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NUMERICAL RELATIONSHIPS BETWEEN MAGNETIC PARAMETERS MEASURED IN QUATERNARY SEDIMENTS, AND GLOBAL PALEOCLIMATIC PROXIES

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ABSTRACT

The complexity of most geological and geophysical problems prompts sometimes the use of non linear mathematical methods to handle them. A neuro fuzzy system (NFS) that combines fuzzy logic with neural networks, is applied here to the study of a paleoclimate section extracted from the Quaternary sedimentary fill of the Mucubají Lake (western Venezuela). The purpose of this work is to find a set of numerical relationships that could predict the connections between global paleoclimate proxies (δ18O´s) and rock magnetic parameters measured in core samples (*i.e*. magnetic susceptibility χ, S-ratio, SIRM and ARM). An uneven correlation between inferred and actual δ18O´s is obtained after using χ as the sole input variable to train the NFS. Hence χ does not seem to reflect all the sedimentary features related to climate changes. A low quality inference is also obtained when S-ratio and χ are employed as input variables. Such a result is explained because the absence of high coercivity magnetic minerals in these rocks (*i.e*. hematite and goethite) suggesting that both the sediments and their sources suffered little or none chemical alteration. Finally SIRM and ARM are used, together with χ, as input variables too. These parameters, that carry magnetite grain sizes information, markedly improve the inference of the δ18O´s. The ARM/SIRM granulometric parameter appears to be related in a complex way to the paleoclimate record. Indeed, the wavelet-like shape of the ARM/SIRM profile, at the onset and the end of the Younger Dryas, seems to be associated to global temperature transitions and local tectonism. Our novel approach to the assessment of a specific paleoclimate case study shows the potential of the NFS technique in solving problems where traditional univariate and multivariate linear regression methods could prove inadequate.

Keywords: Magnetic rock properties, Cuaternary sediments, paleoclimatology, ANFIS.

INTRODUCTION

The use of univariate or multivariate linear regression analyses is a common practice when it comes to correlate different paleoclimate proxies. Nevertheless, in most cases geological and geophysical systems encompass complex sets of dispersed data that prompt the use of alternative non linear ways to handle them. Neural networks and/or fuzzy logic have been employed in the past to deal with this kind of problems (*i.e*. Hurtado *et al*., 2008). The Neuro Fuzzy System (NFS), a hybrid algorithm that combines both fuzzy logic and neural networks, was previously used by Hurtado *et al*. (2008) to predict permeability values in some Venezuelan oil wells. More recently, Da Silva *et al*. (2010) also employed NFS to find a set of non linear relationships between Miocene global climatic changes (benthic foraminifera $\delta^{18}O$´s) and magnetic parameters (*i.e*. S-ratios and susceptibility) in a Colombian stratigraphic well.

In this work we apply the NFS to the study of some rock magnetic experimental data (χ, S-ratio, SIRM and ARM) measured in a paleoclimate section that includes two stratigraphic intervals of a single core drilled in the Quaternary sedimentary fill of the Mucubají Lake (western Venezuela). Our goal is to look for a set of numerical relationships that could predict, in a satisfactory way, the likely connections between global paleoclimate proxies (*i.e*. $\delta^{18}O$) and the magnetic data that might describe the variations of types and concentrations of magnetic minerals (*i.e*. χ and S-ratios) and/or their grain size distributions (SIRM and

ARM).

The Mucubají Lake is part of a network of glacial lakes located in the western Venezuela Andean range. This lake was affected by the Andean tectonic through the Boconó Fault, and by alternated glacial and interglacial periods (Carrillo *et. al*, 2008). The Mucubají Lake can be considered an excellent natural laboratory for the NFS study proposed here, since its geological history reveals that it has undergone a series of events related to climate change, possibly encrypted in the lithological and magnetic properties of a rapidly accumulated continuous stratigraphic sequence.

The $\delta^{18}O$´s used here, and reported by the National Oceanic and Atmospheric Administration (NOAA), are ratios of precipitation inferred from deep-lake ostracods from the Ammersee lake in southern Germany (Von Grafenstein *et al*. 1999).

