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Application of the pseudo-Thellier technique to a paleomagnetic record from lake El Trébol (Patagonia, Argentina)

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Resumen

La técnica de pseudo-Thellier se aplicó con la finalidad de obtener registros de paleointensidades relativas utilizando un testigo de sedimentos del Lago El Trébol (Patagonia, Argentina).

En un conjunto de muestras, se llevaron a cabo mediciones de la magnetización remanente natural residual (NRM_{left}) luego del proceso de desmagnetización por Campos Alternos en función de la intensidad de la magnetización remanente anhistérica (ARM_{gained}) en el mismo valor de campo. Dos versiones del método de re-muestreo jackknife se usaron para estimar el error de los registros de paleointensidades.

Los resultados obtenidos mediante el método de pseudo-Thellier se compararon con trabajos previos de los autores en los cuales la magnetización remanente a 20mT (NRM_{20mT}) fue normalizada usando la magnetización remanente anhistérica a 20mT (ARM_{20mT}), la magnetización remanente isotérmica de saturación a 20mT ($SIRM_{20mT}$) y la susceptibilidad magnética (k) (Gogorza *et al*., 2006). Los registros obtenidos a partir del método de pseudos-Thellier muestran un acuerdo razonable con los obtenidos mediante el método standard de normalización (NRM_{20mT}/ARM_{20mT}).

Palabras clave: Pseudo-Thellier, paleointensidad relativa, lago El Trébol, re-muestreo jacknife.

Abstract

The pseudo-Thellier technique was applied to obtain relative paleointensity determinations using a sediment core from Lake El Trébol (Patagonia, Argentina).

Measurements of intensity of natural remanent magnetization left (NRM_{left}) after AF demagnetization versus intensity of anhysteric remanent magnetization gained (ARM_{gained}) at the same peak were carried out on a set of samples. Two versions of a jackknife resampling scheme were used to get error estimates on the paleointensity.

The pseudo-Thellier paleointensity records were compared with the authors previous results where the remanent magnetization at 20mT (NRM_{20mT}) has been normalized using the anhysteric remanent magnetization at 20mT (ARM_{20mT}), the saturation of the isothermal remanent magnetization at 20mT ($SIRM_{20mT}$) and the low field magnetic susceptibility (k) (Gogorza *et al*., 2006). The pseudo-Thellier record shows a reasonable agreement with the standard method of normalization (NRM_{20mT}/ARM_{20mT}).

Key words: Pseudo-Thellier, relative paleointensity, lake El Trébol, jackknife resampling, robust-resistant slope estimation.

Introduction

Many efforts have been made to recover the paleointensity from sedimentary records taking into account the potential that lake sediments have for providing continuous and high-quality records of the past geomagnetic field.

The conventional method of extracting geomagnetic field information from the signal consists in normalizing the "cleaned" natural remanent magnetization (NRM) at some demagnetization level with some normalizer. Different normalizers have been proposed, such as the anhysteretic remanent magnetization (ARM), the saturation isothermal remanent magnetization (SIRM) and the magnetic susceptibility k (Tauxe, 1993). It is assumed that the normalizers minimize the effects of magnetic grain-size distribution and variation of magnetic input, for example, as determined by environmental effects.

Several studies have been carried out to recover the relative paleointensity from marine and terrestrial records (Brachfeld and Banerjee, 2000; Sagnotti *et al*., 2001; Nowaczyk *et al*., 2001; Pan *et al*., 2001; Stoner *et al*., 2002; Brachfeld *et al*., 2003; St-Onge *et al*., 2003; Gogorza *et al*., 2004, 2006). Each study holds that their results represent the true geomagnetic field intensity and are free of environmental effects. Although the criteria summarized by Tauxe (1993) are strict, one must be aware that there might still be some climate influence left in the normalized NRM record and that we might not be looking at a purely geomagnetic signal (Kruiver *et al*., 1999).

Another way to obtain paleointensity records from sediments is the pseudo-Thellier method, based on AF demagnetization and ARM or IRM acquisition (Tauxe *et al*., 1995). The goal of this method is to diminish the environmental contamination of the paleointensity signal better than the conventional normalizing methods (Kruiver *et al*., 1999).

In this paper we compare the results of paleointensity records obtained from sediment cores of Lake El Trébol (Patagonia, Argentina) using a conventional normalizing method (Gogorza *et al*., 2006) and with the pseudo-Thellier method with ARM. Here, we investigate whether the pseudo-Thellier method yields different results for this sediment core.

