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Detailed study on the anisotropy of magnetic susceptibility of arctic marine sediments

Norbert R. Nowaczyk

GeoForschungsZentrum Potsdam, Projektbereich 3.3, *Telegrafenberg Haus C,* 14473 *Potsdam, Germany. E-mail: nowa@gfz-potsdam.de*

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SUMMARY

Five sediment cores from three different areas, the Jan Mayen Fracture Zone in the Greenland Sea, the Fram Strait and the Makarov Basin in the Arctic Ocean have been subjected to a detailed analysis of the magnetic fabric by analysing their anisotropy of magnetic susceptibility (AMS) as a supplementary parameter to already existing palaeo- and rock magnetic data sets. Intervals of reversed inclinations documented within the five cores can be interpreted as geomagnetic excursions because all the investigated sediments are characterized by an undisturbed magnetic fabric as expected for layered sediments, that is, an oblate anisotropy ellipsoid with its short principal axis oriented vertically. Excursional directions are also not associated with significant changes in rock magnetic parameters. However, cores from the Arctic Ocean, in particular, exhibit a strong cyclicity in their anisotropy parameters. Here, sand-rich layers are characterized by a low anisotropy, whereas clay rich layers yielded highest anisotropy degrees of up to 9 per cent indicating an AMS mainly controlled by the matrix properties of the sediment. A simple three-axis determination of the anisotropy of anhysteretic remanent magnetization (AARM) on one of these cores surprisingly yielded an even higher degree of anisotropy of the ferrimagnetic fraction of up to 18 per cent, i.e. twice as high as determined for the susceptibility, which is also influenced by the paramagnetic fraction. This implies a strong contribution of this sediment fraction to the overall magnetic susceptibility of the investigated Arctic Ocean deposits.

Key words: anisotropy of anhysteretic remanent magnetization, anisotropy of magnetic susceptibility, geomagnetic excursions, magnetostratigraphy, rock magnetism.

INTRODUCTION

Analyses of the magnetic fabric of sediments, generally by the determination of the anisotropy of magnetic susceptibility (AMS) can principally provide information concerning the pattern of palaeocurrents (e.g. Park *et al.* 2000; Liu *et al.* 2001) or tectonic stress within rocks (Borradaile & Henry 1997). Kissel *et al.* (1998) could show that the degree of AMS in some North Atlantic sediments is positively correlated to oscillations in bulk susceptibility with minima (maxima) in susceptibility and a high (low) degree in AMS coinciding with cold (warm) periods, reflecting a modulation in the amount of deposited magnetite. The variations of the degree of anisotropy are therefore climatically controlled. Kissel *et al.* (1998) discuss the fact that the fabrics should mainly result from depositional effects, in connection with climatic changes, although differential compaction might have been active, too.

Another possible application of AMS determination is the detection of, possibly artificially induced, disturbances of unconsolidated sediments such as coring disturbances or subsampling (Copons *et al.* 1997). An often used argument, especially in the discussion on the presence or absence of geomagnetic excursions during the Brunhes Chron in high-resolution magnetostratigraphic records, is that the observed anomalous directions are caused by unrecognized disturbances of the sedimentary fabric (e.g. Marino & Ellwood 1978). Rosenbaum *et al.* (2000) proved that intervals with shallow inclinations that previously have been interpreted as geomagnetic excursions by Glen & Coe (1997) were more probably caused by a disturbed magnetic fabric owing to core deformation during drilling. In another study by Nowaczyk & Frederichs (1999) the application of AMS analysis also succeeded in separating disturbed sections of the core top, which was distorted because of overpenetration of the coring gear, from the undisturbed layers further down. Here, several intervals of reversed directions then could be interpreted as real records of geomagnetic field excursions, because they are sited in undisturbed and rock magnetically homogenous sediments. Jordanova *et al.* (1996) discuss another effect that may occur during sampling of dry terrestrial sediments. They observed a significant compaction of loess sediments during sampling of up to 30 per cent, depending on the applied sampling technique. Here, the fabric was distorted by the sampling procedure with a higher degree of distortion when the compaction was higher.

In this study, new comprehensive results on AMS analyses performed on sediment cores exhibiting geomagnetic excursions are presented. The five cores from three different sites separated by

Table 1. Locations of sediment cores. Letters indicate the type of coring gear: (a) 10 cm diameter piston corer, (b) 30 × 30 cm^2 Kastenlot corer, (c) 15 × 15 cm^2 Kastenlot corer. Numbers refer to publications of palaeo- and rock-magnetic results: (1) Nowaczyk *et al.* (2001), (2) Nowaczyk *et al.,* in prep, (3) Nowaczyk (1997), (4) Nowaczyk & Antonow (1997).

Core number	Latitude	Longitude	Water depth (m)	Length (cm)	Area	Samples
PS2180-2[a]	87°38.6′N	156°58.3′E	3991	1296	Central Arctic Ocean[1]	251
PS2178-3[a]	88°00.3′N	159°10.1′E	4009	1372	Central Arctic Ocean[1]	436
PS2178-5[b]	88°01.5′N	159°40.5′E	4008	831	Central Arctic Ocean[1]	207
PS1535-6[b]	78°45.4′N	1°49.5′E	2555	390	Fram Strait[2]	71
PS1707-2[c]	72°36.9′N	13°48.4′W	2122	530	Jan Mayen Fracture Zone[3,4]	106

approximately 2000 km were already analysed for their rock magnetic properties such as low-field bulk susceptibility (κ_{LF}) and anhysteretic and isothermal remanent magnetizations (ARM, IRM) as listed in Table 1. From that point of view there are no indications to assume that the well-documented reversed directions within the cores should be interpreted as artefacts and not as documentations of geomagnetic excursions. However, in principle, disturbances, either of depositional origin, such as slumps, or coring-induced cannot be detected by bulk parameters. Therefore, the still well-preserved samples were subjected to a detailed analysis of their magnetic fabric, in order to finally check the reliability of the palaeomagnetic record. Another motivation was to clarify what is behind the fact that sediment cores recovered with different coring gears suffer (apparent) compaction (in the case of gravity cores) or elongation (in the case of piston corers) without changes in the major physical bulk parameters related to the volume such as the bulk susceptibility or density.

MATERIAL AND METHODS

Five sediment cores from the Makarov Basin (central Arctic Ocean), the Fram Strait and the Jan Mayen Fracture Zone (Fig. 1) were chosen for a detailed analysis of their magnetic fabric by determining the anisotropy ellipsoid of magnetic susceptibility. The cores were sampled with plastic boxes with a spacing of 3–5 cm, yielding a collection of 1071 samples (Table 1). The samples measure 20 mm in the x- and z-directions but only 15.5 mm in the y-direction, i.e. they are not equally sized in all three directions—another motivation to test whether this might affect the analysis of the anisotropy ellipsoid or results from palaeomagnetism.

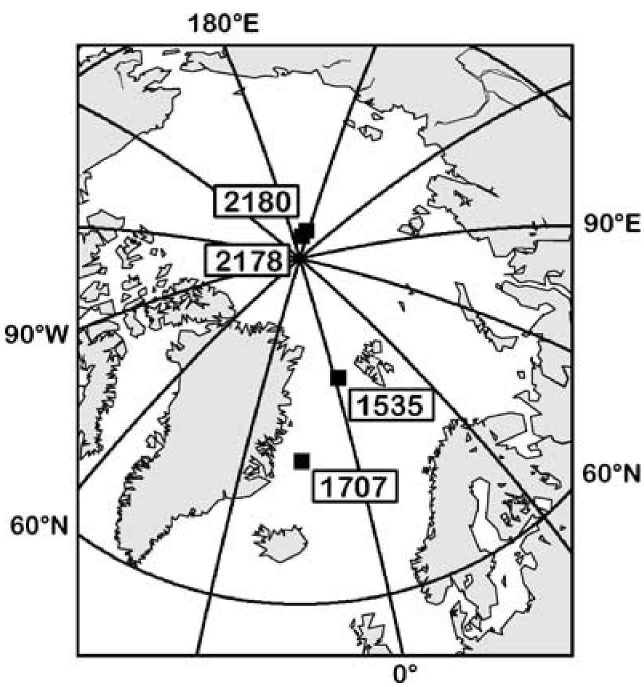


Figure 1. Location map of investigated sites.

Since sampling, the samples were always kept at +4°C in order to protect them from drying. During processing, the samples were stored in a refrigerator, when not measured. In addition, after sampling and during longer processing breaks, the samples, together with wet foams, were sealed in plastic bags. For the determination of the anisotropy ellipsoid of magnetic susceptibility an AGICO KLY-3S was used. During analysis susceptibility is measured numerous times while the sample is rotating around the x-, y- and z-axes, respectively. This is done after zeroing the instrument with the sample inside the measuring coil. This means that during rotation only the deviation of the ellipsoid from a sphere is determined so that the most sensitive range can be used in most cases. Absolute values of the susceptibility anisotropy ellipsoid are then determined from an additional bulk measurement. Calculation of the anisotropy tensor, represented by the general susceptibilities K_{max} (maximum), K_{int} (intermediate) and K_{min} (minimum), and their respective orientation angles, declination (D) and inclination (I), was then performed using AGICO software (Brno, Czech Republic). The orientation angles are given with respect to sample coordinates because the samples are only semi-oriented, i.e. the z-axis is oriented parallel to the vertical direction and the x- and y-axes lie within the horizontal plane, but with an unknown azimuth. For the degree of AMS the ratio $100(K_{max} - K_{min})/K_{max}$ is used and is therefore given in per cent, whereas the shape (factor) of the ellipsoid is estimated by the ratio $(K_{max}K_{min})/K_{int}^2$, with ratios <1 (>1) indicating an oblate (prolate) ellipsoid.

In addition to AMS analyses core PS2178-5 was chosen for a simple test of the anisotropy of anhysteric remanent magnetization (AARM). The ARM was imprinted first along the z-axis (ARM|| z), using 100 mT alternating field (AF) amplitude and 50 μT static field amplitude, then measured and demagnetized with 100 mT AF amplitude. Subsequently, the same procedure was performed also for the y- and x-axes (ARM|| y and ARM|| x), respectively.

