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Palaeomagnetism of the AND-1B Core, ANDRILL McMurdo Ice Shelf Project, Antarctica

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Abstract - Preliminary palaeomagnetic data are presented for the AND-1B drill core. A total of 1309 samples were collected from the drill core immediately following recovery and splitting. Natural remanent magnetisation (NRM) and bulk magnetic susceptibility data were determined for all samples using a Molspin spinner magnetometer and Bartington Instruments susceptibility bridge, respectively, immediately after collection. Polarity was determined for the upper 700 m of the drill core from 615 stepwise alternating field (AF) and thermally demagnetized samples with an average sample spacing of ~80 cm between 32 and 240 mbsf and ~2 m between 240 and 700 mbsf. Stepwise demagnetised samples were measured on 2G Enterprises long-core cryogenic magnetometers at the University of Otago and the *Istituto di Geofisica e Vulcanologia*. A magnetic polarity zonation was constructed for the interval between 32.33 and 700 mbsf, with roughly equal normal and reversed polarity represented. Above 32.33 mbsf, poorly consolidated diamictite strata prevented sample collection. The remaining record was subdivided into 15 magnetozones (8 normal and 7 reversed). Magnetozone boundaries are defined at the midpoint between samples of opposite polarity or by samples with transitional polarity. It was not possible to isolate characteristic remanence (ChRM) directions on orthogonal component plots and hence polarity for several ~10 m intervals in the core. Future work will include determination of a polarity zonation for the lower 585 m of the drill core and halving data spacing between 240 and 700 mbsf.

INTRODUCTION

On-ice palaeomagnetic studies of the AND-1B drill core focused on the initial characterisation of the magnetic properties of the core and the development of a magnetic polarity zonation for the core. Polarity was determined from inclination angles alone due to the lack of azimuthal orientation data for the drill core. This does not pose a problem for the determination of polarity as the long-term geomagnetic field at the high latitude of the drill site (~78°S) is near vertical (±83° inclination, assuming a geocentric axial dipole field).

Natural remanent magnetisation (NRM) direction and intensity and high and low frequency susceptibility was determined for all but a few samples in Antarctica before the samples were packed into mu-metal shields and shipped to the University of Otago in New Zealand and the *Istituto Nazionale di Geofisica e Vulcanologia* (INGV) in Italy for demagnetisation studies in order to decipher primary magnetic components from secondary and drilling-induced overprints. All samples from the lithified interval of the PQ core, 40 - 240 metres below sea floor (mbsf) and all pilot samples down to 625 mbsf depth were fully demagnetised before the drilling season was completed. Following completion of the drilling season, additional samples from the upper 240 m of the core were AF demagnetised in the palaeomagnetic laboratory of INGV in Rome, and alternate samples between 240 and 700 mbsf were thermally demagnetised in the Otago Palaeomagnetic Research Facility, Otago University, Dunedin.

SAMPLE COLLECTION

A total of 1309 samples were collected between 19.94 and 1284.81 mbsf from the working half of the AND-1B drill core. This included 126 pairs of samples collected for a pilot study to assess the most suitable demagnetisation technique for the routine treatment of remaining samples. All samples were collected immediately following the core splitting and description. The average sample spacing was approximately 1 m; however, this varied depending on lithology and sample spacing was often greater in thick, coarse-grained diamictite intervals. A sampling interval of ~1 m was chosen as predictions from seismic reflection survey correlations indicated a potential average sedimentation rate of ~100 m/m.y. Thus, a 1 m sample interval should be equivalent to ~10 000 years, which should ensure that any short Late Miocene and Pliocene polarity subchrons are adequately sampled if they are encountered in the drillhole. Paired samples were taken every ~10 m, on average, for the pilot study.

The few samples between 19 and 24 mbsf were collected with standard 6 cm^3 plastic cubes, which were pushed into the split core face; an up direction arrow marked, and then removed using a stainless steel wire cutter. Below 24 m, the core was lithified enough to enable standard discrete palaeomagnetic samples (25 mm diameter × 22 mm height) to be collected using an electric water-lubricated diamond drill press. Samples were collected by removing the split core, marking the up-direction and drilling a sample through the centre of the core (Fig. 1). Once collected, samples were labelled sequentially downcore and marked with up arrows and a fiducial line on the top of the sample cylinder running from core centre to core circumference. The 40 mm radius of the PQ core enabled two specimens to be cut from each PQ core sample, although the second (outside) specimen was of smaller volume (5.4 cm^3 as opposed to 10.8 cm^3).

Samples were generally taken from fine-grained horizons (siltstones and mudstones) but, despite varying the sampling interval, this was not always possible and some coarser grained lithologies (sandstones and diamictites) were sampled. Where possible, samples collected from diamictite intervals in the core were drilled from silty horizons without visible clasts in an attempt to minimise spurious contributions to the magnetic signal, especially from volcanic clasts. Whether or not this has been achieved will only be demonstrated once the samples have been x-rayed to check for any hidden clasts. Previous palaeomagnetic studies on McMurdo Sound drill cores (*e.g.* Florindo et al. 2005; Wilson et al. 1998) have demonstrated that it is possible to recover reliable magnetic polarity information from fine-grained (silt-sized) horizons within diamictites. Samples collected from fractured intervals of the core were glued as required using non-magnetic glue.