Geologic Setting

The sediment core studied in this work is core lt98-2 from Lake El Trébol (41°04'S 71°29'W). Lake El Trébol, a closed basin, is an oligotrophic, small lake (surface area: 0.4km^2, maximum depth=11m), located at 758m a.s.l. on the east side of the Andean Patagónica Cordillera, in a wooded area with moderate human influence. Presently, there are no perennial stream discharges into the lake and the hydrological budget is dominated by groundwater influx and losses by evaporation (Bianchi *et al*., 1999; Gogorza *et al*., 2006).

Lake El Trébol sedimentary stratigraphy shows strong similarities to others obtained by the authors from surrounding lakes (Gogorza *et al*., 1999; 2001; 2002). The push corer reached the basement (or erratic blocks), passing through a sedimentary column, which is represented by the cores (Irurzun *et al*., 2006; Gogorza *et al*., 2006).

Material and Equipment

The core investigated in this paper (lt98-2) was recovered at water depths of about 10 m from Lake El Trébol in 1998 using a push corer installed on a raft with a central hole (Gogorza *et al*., 2006).

One half of each core was subsampled with cubic plastic boxes of 8 cm^3. A total of 281 samples were obtained.

A Spinner Fluxgate Magnetometer Minispin, Molspin Ltd. was used for measurements of remanent magnetization and a Shielded Demagnetizer Molspin Ltd. was used to isolate the magnetization components. A Pulse Magnetizer IM-10-30 AC Scientific and Shielded Demagnetizer Molspin Ltd. with an ARM device were used for IRM and ARM acquisition experiments, respectively.

Experimental Methods

Paleomagnetic Analysis

In order to test the stability of the NRM and to remove any viscous overprints, progressive alternating field (AF) demagnetization was carried out. In the orthogonal demagnetization (Zijderveld) diagrams, we generally observed straight lines that passed through the origin of the demagnetization diagram, indicating a single component and stable characteristic remanent magnetization. A limited number of samples show a small viscous remanent magnetization (VRM) that is progressively destroyed at 10 or 15mT. Further steps revealed a high stability of the magnetization directions (Irurzun *et al*., 2006).

Paleointensity determinations were carried out according to Tauxe *et al*. (1995) with the pseudo-Thellier method on a group of 40 selected pilot samples from core lt98-2. The NRM is demagnetized using an alternating field (AF) in 13 steps up to 95mT using steps of 5-10mT. Then the ARM is imparted at the same field steps as the NRM demagnetization. The ARM acquired at 95mT AF was demagnetized in the same way as the NRM. Finally, the sample is subjected to an increasing field to analyze acquisition of IRM using the same field steps as the initial demagnetization of the NRM, continuing to saturation. This SIRM was also demagnetized (Tauxe *et al*., 1995). The results obtained after this procedure for sample 280 are plotted in Fig. 1. The average median destructive field (MDF) is 23±2mT for the NRM, 25.7±0.5mT for ARM and 26±1mT for SIRM. ARM acquisition and demagnetization curves show a crossing at about 37% and a comparable crossing for IRM data at about 27%. The ARM data are, thus, more stable against demagnetization than the IRM (Tauxe *et al*., 1995).

Rock Magnetic Analysis

In order to study the nature of the magnetic minerals in the sediments, a set of experiments were carried out by Gogorza *et al*. (2006). The following measurements were performed for all samples: NRM; magnetic susceptibility at low frequency (specific, X and volumetric, k); isothermal remanent magnetization (IRM) in increasing steps up to 1.2T, reaching the SIRM; back field, in growing steps until cancelling the magnetic remanence; anhysteric remanent magnetization (ARM_{100mT}), with a direct field of 0.1mT and a peak alternating field of 100mT. Associated parameters calculated by Irurzun *et al*. (2006) were also used: S-ratio (IRM_{-300mT}/SIRM), remanent coercitive field (B_{CR}), SIRM/

