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Detection and correction of inclination shallowing in deep sea sediments using the anisotropy of anhysteretic remanence

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Key words. – Inclination error, Anisotropy, Susceptibility, Anhysteretic remanent magnetization, Preferred orientation.

Abstract. – Paleomagnetic data from recent Pleistocene to recent deep sea sediments from the continental rise of eastern North America exhibit a cyclical inclination shallowing, up to 30° with respect to the geocentric axial dipole value. This shallowing is strongly correlated with a ratio of anhysteretic remanent magnetization (ARM) anisotropy determined from a four position ARM anisotropy method. It is therefore proving that inclination variations in these cores are not due to paleosecular variation but in part to a bias in the remanence recording processes linked to depositional anisotropy. This study suggests that ARM anisotropy could provide a method to identify and correct for inclination shallowing in natural sediments.

Détection et correction des erreurs d'inclinaison dans des sédiments océaniques profonds par l'anisotropie de susceptibilité anhystérétique

Mots clés. – Erreur d'inclinaison, Anisotropie, Susceptibilité, Aimantation rémanente anhystérétique, Orientation préférentielle.

Résumé. – Des données paléomagnétiques provenant de sédiments océaniques profonds, d'âge pléistocène récent à actuel, et prélevés à la base du talus continental Nord Atlantique, ont montrés une erreur d'inclinaison cyclique jusqu'à 30° par rapport à la valeur du dipole axial géocentrique. Cette erreur d'inclinaison est fortement corrélée avec le degré d'anisotropie de l'aimantation rémanente anhystérétique (ARA), déterminée à partir d'une méthode utilisant quatre positions de mesure d'ARA. Cette corrélation prouve que les variations de l'inclinaison dans ces carottes ne sont pas dues aux paléovariations séculaires mais au moins en partie à un biais introduit lors du processus d'enregistrement de la rémanence et lié à l'anisotropie de dépôt. Cette étude suggère que l'anisotropie d'ARA pourrait constituer une méthode pour identifier et corriger les erreurs d'inclinaison dans les sédiments.

I. – INTRODUCTION

Unconsolidated recent sediments have been shown to be accurate and stable recorders of paleomagnetic field directions. Lacustrine and marine sediments are therefore widely used for magnetostratigraphic, paleomagnetic secular variation (PSV) and reversal studies. However, some sediments exhibit a natural remanence inclination (I_{NRM}) systematically shallower than the geomagnetic field inclination (I_f) at their locations [e.g. Blow and Hamilton, 1978; Morgan, 1979]. This inclination shallowing, ($\Delta I = I_f - I_{NRM}$), is related to the preferred orientation of the axes of the remanence carrying magnetic grains within the horizontal plane.

Inclination shallowing and preferred orientation are both caused by gravitational torques and compaction effects, which tend to overcome the magnetic torques that would alone produce an overall magnetization parallel to the ambient field.

This preferred orientation, also exemplified by the usual occurrence of magnetic anisotropy in those sediments, has been attributed either to depositional effects, mainly controlled by grain size and shape [King, 1955; Verosub, 1977], or to postdepositional compaction (e.g. Anson and Kodama, 1987; Celaya and Clement, 1988; Deamer and Kodama, 1990; Arason and Levi, 1990a].

In fine-grained, slowly deposited and often bioturbated deep-sea sediments, depositional effects are usually not preserved, leading to a post-depositional remanence [Kent, 1973] with no inclination error when the sediment is not compacted. The lack of preferred orientation in such sediments results in very weak anisotropy [Schneider and Rochette, 1990]. Subsequent compaction, significant for burial on the order of 10 to 100 m, can induce inclination shallowing up to 10-20° [e.g. Celaya and Clement, 1988]. On the other hand, sediments from continental margins or lacustrine environments, either laminated or containing a dominant coarse fraction usually carry a large anisotropy and a detrital remanence that can yield a strong inclination error. For example Tauxe and Kent [1984] observed a substantial inclination error in both river-laid ($\Delta I = 25°$) and experimentally deposited sediments which varies as : $\tan(I_0) = f^* \tan(I_f)$. Khan *et al.* [1988], report ΔI of the order of 20° in Siwalik Quaternary sandstones, while we observed a $\Delta I = 30°$ in a