Ten of the oriented samples collected were from mudstone clasts contained within a mudstone breccia unit between 676 and 683 mbsf. These were collected for a conglomerate test, which can provide crucial information about the antiquity of the ChRM measured in the AND-1B core.

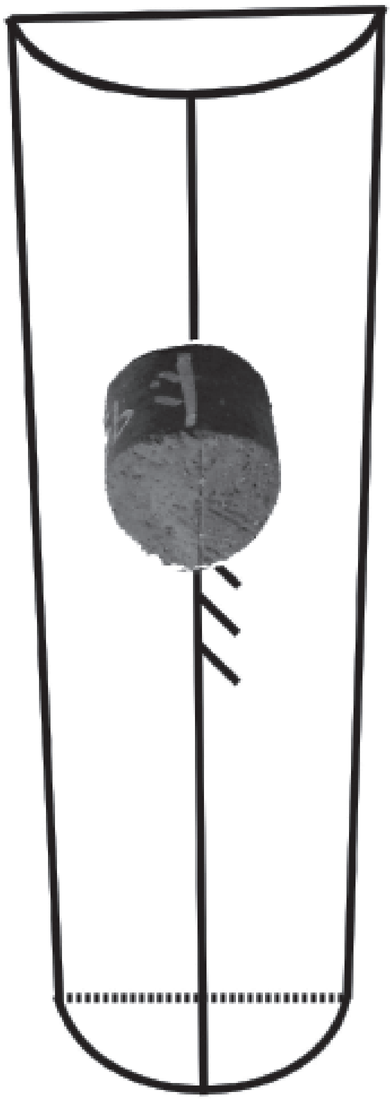

Fig. 1 – Orientation and labelling convention for palaeomagnetic samples collected from the MIS core.

MEASUREMENTS

Natural remanent magnetisation (NRM; direction and intensity) was measured in Antarctica using a Molspin spinner magnetometer. Sensitivity of the Molspin was between 1×10^{-3} Am^{-1} and 1×10^{-2} Am^{-1} depending on drift and uniformity of sample shape. The lower sensitivity was also partly due to the near-vertical ambient field in Antarctica. High- and low-frequency magnetic susceptibility was also measured in Antarctica using a Bartington Instruments magnetic susceptibility meter with MS2B probe. All pilot samples were then shipped in mu-metal shields to the Low Field Paleomagnetic Research Facility (OPRF) at the University of Otago, Dunedin, New Zealand, where they were stepwise demagnetised. At the University of Otago, all measurements of magnetic moment were made on a 2G Enterprises pass-through long-core cryogenic magnetometer. One sample of each pair was subjected to AF demagnetisation at 5 mT steps up to a peak field of 50 mT and then 10 mT steps up to a peak field of 100 mT using in-line static coils. The other sample of the pair was subjected to stepwise thermal demagnetisation at 50°C steps up to peak temperatures of 650°C using an ASC Scientific TD-48 single-chamber oven. The low field magnetic susceptibility was monitored after each heating step in order to detect any heating induced thermochemical alteration in the magnetic mineralogy.

One specimen of each of the discrete samples from the PQ core (<240 mbsf) was then subject to thermal demagnetization at 50°C steps to a peak field of 650°C at the OPRF. The remaining specimen from each sample (126 samples) was shipped to the palaeomagnetic laboratory at INGV for stepwise AF demagnetisation. These specimens were also measured on a 2G Enterprises pass-through long-core cryogenic magnetometer with three perpendicular coils