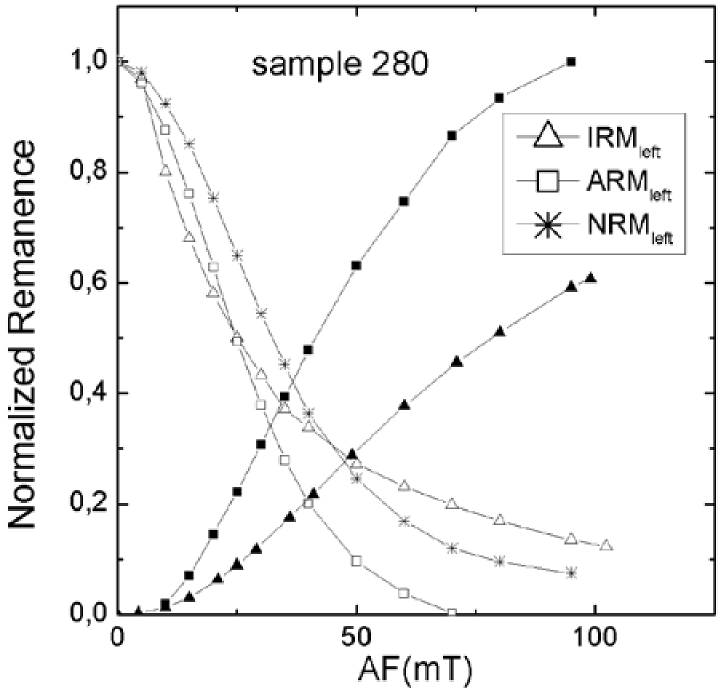

Fig. 1. Remanence normalized by their respective peak values for each remanence type versus applied field.

k, ARM_{100mT}/k and SIRM/ARM_{100mT}. In addition to these studies, hysteresis curves and temperature dependence of SIRM were obtained for a set of discrete samples. These studies show that the dominant remanence carriers are magnetite and titano-magnetite within the pseudo-single domain (PSD) grain size and that the concentration of these minerals varies between 0.01 to 0.1%. A more detailed description of these items is given in Gogorza *et al*. (2006) and Irurzun *et al*. (2006).

Fig. 2 graphically displays the linear behavior of ARM left (ARM_{left}) versus ARM gained (ARM_{gained}) at the same peak field ("Arai Plot" of Nagata *et al*., 1963) and the marked curve behavior of IRM left (IRM_{left}) versus IRM gained (IRM_{gained}) (sample 108). The slight deviation of the ARM_{left} versus ARM_{gained} plot from the linear behavior may be due to the existence of a magnetic interaction. IRM acquisition curves and corresponding DC and AF demagnetization curves were analyzed to test the magnetic interaction (Henkel, 1964; Cisowski, 1981; Kruiver *et al*., 1999). Stepwise acquisition was carried out up to fields of 1.2T; then a progressive demagnetization was applied up to 1.2T for the DC experiment (Fig. 3a) and up to 95mT for the alternating field (AF) (Fig. 3b). Fig. 3a shows that about 90% of the SIRM is obtained between 200 and 300mT. From Fig. 3b we can see that the intersection of the acquisition and AF demagnetization curves is at about 30% of the SIRM. According to Cisowski (1981), if the point of intersection is at 50% of the SIRM, there is no magnetic interaction. It is necessary to take into account that the Cisowski (1981) investigation is focused on magnetic interaction for SD particles and his results might not be applicable to the PSD particles present in our samples (Kruiver *et al*., 1999). From the Henkel plot (Henkel, 1964), IRM_{gained} vs. IRM_{left}, the occurrence of magnetic interaction can be verified (Wohlfarth, 1958). Non-linearity in this plot is typically motivated by interparticle dipolar interactions in fine-particle systems (Cisowski, 1981). The behavior observed in the samples of Lake El Trébol (Fig. 3.c) suggests that no magnetic interaction would be present in our samples. Finally, all samples show similar behavior in the stepwise acquisition experiments (Fig. 3d), independent of the absolute IRM intensities. According to Kruiver *et al*. (1999), the degree of interaction between magnetic particles is dependent on concentration; for this reason, we would have to find different behaviors in samples which have different concentrations. However, all samples deviate to the same extent from the non-interaction line (slope -0.5) in the Henkel plot and the point of intersection in the Cisowski plot (app. 30%) is the same for all samples.

In summary, it is unlikely that magnetic interaction has occurred in the studied sediments. This is supported by the fact that magnetic interaction takes place when the concentration is higher than >0.1-1% and the concentration in our sediments varies between 0.01-0.1% (Gogorza *et al*., 2006).