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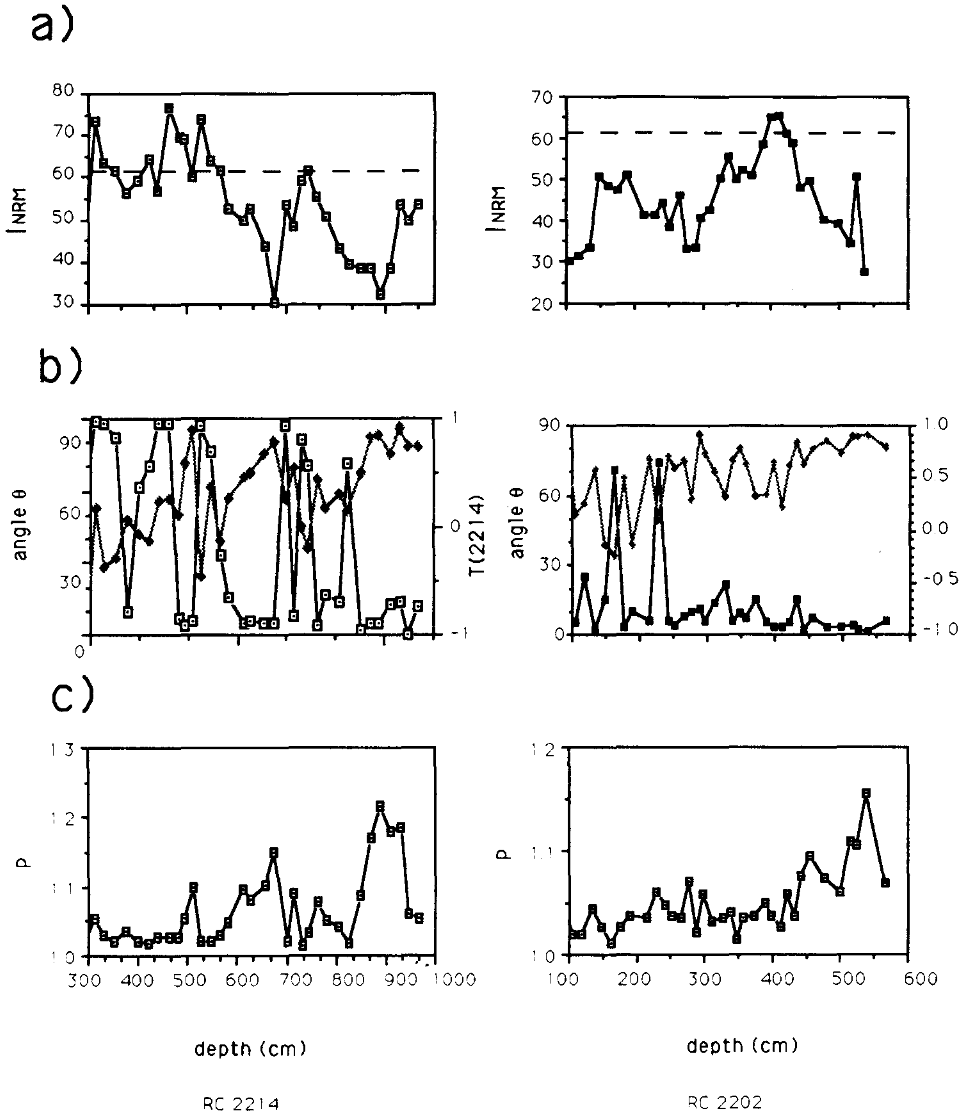

FIG. 1. – Paleomagnetic data and magnetic parameters versus depth in cores RC22-14 and 22-02; (a) inclination of NRM after cleaning in a tumbling AF of 30 mT, compared to GAD inclination; (b) angle θ between minimum AMS axis and sample vertical axis; (c) low field anisotropy of magnetic susceptibility ratio P (K_1/K_3).

FIG. 1. – *Données paléomagnétiques et paramètres magnétiques en fonction de la profondeur dans les carottes RC22-14 et RC22-02 ;* (a) *inclinaison de l'ARN après désaimantation par champ alternatif de 30 mT, comparée à l'inclinaison du dipole axial géocentrique;* (b) *angle θ entre l'axe d'ASM minimum et la verticale des échantillons ;* (c) *degré d'anisotropie de susceptibilité en champ faible P (K_1/K_3).*

flood deposit from February 1990 in the Isère valley (France) [Collombat, 1990].

Considering such high values, it appears that the reliability of paleomagnetic applications of inclination data from sediments, including paleosecular variation and paleolatitude studies, requires a technique to detect and moreover quantify the inclination shallowing independently from estimated paleofield inclination. The most reliable method would be to establish a correlation between anisotropy degree and ΔI, as successfully done by Jackson *et al.* [1991] for artificial sediments deposited in the laboratory. They found a good agreement between their data and the relation

$$\tan(I_f) = P^*\tan(I_{NRM}) \qquad \{1\}$$

where P is the ratio between maximum and minimum principal axes of the magnetic ellipsoid, i.e. horizontal and vertical values. The purpose of this letter is to investigate this correlation for natural sediments.

Magnetic anisotropy is most commonly evaluated using low field susceptibility (AMS). However, this technique, although characterized by a high rapidity and precision, has two disadvantages for the purpose of comparison with the NRM: low field susceptibility is influenced (1) more by larger multidomain than single domain or pseudo-single domain grains, in contrast to NRM, and (2) by the matrix minerals, mainly paramagnetic clays for sediments [Rochette, 1987]. It is therefore preferable to measure the anisotropy of the NRM carrying particles. This is possible by using the anisotropy of anhysteretic remanence (AAR) [McCabe *et al.*, 1985; Jackson *et al.*, 1991].

II. – SAMPLING AND DATA ANALYSIS

Samples from two piston cores (RC 2214 and RC 2202) from the Nova Scotia continental rise (depth : 4210-4925 m; 41°N, 61°W) were selected for this study, as the original investigation by Shor *et al.* [1984] showed a strong anisotropy and variable inclinations between 30° and 70° compared to the expected 61° geocentric axial dipole (GAD) inclination (fig. 1a). The sediments are laminated red-brown lutite of Pleistocene age within Brunhes epoch. Unfortunatly no better age constrain is available but the large detrital input favours the hypothesis that the whole sequence was deposited in the last climatic cycle. Silicate grain size varies from clay to sand size with a magnetic mineralogy dominated by magnetite. Detailed lithologic and magnetic properties of both cores are summarized in Shor *et al.* [1984].

Because the sites are located at middle latitudes (40° to 42°) they are most sensitive to inclination shallowing. Moreover, the recent age of the sediments excludes the hypothesis of a tectonic drift to explain the low inclination values, while a paleosecular variation signal should show smaller excursions (about ± 6-8°) with a symmetric oscillations around the dipole value. Therefore, the piston cores RC 2202 and RC 2214 provide suitable material for studying the association of anisotropy and inclination shallowing.