DISCUSSION OF RESULTS

Standard palaeo- and rock magnetic results, such as the determination of the bulk susceptibility, determination of the characteristic remanent magnetization (ChRM) after stepwise alternating field demagnetization, acquisition and/or demagnetization of anhysteretic and isothermal remanent magnetizations (ARM and IRM), are already published as indicated in Table 1. In order to demonstrate the homogeneity of the sediments and to better evaluate the new results from anisotropy determinations, major rock magnetic parameters, i.e. data related to the concentration (ARM intensity), the grain size (ARM/SIRM ratio) and the coercivity (S-ratio) of magnetic

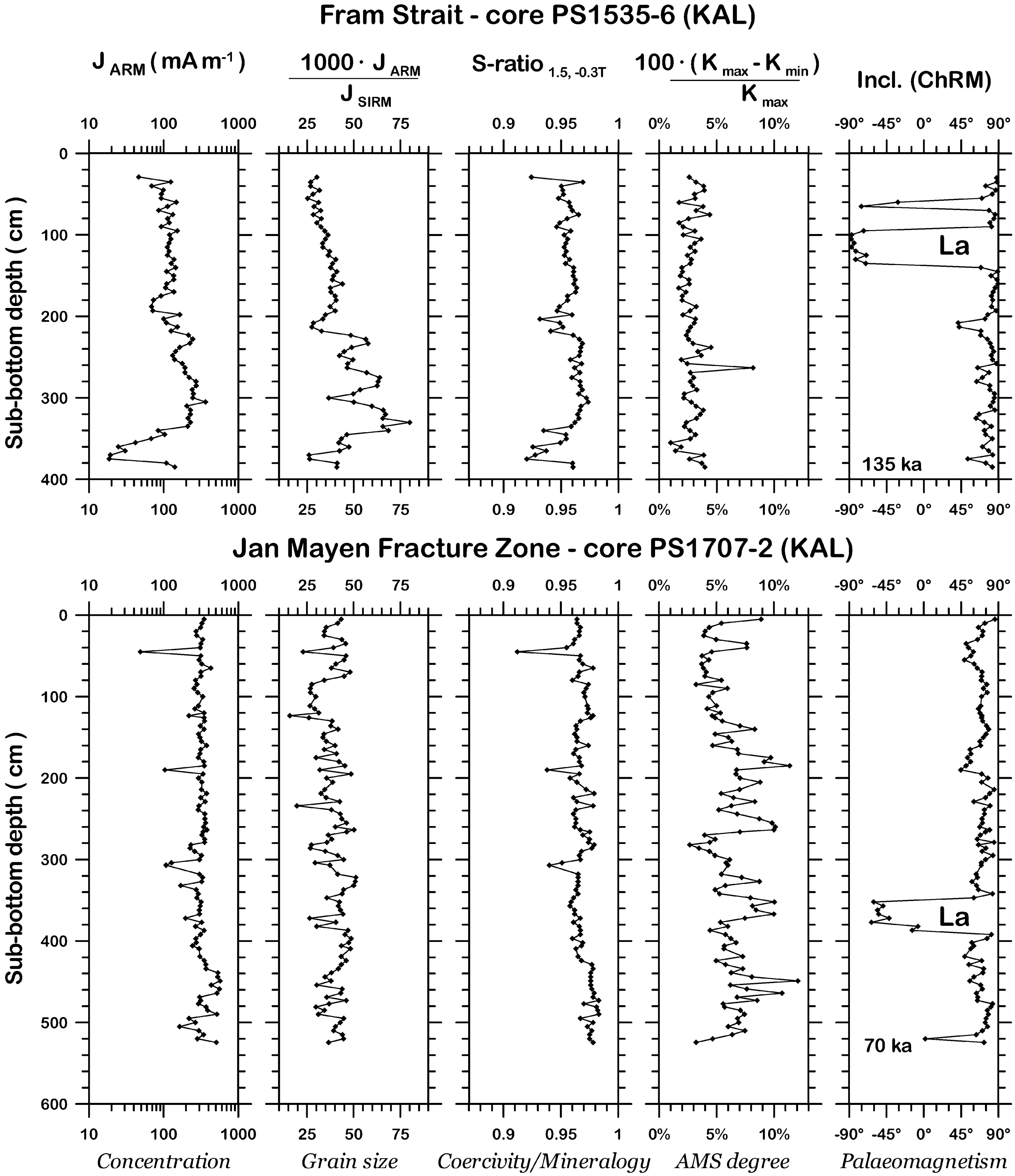


Figure 2. (a) Basic rock and palaeomagnetic data from cores PS1707-2 and PS1535-6: parameters related to concentration (J_{ARM}), grain size of the magnetic particles ($1000 \times J_{\mathrm{ARM}}/J_{\mathrm{SIRM}}$) and coercivity and/or mineralogy (S-ratio), together with AMS degree and ChRM inclination. J_{ARM}—intensity of anhysteretic remanent magnetization, J_{SIRM}—intensity of saturated isothermal remanent magnetization, S-ratio: $= 0.5 \times [1 - (J_{\mathrm{IRM}}(-0.3\ \mathrm{T})/J_{\mathrm{IRM}}\ (1.5\ \mathrm{T})]$, ChRM—characteristic remanent magnetization. La—Laschamp excursion (~40 ka). Ages of the core bases are indicated at the bottom of the inclination logs.

minerals, and palaeomagnetic information (ChRM inclination) of one core from each location are summarized in Fig. 2, together with data on the degree of AMS. A more detailed compilation of down-core variations of various AMS parameters together with ChRM inclinations for all five cores are presented in Fig. 3. The corresponding stereographic projections with the orientations of K_{min}, K_{int} and K_{max} together with plots of K_{min} inclinations versus the degree of AMS are shown in Fig. 4. In general, the magnetic

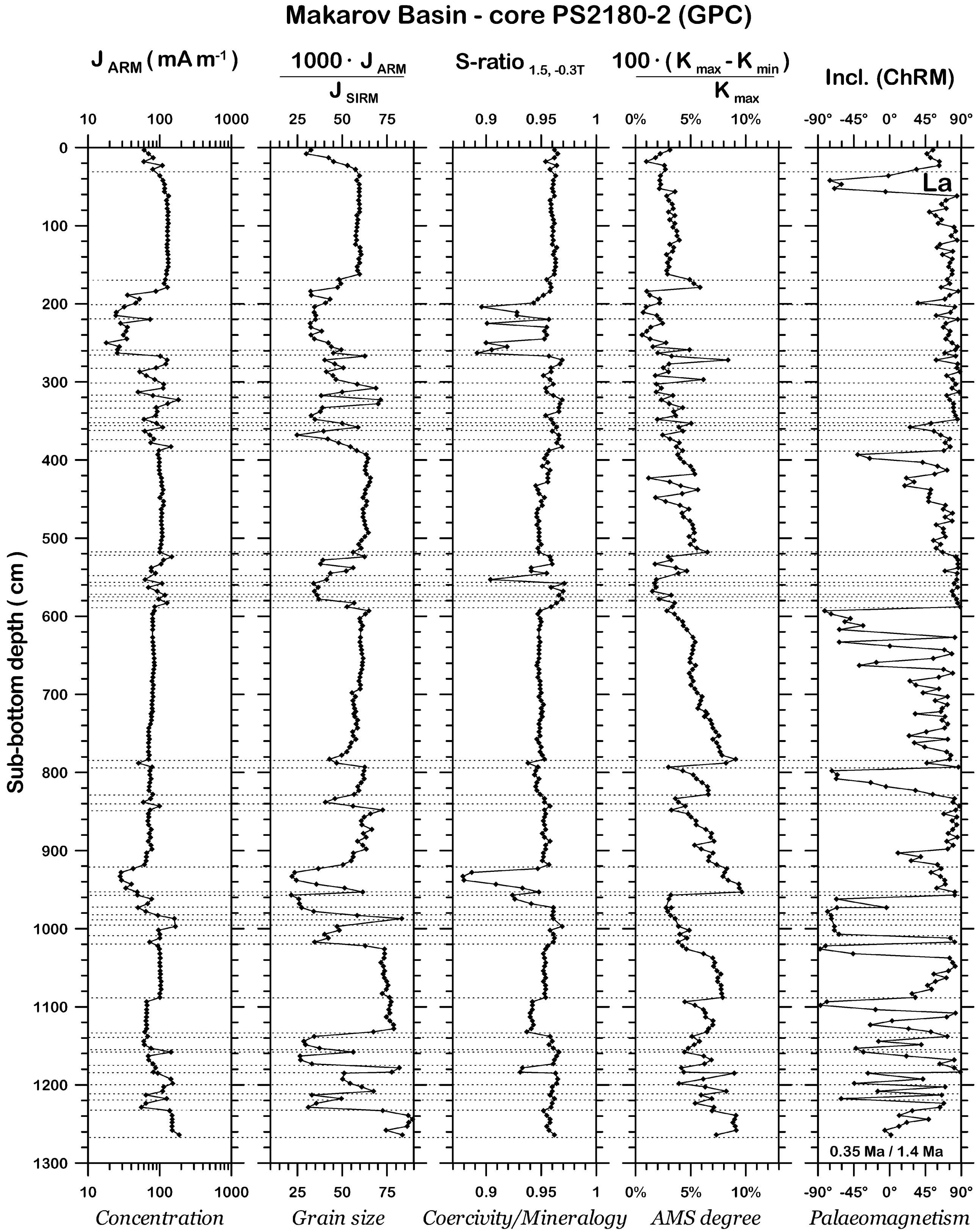


Figure 2. (b) Basic rock and palaeomagnetic data from core PS2180-2. Horizontal dashed lines indicate lithological boundaries visible within the core. Two different age models are discussed for this core (Nowaczyk *et al.* 2001). La—Laschamp excursion (∼40 ka).