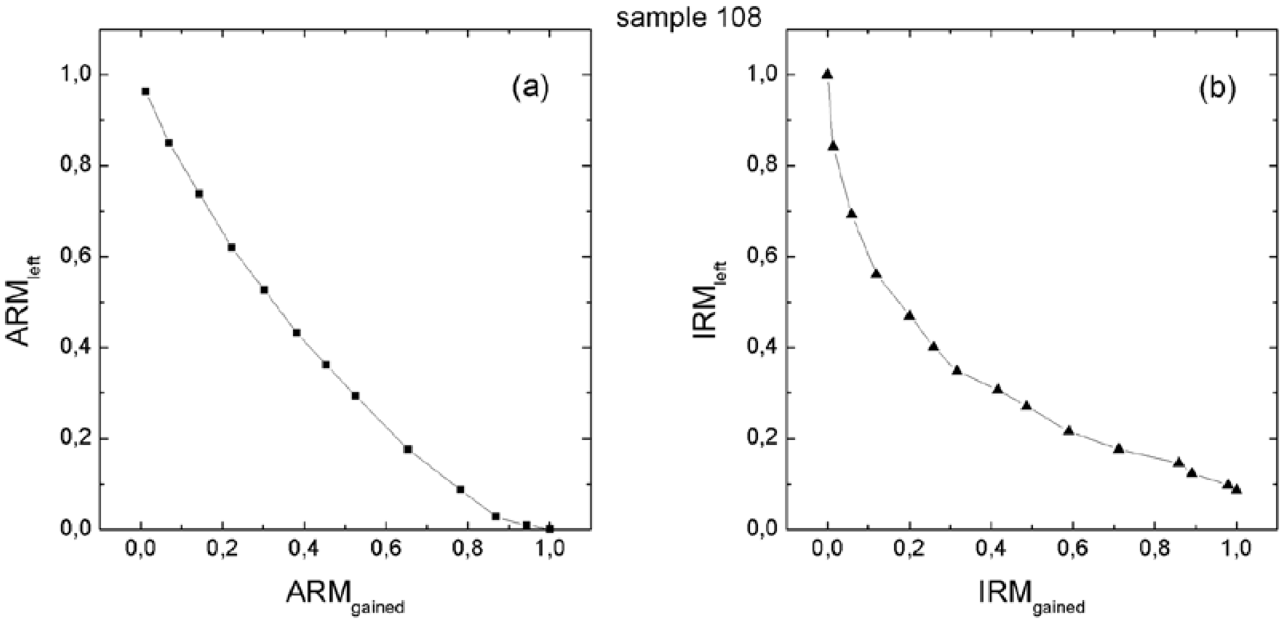

Fig. 2 (a). ARM$_{left}$ after demagnetization to a given peak field (open square in Fig. 1) plotted on ARM$_{gained}$ at the same peak field value (solid square in Fig. 1). (b) same as (a) but for IRM$_{left}$ (open triangles in 1), on IRM$_{gained}$ (closed triangles in Fig. 1).

Age Control

The sediments of lake El Trébol are dated by correlation between the Declination and Inclination curves obtained in Irurzun *et al*. (2006) and the PSV curves from lake Escondido (Gogorza *et al*., 2002). The dating is based on visual inspection of the curves (Fig. 10 in Irurzun *et al*., 2006). On the basis of this correlation, 44 tie points provide age estimates. Ages of the most distinct declination peaks are transferred to the lake El Trébol record and inclination features are matched. Minor changes in inclination and declination are then correlated.

The resultant age scale was tested by three accelerator mass spectrometer (AMS) radiocarbon dates obtained for that work by the AMS Laboratory of the University of Arizona, which were converted into calendar years using the calibration curves of Stuiver and Reimer (1993). The information about each sample, including radiocarbon years before present (RCYBP) and calibrated ages, is listed in Table 1 in Irurzun *et al*. 2006.

The "pseudo- Thellier" normalization

The pseudo-Thellier approach turned out to be successful in estimating relative paleointensities from sedimentary cores (Tauxe, 1995; Kok, 1998; Kruiver *et al*., 1999; Brachfeld and Banerjee, 2000; Pan *et al*., 2001; Snowball and Sandgren, 2004). In this paper, paleointensity determinations on 40 samples by the pseudo-Thellier method, following Tauxe *et al*. (1995), are achieved using ARM.