Experimental

Our paleoclimate section includes two cores from a composite core MUCL 02-02 (Carrillo, 2008), namely MUCL 02-02-03B (top) and MUCL 02-02-02-B (bottom). Samples were taken continuously and prepared in cubic plastic boxes (2 x 2 cm). We only worked with those 64 that are related to the paleoclimate record, namely we eliminated the stratigraphic levels that correspond to instantaneous and turbiditic events at the top and bottom of the section.

The global $\delta^{18}O$ data from the NOAA (von Grafenstein *et al*. 1999) in Figure 1, are age-linked to rock magnetic profiles (*i.e*. χ, SIRM, ARM and S-ratio) by the Carbon 14 age of 12,890 B.P. measured at MUCL

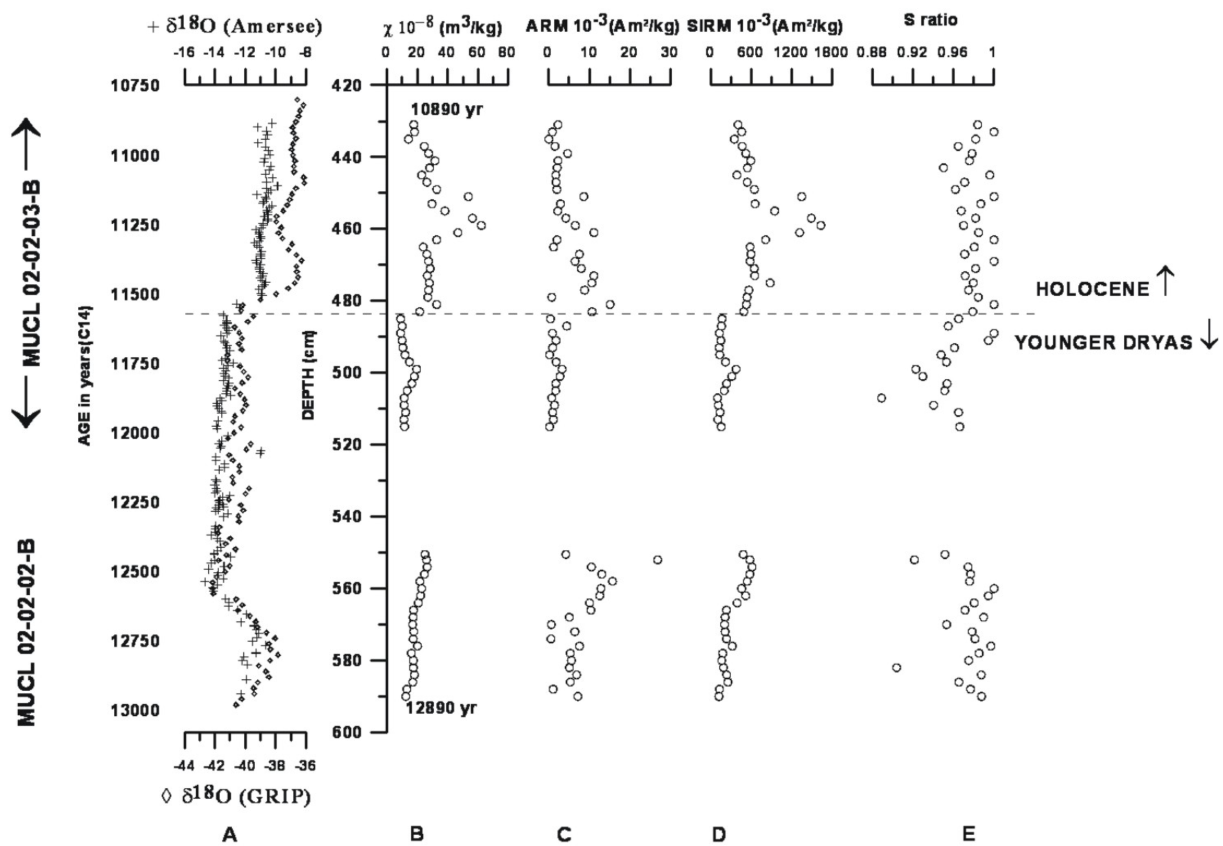

Figure 1. Profiles of χ, ARM, SIRM and S-ratio values measured in the paleoclimate section from Mucubají Lake, namely MUCL 02-02-03-B and MUCL 02-02-02-B The profile with the $\delta^{18}O$ ratios of precipitation, inferred from the Ammersee lake in southern Germany (after von Grafenstein,1999), and used in this work as a gobal paleoclimate record, is included in this figure too.

02-02-02B and the next youngest Carbon 14 age available of 10,890 B.P. measured at neighboring core MUCL 02-02-01 (Carrillo *et al*., 2008). Thus we assumed, for our 160 cm – thick synthetic profile where instantaneous sedimentary events were extracted, a constant accumulation rate of 0.08 cm/yr at the bottom of MUCL 02-02. Moreover, Carrillo *et al*. (2008) have previously anchored a major rise of the magnetic susceptibility in MUCL 02-02-03B to the temperature transition between the end of the Younger Dryas and the beginning of the Holocene, described by regional and global paleoclimate records from Greenland and the Cariaco Basin.

For the measurement of the magnetic susceptibility at room temperature, we employed a Bartington MS2 System with a MS2B. The readings of χ were repeated 5 times and a standard deviation of less than 10% was calculated for each sample-average. We also measured the saturation isothermal remanent magnetization (SIRM) and S-ratios ($IRM_{-0.03T}/SIRM_{+3T}$) in a Molspin minispin rock magnetometer with a sensitivity better than 1 x 10^{-7} emu/cc at 24 sec. In these experiments the SIRMs were induced in an ASC IM-10-30 pulse magnetizer with interchangeable coils, capable of generating fields in excess of 28 KGauss. The anhysteretic remanent magnetization (ARM) was determined in a LDA-3 AF demagnetizer using a 100 mT initial AF peak field and a DC field of 50 μT.

