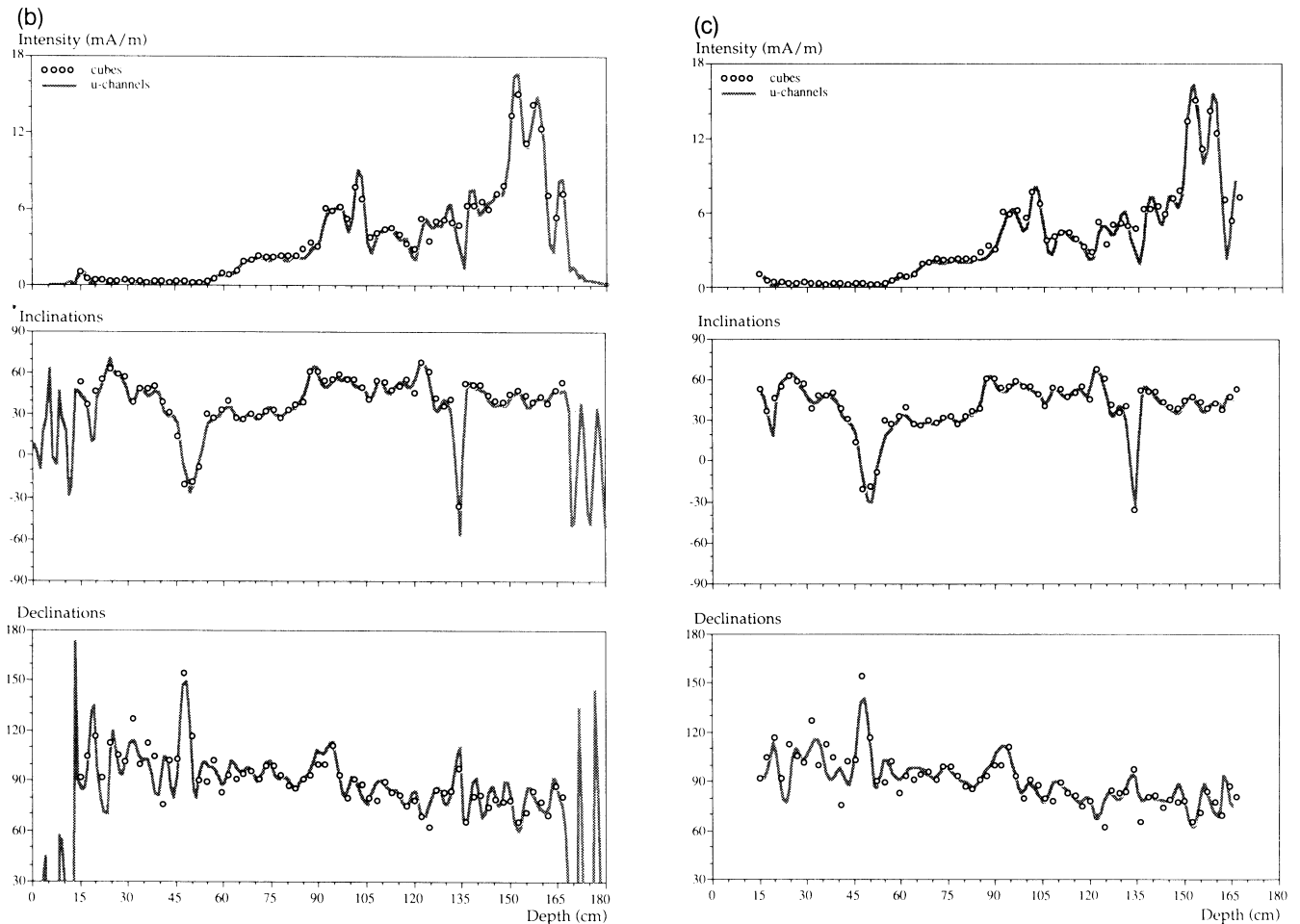
(b)

Intensity (mA/m)

(c)

Intensity (mA/m)

Figure 6. (*Continued.*)

time-domain method of Constable & Parker (1991) clearly does better and produces a remarkable fit to the individual sample results. Both declinations and inclinations are quite consistent with the single-sample measurements, so that the directional change due to the reversed sample is completely recovered. However, the low in the deconvolved intensity record (not present in the individual sample results) shows that we are not quite recovering all of the intensity of the reversed sample. Thought of in terms of XYZ components, the deconvolution method does succeed in changing their sign and in reproducing the correct proportion of each component, but does not recover all of the intensity on each component after going through zero. In fact, this experiment illustrates that directional data is more easily recovered than intensity.

