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# Correlation Between Miocene Global Climatic Changes and Magnetic Properties Using Neuro Fuzzy Logic Analysis

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## SUMMARY

We have used the hybrid algorithm of neuro fuzzy logic (NFL), to establish a correlation between global climatic changes (benthic foraminiferal δ18O data), experimental S-ratios and magnetic susceptibility (χ), in 44 samples of the Colombian stratigraphic well Saltarín 1A (Llanos foreland basin). χ and S-ratios were linked to global δ18O data based on a constant accumulation rate for the stratigraphic interval flanked by the two age constrains available. A good inference (over 64 %) is obteined using 4 fuzzy closters or TKS type relationships. A stronger correlation is perhaps prevented by the likely influence of local and regional tectonic events and climatic changes that could have affected the Colombian Llanos foreland basin during Miocene times. For the Guayabo and León lithologies, it seems late diagenesis of the primary magnetic minerals and the assumption of a constant accumulation rate might have a minor influence on these results.

## Introduction

The inference of a relationship to connect data of different physical nature, in order to characterize distinct systems, is a common practice in geosciences. The complexities involved in geological and geophysical problems, give rise to an increasingly dispersion of these data. In such situations there is not an obvious trend that could be easily adjusted by a single linear or multilinear relationship ever is the set of data points is divided in smaller subunits (Finol et al., 2001).

Some mathematical approaches apply concepts of either neural networks and/or fuzzy logic to deal with non-linear relationships between two or more variables (Cuddy and Glover, 2000). The Neuro Fuzzy Logic (NFL) method, a hybrid algorithm that combines fuzzy logic with neural networks, has been previously used in the prediction of complex petrophysical parameters (Hurtado et al., 2009). In most situations the results obtained have given rise to a set of numerical connections between the different variables involved as well as additional lithological information about an area of particular interest (Finol et al., 2001 and Hurtado et al., 2009, among others).

In this work we use for the first time, the NFL hybrid method trying to establish a correlation between global climatic changes (i.e. benthic foraminiferal $\delta^{18}O$ data) and magnetic parameters (i.e. S-ratio and/or initial magnetic susceptibility) as a finite series of flexible local models (Finol y Jing, 2002). Benthic foraminiferal $\delta^{18}O$ values have been taken from the deep-sea oxygen record, based on data compiled from more than 40 DSDP and ODP sites by Zachos et al. (2001). These paleoclimatic indicators echo changes in global ice volume and therefore can be used for correlations worldwide.

With the purpose of establishing a connection between magnetic parameters, directly measured on rocks from the Saltarín 1A, and global benthic foraminiferal $\delta^{18}O$ data, we have assumed a constant accumulation rate for a depth interval between the only two palinological ages available for this well (Carlos Jaramillo, personal communication). Namely 305 m (top of the mid Miocene ca.11.6 Ma) and 610 m (top of the lower Miocene ca 16 Ma).

## Methodology

We used a hybrid Adaptive Neuro Fuzzy Inference System (ANFIS) with five layers that can be interpreted as a neural network with fuzzy parameters or a fuzzy system with distributed parameters. This hybrid NF system is equivalent, under some constrains, to a Takagi, Sugeno, Kang (TSK) model (Finol and Jing, 2002). A TSK system consists of a set of fuzzy if then rules of the form:

$R_i$: *If* $x_1$ *is* $C_{i1}$ *and* $x_2$ *is* $C_{i2}$ *and ... and* $x_n$ *is* $C_{in}$
*Then:* $y_i = c_{i1}x_{i1} + c_{i2}x_{i2} + \ldots + c_{in}x_{in} + c_{i0}$

In this sense, the output values yi are considered as a linear or constant function of the input variables $x_j \left(j = 1,2,\ldots,n\right)$. $R_i \left(i = 1,2,\ldots,m\right)$ 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.

To train our fuzzy model we used the benthic foraminiferal $\delta^{18}O$, as the output variable, and $\chi$ and S-ratios ($IRM_{-0.03T}/SIRM_{+3T}$) as input variables. The $\chi$ and S-ratios were measured for 44 samples from the Colombian stratigraphic well Saltarín 1A. These samples were taken at approximately every 5 meters of depth between stratigraphic levels 304.75 and 610 meters. They are mainly mudstones, sandy and silty mudstones and sandstones from the Guayabo, León and Carbonera formations. To train the system we introduced the data in both, logarithmic and linear forms. For the variables in linear form, three models were tested: Model A: $\delta^{18}O = a(S - ratio) + b\chi + c$; Model B: $\delta^{18}O = a_1(S - ratio) + c_1$; Model C: $\delta^{18}O = b_2\chi + c_2$. For the logarithmic variables, equivalent relationships were used. In this work, linear, triangular, bell, pi, and Gaussian membership functions were tested.