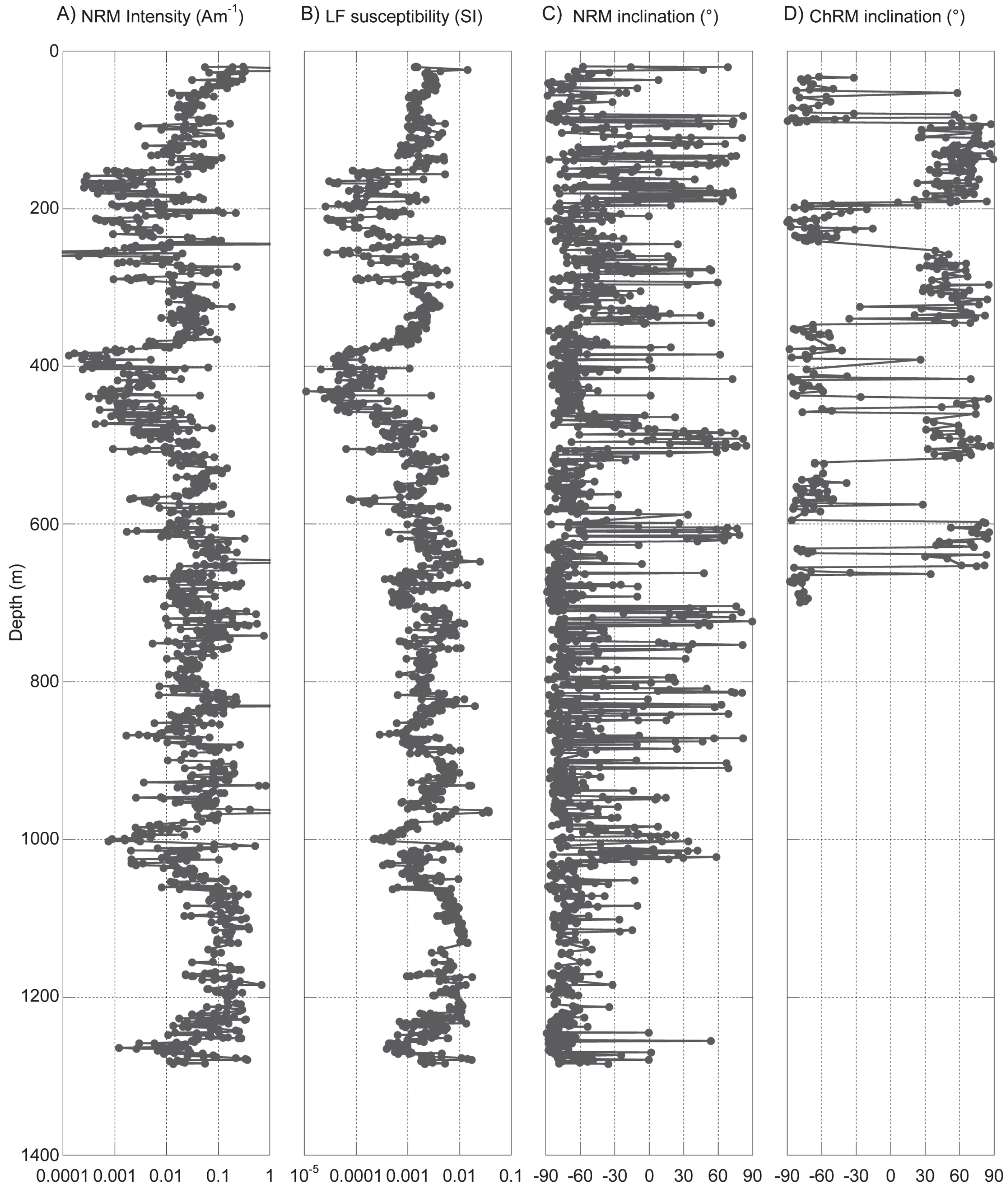

Fig. 2 – Downcore variations of (A) natural remanent magnetisation (NRM) intensity, (B) low-frequency magnetic susceptibility, (C) NRM inclination, and (D) inclination of characteristic remanent magnetisation (ChRM) for the MIS core.

in-line with the magnetometer for AF demagnetisation. AF demagnetisation was carried out in 15 steps (incremental steps of 5 mT from 5 to 50 mT and of 10 mT from 50 to 100 mT) up to a peak field of 100 mT. Alternate HQ and NQ core samples were shipped to the OPRF and INGV laboratories, respectively, for subsequent demagnetisation. At the time of writing, 90 pilot samples have been demagnetised (45 AF and 45 thermally demagnetised) and 195 of the alternating samples have been stepwise demagnetised from between 240 and 700 mbsf, providing demagnetisation data at an average interval of ~2 m.

RESULTS

NRM MEASUREMENTS

NRM intensities generally vary between 5×10^{-5} Am^{-1} and 0.5 Am^{-1} with higher values of intensity recorded in rare discrete tuffaceous or basaltic horizons (Fig. 2). Intervals of low intensity ($<5\times10^{-4}$ Am^{-1}) coincide with diatomaceous units above 600 mbsf in the core (*cf.* Florindo et al. 2003). Intervals of moderate intensity (~10^{-3} Am^{-1}) coincide with siliciclastic mudstone units below 600 mbsf in the core and higher-intensity intervals ($>10^{-3}$ Am^{-1}) coincide with diamictite or volcaniclastic units throughout the core. Throughout the AND-1B core, downcore magnetic susceptibility values show a very strong correlation with NRM intensity values throughout the core (Fig. 2), indicating that changing magnetic grain concentrations dominate the NRM intensity signal. Subtle differences occur in the tuffaceous intervals, intervals with significant amounts of dispersed volcanic glass between 600 and 700 mbsf, and also in the upper 50 m of the core where differences in grain type and size may contribute to varying magnetic intensities and susceptibilities.