It can be seen that the temporal-domain method does not introduce significant noise beyond the ends of the u channel, as does the frequency-domain method. The effects of the geometry of the response curves have been adequately removed and a two-fold increase in resolution is obtained. Deconvolution of a 1.5 m u channel measured every centimetre requires about 2 hr with the DEC Station 5200 used at Gif.

These results demontrate that the 4 cm response curves on the new pass-through magnetometer can yield results at the same resolution as that possible using conventional discrete samples. Since single-sample reversals are not a likely occurrence and represent an extreme of variability, the methods described above do, for practical purposes, produce resolutions and measurement accuracy identical to those of single samples. This resolution can be seen by observing the fit obtained throughout the non-reversing part of the cube experiment (Figs 6b and c). Although for the study of fast geomagnetic events, sampling of thin slices of sediment would probably be necessary, deconvolution yields a very precise view of the real duration of the event and may thus allow to decide whether or not slicing is worthwhile.

4 APPLICATIONS

In this section, we illustrate the power of the u-channel continuous measurement using two example studies. The first illustrates the wide range of possible rockmagnetic characterizations using the continuous technique, with results shown from North Atlantic sediment cores. This kind of information has a large potential use in palaeoceanographic and environmental magnetism work and can, in addition, aid greatly in intercore correlation. The second study is a palaeomagnetic study of directional and relative palaeointensity variations again in a North Atlantic Ocean sediment core. All the long-core measurements presented in this section are raw data having a spatial resolution of 4 cm.

4.1   Magnetic characterization using *u*-channel measurements

Many rock magnetic parameters give information concerning either the concentration of magnetic minerals, or their grain size, or both. Such information is of importance to palaeoceanographic and environmental magnetic studies because changes in magnetic concentration and grain size are directly related to changes in sedimentation rates and sediment provenance.

We first present the measures of parameters which are generally used as a bulk indication of the variation in concentration of magnetic minerals within a sediment core. They (especially susceptibility) are often used for broad characterization and intercore correlations. We then describe some of the parameters which can be derived from these measurements, or measured themselves, and which give us more detailed information about changes in the magnetic character of the grains within a sediment. These parameters allow separation, to varying extents, of the effects of grain size variation and concentration variation. For simplicity we have not considered possible effects of magnetic mineralogical variation.

4.1.1   Parameters relating primarily to concentration

(a) Susceptibility.

Because susceptibility (χ) is often directly related to carbonate content it is increasingly being used in palaeoceanography for intercore correlation and rapid identification of oxygen-isotope stage boundaries. Susceptibility responds also, however, to changes in grain size and is particularly related to the coarser (pseudo-single domain–multidomain) part of the size spectrum. In Fig. 7 we compare results from a *u* channel taken with a small diameter Bartington Instruments succeptibility coil (set up described in Section 2.4), with those obtained from single cubic specimens from the same portion of core SU9004 from the North Atlantic, and measured with a Kappabridge susceptibility meter. The continuous measurement of a 1.5 meter *u* channel requires about half an hour.

(b) Anhysteretic Remanent Magnetization.

Anhysteretic Remanent Magnetization (ARM) is a parameter that also responds to concentration and grain-size variation. However, it is preferentially carried by fine particles and is therefore more sensitive to variation in the fine-grained fraction. Relative variations of ARM and χ have been used to investigate grain-size variation, following King *et al.* (1982) King, Banerjee & Marvin (1983).
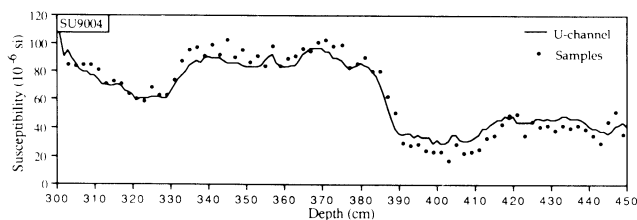
Figure 7. Comparison of the measurements of the low-field magnetic susceptibility made on single cubic samples and *u* channel for one section of the core SU9004. The symbols are the same as in Fig. 6.
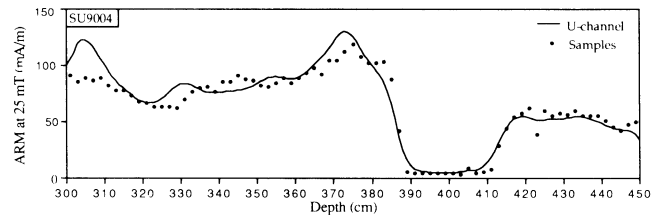
Figure 8. Comparison of discrete and continuous measurements of ARM made on the same section as in Fig. 7. The continuous record well reproduces the drastic change of the ARM. The symbols are the same as in Fig. 6.