The cores were re-sampled for the present study with a mean interval of 20 cm. Progressive demagnetization of pilot samples up to 100 mT shows that 30 mT is sufficient to remove the viscous component resulting from a ten year storage in the repository field, and that no high coercivity components are present. The 68 samples were demagnetized in an alternating field of 30 mT and measured with a Molspin spinner to define the characteristic remanent magnetization. NRM intensity is of the order of 10 mA/m, well above the sensitivity of the spinner (0.05 mA/n). The AMS of all samples was determined using a high sensitivity bridge : KLY-2 manufactured by Geofizika, Brno. Useful parameters derived from the principal axis of the susceptibility ellipsoid $K_1 \geq K_2 \geq K_3$, are $P = K_1/K_3$, $F = K_2/K_3$, the angle θ between core axis and K_3 and the parameter T characterizing the shape of the susceptibility ellipsoid [Jelinek, 1981] which varies between + 1 for an oblate shape and – 1 for a prolate shape. The corresponding anhysteretic anisotropy parameters, defined by the ratio of the principal ARM magnitude are $Pa = ARM_1/ARM_3$ and $Fa = ARM_2/ARM_3$.

For both cores AMS and NRM data versus depth are in complete agreement with the original data from Shor *et al.* [1984].

The ARM was acquired in an alternating field of 90 mT in the presence of a 1 mT steady field. Measurements were made after a 5 minute delay, to reduce the impact of any short-period viscosity. ARM were given and measured in four directions : up, down and along the two perpendicular horizontal edges of our cubic samples. We define the ARM anisotropy ratio (Ha) as the ratio of mean ARM induced in the horizontal plane to mean ARM induced in the vertical direction. The measurement procedure enabled us to estimate the repeatability of the measurements in the vertical direction and to average the anisotropy within the bedding plane. This anisotropy due to paleocurrents [Shor *et al.*, 1984], is indeed quite important as shown by an averaged relative difference of 1.2 % between the two horizontal measurements. The measurement noise, determined by an average relative difference of 0.5 % between the two horizontal measurements, allows us to define a noise level of ± 0.01 for Ha ($\Delta Ha/Ha \approx 2\ \Delta ARMv/ARMv$).

The expression of our ratio is :

$$H_a = \frac{ARM_{NS} + ARM_{EW}}{2\ ARM_V}$$

How does this parameter compare to the more usual Pa and Fa parameters derived from the principal axes of the ARM ellipsoid?

If we assume that the vertical axis corresponds to the minimum axis of magnetic anisotropy ($ARM_3 = ARM_V$) and that $ARM_{NS} + ARM_{EW}$ is a good estimate of $ARM_1 + ARM_2$ (see appendix for justification of these approximations), the expression of our ratio as a function of the principal anisotropy parameters becomes :

$$H_a \approx \frac{ARM_1 + ARM_2}{2\ ARM_3} = \frac{P_a + F_a}{2}$$

This procedure involving 4 measurements, is much less time-consuming than the complete ellipsoid determination which requires 9 or 15 measurements depending on the procedure used. For the purpose of correlating AAR and inclination error in samples with triaxial symmetry ($Pa \neq Fa$) the use of Pa parameter in equation {1} is correct if the field has the same declination as ARM_1 but Pa must be replaced by Fa if the field azimuth is parallel to ARM_2. Therefore in the general case one should use the average of Pa and Fa.

Our Ha parameter is only appropriate if the assumption of planar horizontal fabric is reasonably fulfilled (θ close to 0 and T close to 1). This can be tested using the AMS results, assuming that AMS and AAR ellipsoids are coaxial. In order to verify this assumption, the full AAR ellipsoid was determined using a cryogenic magnetometer in the Institute of Rock Magnetism of Minneapolis for 10 selected samples covering the whole range of P and θ values (stereoplots of fig. 2a).

These results show that AMS and AAR directions are very similar, with practically coincident individual directions. This is particularly visible (fig. 2a) for the four samples exhibiting θ > 10°. The good agreement between Ha (4 measurements sheme) and (Pa + Fa)/2 from these 10 samples appears excellent (fig. 2b).

The equivalence between AMS and AAR ellipsoids, directly checked on the selected samples can also be appreciated on the whole dataset by comparing Ha and P (fig. 3) : a very good linear correlation is observed with a slope of 2 and a regression coefficient of 0.97. In fact this is in agreement with the relationship $P_{TRM} = P^2$, predicted and experimentally verified for TRM anisotropy by Cogné [1987].

So it appears justified to use AMS to select samples with planar horizontal fabric. In such samples Ha is a valid approximation of the anisotropy degree that could control inclination shallowing. In order to take into account θ values

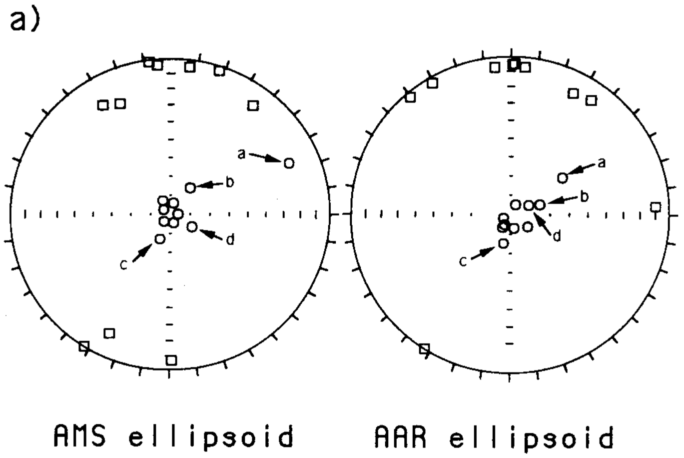

FIG. 2a. – Directions of the principal axes for anisotropy of anhysteretic susceptibility (AAS) ellipsoïd compared to that of anisotropy of magnetic susceptibility (AMS). K_1 are shown by empty squares and K_3 by empty circles. a, b, c, d are showing respectively sample 422, 780, 930 and 968 from core RC2214.