NRM inclination values are dominantly vertical upcore (-90°) and indicate a pervasive drilling induced overprint from the drill string (Fig. 2). Horizontal inclination values (0°) are also observed throughout the core, although significantly less commonly and may represent radial overprints also induced by drilling. Discrete intervals with highly variable NRM inclination values, such as between 90 m and 192 mbsf, appear on demagnetisation to be dominantly reversed (downcore) in their polarity, indicating that, despite strong drilling induced partial remagnetisation, a significant proportion of the primary remanence is not overprinted (Fig. 2).

PILOT SAMPLES

Orthogonal vector component plots of representative pairs of pilot sample analyses are presented in Figure 3. Results of the analysis of the pilot samples from the upper 650 m of the MIS core demonstrate significant variability in the magnetic characteristics of the core. All samples demonstrate a drilling induced overprint, which varies in strength with up to 20 mT or 200°C, respectively, required to remove it (*e.g.* Fig. 3C). Radial overprints appear more pervasive and particularly difficult to demagnetise using AF methods (*e.g.* Fig. 3D). In some cases, AF and thermal methods were equally effective in demagnetising samples and identifying the primary remanence component (*e.g.* Fig. 3A). However, more commonly, thermal demagnetisation was more effective in removing overprints and identifying the primary remanence directions (*e.g.* Figs. 3C, 3D, 3E).

Significant pyrite content was noted in association with the volcanic-dominated intervals of the core, and ferrimagnetic iron sulphide minerals may have contributed to the difference in behaviour between thermal and AF demagnetisation methods, with the sulphides easily acquiring direct-field drilling-induced overprints which are more effectively removed by thermal methods rather than AF methods.

All pilot samples were taken from reasonably fine-grained intervals and thus display a range of coercivity or unblocking temperature spectra, with drilling-induced overprints generally accounting for 50% of total sample intensity. Magnetic intensity was generally reduced to zero by the 600°C heating step, indicating that remanence is held by magnetite. Characteristic remanent magnetisation components were determined from principle component analysis (Kirschvink 1980) usually with the best-fit line constrained through the origin, but occasionally small high temperature components displaced the line of best fit from the origin of orthogonal vector component plots. However, this high-temperature component represents less than the final 10% of the total sample intensity and is generally horizontal (*e.g.* Fig. 3H) and thought to be a secondary radial overprint component.

ROUTINE SAMPLE DEMAGNETISATION

Following the results of the pilot study, thermal demagnetisation was chosen for routine sample demagnetisation of samples from the upper 700 m of the core. Two specimens are available from most sample depths in the PQ core interval (<240 mbsf). The larger volume (10.8 cm^3) specimen was subjected to thermal demagnetisation and the smaller volume specimen (5.4 cm^3) was subjected to AF demagnetisation for comparison. Alternate samples from HQ core between 240 and 700 mbsf were subjected to thermal demagnetisation. Alternate samples below 700 mbsf will also be subjected to thermal demagnetisation. All remaining samples will be subjected to thermal or AF demagnetisation depending on the thermal demagnetization behaviour of the lower part of the core.

With a ~1 m sampling interval for routine sampling, many samples were taken from coarser than ideal lithologies (sandstones and diamictites). Samples from the diamictite units are expected to retain a reasonable magnetic remanence given a reasonable fine component. However, several of the diamictite units were clast rich, and palaeomagnetic samples from these units inevitably contained clasts, which dominated the magnetic signal but did not represent past field directions.

Above 240 mbsf, 180 samples were stepwise thermally demagnetised including 11 thermally demagnetised samples from the pilot study. Representative sample demagnetisation behaviour is illustrated in Figure 4. As expected, a greater range of sample behaviour is observed with relatively low unblocking temperature spectra encountered in many of the coarser units (suggesting dominance of multi-domain magnetite), with more pervasive drilling-induced overprints encountered. Most samples lose intensity on demagnetisation to 600°C, indicating a dominance of magnetite, but a higher-temperature component persists in several samples from the diatomaceous intervals between 150 and 200 mbsf depth. Sample 24 (Fig. 4A) illustrates the dominance of drilling-induced overprints in the coarser lithologies. A drill-string overprint is observed in the low unblocking temperature range (<200°C) and a radial overprint in the higher unblocking temp range (>200°C). Sample 77 (Fig. 4B) illustrates a reversed polarity sample with minimal drill-string overprint. Samples 116 (Fig. 4C) and 174 (Fig. 4H) illustrate