We produced an ARM in *u* channels using Schonstedt AF demagnetizing coils within a large set of Rubens coils (1 m side). These coils provide a region of constant DC field that is approximately 40 cm long, along the same axis as, but towards one end of the AF coils. The *u* channel was pushed through the AF coils, which were kept at a constant alternating field of about 70 mT, into, and through this region of constant DC field. The ARM is therefore acquired during the movement of the *u* channel through the system: as the AF field decreases with distance from the demagnetizing coils, the *u* channel experiences constant field throughout the major decrease in alternating field intensity. The entire operation requires only one or two minutes. In general, higher alternating fields of 100 mT or greater are desirable for these experiments so that the full range of coercivities is engaged in the remanence. However, we do not believe that this limited range of AF field significantly affects the results. Example results, obtained from the same section of Fig. 7, are given in Fig. 8 and results compared with those from discrete samples. It can be seen that the two sets of results are quite consistent and that the *u*-channel method correctly reproduces the rather conspicuous and sharp changes in ARM values.

It is possible, of course, to make the ARM acquisition procedure into an in-line one by surrounding the in-line demagnetization coil system with sufficiently long solenoid windings to give the DC field. A filtering circuit would then be used to block the induced signal caused by the alternating field.

(c) Isothermal Remanent Magnetization (IRM) and Saturation IRM (SIRM).

Isothermal Remanent Magnetization (IRM) experiments are accomplished by passing the *u* channels through the poles of an electromagnet. For large access magnetometers, the saturation IRM (SIRM) often exceeds the dynamic range of the instrument. However, in small access systems, the limited volume of the response region allows the measurement to be made. Results for the *u* channel from a North Atlantic piston core (SU9009) are illustrated in Fig. 9. For comparison with the above results, we present a log of the saturation magnetization saturation remanence (Mrs), obtained from individual samples measured with a Micromag alternating gradient magnetometer. These last measurements have been done every 4 cm using very small pellets (average volume 3 mm^3). Measurements were calibrated to the weight which was carefully measured for each pellet. On the other hand, the net weight of the sediment in the volume 'seen' by the SQUID sensors is not precisely known. Assuming constant density, the two curves
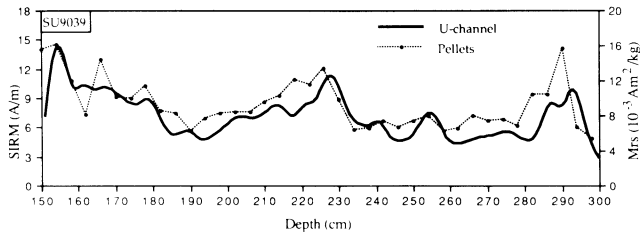
Figure 9. Comparison of discrete measurements of Mrs obtained using small pellets (every 4 cm) (circles) and of the continuous *u*-channel measurement of the SIRM (solid line) for a section of core SU9039.

obtained from pellets and from *u* channels should show similar trends. This is largely the case, as shown in Fig. 9.

4.1.2 Parameters relating to grain size variation

(a) ARM versus susceptibility ratios $(ARM)/\chi$.