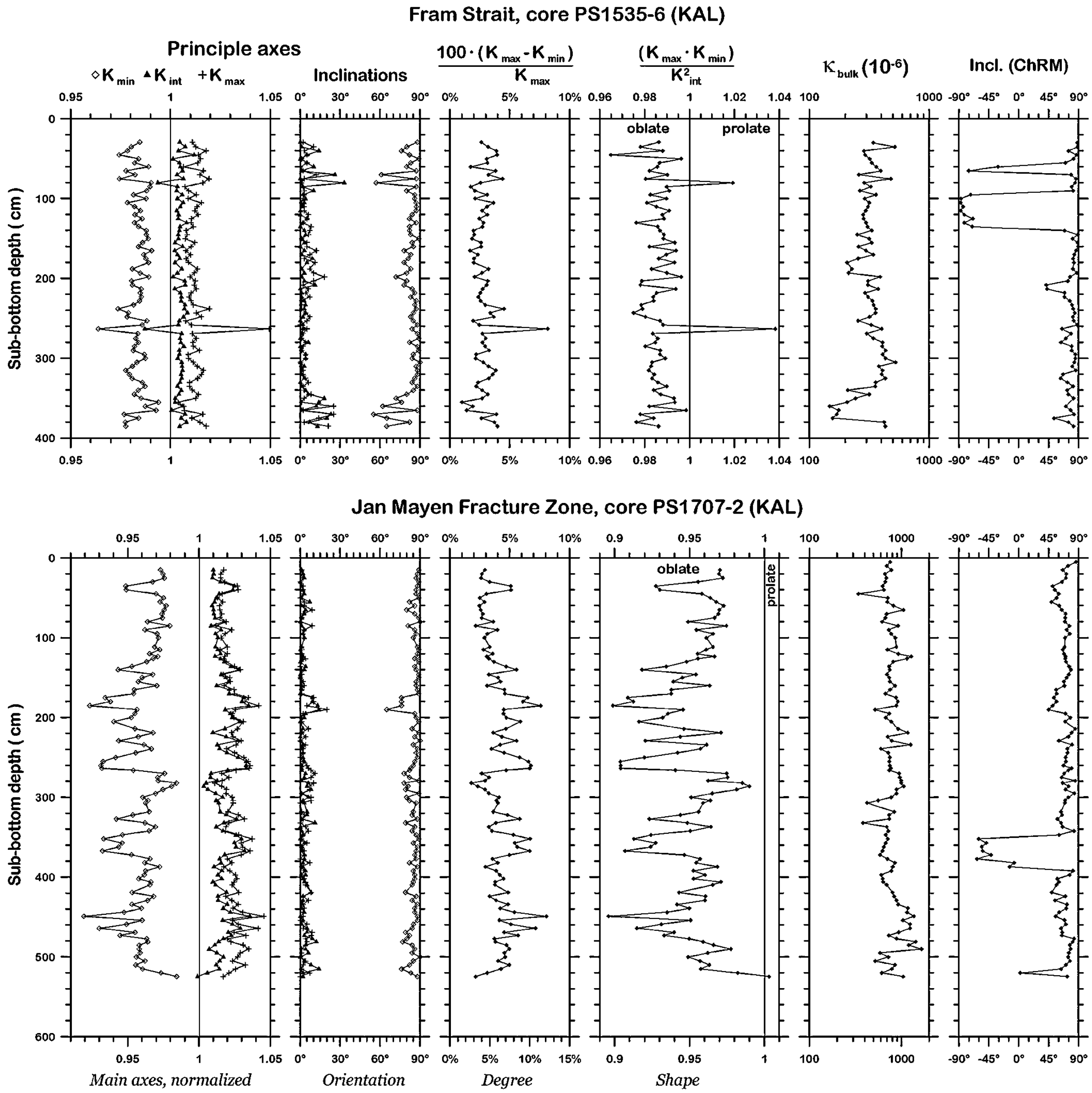


Figure 3. (a) Results from determination of the anisotropy of magnetic susceptibility as a function of sub-bottom depth for cores PS1535-6 and PS1707-2: sizes of the principal axes K_{max}, (maximum), K_{int} (intermediate) and K_{min} (minimum), their inclinations, the degree of AMS, the shape factor of the anisotropy ellipsoid and the bulk susceptibility together with inclination of the characteristic remanent magnetization (ChRM). (b) AMS data for cores PS2178-3 and PS2178-5. (c) AMS data for core PS2180-2.

fabrics of the cores can be characterized by flat-lying oblate ellipsoids (shape factor <1), i.e. K_{min} inclinations cluster around 90°. The intermediate and long axes are nearly of the same length, i.e. the ellipsoid can be described as a sphere flattened along the vertical (z-) axis. Only within the upper approximately 5 m of Makarov Basin sediments (sites PS2178 and PS2180) does the orientation of K_{min} show a more random distribution in some intervals, but this appears to be caused by a low degree of AMS, and, according to this, a shape factor around 1 (Fig. 3). Low AMS degrees in core PS2178-5 also coincide with sediment layers of significantly increased sand content (some 20–30 weight per cent), whereas (relatively) high AMS degrees correlate with more or less sand-free, that is, silty to clayey sediments (Fig. 5). Taking into account that the generally flat shaped clay minerals tend to orient perpendicular to the main stress axis, that is, the vertical axis during compaction, whereas (rounded) sand grains do not have a preferred direction to align with, it appears quite likely that the degree of AMS is mainly a function of the matrix grain size and also shape properties and not just a function of the properties of the magnetic minerals alone. The degree of AMS would then reflect more or less the degree of the compaction of the sediment. The plots of K_{min} inclinations versus degree of AMS (Fig. 4) show that the lower the degree of AMS is the more scattered K_{min} inclinations are. Below approximately 2–3 per cent, K_{min} inclinations seem to become randomly oriented. These are mainly the sand-rich layers where a lack of preferred orientation might lead to randomly oriented principal axes. In addition, when the anisotropy approaches a degree of 0 per cent, the axis orientations of the ellipsoid, which then transforms into a sphere, are

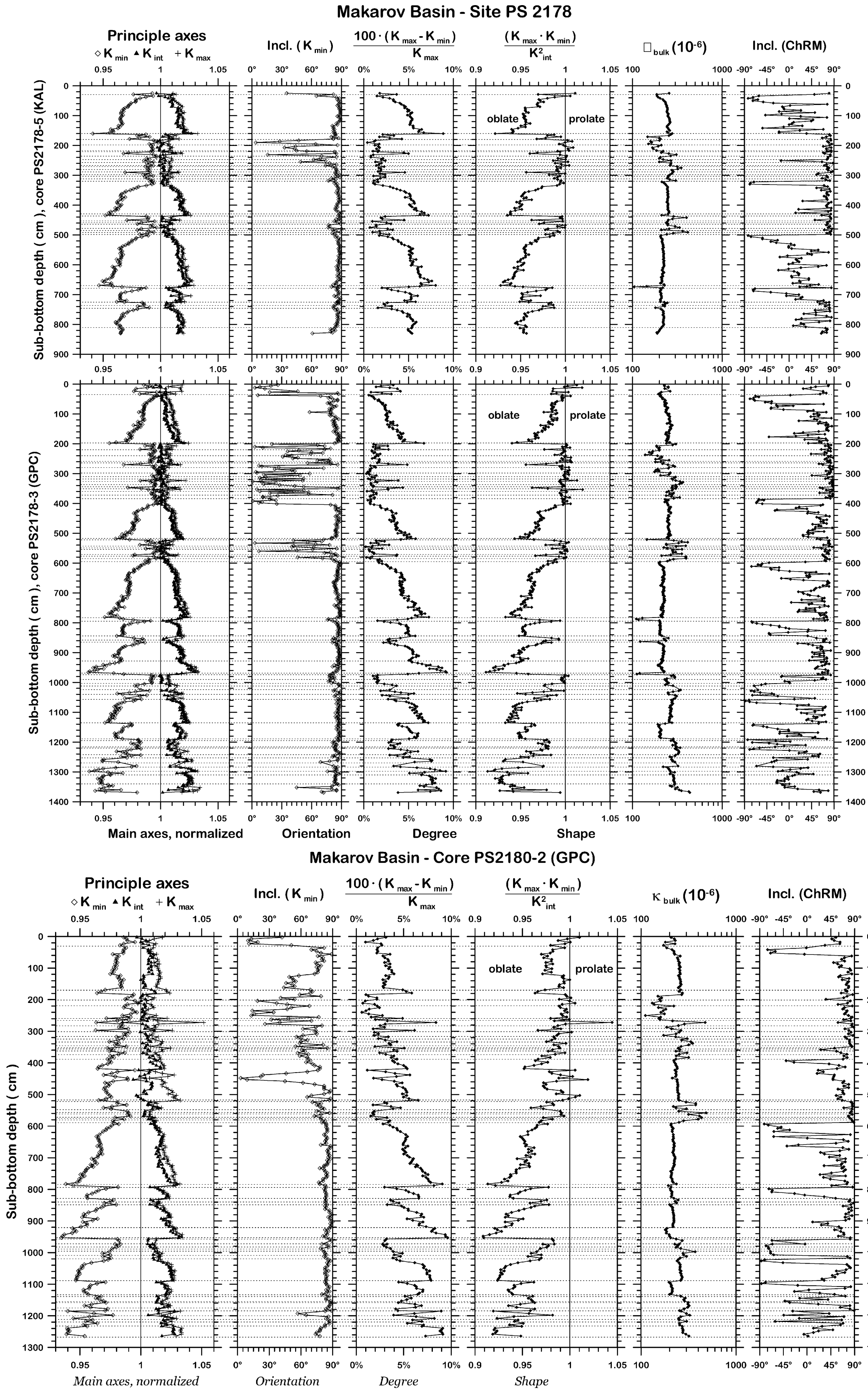


Figure 3. (*Continued*)