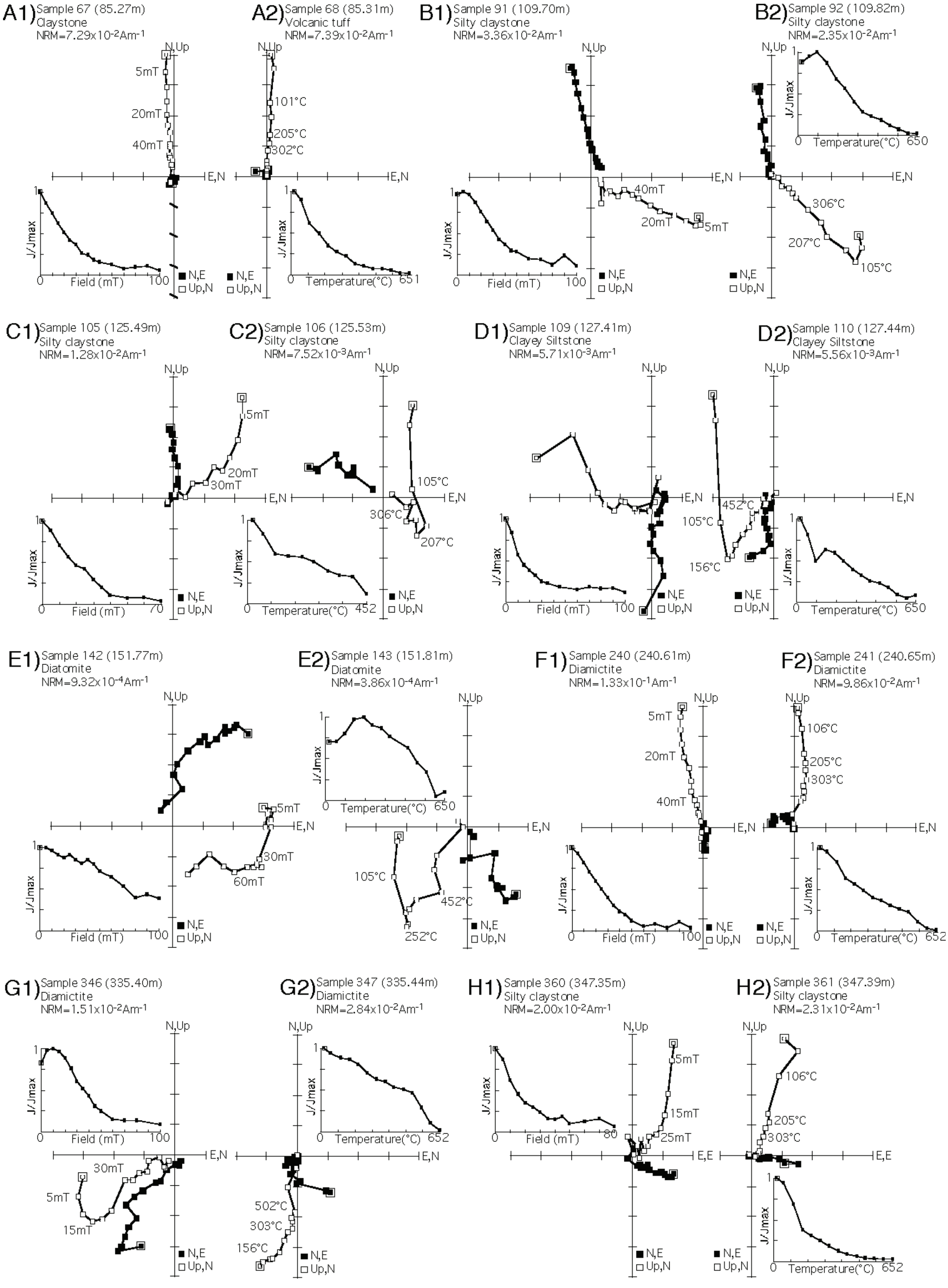

Fig. 3 – Orthogonal vector component diagrams of demagnetisation behaviour of representative samples from the pilot study of the MIS core: (A1) and (A2) comparison of AF and thermal demagnetisation of samples from 85.27 and 85.31 mbsf, respectively; (B1) and (B2) comparison of AF and thermal demagnetisation of samples from 109.70 and 109.82 mbsf, respectively; (C1) and (C2) comparison of AF and thermal demagnetisation of samples from 125.49 and 125.53 mbsf, respectively; (D1) and (D2) comparison of AF and thermal demagnetisation of samples from 127.41 and 127.44 mbsf, respectively; (E1) and (E2) comparison of AF and thermal demagnetisation of samples from 151.77 and 151.81 mbsf, respectively; (F1) and (F2) comparison of AF and thermal demagnetisation of samples from 240.61 and 240.65 mbsf, respectively; (G1) and (G2) comparison of AF and thermal demagnetisation of samples from 335.40 and 335.44 mbsf, respectively; (H1) and (H2) comparison of AF and thermal demagnetisation of samples from 347.35 and 347.39 mbsf, respectively.