Because of the differing responses of χ and ARM to the coarser and finer grain size fractions, the $(ARM)/\chi$ ratio is thought to indicate relative changes in magnetic grain size (King *et al.* 1982). In Fig. 10(a), we give the (ARM) and χ records for core SU9039 and in Figs 10(b) and (c) we illustrate the ARM versus χ plots for the lower and upper part of this particular *u* channel respectively. Because susceptibilities and ARMs were measured with two different instruments, the volume of sediment involved in the two measurements is not exactly the same. The $(ARM)/\chi$ ratios must be calibrated to reflect this slight difference. As seen
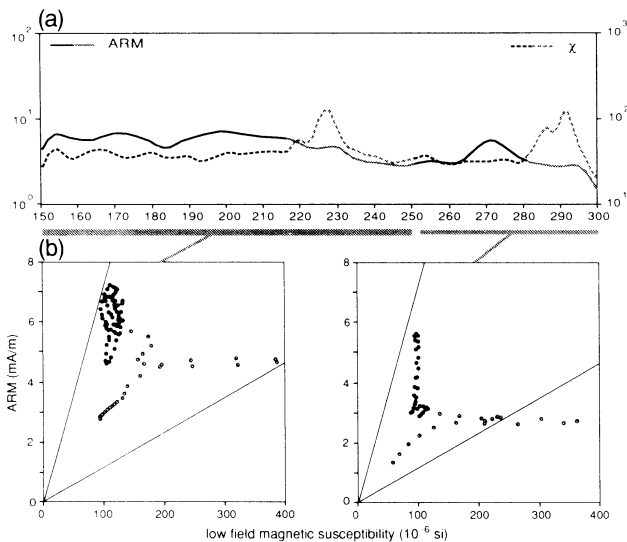

Figure 10. Comparison of continuous measurements of ARM and low-field susceptibility from core SU9039 (χ). (a) Overlapping curves of ARM and χ on a log scale designed to illustrate their relative variation. (b) ARM versus χ plots which illustrate two excursions in the ARM/χ ratio. The two plots are extracted from results shown in (a) between 150 and 250 cm and between 250 and 300 cm respectively. Plots (a) and (b) illustrate in different ways a repeated change in magnetic characteristics involving first a change purely in χ (to coarse values) followed by a change purely in ARM (to finer values). This shows the interesting structure in the Heinrich peaks of the North Atlantic.

from Fig. 10, this ratio indicates a relatively constant grain size for most of the core, but there are two regions were there are significant excursions in the ratio. For ARM versus χ plots (Figs 10b and c), points that lie along a straight line through the origin indicate variation in grain concentration at a constant grain size, while deviations from the straight line (changes in gradient) indicate relative variation in grain size. Fig. 10(a) is designed to break down the variation of ARM and χ and to illustrate their relative variation. This plot and the ARM versus χ plots illustrate that the two excursions are characterized by the same sequence of variations: for example, beginning at 300 cm there is a change, with time, to coarser grain sizes, involving exclusively a change in χ without change in ARM. This is followed, starting at about 280 cm, by a movement to finer grain sizes which is accomplished by a variation in ARM without change in χ. This complete sequence of variations is then repeated later at 230 cm.

To illustrate the potential importance of this kind of data, we observe that these excursions in grain size are related to climatic variations. In fact these events are the Heinrich peaks observed elsewhere in the North Atlantic (Heinrich 1988; Broecker *et al.* 1992). The magnetic results reveal a fairly complex series of grain size and concentration changes which could provide important information on the nature and cause of these events.

In many others of our cores that we have studied from the North Atlantic, comparison with the carbonate or isotope curves for the same cores reveals that these kind of events in grain size are associated with the colder climatic events. Troughs in ARM occur immediately before a cooling and susceptibility peaks coincide with the cold interval. These results are duplicated in nearby cores within a range of 400 km.

(b) Medium destructive fields (MDF) of NRM and ARM, and H_{rc} determination.

These parameters all describe the resistance of the remanence to demagnetization (or magnetization). They are thus related to coercivity and hence to grain size and shape. Here we compare their values on a section of core from the North Atlantic Ocean.

The MDF of remanence is an indication of resistance to AF demagnetization. In the continuous measurement, the calculation of MDF down a core can be done using linear interpolation between demagnetization steps. As the ARM is related to the same fraction of magnetic grains involved in NRM, their MDFs should show similar trends. This is observed in Fig. 11(a).