Fig. 4 shows the pseudo-Thellier results of the sample 176. Fig. 4a shows stepwise AF demagnetization of NRM and acquisition of ARM, with the intensities normalized to their peak values. The best fit slope (m_a) is obtained from the Arai plot (Fig. 4b), the NRM intensity left after demagnetization versus the ARM acquisition intensity (at the same peak field), by using two versions of a jackknife resampling procedure (Efron, 1982). Fig. 4c represents a histogram of the calculated slopes (ma). The solid line represents the best-fit slope; dashed lines point out the upper and lower limits of 90% of possible m_a values.

In one of the estimation procedures (Method 1), we followed the methods of Kok (1998) and Kruiver *et al*. (1999). The proposed method produced in every sample several regression slope estimates based on combinations of Jackknife subsamples (all, all but one, all but two and all but three, if possible) of field values lying between 20mT and 60mT (a minimum of three points in each subsample was required by the slope formulae) in most of the cases (Kok, 1998). In the other estimation procedure (Method 2), a modified version of that method was used to produce the slope estimates. In method 2, the Jackknife resampling was combined with Theil´s complete method of robust-resistant regression slope estimation (Glaister, 2005).

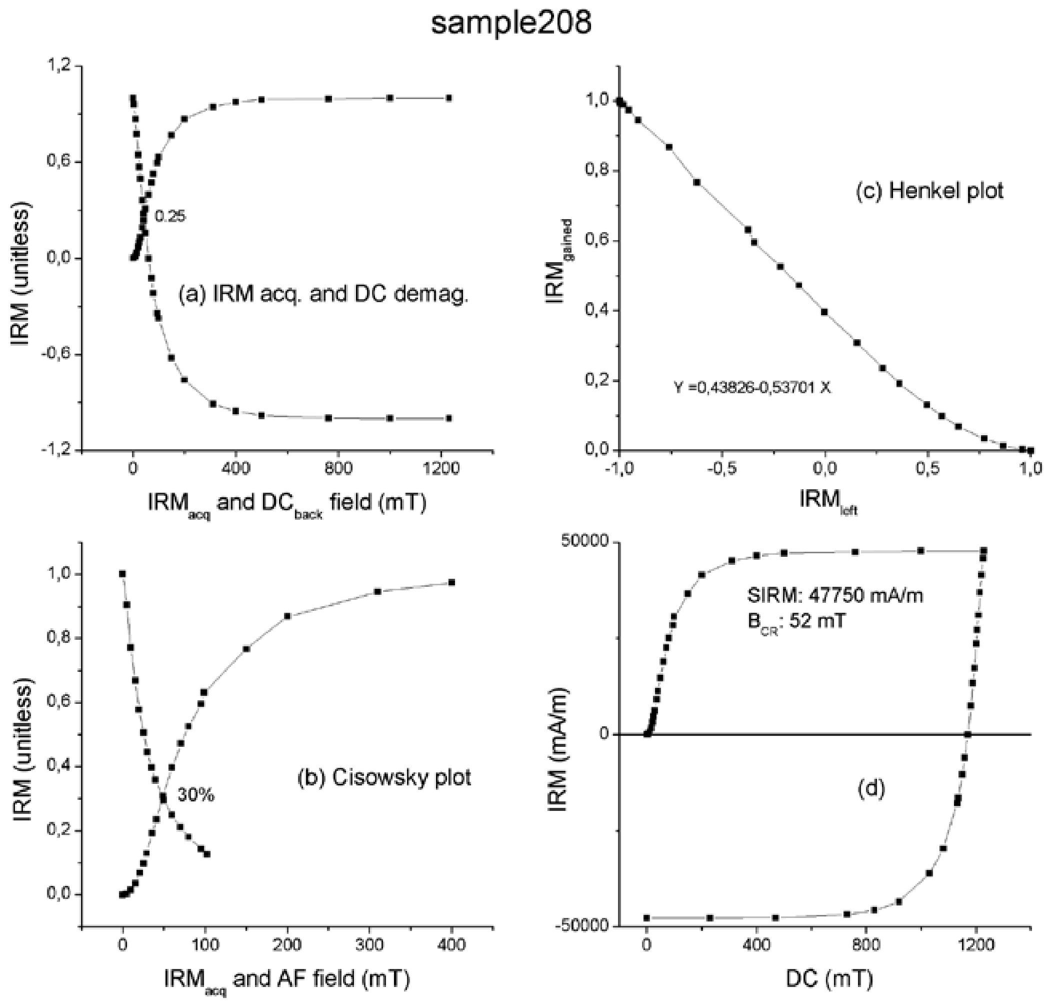

Fig. 3 (a). IRM acquisition and subsequent DC demagnetization with a back field of sample 208. (b) Cisowski plot: IRM acquisition and subsequent AF demagnetization. All intensities are normalized by their maximum values. (c) Henkel plot: IRM acquired at given peak versus IRM left at the same back field. (d) Representative curve of IRM acquisition.