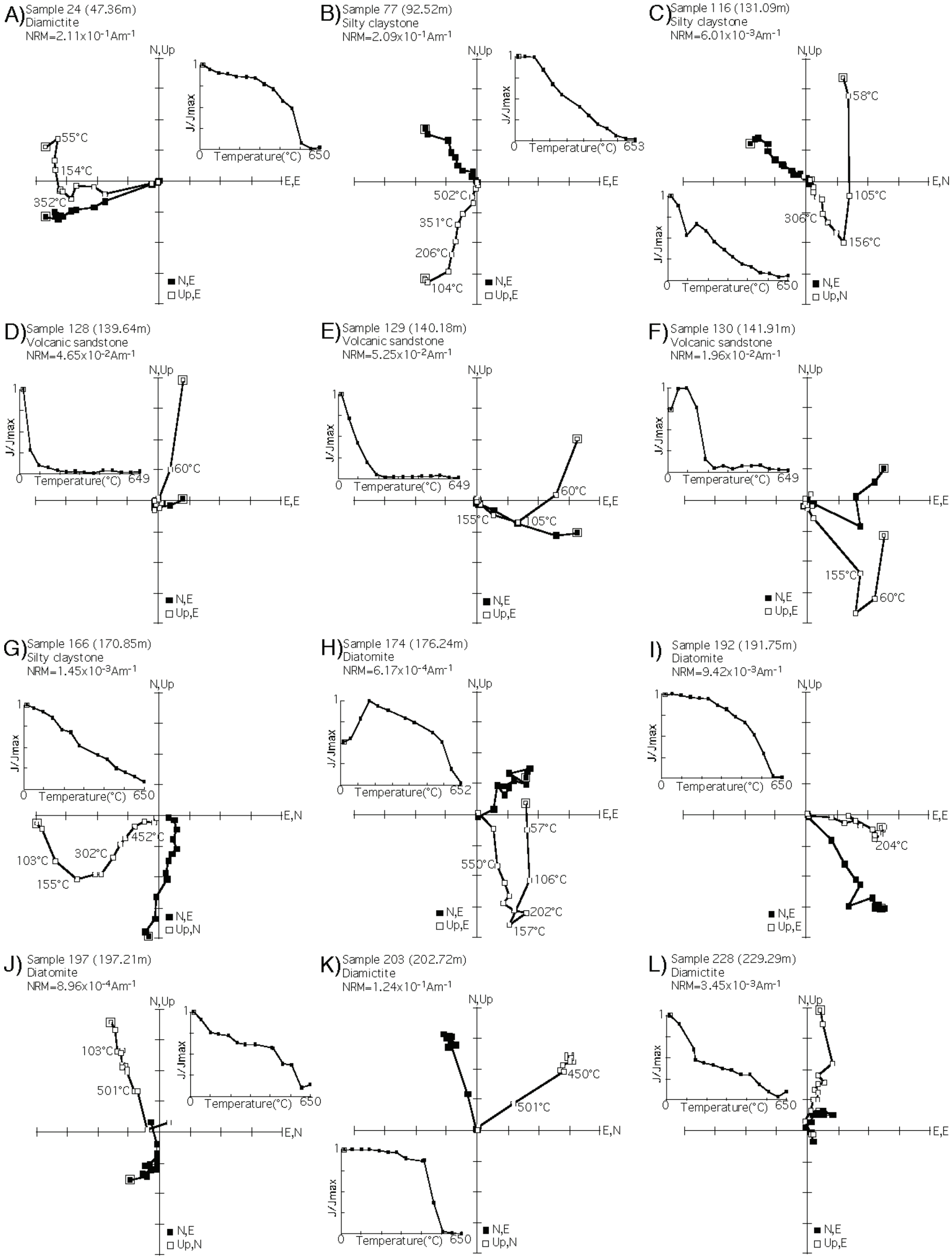

Fig. 4 – Orthogonal vector component diagrams illustrating the range of demagnetisation behaviour of samples from the MIS core: (A) drill string and radially overprinted sample from 47.36 mbsf; (B) and (C) reversed-polarity samples from 92.52 and 131.09 mbsf, respectively; (D), (E) and (F) a range of drill-string-overprinted low unblocking temperature spectra samples from 139.64, 140.18, and 141.91 mbsf, respectively; (G) sample from 170.85 mbsf with overlapping drill-string overprint and reversed-polarity ChRM unblocking temperature spectra; (H) reversed-polarity sample from 176.24 mbsf; (I) radially overprinted sample from 191.75 mbsf; (J) normal-polarity sample from 197.21 mbsf; (K) sample with narrow unblocking temperature range from 202.72 mbsf, and (L) normal-polarity sample from 229.29 mbsf.

the dominant behaviour in the samples demagnetised thus far – reversed-polarity samples with drill-string overprints and characteristic remanences occupying different ranges of the unblocking temperature spectra, whereas sample 116 (Fig. 4C) demonstrates drill-string overprint and characteristic remanence (ChRM) components with overlapping unblocking temperature spectra.

Figures 4D, 4E and 4F illustrate demagnetisation behaviour and progressively increasing unblocking temperature spectra in progressively coarser volcanic sand horizons between 139 mbsf and 142 mbsf in the core. Of the three samples, it was possible to determine polarity only in sample 130 from 141.91 mbsf (Fig. 4F).