After measuring SIRM it is possible, with a minimum of additional measurements, to determine the remanent coercivity (H_{rc}). This is done by applying small fields in the opposite direction to the SIRM field. The back field which reduces the SIRM to zero is called the H_{rc}. In practice, once the range of H_{rc} values is determined in a core, it would be sufficient to apply only two backfields which straddle zero magnetization. The H_{rc} determination could therefore be made with just three pass-through measurements. Results are illustrated in Fig. 11(b) for comparison with the results from discrete sample measurements on the Micromag alternating gradient magnetometer. There are some limited differences between the two plots. However, the two measurements yield closely the same absolute values for the
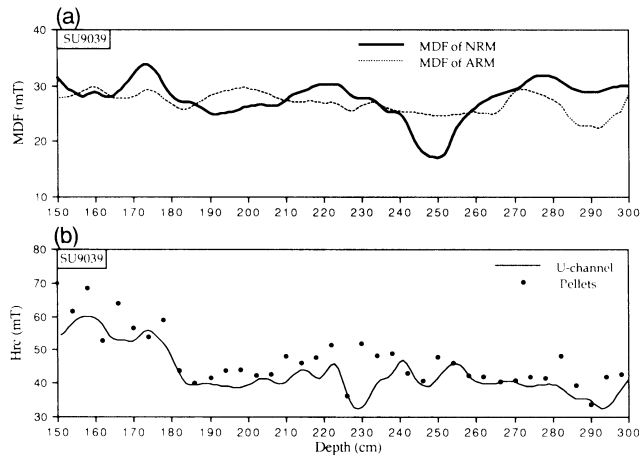
Figure 11. (a) Continuous measurements of the MDF of the ARM and of the NRM for a section of the core SU9039. (b) Comparison of the H_{rc} measured on pellets and continuously on u channels for the same section.

MDF and the same trends are observed along the u-channel length.

Summarizing, it appears that the characterization of the main rock magnetic aspects of sedimentary marine cores can be performed directly using u channels with the accuracy required for most oceanographic and geophysical applications, in a much faster way than using conventional single-sample techniques.

4.2 Direction and normalized intensity in a North Atlantic piston core

In order to illustrate the applicability of the continuous technique we present here a limited number of results obtained from a North Atlantic piston core. The details of this work and analysis of results will be presented elsewhere (Weeks *et al.* 1993). The objective of the study was to use rock magnetic parameters such as ARM and χ to normalize the NRM intensity of a deep-ocean piston core in order to
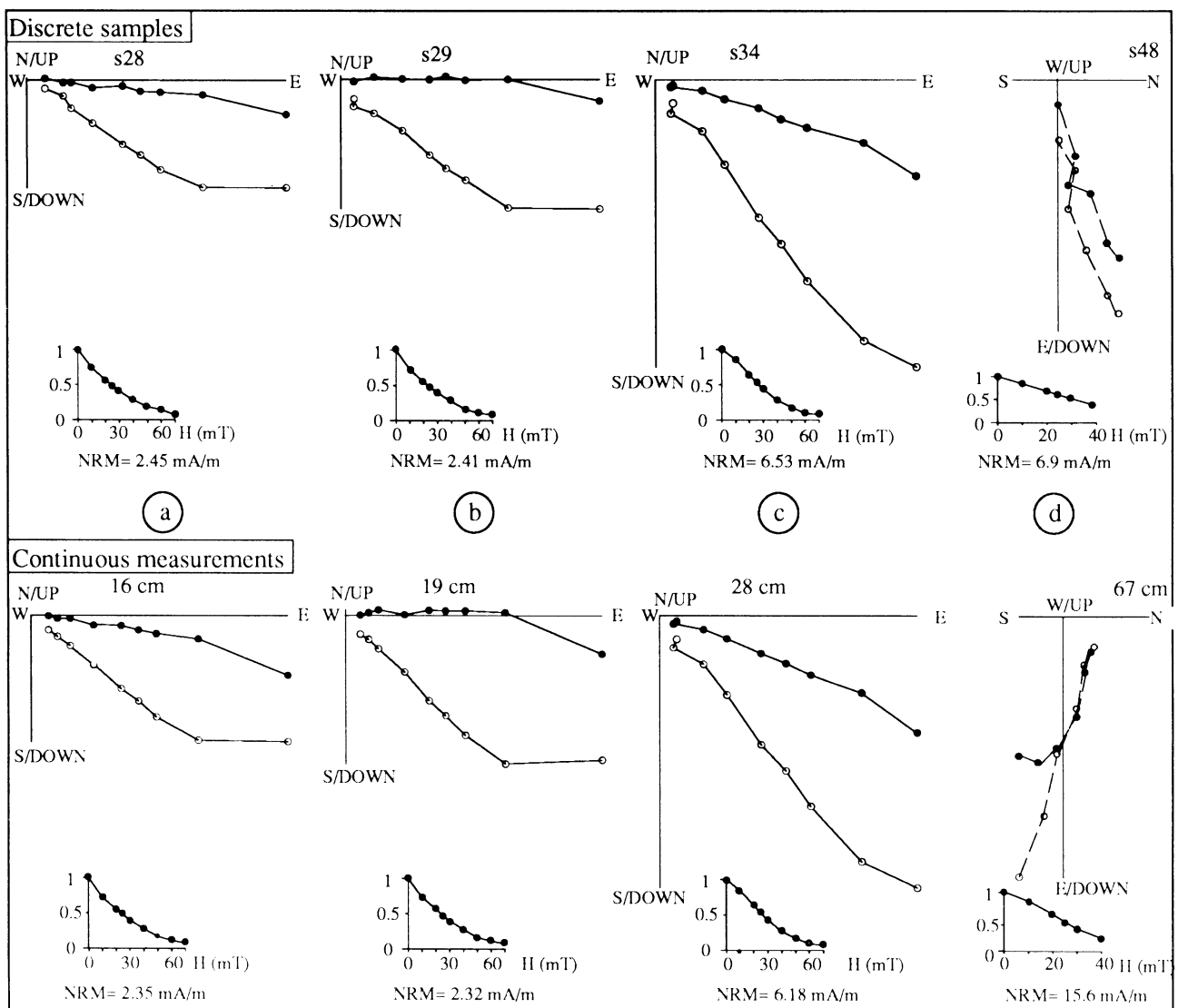