In both methods, the best slope estimate for each sample was identified as the slope using a specific optimizing criterion: for the first one, the slope estimate with minimum relative error (Kok, 1998); for the latter, the slope estimate achieving the minimum sum of absolute deviations between experimental values and the slope estimates.

In addition, two measures of estimation goodness were calculated for each method, to compare the results: i) a 90% bandwidth is obtained, as in Kok (1998), and the percentage of points lying inside that band was given (37.2% applying the robust-resistant estimation method and 8% if the other method is used); ii) the sum of absolute deviations between the line joining best slopes and the experimental values is calculated. Based on both measures, it was observed that Method 1 (robust-resistant estimation method) performed better.

In order to compare the results, the conventional paleointensity records obtained by Gogorza *et al*. (2006) taking NRM_{20mT}/ARM20mT and the pseudo-Thellier paleointensity are shown in Fig. 5a using Method 1 and in Fig 5b using Method 2. With the aim of comparing them, both are normalized by their mean values. We have taken NRM_{20mT}/ARM_{20mT} as a conventional paleointensity estimate because the pseudo-Thellier method uses ARM as well (Kruiver *et al*., 1999).

It is necessary to note that both methods applied to the pseudo-Thellier data provide an estimate of errors in the paleointensity. This error constitutes the information enclosed in the sample about NRM and ARM acquisition (Kruiver *et al*., 1999).

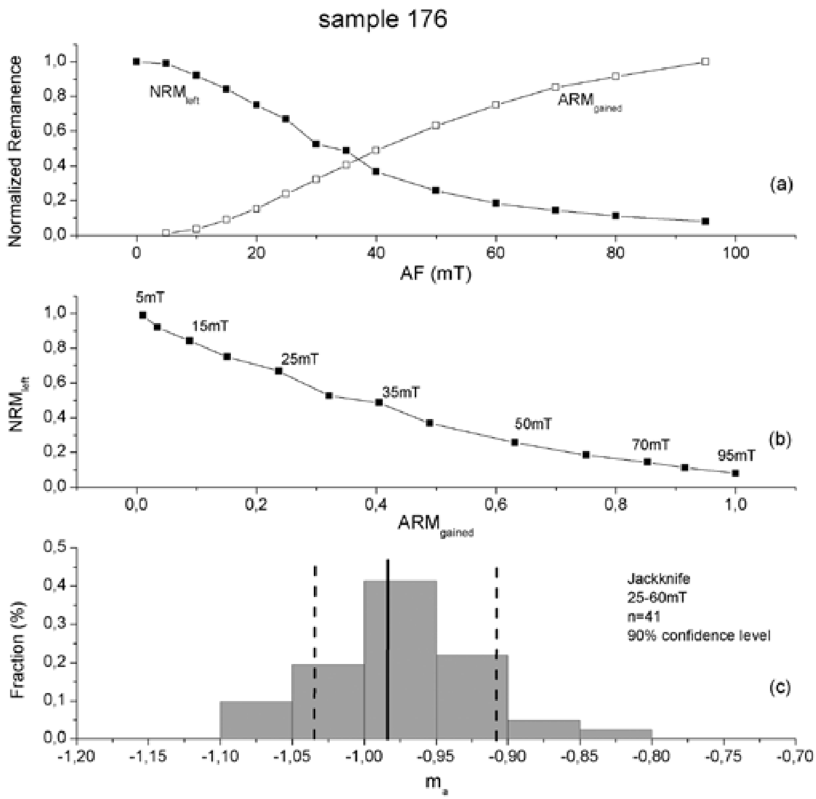

Fig. 4. Pseudo-Thellier method for sample 176. (a) Stepwise AF demagnetization of NRM and acquisition of ARM; intensities are normalized by their maximum values. (b) NRM intensity left after demagnetization to a given peak field versus ARM intensity gained at the same peak field. (c) histogram of possible ma values. Solid line: best-fit slope through at least four successive data points; dashed lines: upper and lower limits of 90 per cent of possible ma values. Jackknife parameter: n is the number of calculated slopes.