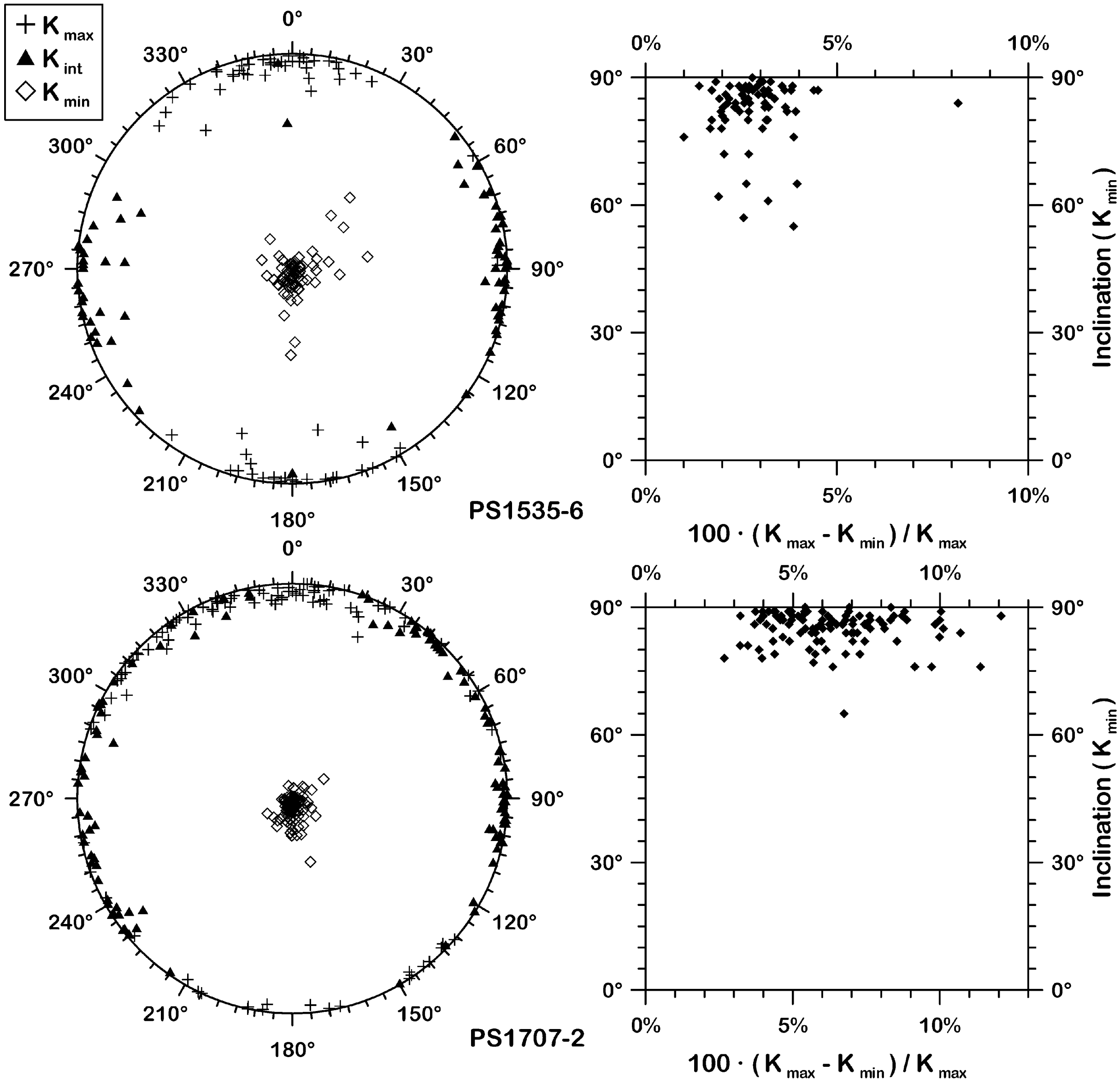
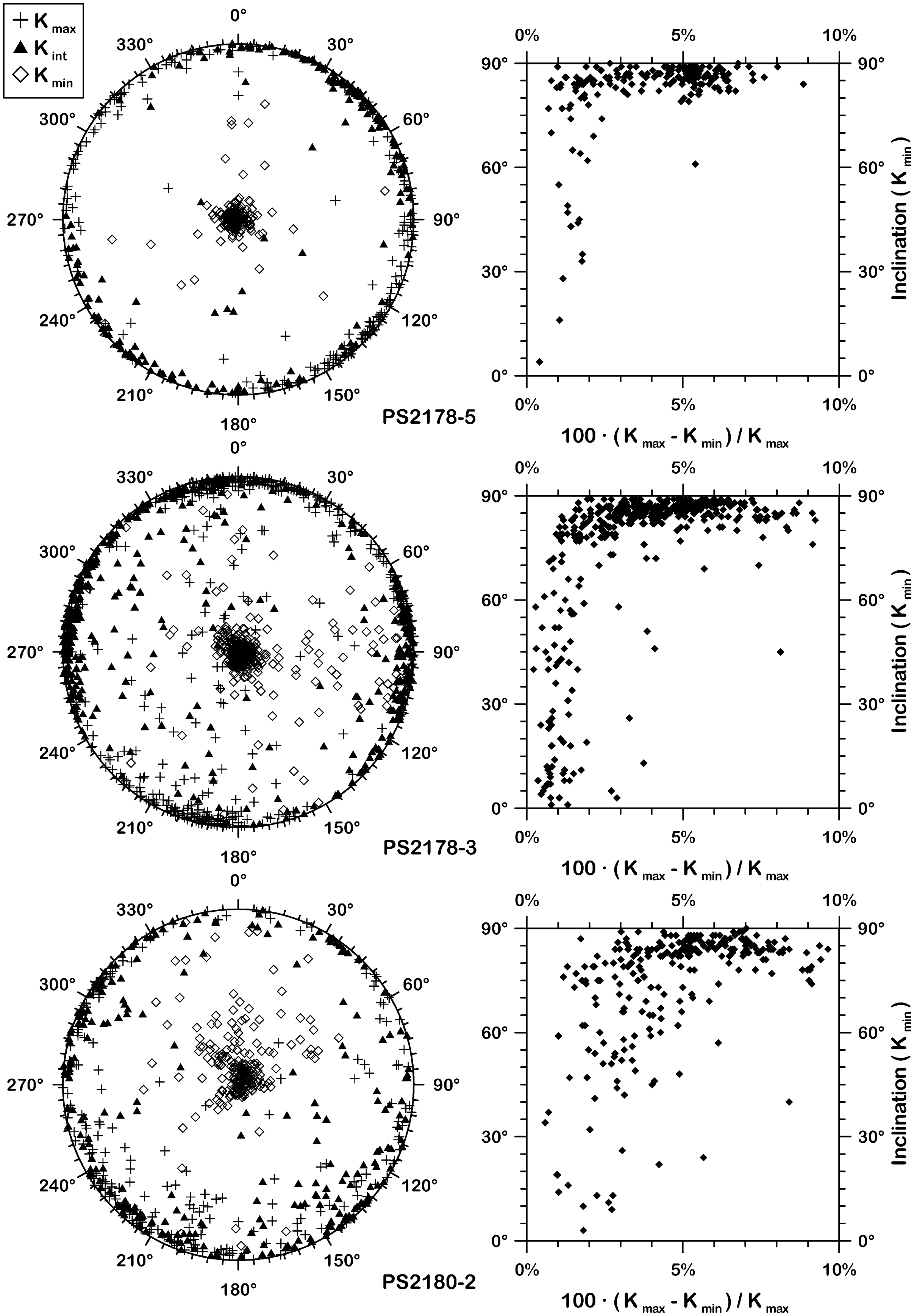


Figure 4. (a) Stereographic projections of the directions of the principal susceptibility axes K_{max}, K_{int} and K_{min} and inclination of K_{min} versus the degree of anisotropy from cores PS1535-6 and PS1707-2. (b) Cores PS2178-3, PS2178-5 and PS2180-2.

undefined anyway. Obviously, in the case of Makarov Basin sediments, a 2–3 per cent degree of AMS is the lower limit for reasonable results in determining the orientation of an anisotropy ellipsoid. It is interesting to note that a higher sand content does not lead to a noisier palaeomagnetic record. Instead, the more silty to clayey intervals show scattered ChRM inclinations in the Kastenlot core. In the parallel piston core this effect is less pronounced (compare Figs 3 and 5).

Sediments from Fram Strait (PS1535-6) and the Jan Mayen Fracture Zone (PS1707-2) are less 'problematic'. Their magnetic fabrics with oblate ellipsoids are well defined (Figs 3 and 4), with AMS degrees approximately twice as high at site PS1707 (between 3 and 12 per cent) when compared with site PS1535 sediments (between 1 and 5 per cent). As in core PS2178-5 (KAL) there is no real trend to higher AMS degrees with increasing depth. Only the approximately 13 m long piston cores from the Makarov Basin show slightly higher AMS degrees in their lower halves, probably caused by the burden of the overlying sediments.

Geomagnetic excursions expressed by steep negative ChRM inclinations are present in all five cores. ChRM directions, generally cleaned from a steep normal polarity viscous overprint by stepwise alternating field demagnetization, have been determined by principal-component analysis (Kirschvink 1980). As explained by Nowaczyk *et al.* (2001), geomagnetic excursions coincide with severe sedimentation events in the permanently ice-covered Makarov Basin, where sedimentation is obviously more episodic, possibly with numerous hiatuses, rather than being continuous. This led to quite a different palaeomagnetic record when compared with the results from the Fram Strait and the Jan Mayen Fracture Zone, which are much closer to open ocean conditions, at least in recent times. The most prominent excursion, the Laschamp excursion (~40 ka), marked by 'La' in Fig. 2, could be identified at