Figure 12. Zijderveld plots from AF demagnetizations and measurements on discrete samples and in the continuous mode. Results are from core SU9008 in the North Atlantic and discrete and cubic sample results are from comparable depths. Samples s28, 29 and 34 corresponding to depths 16, 19 and 28 cm respectively (a, b and c), illustrate isolation of stable single component directions, while sample s48 corresponding to depth 67 cm (d) shows a case where a stable single component is not reached.

attempt to remove the effects of changes in magnetic grain concentration and obtain a record of relative geomagnetic field intensity variation.

A North Atlantic piston core of length 7.5 m was sampled using both u channels and discrete cubic samples taken every 2.2 cm. The NRM was demagnetized at several AF values up to 40 mT. At this point in a palaeomagnetic study, an analysis is usually made of the stability of the remanence; Zijderveld plots are often used to define stable, primary magnetization directions. In the continuous measurement, directional stability can be assessed by examining the differences between demagnetization steps. However, it is also possible to generate Zijderveld plots, at any desired location in the core, from the u-channel data (Fig. 12). We have produced software which displays an animation of the Zijderveld plots with distance along core. This enables a rapid scan to be made for regions where there are difficulties with the directional data. Although this should be done after deconvolution, we have illustrated here how this scanning procedure enables depths where there are problems to be identified from the raw data. We show results from core SU9008 both for depths yielding stable primary directions (Figs 12a, b and c) and for a depth region where demagnetization does not succeed in isolating the higher coercivity component (Fig. 12d). The equivalent plots from the discrete sample results at the same locations are also given for comparison. The declination and inclination values obtained from the discrete samples (measured on the *HH* coils of the 'conventional' 755-R magnetometer with a four-positions measuring routine) are reproduced by continuous u-channel measurements within 1° or 2°. Details of the demagnetization plots such as the small secondary component observed in Figs 12(a), (b) and (c) at the first steps of demagnetization, are virtually identical in the two cases.

An alternative approach to scanning for directional stability is to generate a down core log of a statistic, such as Maximum Angular Deviation (MAD) angles or α_{95}, from linear fits to demagnetization data. These parameters could easily be calculated, in the software, from the long-core demagnetization data. This would provide useful information for establishing criteria for rejection or acceptance of data.

In Fig. 12(d) a region is identified where the higher coercivity, end point component is not isolated. This may indicate a change in magnetic mineralogy and the increasing presence of a high coercivity mineral such as haematite. Should this be the case then thermal demagnetization of individual samples is required to isolate the haematite component (since thermal demagnetization of u channels is not at present feasible). However, the u-channel techniques do effectively isolate depths of cores, should they exist, where this additional analysis is required and avoid its time-consuming application to the entire core.