**Results**

To quantify the performance of the fitting, we used the $R^2$ correlation between inferred and experimental S-ratio data, and the Root Mean-Square Error ($RMSE$) values calculated according to: $RMSE = \sqrt{\sum_{i=1}^{n}\left(Y_{\inf} - Y_{\exp}\right)^2 / n}$, where $Y_{\inf}$ and $Y_{\exp}$ are the inferred and experimental values, respectively, and $n$ is the number of data points.

After numerous trials, the best inference with the NFL was always accomplished by using model A, with linear variables, and a Gaussian membership function. The number of Fuzzy rules was varied from 2 to 4, in order to monitor a possible improvement of the inference. Figure 1 shows the results obtained by training the neuro fuzzy system with 100% of the S-ratio and $\chi$ experimental values and benthic foraminiferal $\delta^{18}O$ data available (44 sets of data points) using Model A. For the first case (figure 1a) we used one fuzzy rule for S-ratio data and two fuzzy rules for $\chi$ values. The corresponding cross plot of inferred and actual values of $\delta^{18}O$ reveals a poor inference with a correlation coeficient $R^2$ = 0.1586. For the second case (figure 1b) we used two fuzzy rules for S-ratio and one fuzzy rule for $\chi$. Once more, the corresponding cross plot of inferred and actual values of $\delta^{18}O$ reveals a poor inference with a correlation coeficient $R^2$ = 0.2975. Finally, for the last trial, we used two fuzzy rules for each S-ratio and $\chi$ data (figure 1c, and table I) obtaining a reasonably good correlation with $R^2$ = 0.6376 and a RMSE = 0.17389957. This result seems to indicate a link between magnetic proxies, measured in samples from stratigraphic well Saltarín 1A, and global climate changes mirrored by the variability of benthic foraminiferal $\delta^{18}O$ data.

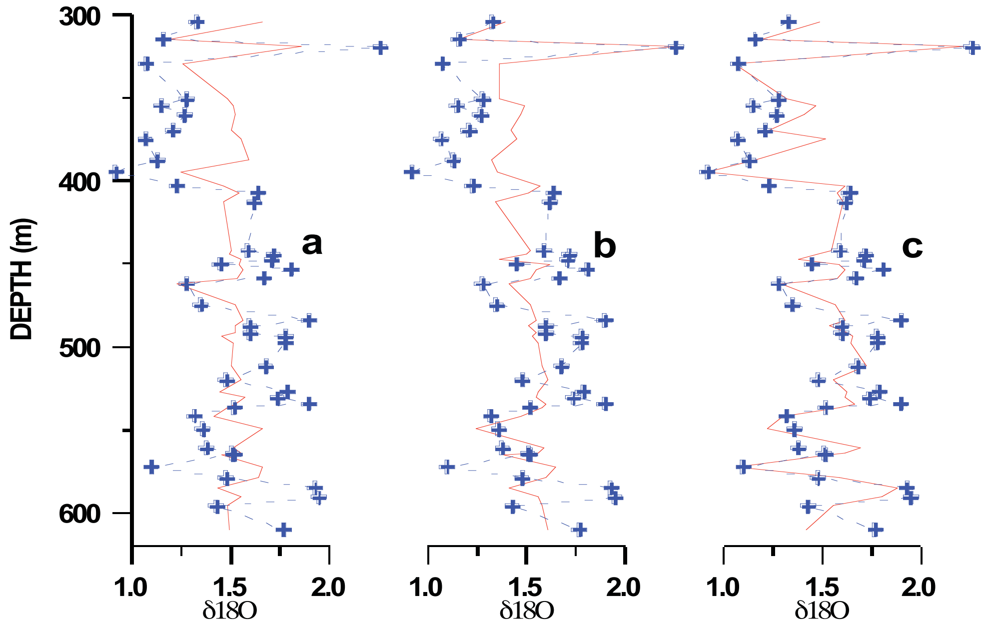


***Figure 1:*** *Benthic foraminiferal $\delta^{18}O$ inference (solid lines) for the parameters [S-ratio $\chi$] with: a) [1 2], b) [2 1] and c) [2 2] rules respectively, and the experimental data (crosses and dashed lines).*

Table I shows the 4 fuzzy rules obtained for the best training (2 membership funcions for each variable). The S-ratios and $\chi$ ranges (columns 1 and 2, respectively) for each of the fuzzy rules are also presented.