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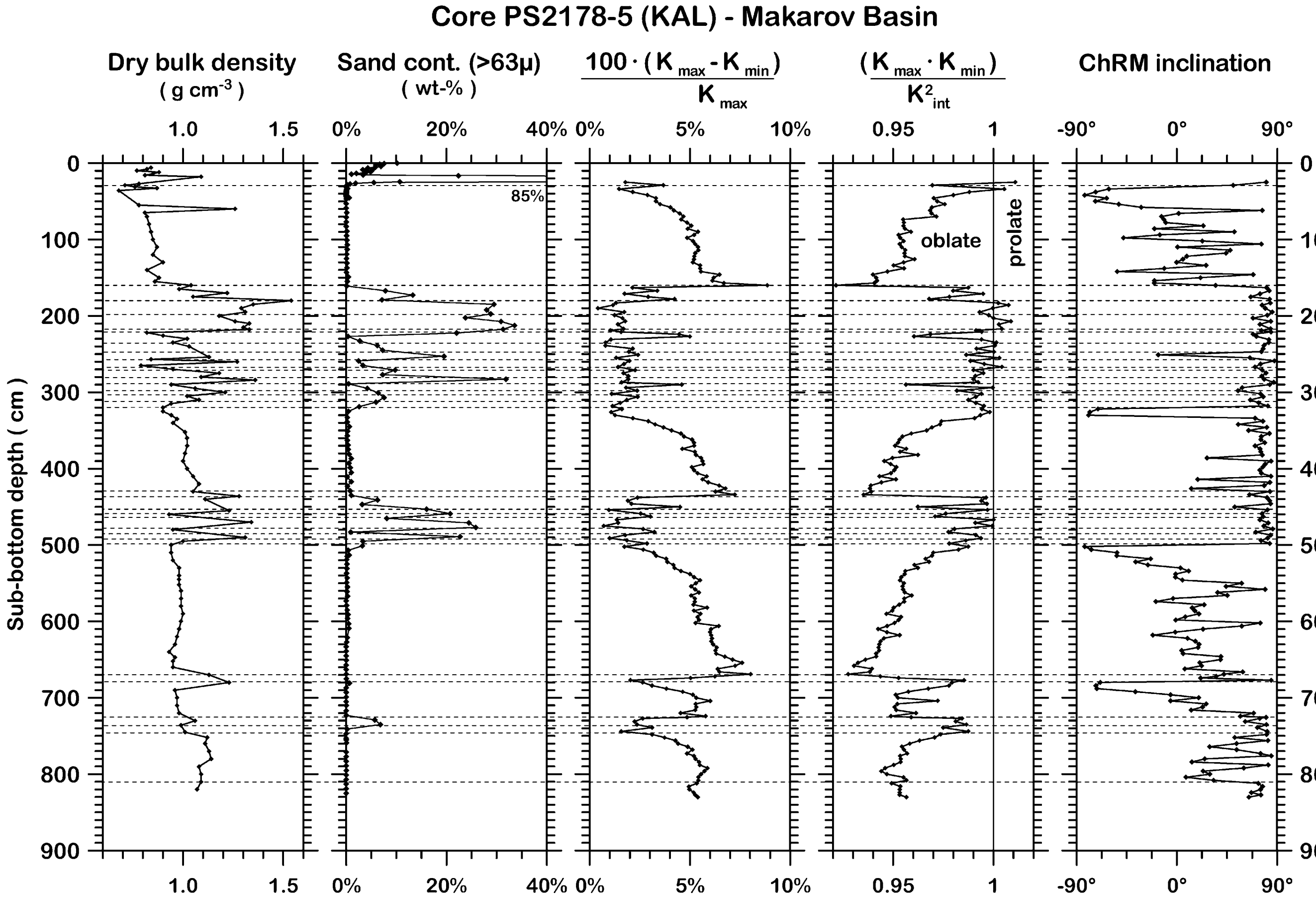

Figure 5. Physical properties, dry bulk density and sand content (Nowaczyk *et al.* 2001), AMS parameters, degree and shape factor of AMS, and ChRM inclination of core PS2178-5 (Makarov Basin). Horizontal dashed lines indicate lithological boundaries visible within the core.

all three locations: at around 40 cm in the Makarov Basin cores (PS2178 and PS2180), between 95 and 140 cm in PS1535-6 (Fram Strait), and 340 and 390 cm in core PS1707-2 (Jan Mayen Fracture Zone). The unequivocal identification could be obtained by means of accelerator mass spectrometry (AMS) ^{14}C datings (Nowaczyk & Antonow 1997; Nowaczyk *et al.* 2001; Nowaczyk *et al.,* in prep.).

As can be seen in the stratigraphy plots of Fig. 3 and also in the diagrams of Fig. 6, steep negative (reversed polarity) ChRM inclinations are always associated with steep inclinations of $K_{\min}$, such as for nearly all other sediments with steep positive (normal polarity) ChRM inclinations. This means that reversed ChRM directions at all three locations investigated are associated with a similar, above all undisturbed magnetic fabric such as the remaining normal polarity intervals, so that there should be no doubt concerning their palaeomagnetic origin. Moreover, rock magnetic parameters also do not show any suspicious deviations associated with polarity transitions (Fig. 2). Only some more sandy Makarov Basin sediments exhibit shallow $K_{\min}$ inclinations, but here in turn no non-normal polarity directions are recorded. A few samples with reversed ChRM inclinations in core PS2178-3 are associated with shallow $K_{\min}$ inclinations (Fig. 6). However, these samples are sited within sections of low AMS degree (Fig. 3), where the orientation of the axes of the ellipsoid are less well defined anyway (see above). Nevertheless, it is astonishing that in cores from Makarov Basin reversed inclinations are nearly always sited in the top part of sand-free sediment packages with the AMS degree decreasing from the bottom to the top. Since these packages are extremely homogenous both in terms of available sedimentological (Fig. 5) and rock magnetic properties (Fig. 2), it must be concluded that these intervals represent geomagnetic excursions. In addition, the topmost (Laschamp) excursion is synchronous with the documentation of the Laschamp excursion further south (PS1535 and PS1707). Although nearly all reversed inclination intervals are sited within sedimentologically/rock magnetically homogenous intervals with topward-decaying AMS degree, not each of such intervals exhibits reversed directions (e.g. at 840 cm in core PS2180-2). Up to now, no study has been reported in the literature concerning a self-reversal within sediments, i.e. a record of reversed ChRM inclinations, including a soft normal overprint, artificially produced by sediments with decaying degree of anisotropy while all other rock magnetic parameters and sedimentological properties do not change. Moreover, the degree of anisotropy of sediments contemporary to the Laschamp excursion is not the same at the three investigated sites: 4–10 per cent in PS1707-2 (Jan Mayen Fracture Zone), 2–3 per cent in PS1535-6 (Fram Strait) and 2–4 per cent in cores PS2178/2180 (Makarov Basin). Therefore, it appears to be very unlikely that the reversed direction in Makarov Basin sediments are an artefact linked with the degree of anisotropy.

Possibly, the decaying degree of anisotropy in sand-poor Makarov Basin sediments is caused by a decay in the silt/clay ratio that has not been investigated. A higher silt content should prevent the sediments from undergoing stronger compaction compared with sediments with a lower silt content, or even consisting of just clay

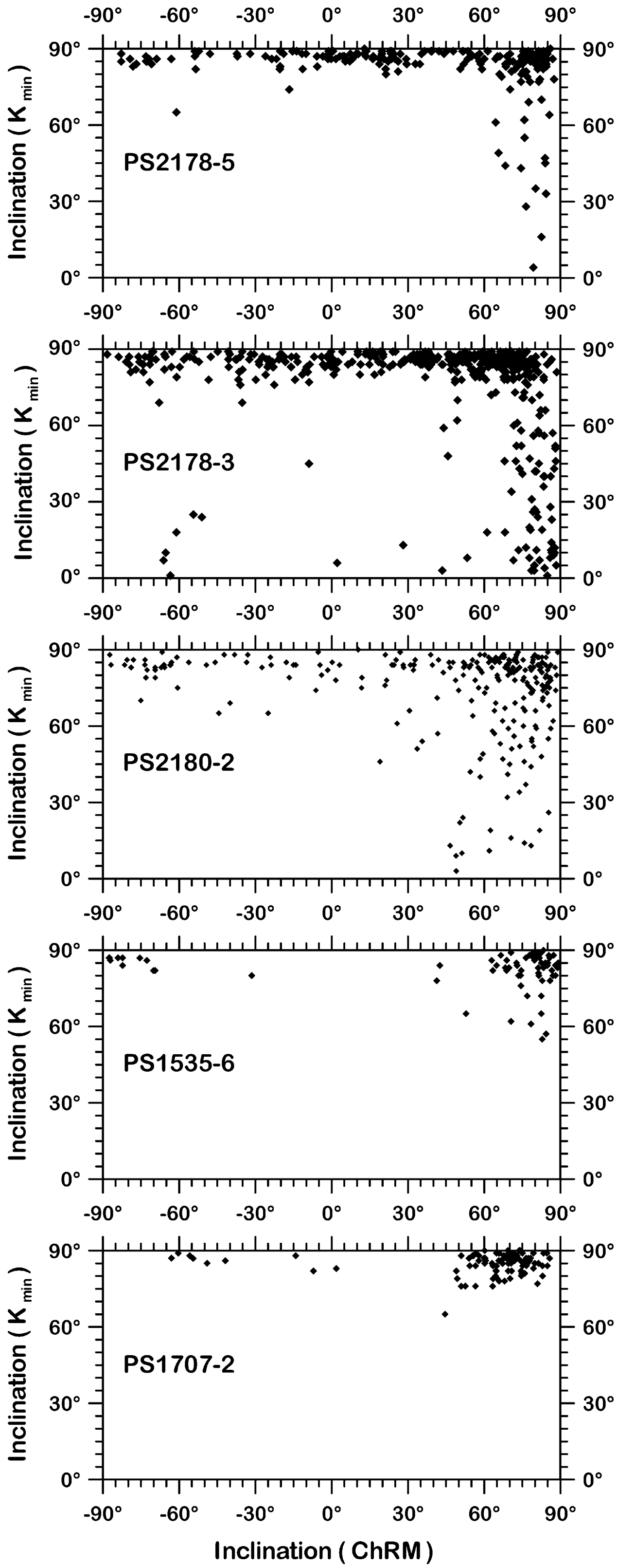

Figure 6. Inclination of $K_{\min}$ versus ChRM inclination (see also Fig. 2).

minerals. Nevertheless, the observation of this strange coincidence should be studied in more detail by future investigations.

The Makarov Basin sedimentary sequence might reflect not just a coincidence of, but a link between sedimentation events, that is, erosion and transportation of sediments induced by climatical changes, on the one hand, and geomagnetic events (excursions), on the other hand, as postulated by Worm (1997), whatever the link between the two processes might be. Unfortunately, no sufficiently reliable age model for Makarov Basin sediments older than approximately 50 ka could be established (Nowaczyk *et al.* 2001) in order to prove this postulation.