After establishing the stability of remanence, the procedure for intensity normalization is usually to measure susceptibility and ARM and to use these as normalizing parameters. An ARM was then generated in both the u-channel samples (method described above) and discrete samples. Using the NRM demagnetization, a value of the demagnetizing field is chosen at which only the primary component of the NRM remains. The value of ARM demagnetized at that value is then used to normalize the
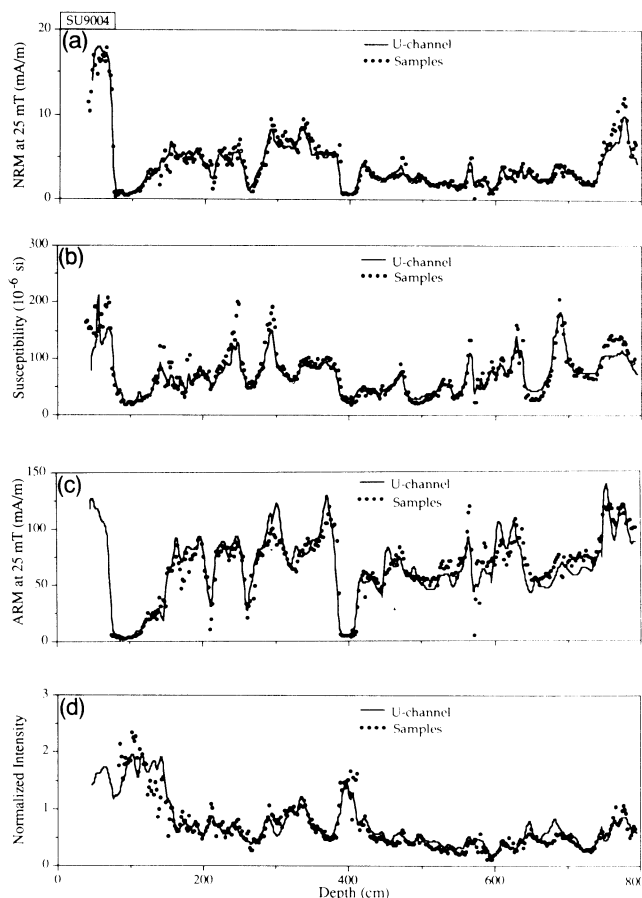

Figure 13. Results from both continuous and discrete measurements of core SU9004. (a) The NRM after AF demagnetization at 25 mT. (b) Low-field magnetic susceptibility. (c) ARM after AF demagnetization at 25 mT. (d) The ratio NRM/ARM gives the normalized intensity curve for SU9004.

NRM demagnetized at the same value. Sometimes the susceptibility is used as an alternative normalizing parameter for the demagnetized NRM.

The complete set of results used in this normalization procedure is illustrated in Fig. 13 for both the u-channel and discrete samples. In order to compare the cubic sample and u-channel results on the same scale, the u-channel data are normalized by a factor which is the ratio of the total area of the response curves to the area of response curve occupied by a discrete sample (the central 2.2 cm of the curves). The results illustrate how well the u-channel measurement compares with respect to the exhaustive measurement of single samples. Only very limited and localized differences appear for ARM and thus for normalized NRM between continuous and discrete sample measurements. On the whole, the agreement between the individual sample results and the continuous measurements is excellent for all parameters, including the final normalized NRM. Of course, other combinations of these parameters can be obtained with the same accuracy. The smoothing effect can be observed in the attenuation of narrow peaks and troughs in intensity. However, the effect is not strong and could easily be removed with minimal deconvolution.

5 CONCLUSIONS

The long-core measurement has been shown capable of reliably producing results at the same resolution as that possible using conventional, discrete cubic samples. Most, if not all, of the conventionally useful rock-magnetic parameters can be measured in this mode which is much faster than the single sample method conventionally used up to now. Although no attempt has yet been made to measure hysteresis parameters in the long-core mode, there is no reason, in principle, why a loop plotting form of measurement could not be made on a long core. This could provide either continuous or stepwise determination of hysteresis parameters. The only measurements which cannot be made are those, such as Curie point determination and thermal demagnetization, which require heating of the sample.

Both the speed of operation and the accuracy of the long-core measurement of NRM and rock magnetic parameters promise to make possible the practical application of magnetic methods to ocean sediment and other kinds of cores on a previously impossible scale. Using these methods, it becomes practical to accurately and rapidly extract parameters which may be intimately related to climatic, or sediment provenance changes. In addition, the application of a variety of normalization techniques could permit movement towards more reliable relative field intensity measurements.

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