Computational Results

Once the correlation between the paleoclimate section and the global $\delta^{18}O$ values was obtained, we used an adaptative neuro fuzzy inference system (ANFIS) to find some numerical relationships that could link magnetic and global paleoclimate proxies. The ANFIS is a computational tool that builds a system of fuzzy inference, out of a set of input and output variables. The parameters of the membership functions, that assign fuzzy values to the input variables and to the fuzzy rules, are adjusted via neural retropropagation algorithms allowing the system to learn from the data that is using. For this work we employed the command ANFIS from MATLAB 6.5 that enables the use of fuzzy rules with AND and OR links, 11 different membership functions and either network or group partitions.

The five layers ANFIS applied here are equivalent, under some constrains, to a Takagi, Sugeno, Kang (TSK) model (Finol and Jing, 2002) that consists of a set of fuzzy if/then rules:

R_i: If x_1 is C_{i1} and x_2 is C_{i2} and … and x_n is C_{in}

Then: $y_i = c_{i1}x_1 + c_{i2}x_2 + \ldots + c_{in}x_n + c_{i0}$

The output values y_i are a linear or constant function of the input variables x_j $(j = 1,2,\ldots,n)$. R_i $(i = 1,2,\ldots,m)$ is the ith fuzzy rule; $C_{i1},\ldots C_{in}$ are the antecedent linguistic variables and $c_{i1}, c_{i2}, \ldots, c_{in}$ the consequent parameters (Da Silva *et al*., 2010 and Hurtado *et al*., 2008).

To train our fuzzy model we used $\delta^{18}O$ values as output and χ, S-ratio, SIRM and ARM as input variables. The hybrid method we employed to train the system combines a retro propagation neural network with the least square method. Therefore, the training of the ANFIS adjusts the parameters of both the fuzzy rules and the membership functions up to the point in which the maximum number of iterations is reached, or the training error keeps within the level of tolerance.