Comparisons between different core types—site PS2178

Fig. 7 shows the correlation of the three cores from the Makarov Basin on basis of the degree of AMS. The correlation is further supported by results on ChRM inclination, various rock magnetic parameters and sediment colour yielding very dense transfer functions (Nowaczyk *et al.* 2001). Core PS2178-3 is used as a master core. After transforming depth values of the other cores to this master core, it becomes obvious that AMS results from all three cores, concerning relative changes, correlate in detail (Fig. 8). In Fig. 9 only the transfer function from the 30 × 30 cm^2 Kastenlot to the 10 cm diameter piston core from site PS2178 is shown. The solid line indicates a 1:1 correlation. However, the correlation tie points show a systematic prograding offset from this line, i.e. the same horizons in the piston core are sited at successively deeper depths when compared with the Kastenlot core (the shaded area in Fig. 9). The transfer function then approaches a 1:1 correlation at around 700–800 cm, as indicated by the dashed line in Fig. 9, but with an offset of more than 100 cm, on the depth scale of core PS2178-3. This is also the interval where the differences in degree of anisotropy of the two different core types approach zero. Fig. 10 shows the comparison of the degree of AMS between piston core PS2178-3 and Kastenlot core PS2178-5 with respect to a common depth scale of master core PS2178-3. Obviously, the anisotropy is lower within the piston core for the upper ∼8 m. Further down-core the anisotropy is similar in both cores. Piston cores tend to elongate the sedimentary column to a certain extent, because of the suction of the piston, but without affecting most of the physical properties (e.g. Nowaczyk *et al.* 2001). Even density values seem to be unaffected by this process (Bergmann 1996). The elongation is obviously accompanied by a proportional thinning of the recovered sediment column, i.e. a constant-volume deformation of the sediments, which was frequently visible during the coring campaign. The remaining volume within the liner was generally filled with water, which had probably penetrated between the liner wall and the piston into the liner volume. Since the sediments are water-saturated, and, because of the incompressibility of water, the sediment cores cannot be simply elongated without a reduction of the diameter. So, each parameter based on a certain volume is not susceptible to this type of constant-volume but shape-affecting deformation. Only directional-dependent parameters such as the anisotropy of susceptibility are influenced by such processes.

Gravity cores, in turn, can suffer from an apparent ‘compression’ of the sediments. In fact, and again because of the incompressibility of water, this is caused by a squeezing out of soft layers between hard layers before they are recovered by the coring gear (e.g. this is visible when subsampling box cores with a tube), so that there is a selective loss of material. Another source of apparent compression are optically visible shear cracks with angles of approximately 45° with respect to the layering. Such cracks result from tri-axial stress. Offsets along these cracks lead to shortening of the gravity core. They start to become visible at around 2–3 m and may reach some centimetres at 10 m core length in gravity cores with a diameter of 12 cm. This effect is significantly reduced in 30 × 30 cm^2 Kastenlot cores and becomes slightly visible only at core depths of 6–7 m,

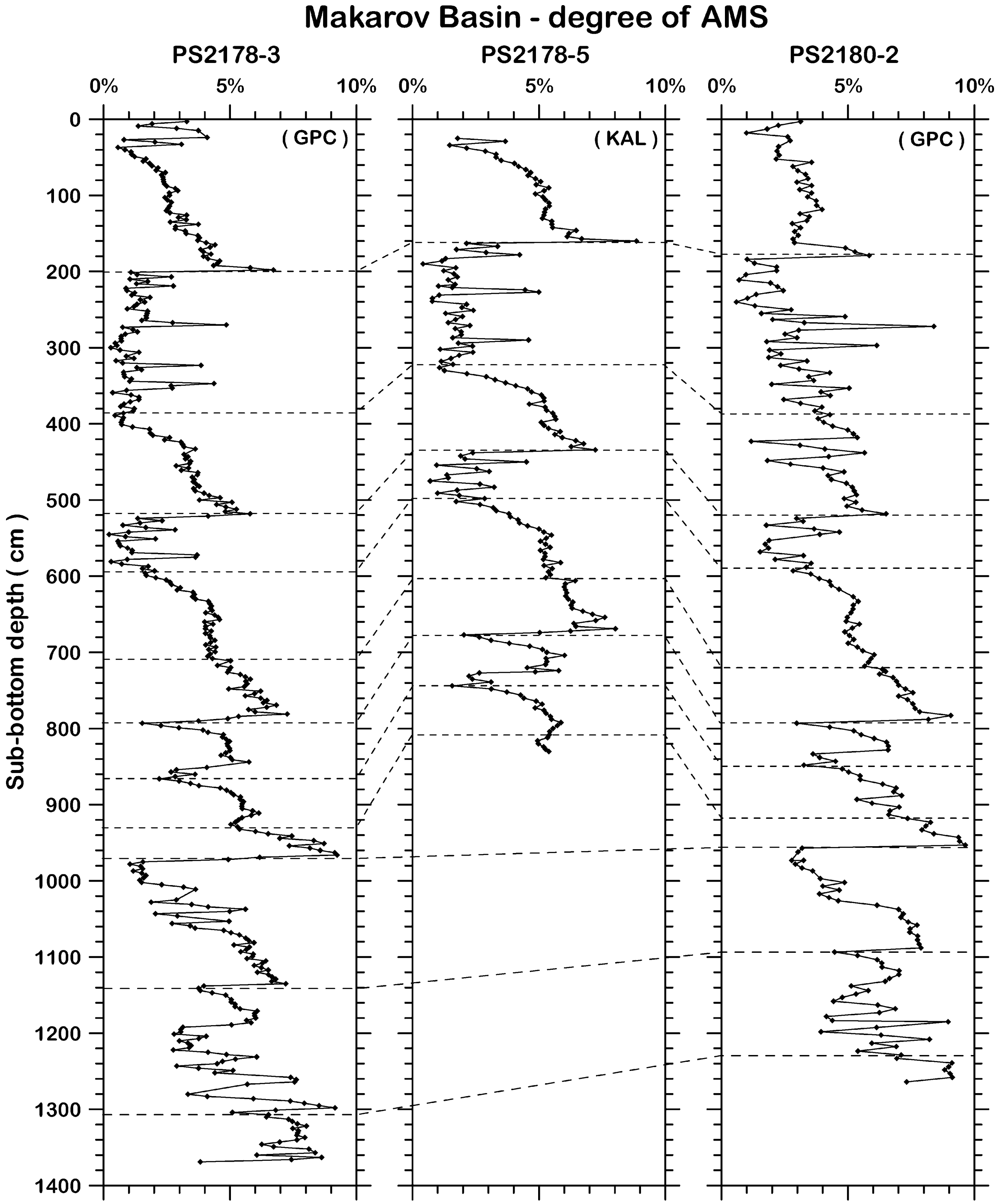

Figure 7. Degree of AMS for the three cores from the Makarov Basin. Dashed lines indicate correlation of the three cores based on the results shown in the figure and on palaeo- and rock magnetic results (Nowaczyk *et al.* 2001). GPC—giant piston corer, KAL—Kastenlot corer.

which is one of the main reasons why these large volume gears are deployed. Core recovery, that is, the difference between penetration and recovered core length, is generally 96–99 per cent in the case of these coring gears. A downward shift of a layer from 6 to 7 m in the piston core when compared with the parallel Kastenlot core, equal to an elongation of approximately 15 per cent, therefore must be mainly explained by a lengthening (and proportional thinning) of the piston core. Results from site PS2178 give just one example of a comparison between a piston core and a Kastenlot core based on AMS data, which should be reproduced at further coring sites in the future.

Comparison between AMS and AARM

Because of the minimum distortion of the sediment fabric within Kastenlot cores, when compared with piston cores, Kastenlot core

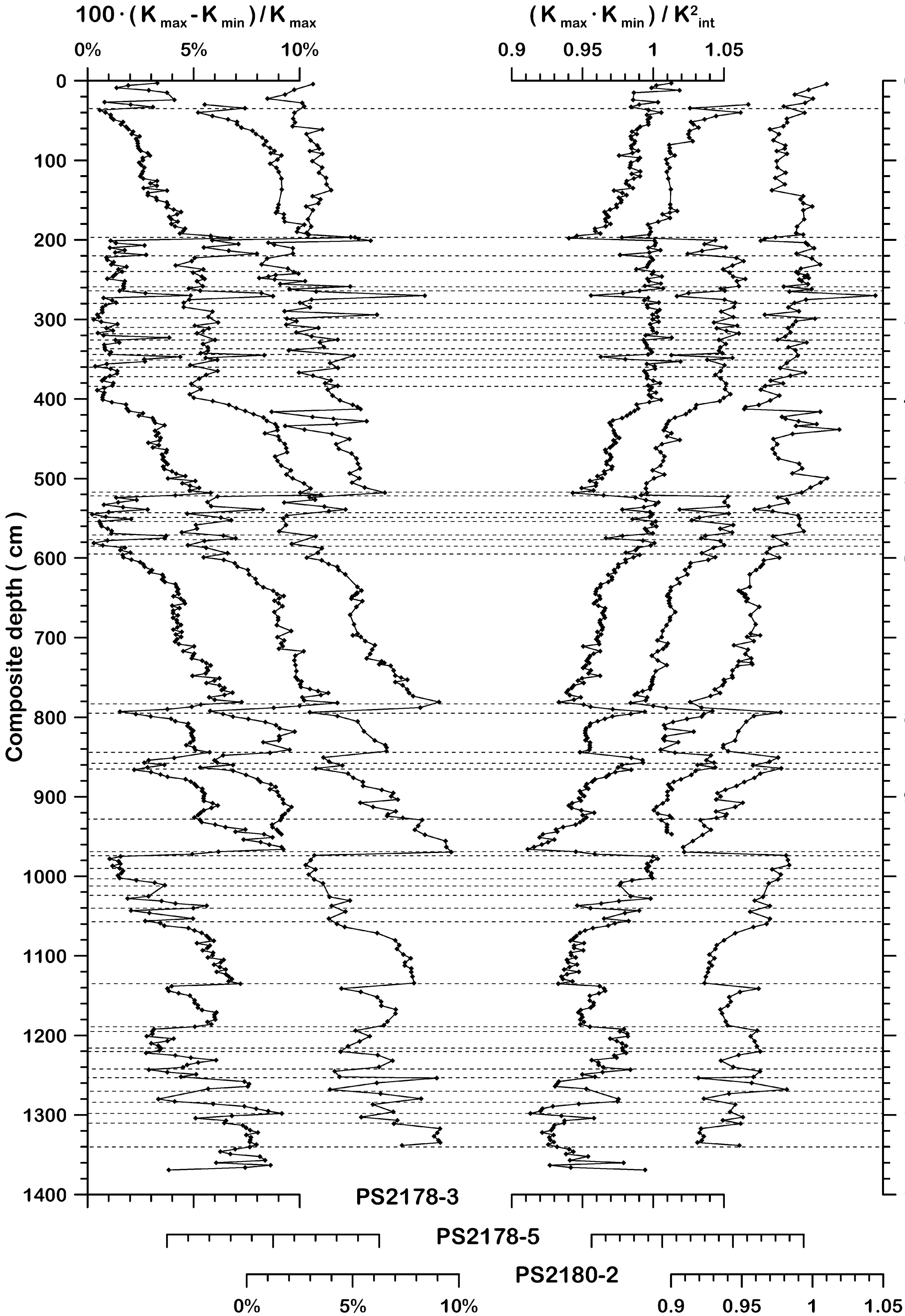

Figure 8. Degree of AMS and shape factor for the three cores from the Makarov Basin after recalculation to composite depth (PS2178-3). Dashed lines here indicate lithological boundaries visible within the cores.