FIG. 2a. – *Comparaison des directions des axes de susceptibilité principaux pour l'ellipsoïde d'ASA et celui d'ASM. Les carrés vides représentent l'axe K_1 et les cercles vides les axes K_3. a, b, c, d désignent respectivement les échantillons 422, 780, 930 et 968 de la carotte RC2214.*

different from 0 due to sampling uncertainties we have designed a corrected parameter H'a. Assuming that the anhysteretic and low field susceptibility fabrics are coaxial, it is indeed possible to correct Ha for the difference between the sample and geographic reference frames, corresponding to the θ angle. The expression of corrected H'a value as a function of Ha and θ is given in the appendix. Paleomagnetic inclination can also be "bedding corrected" using the AMS magnetic foliation.

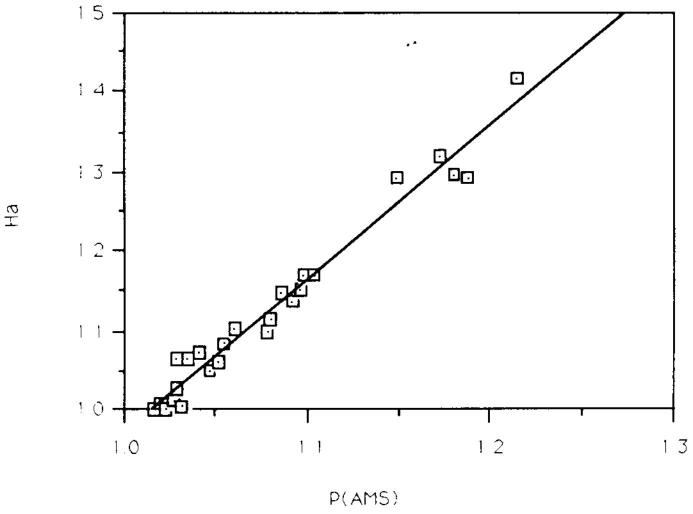

FIG. 3. – Relation between the ARM anisotropy ratio Ha and the AMS ratio P.

FIG. 3. – *Relation entre le degré d'anisotropie de susceptibilité anhystérétique Ha et le degré d'ASM. P.*

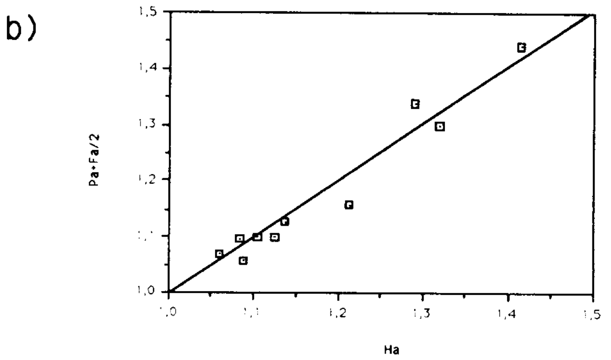

FIG. 2b. – Correlation between the ratio Ha and the corresponding ratio Pa + Fa/2 using the anisotropy parameters as determined by full ellipsoid determination.

FIG. 2b. – *Corrélation entre le taux d'anisotropie Ha et le taux correspondant* Pa + Fa/2 *lorsqu'on utilise les paramètres d'anisotropie résultant de la détermination du tenseur total d'anisotropie.*

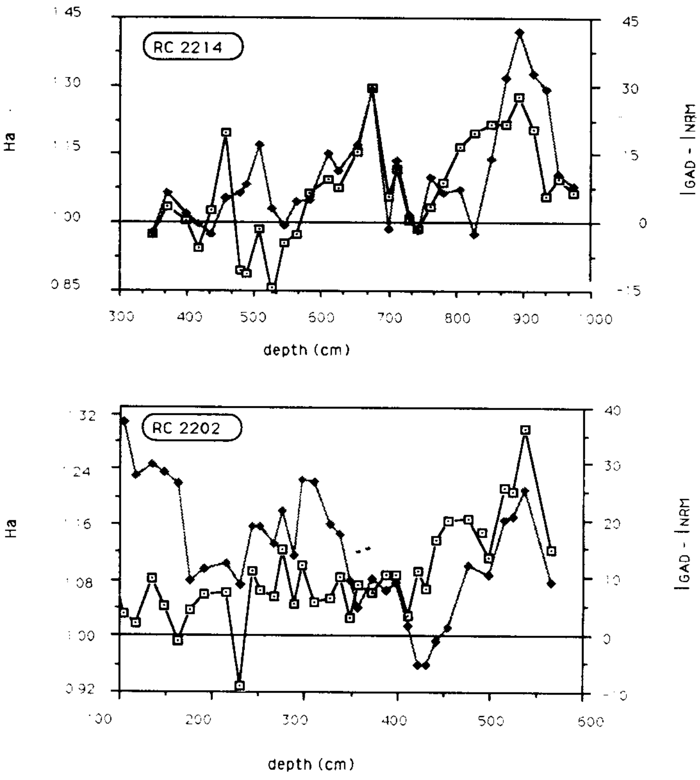

FIG. 4. – Correlation between ARM anisotropy ratio Ha and reduced inclination of NRM demagnetized in 30 mT.
— Ha (diamonds, shaded line) and I_{GAD}-I_{NRM} (squares, solid line) for core RC2214.
— Ha (squares, solid line) and I_{GAD}-I_{NRM} (diamonds, shaded line) for core RC2202.