As expected, differentiating the drilling-induced overprints is more straightforward for samples with reversed characteristic magnetisations. However, the demagnetisation intensity decay diagrams usually show a distinct loss of intensity in the 0–200°C heating range, which we interpret to be an enhanced upcore magnetisation from the drill string (*e.g.* Figs. 4J & 4L). Characteristic orthogonal components were therefore only picked in the 200-600°C demagnetisation range to minimise any potential overlap from drilling induced components. Sample 203 (Fig. 4K) unblocks over a very fine temperature range between 450°C and 550°C. While unusual, this sample does illustrate the degree to which magnetic grain size can be influenced by sedimentary facies.

MAGNETIC POLARITY STRATIGRAPHY

Between 20 and 240 mbsf in the core, the average sampling interval was ~80 cm with characteristic remanence (ChRM) directions identified from orthogonal vector component plots of demagnetisation data for 138 of the 180 thermally demagnetised samples and 124 of the 150 AF demagnetised samples (including pilot samples). Between 240 and 700 mbsf in the core, polarity data is available from thermally demagnetised samples at ~2 m average spacing. ChRM directions were identified on orthogonal vector component plots for 32 of the 45 AF and 171 of the 240 thermally demagnetised samples from between 240 m and 700 mbsf (including pilot samples). It was not possible to identify ChRM components from principal component analysis of 150 (24%) of the 615 samples demagnetised thus far, due to the presence of clasts within samples and the pervasive drilling-induced overprints in coarser-grained intervals. This is no surprise given that more than 50% of the sedimentary record above 700 mbsf in the AND-1B drill core is sandstone or diamictite.

Inclination data and a preliminary magnetic polarity zonation for the upper 700 m of the AND-1B drill core are shown in figure 5. It was not possible to determine ChRM directions from orthogonal vector components plots for samples taken from the predominantly diamictite intervals above 32.33 mbsf and between 242.17 and 253.47 mbsf, the sandy interval between 363.23 and 376.30 mbsf, and the diatomite between 391.63 and 403.73 mbsf.

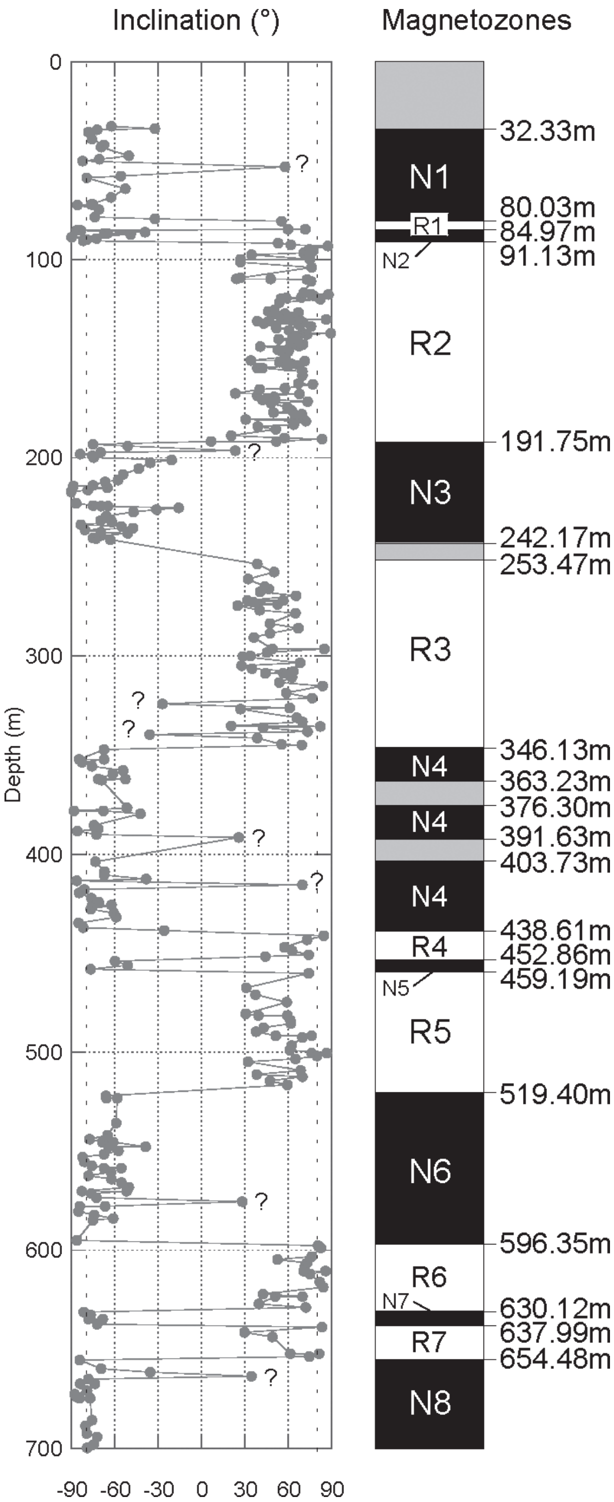

Fig. 5 – Log of magnetic polarity zonation for the upper 700 m of the AND-1B core; Black = normal-polarity magnetozones defined by high-resolution (<1 m) sample spacing. White = reversed-polarity magnetozones. Intervals marked in grey represent significant intervals (>10 m thick) for which characteristic remanence directions could not be determined from orthogonal component plots, and hence, polarity could not be determined. Discrete samples with opposing inclinations to the magnetozone they lie within are marked by a '?'. Magnetozone boundaries are defined at the midpoint between samples of opposing polarity or by transitional samples.