Besides the possibility of establishing numerical relationships and predictive formulae, we also tried to discriminate the combinations of magnetic parameters that enable the best inference of the $\delta^{18}O$´s. The first computational trials we carried out used only one magnetic property as input variable and 2, 3 or 4 membership functions with their corresponding fuzzy rules. These tests were repeated with every experimental magnetic parameter. Afterwards, we checked the quality of the inference obtained using various pairs of these parameters as input variables. Once more we employed a maximum of 4 fuzzy rules. In order to test the flexibility of the system we limited the number of fuzzy rules to no more than 4. Moreover, we trained the system with only 60 % of the data available randomly chosen and evenly distributed along the whole section. The output (inferred $\delta^{18}O$ values) was then compared with its experimental counterpart and the performance of the fitting was tested using the correlation factor R^2 and the Root Mean-Square Error (RMSE).

Figure 2 depicts the final optimal results obtained, between experimental and actual δ18O´s, after completing a large number of computational tests. Table 1 shows the parameters of the Gaussian membership functions [Δh1/2 Center], their corresponding fuzzy rules and the quality of the inference measured from the RMSE and R^2 values. The inferred $\delta^{18}O$ shown in Figure 2a are obtained using χ as the sole input variable and 3 fuzzy rules ($R^2 = 0.44$, RMSE = 0.1205). The next best inferences are the ones depicted in Figure 2b (*i.e.* [4χ 1S-ratio] $R^2 = 0.39$, RMSE=0.1353); Figure 2c (*i.e.* [4χ 1SIRM] $R^2 = 0.59$, RMS = 0.2035); Figure 2d (*i.e.*[1 χ 4ARM] $R^2 = 0.66$, RMSE = 0.0912) and Figure 2e (*i.e.* [4ARM 1SIRM] $R^2 = 0.66$, RMSE = 0.0908).