FIG. 4. – *Corrélation entre le degré d'anisotropie d'ARA Ha et l'anomalie d'inclinaison de l'ARN démagnétisée à 30 mT.*
— Ha (losanges, traits grisés) et I_{GAD}-I_{NRM} (carrés, traits pleins) pour RC2214.
— Ha (carrés, traits pleins) et I_{GAD}-I_{NRM} (losanges, traits grisés) pour RC2202.

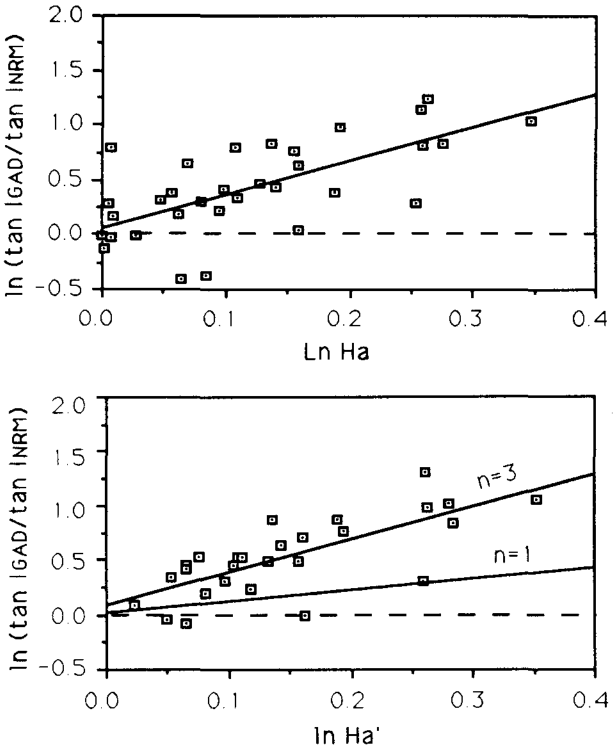

FIG. 5. – Plot of ln(tan(I_{GAD})/tan(I_{NRM})) versus ln(Ha) for samples of RC2214 and 2202 below 5 m; (a) all samples with uncorrected data; (b) I_{NRM} and Ha data corrected from angle θ with rejection of samples with $\theta > 20$.

FIG. 5. – *Relation entre ln(tan(I_{DAG})/tan(I_{ARN})) et ln(Ha) pour les échantillons de RC2214 et RC2202 en-dessous de 5 m ;* (a) *données non corrigées pour la totalité des échantillons ;* (b) *données de I_{ARN} et Ha corrigées d'après l'angle θ après rejet des échantillons dont $\theta > 20$.*

III. – CORRELATION BETWEEN ANISOTROPY AND INCLINATION

On a plot of Ha and reduced inclination (i.e. the difference between GAD inclination and characteristic inclination I_{NRM}) versus depth (fig. 4), these parameters appear very strongly correlated in the two cores for samples below 5 m depth, except for 3 samples between 8 and 9 m in core 2214. As expected reduced inclinations near zero correspond to nearly isotropic samples (Ha = 1). Such a correlation suggests that paleosecular variation is not the main cause of our inclination variation and argues for the alternative explanation of inclination shallowing : $I_{NRM} - I_{GAD} \approx \Delta I$. For the samples above 5 m depth, the correlation is not so distinct but this is likely due to disorganization within the soft sediment related to the coring [Shor *et al.*, 1984].

The ferm of the relation between If, I_{NRM} and anisotropy should be similar to equation {1}. In order to propose a relation to correct ΔI, we have ploted ln (Tan I_{GAD}/Tan I_{NRM}) versus ln (Ha). Samples below 5 m of both cores show a reasonable linear correlation (fig. 5a), with a regression coefficient of 0.534. However, the slope of the correlation line, corresponding to a n coefficient, power of Ha, in equation {1} is 3.05 instead of the expected value of unity following Jackson *et al.* [1991].

AMS results (fig. 1c) also show a surprisingly good correlation between P ratio and reduced inclination below 5 m, proving once more that both AMS and AAR techniques measure qualitatively the same fabric. Logarithmic correlation with inclination on the same set of data yield a coefficient of 0.548 and a slope of 5.7. However high field susceptibility measurements on two samples from our RC cores show that the contribution of paramagnetic matrix minerals to the low field susceptibility [Rochette, 1987] is of the order of 20 %. Therefore the relationship established in these cores between P ratio and inclination shallowing would be strongly dependent on lithology and not directly applicable to other sediments.

The θ angle is usually close to zero with shape parameter in the oblate field (T > 0) as expected for an undisturbed sedimentary fabric (fig. 1b). Rejection of samples with θ > 20° can be considered to improve the dataset. In fact many of the rejected samples are from above 5 m, especially for 2214, and correlate with T values in the prolate field, thus confirming the suggested physical disturbance of the top of the cores. θ values near 90 correlate with Ha values near or below 1. In such cases Ha values are meaningless because they are estimated assuming that θ = 0. The fact that both ARM and AMS fabrics appear to have a maximum along the vertical, rules out an explanation of the high value of θ involving reverse fabric due to single domain magnetite [Rochette, 1988]. In such a case the ARM should show a minimum along the vertical.