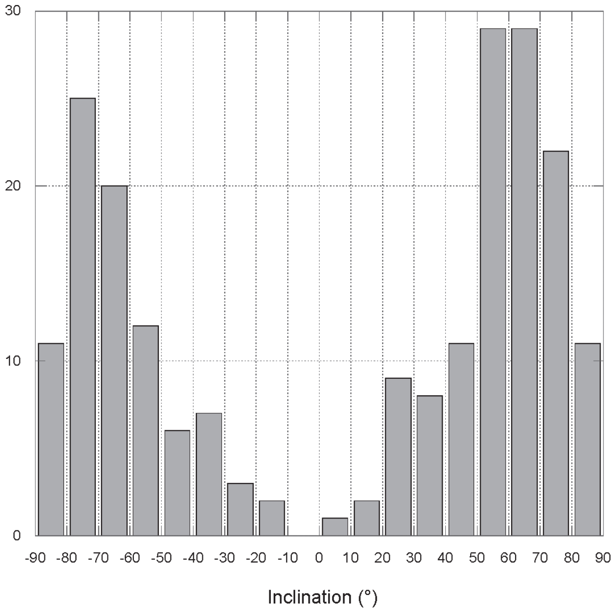

Fig. 6 – Histograms of palaeomagnetic inclinations without correct stratal tilt for the MIS drill core. Median inclinations are lower than expected at the latitude of the MIS drill site (78°S; ±83° inclination). The slight shallowing may be due to the borehole not being vertical or alternatively to tilting of the strata. The lower-angle inclinations generally relate to samples from transitional polarity as well as discrete samples with opposing inclinations of the magnetozone they lie within (Fig. 5).

A magnetozone was only assigned to intervals with two or more samples with similar inclination. Single samples with inclination different from surrounding samples were not assigned to a separate magnetozone but labelled with a '?' in figure 5. Magnetozone boundaries are placed at the midpoint between samples of opposite polarity unless an obvious stratigraphic disconformity separates magnetozones.

Normal and reversed magnetozones are generally equally distributed in the record between 30 and 700 mbsf (Fig. 5). While it is not possible to conduct a reversals test, normal and reversed inclination values are equally distributed (Fig. 6) and magnetozones do not coincide with lithological units or subdivisions. For ease of description and correlation, magnetozones are numbered sequentially downcore. The numbering is preliminary and may change with further analyses. Normal polarity (magnetozones N1 and N2) dominates the interval between 32.33 and 91.13 mbsf, with a short reversed-polarity magnetozone (R1) between 80.03 and 84.97 mbsf (Fig. 5). Reversed polarity (magnetozones R2 and R3) dominates the interval between 91.13 and 346.13 mbsf, with a normal-polarity magnetozone (N3) between 191.75 and 242.17 mbsf. The magnetozone R2/N3 boundary is defined by a transitional polarity sample at 191.75 mbsf. The magnetozone N3/R3 boundary is more poorly defined as it occurs within a predominantly diamictite interval and it was not possible to identify ChRM directions on orthogonal component plots from samples between 242.17 and 253.47 mbsf.

Magnetozone N4 (346.13–438.61 mbsf) contains two short intervals (363.23–376.30 mbsf and 391.63–403.73 mbsf) for which it was not possible to determine ChRM directions on orthogonal component plots. Reversed polarity (magnetozones R4 and R5) dominates the interval between 438.61 and 519.40 mbsf, with a short normal-polarity magnetozone (N5) between 452.86 and 459.19 mbsf. Magnetozone boundaries are relatively well defined with an average sample spacing of 1.75 m. The interval between 519.40 and 596.35 mbsf is normal polarity (magnetozone N6), and reversed polarity (magnetozones R6 and R7) dominates the interval between 596.35 and 654.48 mbsf, with a short normal-polarity magnetozone (N7) between 630.12 and 637.99 mbsf. Again, magnetozone boundaries are relatively well defined with an average sample spacing of 2.21 m. Magnetozone N8 is defined below 654.48 mbsf; however, the base of magnetozone N8 is not yet defined as demagnetisation data are only presented down to 700 mbsf.

Only NRM data are available between 700 mbsf and the bottom of the drill core (1284.87 mbsf). These data are dominated by a strong drill-string overprint (Fig. 2C). However, by comparison with the upper part of the core, several intervals (*e.g.* ~750 and 1000 mbsf) may reveal reversed ChRM polarity directions when demagnetised.

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