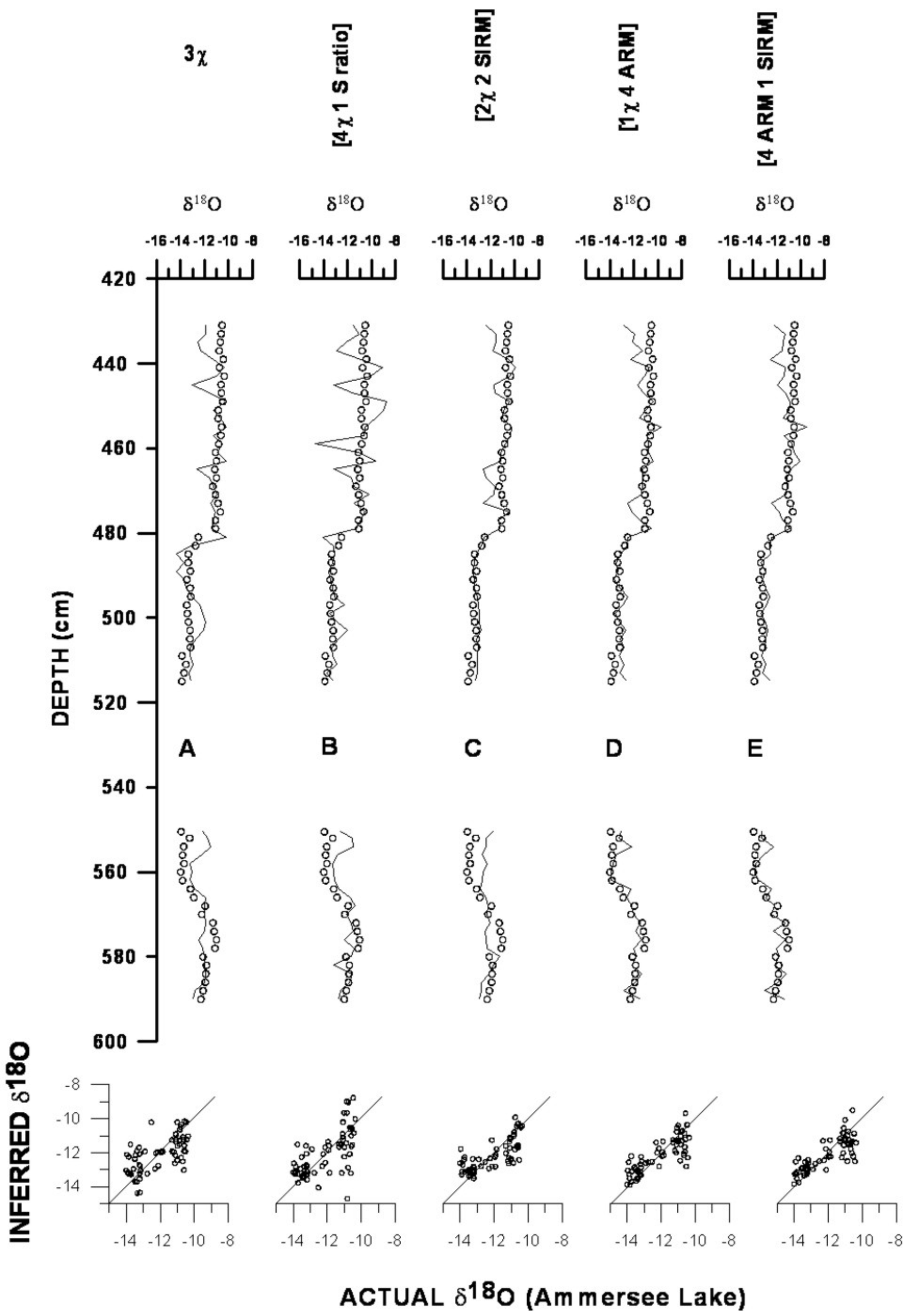

Figure 2.
Results of the NFS $\delta^{18}O$ inferences, after training the system with 60% randomly chosen samples, are shown for the 5 best cases and the whole data collection:
(a) 3χ ($R^2 = 0.45$, RMSE = 0.1205)
(b) [4χ 1S-Ratio] ($R^2 = 0.40$; RMSE=0.1353)
(c) [4χ 1SIRM] ($R^2 = 0.59$; RMSE = 0.2035)
(d) [4ARM 1SIRM] ($R^2 = 0.66$; RMSE = 0.0908)
(e) [4χ 1ARM] ($R^2 = 0.66$; RMSE = 0.0912).

Discussion

Figures 1 b, c, d and e show the profiles of χ, S-ratio, SIRM and ARM respectively, measured at different levels of the two Mucubají cores that we have analyzed (*i.e*. MUCL 02-02-02B and MUCL 02-02-03B). From these profiles some similar trends between the magnetic parameters and their corresponding global paleoclimatic proxies (*i.e*. $\delta^{18}O$) are easy distinguishable. Indeed in the Mucubají Lake, where the main drainage into the lacustrine basin came from its tributaries, the magnetic susceptibility must have been linked to the terrigenous input that characterized warm and humid (surface runoff) periods such as the onset of the Holocene. Thus at approximately 480 cm, there is an anomalous upwards rise of both magnetic and non magnetic proxies. Conversely, in cold weather (*i.e*. Younger Dryas with lower $\delta^{18}O$´s) the intensity of the alteration probably decreased together with the magnetic susceptibility.

From the multiple computational trials we carried out, using just one single input variable at a time, magnetic susceptibility yields the optimal results. However, a qualitative examination of figure 2a shows that the ability of the NFS to infer $\delta^{18}O$´s throughout the whole section is still inadequate. In fact, the best inference obtained using 3χ yields a $R^2 = 0.45$ and a RMSE = 0.1205. This is probably due to the fact that there is no a univocal correlation between χ and global paleoclimate proxies. Indeed, magnetic susceptibility values might have also been affected by the presence of paramagnetic minerals in these rocks. Moreover, χ values are not very sensitive to changes in particle sizes of magnetite either. Thus, in order to compensate the effects of those factors that might have an influence on the information contained in the magnetic susceptibility profile, we combined χ with other input variables such as S-ratio, SIRM and ARM, to test the NFS.