For the remaining 32 samples corrected Ha' and inclination values can be obtained. Such a correction does not improve the grouping of NRM directions as a whole : using the method of McFadden and Reid [1982] the confidence angle for the 32 selected samples increases from 5.7° to 5.9° after correction; however the correlation between inclination and anisotropy ratio is improved after the correction and rejection of samples with large θ values and one sample with anomalously high inclination ($I_{NRM} = 80°$) (fig. 4b). The correlation coefficient became 0.632 but the slope (3.0) is not significantly modified.

IV. – DISCUSSION

Measurements of the ARM anisotropy of the RC deep sea sedimentary cores demonstrate the existence of an anisotropy-induced inclination shallowing. A less biassed image of the geomagnetic field is obtained using the relation : $\tan(I_f) = Ha^n * \tan(I_{NRM})$ with $n \approx 3$, assuming that, on the average, the field would be equal to the GAD model or at least, that I_{NRM} should be statistically independent of Ha.

In our study, the origin of the inclination shallowing and of its variability are important to assess. For a further development of a general method to identify and quantitatively correct inclination shallowing, the validity of such a law in other cases is critical. Let us first consider the sedimentological context. Our sediments below 5 m are laminated reddish-brown silty-clays with a low carbonate content (between 10 and 15 %) and a variable silt content (up to 40 %).

Our results are more likely explained by depositional effects than by compaction, for the following reasons :

— according to the various compaction models of Arason and Levi [1990b] a ΔI = 30° corresponds to a volume change of at least 0.5, a value quite unrealistic for a depth of a few meters in such sediments. The same authors report a $\Delta I = 5°$ and volume change of 0.1 in DSDP clays from similar latitude at a depth of 100 m;

— compaction induced inclination shallowing in a homogeneous lithology such as in the RC cores should produce gently increasing downcore ΔI curves instead of cyclic curves. However the general trend superposed on the cycles, particularly visible on RC2202, may be related to compaction;

— the silt laminations observed in the wet sediment, the large anisotropy ratio measured, together with the presence of paleocurrent lineations all suggest that a strong depositional fabric is present in the sediment. A ΔI value of 30° can be easily produced by deposition [e.g. Collombat, 1990]. Also, experiments have shown that ΔI can be sensitive to relative clay concentration [Lu *et al.*, 1990].

Two models can be proposed for the origin of ΔI and Ha variations :

1) the original fabric is homogeneous along cores but has been reset by bioturbation in some part of the cores. Indeed bioturbation tends to randomize the fabric producing P values near 1 and resetting the DRM to a pDRM strictly parallel to the field, as observed in other deep sea sediments. The observed variability could be due to variable depositional rate, productivity of the plankton, bottom water oxygenation, etc.;

2) the original fabric is actually cyclic. Such cyclicity may be related to the interpretation of Shor *et al.* [1984] in terms of mixed turbidites and contourite facies, the latter being less anisotropic. It may also arise as a consequence of climatically controlled variations in magnetic grain size and matrix composition.

Arguments for the second explanation may be found in RC2214 where the silt content curve [fig. 4 of Shor *et al.*, 1984] shows distinct maxima that match reasonably the maxima on Ha below 5 m. Correlation between azimuth of current flow lineation and Ha values may also be expected. However lineations are essentially along slope (contourite) in RC2202 and downslope (turbidite) in RC2214. The only two samples in RC2214 showing contourite affinity have Ha values near 1, in agreement with the results of Shor *et al.* [1984] revealing stronger fabric for turbiditic levels.

Quantitative measurement of lamination intensity can provide important confirmation on inference based on magnetic fabric. However wet sediment pictures only allow qualitative observation. Therefore in order to visualize and quantify the structure and the organization within the sediment, we made X-ray scanner sections of our samples in collaboration with the laboratoire de Mécanique et Acoustique, CNRS Marseille, using a technique described by Reynaud *et al.* [1989]. The images reflect very accurately radiologic density contrasts, controlled by mineralogy or porosity, on a vertical section of 3 mm width (fig. 6). Most of the samples show an horizontal stratification. However, some samples reveal strongly disorganized structures, particularly in RC2214 above 5 m where the silt fraction is zero.

As indicated on the four scanner images, the inclination error and the Ha ratio are correlated with the degree of organization within the sediment. The sample with stronger anisotropy show well defined continuous laminae. When Ha decreases these laminae become more and more disrupted. This progressive disruption would favor model 1 involving bioturbation. This correlation is yet only qualitative but it provides a further support for a direct link between inclination shallowing and the sediment structure.

V. – A GENERAL METHOD FOR INCLINATION CORRECTION?

To see whether the ARM anisotropy method is applicable to other cases of inclination shallowing, the lacustrine interglacial Riss-Würm deposit near Grenoble («argiles d'Eybens») were investigated. The sedimentology and paleomagnetism of these varved gray silty clays have been studied in an 80 m long core [Montjuvent and Uselle, 1973; Biquand, 1982]. Preliminary results on new samples show a strong anisotropy, with Ha ratio quite constant around 1.6, i.e. larger than the maximum value in RC core, while the averaged inclination of the whole section is not significantly different from the GAD values. On the other hand, our flood deposit with $\Delta I = 30°$ yields Ha ≈ 1.37. Maximum values observed in RC2214 are quite compatible. These examples suggest that the relation derived from RC cores data is not universally applicable to other sections.