**Table 1:** Membership function ranges for S-ratio and $\chi$, and the inference equations obtained when we train with 2 fuzzy sets for each variable ([2 2]).

| Range to each rule for S-ratio | Range to each rule for χ | Equations to [2 2] rules |
|---|---|---|
| [0.240, 0.113] | [19.786, 0.002] | $\delta^{18} = -24.17(S-ratio) - 34\chi + 18.01$ |
| | [19.788, 46.597] | $\delta^{18} = 28.68(S-ratio) + 0.87\chi - 28.6$ |
| [0.105, 1.128] | [19.786, 0.002] | $\delta^{18} = -26.90(S-ratio) + 0.57\chi + 26.83$ |
| | [19.788, 46.597] | $\delta^{18} = 37.97(S-ratio) + 0.02\chi - 36$ |

**Discussion**

Since $\chi$ and S-ratio experimental values are not related to each other by a simple univocal and linear way (Heslop, 2009 and Costanzo Alvarez et al, 2010) it is reasonable to believe that an improved inference of the $\delta^{18}O$ data would be obtained by including both magnetic parameters in the training of the NFL system. Our results confirm this hypothesis. The optimal fitting gives rise to four predictor formulae for different combinations of S-ratio and $\chi$ data intervals (figure 1c). A correlation factor of $R^2 = 0.6376$ and a root mean squared error RMSE = 0.17389957 can be interpreted as the result of a major influence (ca 64%) of the global climatic changes in the magnetic proxies that we have chosen to infer benthic foraminiferal $\delta^{18}O$ data.

The complexities of the problem we are dealing with are most likely related to different factors that could introduce random noise to the magnetic proxies, otherwise directly related to global climatic changes (i.e. $\delta^{18}O$ values). Some of these factors are the probable influence of local and regional tectonic events (e.g. nearby Andean uplift between middle and late Miocene); the local climate changes upon sediment composition (Harris and Mix, 2002) and late diagenesis of primary magnetic minerals (Roberts et al., 1996). The hypothesis of a constant accumulation rate, for a 305 meters thick stratigraphic sequence, in a time period of ca 4.4 Ma, could have also had a consequence upon these results.

We argue that the effect of late diagenesis upon primary magnetic minerals is playing a minor role upon these results. As a matter of fact, the rock magnetic evidence seems to point out at the primary or nearly primary nature of most of the minerals identified in both Guayabo and León Formations. In fact, hematite in an upper subunit of Guayabo appears to be related to a paleoenvironment that includes the presence of oxidized paleosols and a global regression event at the end of the Serravallian stage. Correspondingly, Fe sulfides (e.g. pyrrhotite) in León might be the by-product of early diagenesis in muddy lacustrine sediments, during times of humid climate, high production of organic matter, slow bottom water circulation and rapid burial of the sediment load.

Conversely, we have also identified pyrrhotite in a sample from the upper Carbonera sandstone (between 546.9 to 608.2 m) that seems to be a late diagenesis by-product formed as a consequence of the diffusion of hydrocarbon through these strata. Oil impregnations recognized in these samples support such a presumption. These upper Carbonera strata also coincide with a glauconite-rich region of multiple unconformities or stratigraphic breaks that represent times of no deposition and/or erosion (Bayona et al., 2008).

The presence of some unconformities, in the last 60 m of this stratigraphic section, rules out beforehand the validity of assuming a constant accumulation rate for the upper Carbonera unit. However, although erroneous, this working hypothesis is a good way to independently assess the effectiveness of the NFL method. In fact, after dividing the stratigraphic section in four intervals of equal thickness, and applying the NFL method to infer $\delta^{18}O$ values in each of them, we find that the lower correlation and major dispersion corresponds to this last subsection. Hydrocarbon induced magnetic phases at these levels could have also contributed to such a mismatch.

## Conclusions

From the discussion above it is clear that neither late diagenesis nor the assumption of a constant accumulation rate, appear to be critical factors that have had a significant effect upon the NFL inference over most of the stratigraphic sequence that we have studied here. Thus, we argue that local and regional tectonics and climate change during early and middle Miocene in the Colombian Llanos foreland basin should have been the main factors that prevented a stronger correlation (i.e. over 64 %) of S-ratio and $\chi$ data to global climatic proxies. In fact in Saltarín 1A .

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