The S-ratio measures the relative contributions of low (*i.e*. magnetite) and high (*i.e*. hematite and goethite) coercivity minerals to the total saturation isothermal remanent magnetization. From figure 2b it is clear that when we employ this parameter as an input variable together with χ, even the best NFS results yield a rather coarse inference of the $\delta^{18}O$´s. The weak association of S-ratios to the global climate record is probably due to the inexistence of high coercivity magnetic minerals (*i.e*. S-ratios > 0.88) that would yield a major variability of this parameter along the whole section.

As a further step in our computational trials we use the SIRM parameter as an input variable since it contains extra information about magnetite granulometries. Figure 2c shows an improvement in the inference of the $\delta^{18}O$´s suggesting that not only concentrations of magnetite are linked to paleoclimate changes but also their grain size distributions. Finally, we used ARM´s as input variables (figs. 2d and e) which give rise to the optimal $\delta^{18}O$ inferences ($R^2 = 0.65$) and the highest number of clusters out of the data available when combined with either χ or SIRM. It is important to bear in mind that although SIRM and ARM are both magnetite concentration dependent, the former seems to be particularly sensitive to multidomain grain size distributions of this mineral, whereas the latter to the pseudosingle – single domain range.

From a simple lateral correlation of core samples at the Mucubají Lake, Carrillo *et al*. (2008) claimed that there is not a systematic influence of grain size (whole rock) on magnetic susceptibility data. Thus they concluded that this paleoenvironmental proxy is rather linked to the intensity of alteration of a single source of sediments. However, since ARM depends on both the concentration of magnetite and the size distribution of the fine-grained fraction of this mineral, we argue that the magnetic granulometric features of these sediments must be also related, in a complex way, to the global climate changes that affected the region. In order to demonstrate this hypothesis we directly compared an ARM/SIRM profile (and its first derivative) with the $\delta^{18}O$ data (fig. 3). The ARM/SIRM ratio not only compensates for variations in concentrations of magnetite but is also a granulometric indicator that tends to increase as the grain sizes of this mineral decrease. The first derivative was calculated to highlight the variations of this parameter throughout the whole section. It is noticeable that temperature transitions at the onset and the end of the Younger Dryas, coincide with those stratigraphic levels that display a wavelet-like behavior of the ARM/SIRM profile and its first derivative. Such peculiar features might be the record of short events of wavering energy variations associated to major global climate changes, in the context of a rather stable depositional regime.

Moreover, in the lower part of our paleoclimate section (*i.e.* top of MUCL 02-02-02B), the ARM/IRM ratio shows a behavior that may not account exclusively for temperature transitions, since the wavering appears superimposed on a trend that increases towards the onset of the Younger Dryas. This trend might have a complex tectonic origin, since the Mucubají Lake suffered important morphological transformations due to the displacement of the Boconó fault before and through the beginning of the Younger Dryas (Carrillo *et. al*, 2008). Nevertheless, the wandering of the ARM/SIRM derivative shows similar amplitude changes along the paleoclimate section. The physical meaning of these changes remains open, as well as the possible complex relationships to sedimentological transport processes or in-situ alteration of the magnetic grain size particles involved.