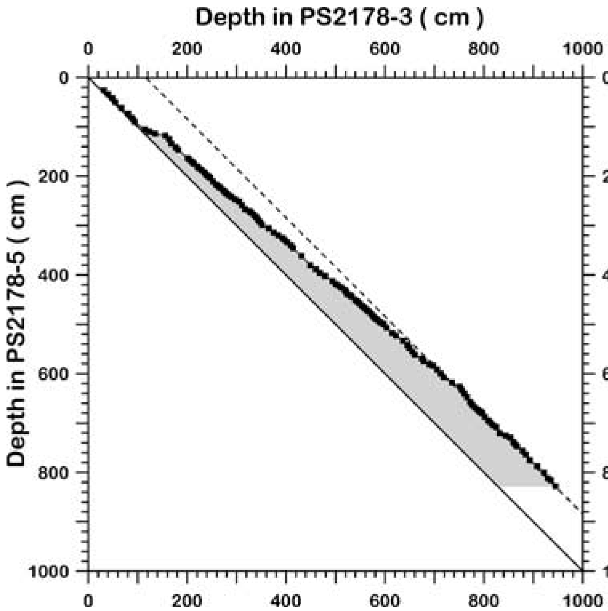

Figure 9. Transfer function of depths between Kastenlot core PS2178-5 and piston core PS2178-3 based on multiparameter correlation between the cores (Nowaczyk *et al.* 2001). The solid line indicate a 1:1 correlation. The shaded area marks the offset of depths of the same horizons within the piston core with respect to the depths in the Kastenlot core. The dashed line indicates an offsetted 1:1 correlation for the lower core sections.

PS2178-5 was chosen for analysis of the anisotropy of remanence in order to investigate the source of the anisotropy of the magnetic susceptibility of Makarov Basin sediments in some more detail. In core PS2178-5, except for samples with a very low AMS degree, nearly all AMS ellipsoids are oriented with their short axis $K_{\min}$ perpendicular to the bedding plane (Figs 3 and 4). Therefore, the estimation of anisotropy of anhysteretic remanent magnetization by just three orthogonally oriented measurements along the coordinate axes of the sample, i.e. two within the bedding plane and one perpendicular to it, appeared to be sufficient. The ratio of ARM$\|x$ to ARM$\|y$ alternates around 1.0 ± 0.05 (Fig. 11), i.e. although the edges of the samples are of different length in the x- and y-directions (15.5 and 20 mm, respectively) the ARM intensities within the horizontal plane, ARM$\|x$ and ARM$\|y$, are not affected by this asymmetry. Also a compaction of the sampled material along the sampling direction (x-axis), as discussed for dry loess sediments by Jordanova *et al.* (1996), obviously did not occur, very probably because the marine sediments are water saturated (incompressibility of water). So, all in all, both anisotropy determinations seem to be not affected by the shape asymmetry of the sample.

The degree of AARM, defined as $100(\mathrm{ARM}_h - \mathrm{ARM} \parallel z)/\mathrm{ARM}_h$ (given in per cent), where ARM_h is the geometric average of ARM$\|x$ and ARM$\|y$, parallels quite well the variations of the degree of AMS. However, surprisingly, the AARM results on core PS2178-5 indicate an even flatter anisotropy ellipsoid for the remanence when compared with AMS (Fig. 11). In other words, the degree of AARM is generally larger, approximately twice as large as the degree of AMS (Fig. 12a), especially in the silty/clayey intervals, whereas it is less within most of the more sandy layers (compare Figs 11 and 5).

In order to estimate the contribution of para- and ferrimagnetic minerals to the overall susceptibility in core PS2178-5 (KAL) two theoretical cases shall be discussed. Taking the degree of anisotropy of remanence of 20 per cent (dashed ellipse in Fig. 12b), and a degree of AMS of 10 per cent (solid ellipse in Fig. 12b), the non-ferrimagnetic (paramagnetic) sediment matrix must be isotropic (dotted circle in Fig. 12b) when both portions contribute 50 per cent to the overall susceptibility. If the paramagnetic matrix is also anisotropic, e.g. with a degree of 5 per cent, and should also be characterized by a flat-lying oblate ellipsoid (dotted ellipse in Fig. 12c), the paramagnetic contribution to the bulk susceptibility is

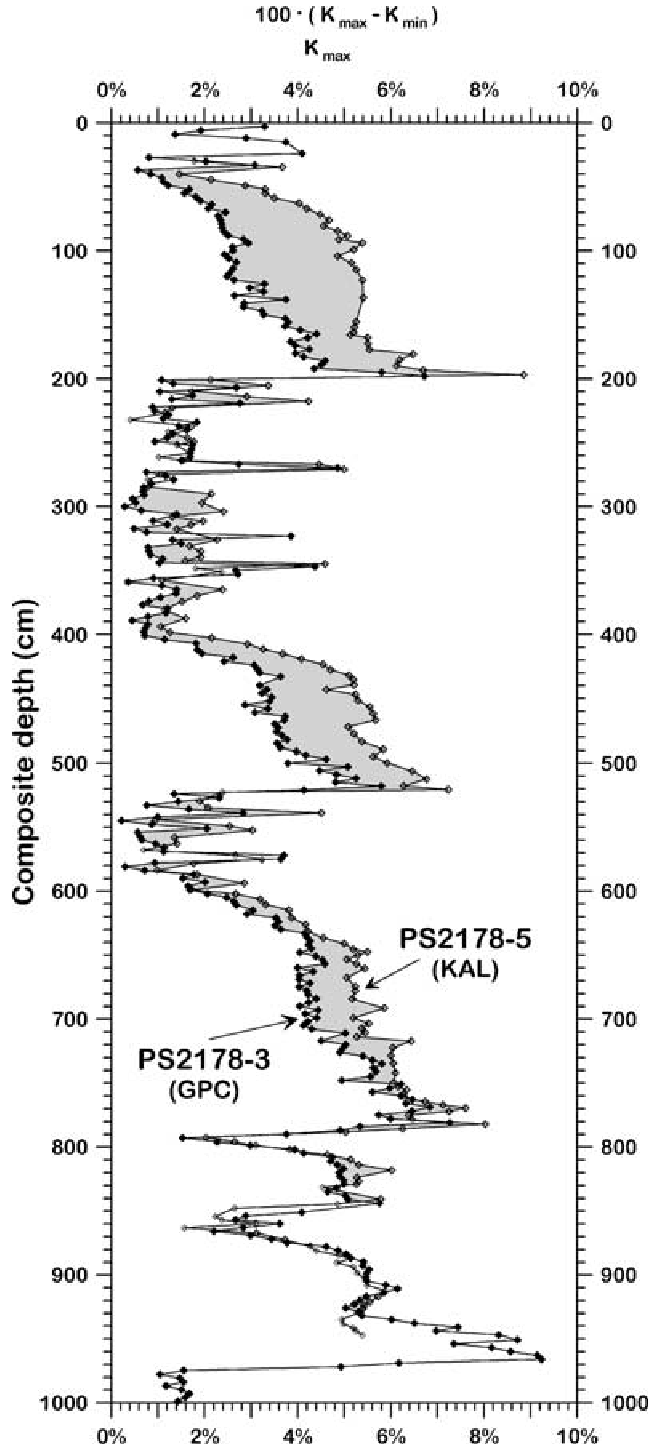

Figure 10. Degree of AMS for the Kastenlot core PS2178-5 and the piston core PS2178-3 with respect to composite depth (PS2178-3). The difference in the AMS degree decrease with increasing depth as visualized by the shaded area between the two curves.