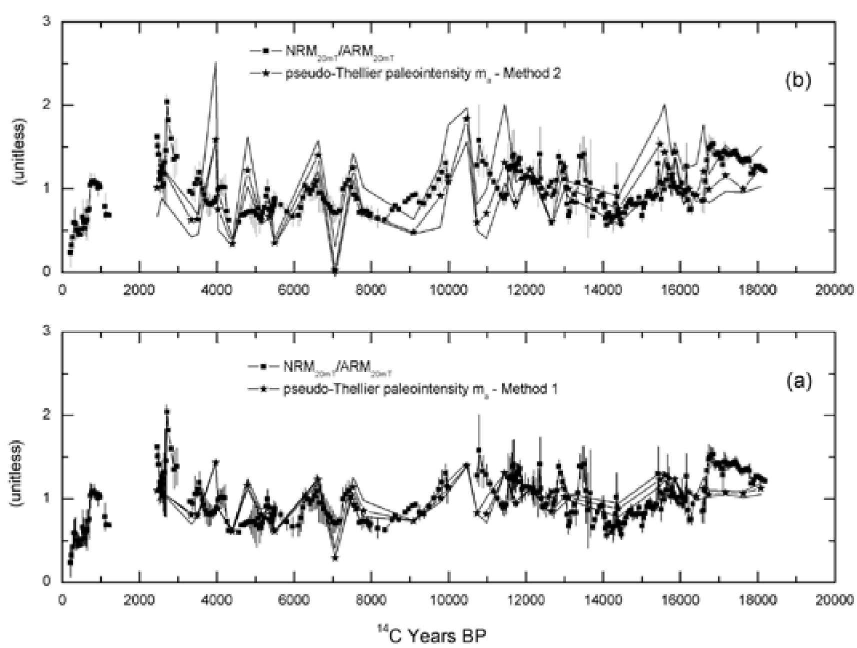

Fig. 5 (a). Comparison of (·) Relative paleointensity estimate using a conventional method: $NRM20_{mT}/ARM_{20mT}$ vs. ^{14}C years BP (Gogorza *et al.*, 2006) with Pseudo-Thellier paleointensity estimate ma. (★) is the best-fit slope m_a through at least four successive data points from NRM_{left} versus ARM_{gained} plot for each sample; solid lines indicate upper and lower limits of 90 per cent confidence level of slope ma determined by jackknife resampling using Method 1. (b) same as (a) but for Method 2.

Results

Relative Paleointensity Results

Relative paleointensity profiles are shown in Fig. 6. Here, the results comparing 40 specimens, using Method 2, are compared with previous estimates of Gogorza *et al.* (2006). The three traditional normalization methods yield profiles with broad similarities but differ in the amplitude of peaks and troughs. The coherence analysis indicates that the parameter ARM_{20mT} is the more appropriate normalization method in these sediments (not coherence frequency above the 95% confidence level) and that the NRM_{20mT}/ARM_{20mT} is not affected by climatic or lithologic factors, but represents a true geomagnetic signal (Gogorza *et al.*, 2006). In order for comparison, each of the four data sets (NRM_{20mT}/ARM_{20mT}, $NRM_{20mT}/SIRM_{20mT}$, NRM_{20mT}/k, m_a) has been divided by its mean value. In the case of the pseudo-Thellier record, this results in positive values of m_a. It is necessary to take into account that the different resolution observed in the records is because fewer samples were studied by the pseudo-Thellier method.