Theoretical considerations may lead to the same pessimistic view. In fact the proposed relation between Ha, I_{NRM} and I_f reflects the relative efficiency of preferred orientation in the acquisition of a magnetic anisotropy and of a deviation of NRM. This is likely to depend on the intrinsic properties of the grains, mainly their size and shape. One can hope that a normalization of Ha by the total anisotropy available in the sample (i.e. the one observed for perfect orientation) would help to overcome that problem. Experiments on orientation in high field of the resuspended sediment will be needed.

On the other hand the processes that orient the grains in natural condition should determine the quantitative relationship we are looking for. Different laws may be expected for compaction and deposition effects, while relative grain size and matrix mechanical behavior are also probably key parameters. One can therefore conclude that development of theoretical models as well as numerous studies where inclination shallowing can be estimated and correlated with Ha are necessary before being able to quantitatively correct paleoinclinations in ancient sedimentary rocks.

For the moment our results on the RC cores strongly suggest that paleoinclination variations should not be equated to paleosecular variation without testing for a relationship between I variation and anisotropy intensity, most preferably measured using the AAR technique. Any statistical correlation between Ha and I_{NRM} should be a warning that there are significant inclination errors. These can be corrected by making I independent of Ha, by whatever law is necessary.

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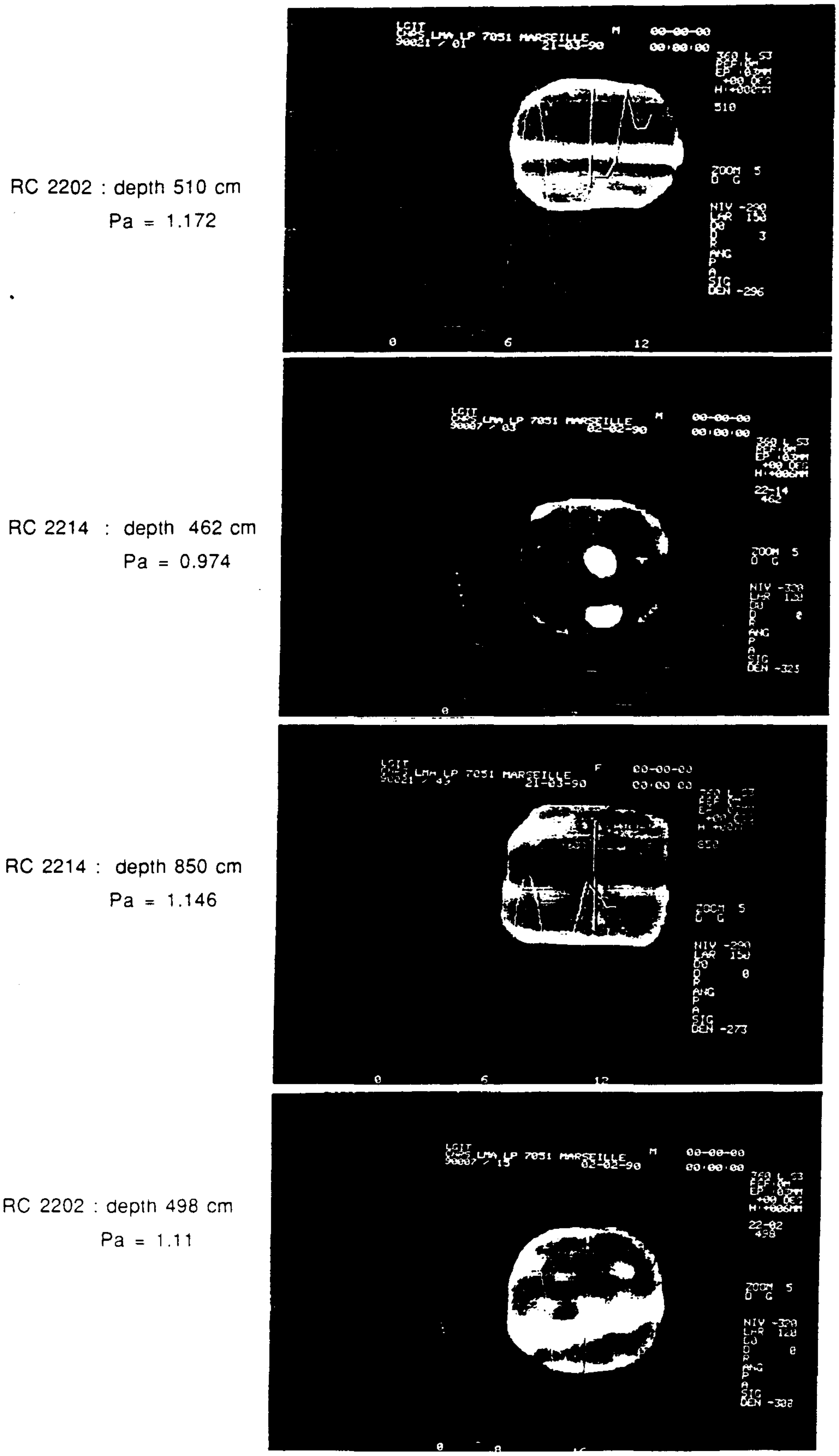

FIG. 6. – X-ray scanner sections of paleomagnetic samples perpendicular to the horizontal bedding plane. 4 cubic samples of 20 mm were selected in RC2214 and RC2202 and round shaped to avoid focusing of the X ray beam. Depth and anisotropy ratio Ha of each sample is indicated.