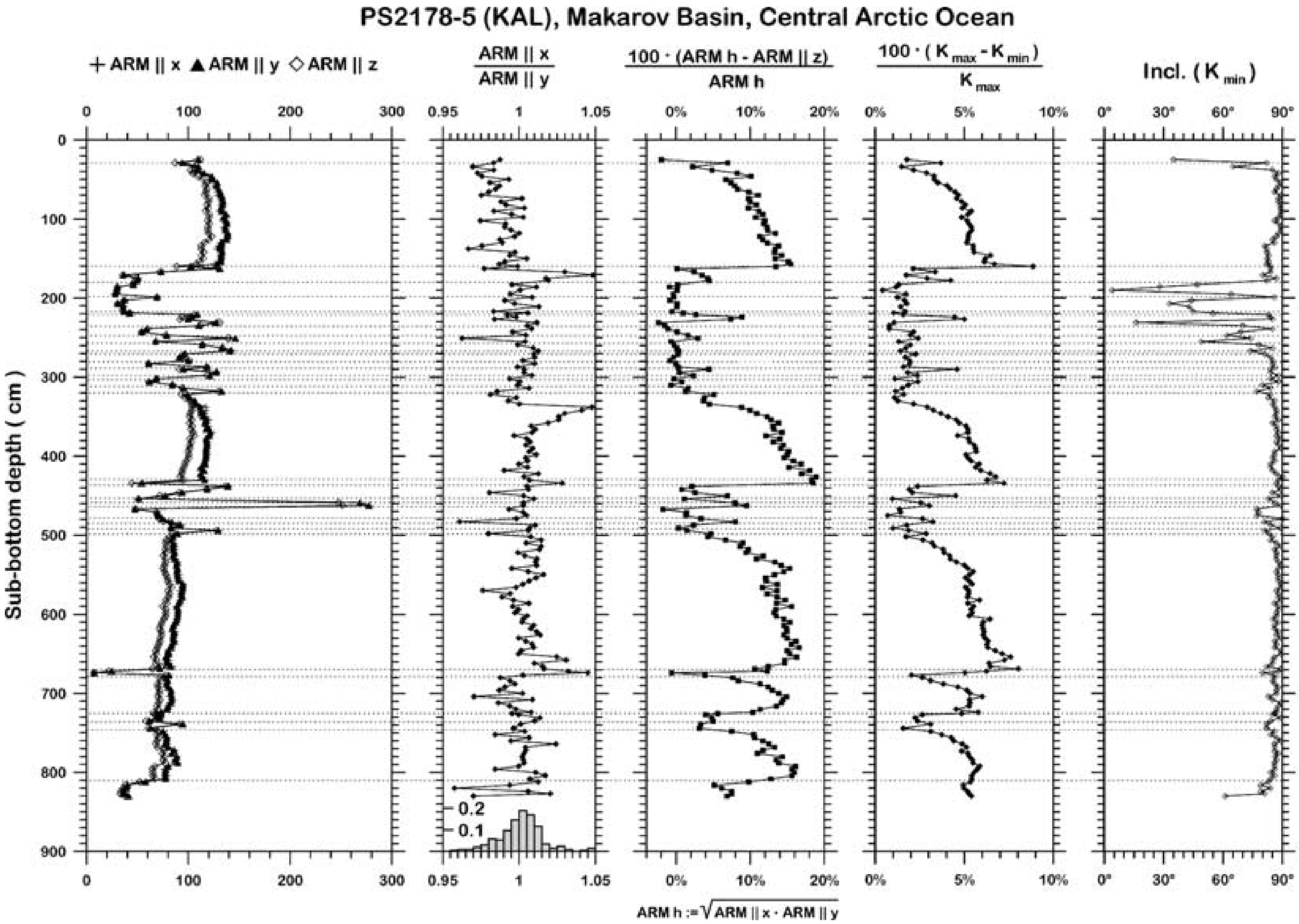

Figure 11. Results from simple experiments of anisotropy of anhysteretic remanent magnetization compared with AMS obtained from Kastenlot core PS2178-5. ARM$\|x$, ARM$\|y$, ARM$\|z$—ARM along the x-, y- and z-axes of the samples, respectively. For further explanation see Fig. 3.

approximately twice as high. Since it is assumed that the general pattern of anisotropy of the magnetic susceptibility is caused by the matrix, i.e. by a different degree of compaction owing to differing sand content, the latter case is more likely for Makarov Basin sediments. However, it must be assumed that if the anisotropy is mainly introduced by a vertical compaction of the sediment, the sediment matrix must contain a large amount of isotropic minerals throughout the whole investigated profile in order to explain the observed differences in the degree of AMS and AARM.

The investigated site is close to the North Pole with the magnetic field lines oriented nearly vertically. If all magnetic particles were oriented parallel to the ambient magnetic field and if they all were needle-shaped with their magnetic moments aligned parallel to the axes of the needles, one should expect a vertically oriented prolate anisotropy ellipsoid of remanence. Obviously, this simple theoretical assumption does not apply to the natural sediments from the high Arctic at all. The mean NRM intensity from Makarov Basin is approximately 0.05 A m^{-1}, whereas the mean ARM intensity is approximately 0.1 A m^{-1}, i.e. approximately 20 times higher. The mean SIRM intensity of approximately 1 A m^{-1} is even approximately 200 times higher than the NRM intensity. This means that just a very small portion of the whole ferrimagnetic fraction really contributes to the palaeomagnetic direction. Thus, information on the magnetic fabric might not necessarily give hints concerning the reliably of palaeomagnetic information, which is carried by just a few per cent of the whole magnetic fraction (ARM/NRM ratio = 20, SIRM/NRM ratio = 200). A degree of remanence anisotropy of 20 per cent in connection with a flat-lying oblate anisotropy ellipsoid instead of a (theoretically expected) upright prolate ellipsoid might imply an inclination shallowing of significantly more than 20 per cent. The dipole inclination at sites PS2178 and PS2180 should be 89°. Taking secular variation into account inclinations should not be shallower than approximately 70°. Instead, there is a quite large portion of directions that are unexpectedly shallow by 0°–45° or so. This cannot be achieved by an inclination shallowing of the estimated range. However, as discussed by Nowaczyk *et al.* (2001), owing to an episodic-type sedimentation, quite a high percentage of intermediate directions have been recorded in the course of the geomagnetic excursions. Moreover, these intermediate directions are associated with low relative palaeointensities. A low-field intensity even decreases the percentage of magnetic particles aligned parallel to the ambient field, which is the basic assumption in the reconstruction of palaeointensities from the detrital magnetism of sediments, so that more scattered directions should be expected.

CONCLUSIONS

High-resolution measurements of the anisotropy of magnetic susceptibility performed on five cores from three different regions showed that nearly all investigated sediments can be characterized by flat-lying oblate AMS ellipsoids with K_{min} more or less

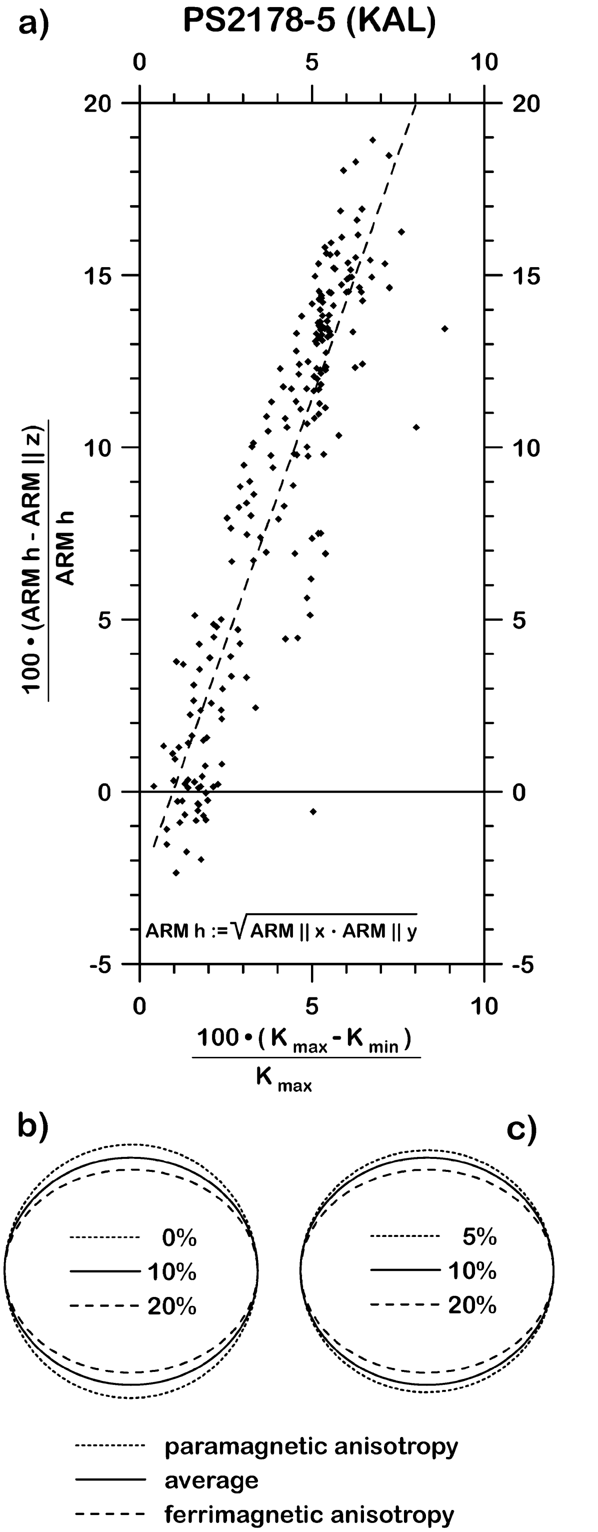

Figure 12. Degree of anisotropy of ARM versus the degree of anisotropy of the magnetic susceptibility in core PS2178-5 (KAL) from the Makarov Basin (a). The degree of remanence is roughly twice as high as the degree of susceptibility. If the approximately 10 per cent degree of AMS (solid ellipses) is produced to 50 per cent by the ferrimagnetic contribution with a degree of anisotropy of 20 per cent as derived from AARM (dashed ellipses) the paramagnetic matrix (dotted circle in b) should be isotropic. If the paramagnetic matrix is characterized by a degree of AMS of 5 per cent (dotted ellipse in c) its contribution to AMS should be twice as high (paramagnetic:ferrimagnetic = 2:1) (see the text).

perpendicular to the bedding plane. Only low AMS degree sediments, in the case of Makarov Basin deposits, characterized by a high sand content of some 20–30 per cent, exhibit arbitrary orientations. This could be explained by a lack of preferred orientation of the large, possibly even rounded sand particles. For reversed ChRM inclination intervals present in all five cores it could be shown that they are sited within intervals characterized by an undisturbed magnetic fabric and by quite homogenous rock magnetic properties. Therefore, they can be interpreted as records of geomagnetic excursions.

Determination of AMS supported by additional simple AARM experiments on one core showed that the asymmetric shape of the sampling boxes do not affect the results. The degree of AARM is roughly twice as high as the degree of AMS, which apparently contradicts a preferred vertical orientation for the carriers of the palaeomagnetic information, i.e. a vertical magnetization direction according to the location close to the North Pole. However, it can be shown that this information is carried by just a few per cent of all magnetic particles.

Concerning coring techniques, the determination of AMS could be a helpful tool in order to analyse the commonly observed stretching effect introduced by the piston coring technique on sedimentary sequences more precisely. All in all the obtained results could show that the analysis of the magnetic fabric can give valuable information concerning sediment cores investigated for magnetostratigraphy in terms of their palaeomagnetic reliability. Analysis of anisotropy data can also provide some tests of common assumptions concerning remanence acquisition in detrital sediments.

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