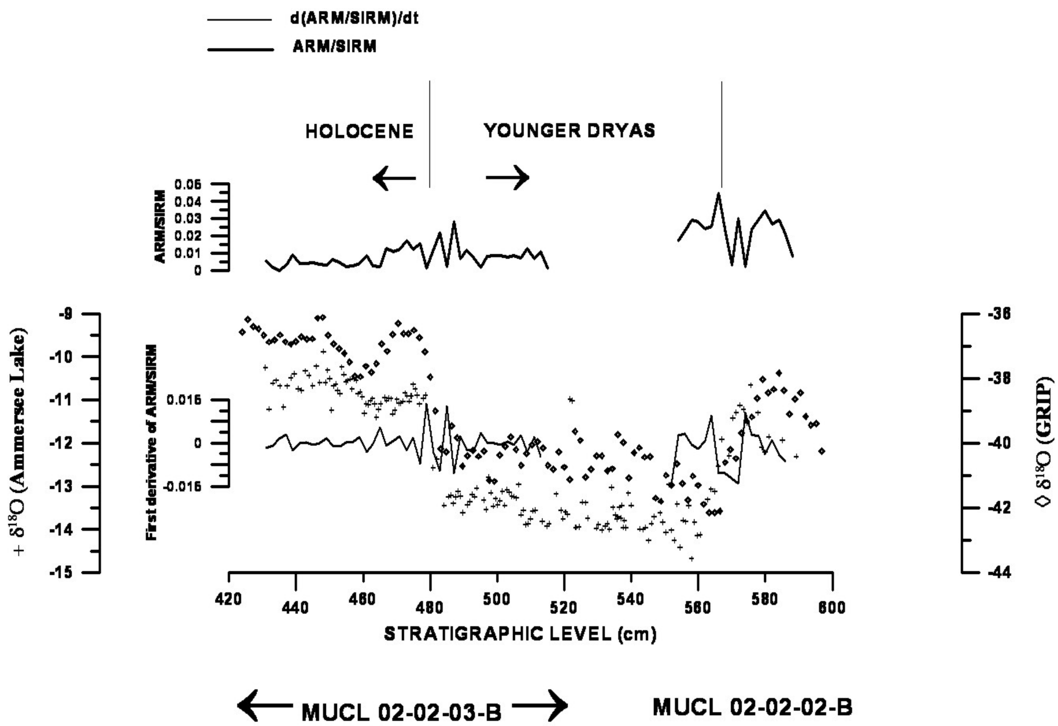

Figure 3 Profiles of ARM/SIRM and their first derivatives, compared with the global paleoclimate record (*i.e.* $\delta^{18}O$ data). First derivatives of the ARM/SIRM were calculated to highlight changes in magnetite particle size distributions related to the major temperature transitions that bracket the Younger Dryas. The dashed line at the ARM/SIRM profile for MUCL 02-02-02-B shows the increasing trend, towards the onset of the Younger Dryas, probably associated to a tectonic event overlapped to the climate transition.

Concluding Remarks

From the multiple computational trials we carried out, using just one single magnetic input variable at a time, magnetic susceptibility (*i.e.* concentration of magnetite) gave rise to the optimal correlation between inferred and actual $\delta^{18}O$. However, the rather low $R^2 = 0.67$ suggests that there is not a univocal link between χ and global paleoclimate proxies in these rocks. This is due perhaps to the effects of the paramagnetic fraction and the varying magnetite grain size distributions throughout the paleoclimate section. Thus, although magnetic susceptibility could be considered as a reliable paleoenvironmental proxy linked to the intensity of alteration of a single source of sediments in Mucubají Lake, it does not seem to fully reflect the sedimentary features related to climate changes in the region.

A rather coarse inference of the $\delta^{18}O$ is also obtained when S-ratio is used as an input variable to train the NFS, together with χ. The weak association of this parameter to the global climate record is probably the consequence that the only magnetic phase in these samples is magnetite. The absence of high coercivity magnetic minerals (*i.e*. hematite and goethite) also revealed by the thermomagnetic curves, suggests that both the lake sediments and their source rocks suffered little or none chemical alteration.

Magnetic parameters such as SIRM and ARM, that include information about grain size distribution of magnetite in these rocks, improve notably the inference of $\delta^{18}O$´s when used together with χ as input parameters. This result suggests that magnetic granulometries might be related, in a complex way, to global climate changes.

A wavelet-like behavior of the ARM/SIRM profile and its first derivative coincide with the time limits that bracket the Younger Dryas when compared with their corresponding paleoclimate proxies. We argue that a complex relationship between magnetite granulometries and climate transitions could be linked to global temperature changes and local tectonism.

This novel approach to the assessment of a paleoclimate problem, applied to the lacustrine Quaternary sediments of Mucubají Lake, shows the scope of the NFS technique in handling geological problems where traditional linear regression methods prove to be limited.

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