Here, we have found sufficient similarities between the pseudo-Thellier data and the average NRM_{20mT}/ARM_{20mT} profile (according to Brachfeld *et al.* (2000)) which is not surprising for young sediments unaffected by viscous overprint. The most conspicuous differences occur in features at 2600-3000 ^{14}C years BP, 10450-11800 ^{14}C years BP and 16800-18350 ^{14}C years BP, which coincide with prominent dissimilarities in the grain size proxies (Figure 3, Gogorza *et al.*, 2006). Changes in the ratios ARM_{100mT}/k and $ARM_{100mT}/SIRM$; higher ratios indicate smaller grain size and a higher proportion of single-domain (SD) grains (Hunt *et al.*, 1995). If, for example, there is an increase in the proportion of finer grains, the NRM_{20mT}/ARM_{20mT} will decrease but the $NRM_{20mT}/SIRM_{20mT}$ will increase, which is noticed at about 11800-12800 ^{14}C years BP; on the other hand, if there is an decrease in the proportion of finer grains, the NRM_{20mT}/ARM_{20mT} will increase but the $NRM_{20mT}/SIRM_{20mT}$ will decrease, as is observed at about 16800-18100 ^{14}C years BP. There are other intervals where differences are observed, but further studies would be necessary in those cases (for ex. 2600-3100, 4700-5200, 6700-7500, 13500-14350 and 14400-15400 ^{14}C years BP). Unfortunately we do not have data in this respect in the pseudo-Thellier profile.

Conclusions

In this paper, we have applied the pseudo-Thellier method to 40 samples from Lake El Trébol and present the results. This technique not only conveniently separates VRM from DRM, but offers a means of

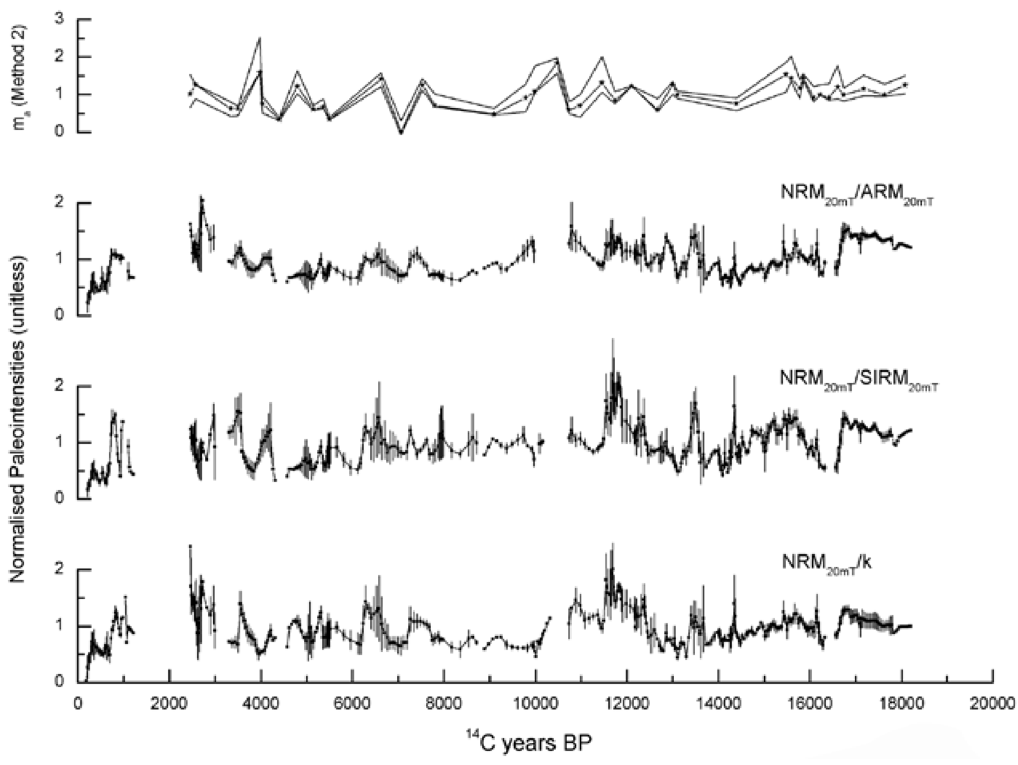

Fig. 6. NRM_{20mT}/ARM_{20mT}, $NRM_{20mT}/SIRM_{20mT}$, NRM_{20mT}/k records and the best-fit slope ma using Method 2 vs. ^{14}C years BP.

assessing the uncertainty of the relative paleointensity estimate (Tauxe *et al*., 1995). The pseudo-Thellier record and the conventional method of normalization (NRM_{20mT}/ ARM_{20mT}) show a reasonable agreement. This similarity would support the conclusion that any technique for relative paleointensity of sediment samples produces reliable results, providing that the sediments meet the criteria for magnetic uniformity necessary for estimates of the relative paleointensity of the geomagnetic field.

The advantage of using a robust-resistant method of regression slope estimation in this type of research should not be surprising, as the influence of outliers, often present due to different kind of perturbations, is minimized.

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