FIG. 6. – *Coupe scanner des échantillons paléomagnétiques perpendiculairement au plan de stratification horizontal. 4 échantillons cubiques de 20 mm ont été sélectionnés puis arrondis afin d'éviter les effets de diffractions des rayons X. La profondeur et le degré d'anisotropie Ha de chaque échantillon est indiqué.*

APPENDIX

The mean value of ARM induced along the two perpendicular directions of the horizontal plane was taken to be the average of the ARM induced along the maximum and intermediate susceptibility axes K_1 and K_2 so that the expression of Ha, which was

$$H_a = \frac{ARM_{NS} + ARM_{EW}}{2\,ARM_v}$$

was approximated by

$$H_a = \frac{ARM_1 + ARM_2}{2\,ARM_3}$$

If we consider any pair of perpendicular radii, N-S and E-W, on an ellipse whose principal axes are ARM_1 and ARM_2, with θ being the angle between r_1 and ARM_1, we have :

$$X = ARM_{NS} + ARM_{EW} = \frac{ARM_1\,ARM_2}{\sqrt{ARM_1^2 \sin^2\theta + ARM_2^2 \cos^2\theta}} + \frac{ARM_1\,ARM_2}{\sqrt{ARM_1^2 \cos^2\theta + ARM_2^2 \sin^2\theta}}$$

$$\frac{d(X)}{d(\theta)} = A \sin 2\theta \left[(ARM_1 \sin^2\theta + ARM_2 \cos^2\theta)^{3/2} - (ARM_1 \cos^2\theta + ARM_2 \sin^2\theta)^{3/2}\right]$$

$d(X)/d(\theta) = 0$ for : $\sin 2\theta = 0$, so for $\theta = 0$ or $\theta = \pi/2$, which gives a maximum value for $ARM_1 + ARM_2$

or for : $ARM_1^2 (\sin^2\theta - \cos^2\theta) = ARM_2^2 (\sin^2\theta - \cos^2\theta)$

so for $\sin^2\theta = \cos^2\theta$, i.e. $\theta = \pi/4$, if $ARM_1 \neq ARM_2$

Hence the minimum of X is :

$$\frac{2\sqrt{2}\,ARM_1 ARM_2}{\sqrt{ARM_1^2 + ARM_2^2}}$$

So we have : $\frac{2\sqrt{2}\,ARM_1 ARM_2}{\sqrt{ARM_1^2 + ARM_2^2}} \leq X \leq ARM_1 + ARM_2$

When $ARM_1 = ARM_2\,(1 + \varepsilon)$, the minimum value for X is very close to $ARM_1 + ARM_2$:

$$2\,ARM_2 \frac{1 + \varepsilon}{\sqrt{1 + \varepsilon/ARM_2}} \leq X \leq 2 ARM_2\,(1 + \varepsilon/2)$$

In our case, ε is 1.2 % on average. Therefore, for the values $ARM_1 = 1.01$ and $ARM_2 = 1$, we have $2.00997 \leq X \leq 2.01$, the maximum error is $< 2.10^{-5}$. Hence, we can say that the approximation $ARM_{NS} + ARM_{EW} = ARM_1 + ARM_2$ is reasonable as well as the first approximation concerning Ha.

On the other hand, the ARM anisotropy ratio Ha was estimated from the ratio of ARM induced in the horizontal plane to that induced in the vertical direction. Therefore, the K_3 axis was linked to the vertical core axis. This leads to an error in Ha values that can be corrected using an expression for a new ARM anisotropy ratio H'a, which is a function of Ha and angle α between the core axis and K_3.

The expression of estimated Ha was :

$$Ha = \frac{ARM_H}{ARM_V} \quad \text{and} \quad Ha' = \frac{ARM_1}{ARM_3}$$

Assuming K_3 and ARM_3 are parallel, $ARM_1 = ARM_2$ and that the magnitude ellipsoid is tilted along the N-S direction, the components of the inducing field directions in the AAR ellipsoid reference as a function of angle α are :

$$H_v \begin{bmatrix} 0 \\ \sin\alpha \\ \cos\alpha \end{bmatrix} \quad H_{NS} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad H_{EW} \begin{bmatrix} 0 \\ \cos\alpha \\ \sin\alpha \end{bmatrix}$$

$$\text{as } \overrightarrow{ARM} = \begin{bmatrix} ARM_1 & 0 & 0 \\ 0 & ARM_2 & 0 \\ 0 & 0 & ARM_3 \end{bmatrix} \cdot \vec{H}$$

and ARM_H is the average of ARM_{NS} and ARM_{EW}, so we have:

$$ARM_V = \begin{bmatrix} 0 \\ ARM_1 \sin\alpha \\ ARM_3 \cos\alpha \end{bmatrix} \quad \text{and} \quad ARM_H = \begin{bmatrix} ARM_1/2 \\ ARM_1 \cos\alpha/2 \\ ARM_3\, \text{sing}\,\alpha/2 \end{bmatrix}$$

$$Ha = \frac{ARM_H}{ARM_V} = \frac{1}{2} \frac{\sqrt{ARM\,1^2 + ARM\,1^2 \cos\alpha^2 + ARM\,3 \sin\alpha^2}}{\sqrt{ARM\,1^2 \sin\alpha^2 + ARM\,3^2 \cos\alpha^2}}$$

As in our approximation $H'a = \frac{ARM_1}{ARM_3}$, this leads to the expression for H'a as a function of Ha and the angle θ :

$$H'a = Ha \sqrt{\frac{1 - \frac{\tan^2\theta}{2\,Ha}}{1 - \tan^2\theta \left(Ha^2 - 1/2\right)}}$$

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