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ENVIRONMENTAL MAGNETISM: APPLICATION TO CAVE SEDIMENTS

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Abstract

Environmental magnetism techniques allow a rapid, low cost and sensitive characterization of sediments and can be applied in a wide range of environments. More specific, magnetic properties can be successfully used to reconstruct paleoenvironmental and paleoclimatic conditions in rockshelter and cave sites. Cave sediments, imprint the environmental conditions at the Earth's surface at the time of deposition since are well protected both at the interior and at the entrance of the cave systems. In addition, many cultural sequences and archaeological artifacts are well preserved in rockshelter and cave sediment records and can be effectively used for paleoenvironmental interpretations. In this study we present data from two different cave sites from Northern Greece. In the first cave (Maronia Cave) magnetic measurements were performed in two cores 80 and 90 cm, respectively, located inside the cave area. High values of magnetic susceptibility are directly linked with the human activity inside the cave, while lower values show deposition under infiltration and fluvial processes. In the second cave (Mikro Eptamilon Cave), magnetic susceptibility and frequency dependent magnetic susceptibility depicted from a sedimentary sequence with a thickness of 200 cm, located in the entrance of the cave. Results lead to conclusions concerning the velocity of the paleo-flow likely related to the paleoclimatic conditions that dominated the broader area.

Key words: *Magnetic susceptibility, human activity, paleoenvironmental conditions, N. Greece.*

Περίληψη

Οι τεχνικές του περιβαλλοντικού μαγνητισμού επιτρέπουν έναν γρήγορο, χαμηλού κόστους και ευαίσθητο χαρακτηρισμό των ιζημάτων και μπορούν να χρησιμοποιηθούν σε διαφορετικά περιβάλλοντα. Πιο συγκεκριμένα, οι μαγνητικές ιδιότητες μπορούν με επιτυχία να χρησιμοποιηθούν για την ανακατασκευή των παλαιοπεριβαλλοντικών και παλαιοκλιματικών συνθηκών σε βραχοσκεπές και σπήλαια. Τα ιζήματα των σπηλαίων αποτυπώνουν τις περιβαλλοντικές συνθήκες που επικρατούσαν στην επιφάνεια της Γης κατά την απόθεσή τους λόγω του προστατευμένου χώρου που βρίσκονται είτε στο εσωτερικό είτε στην είσοδο των σπηλαίων. Επιπρόσθετα, αρκετά αρχαιολογικά ευρήματα είναι καλά προστατευμένα στις βραχοσκεπές και στα ιζήματα των σπηλαίων βοηθώντας μας έτσι αποτελεσματικά στις παλαιοπεριβαλλοντικές ερμηνείες. Στην παρούσα μελέτη παρουσιάζονται δεδομένα από δύο διαφορετικά σπήλαια της Β. Ελλά-

δας. Στο πρώτο (Σπήλαιο Μαρώνειας) πραγματοποιήθηκαν μετρήσεις μαγνητικές επιδεκτικότητας σε δύο πυρήνες 80 και 90 εκ. αντίστοιχα μέσα από το σπήλαιο. Υψηλές τιμές της επιδεκτικότητας συνδέονται με την ανθρώπινη δραστηριότητα μέσα στο σπήλαιο, ενώ οι χαμηλές υποδεικνύουν την απόθεση των ιζημάτων από ποτάμιες διεργασίες. Στο δεύτερο (Μικρό Σπήλαιο Επταμύλων) μετρήθηκε η μαγνητική επιδεκτικότητα και το ποσοστό της εξαρτώμενης από τη συχνότητα επιδεκτικότητα σε μία ιζηματογενή σειρά με πάχος ~ 200 εκ., που βρίσκεται στην είσοδο του σπηλαίου. Τα αποτελέσματα οδηγούν σε συμπεράσματα σχετικά με την ταχύτητα της παλαιοροής που πιθανώς συνδέεται με τις παλαιοκλιματικές συνθήκες που επικρατούσαν στην ευρύτερη περιοχή.
Λέξεις κλειδιά: *Μαγνητική επιδεκτικότητα, ανθρώπινη δραστηριότητα, παλαιοπεριβάλλον, Β. Ελλάδα.*

1. Introduction

During the last decades, environmental magnetism methods have been utilized into a wide range of environments to provide a fast, low cost and sensitive characterization of sediments (Thompson and Oldfield, 1986; Evans and Heller, 2003). Iron-containing minerals are extremely sensitive to environmental processes occurring on Earth's surface and therefore mineral magnetic measurements have been widely applied to assess past environmental changes. Paleoclimatic/environmental alterations have been well documented from lake sediments (e.g. Paasche et al, 2004), loess (e.g. Verosub et al., 1993), marine deposits (e.g. Yang et al., 2008; Aidona and Liritzis, 2012) and archaeological sediments (Aidona et al., 2001; Tsatskin and Nadel 2003), based on mineral magnetic properties.

Furthermore, environmental magnetism techniques have been successfully used in cave sites to detect both past environmental conditions and human imprints. Caves as well as rockshelters act as important sediment traps that record paleoenvironmental conditions, since are well protected environments (Collcutt 1979; Karkanas 2001; Woodward & Goldberg, 2001). Moreover, karstic sites were attractive locations for human activity, preserving many cultural sequences and archaeological artifacts. Magnetic studies on sedimentary sequences mainly found at the entrance of cave systems depict the environmental signal of these sediments; Ellwood et al. (1996, 2004) and Sroubek et al. (2001, 2007) performed paleoclimatic reconstructions from mineral magnetic measurements (magnetic susceptibility and remanence parameters), obtained on clastic sediments deposited into the entrance of caves in the Mediterranean region. Also, magnetic properties have been applied as anthropogenic indicators related to burning activities (e.g. Woodward 1997).

In this study, the suitability of the magnetic susceptibility to record paleoenvironmental conditions on cave deposits is tested in two cave sites from northern Greece, the Maronia Cave and the Mikro Eptamilon Cave. The two karstic sites differ in terms of past human activity; the Maronia Cave is a well known archaeological site in contrast to the Mikro Eptamilon Cave where no archaeological remains were found. Magnetic susceptibility was measured on sediment samples in order to depict both the natural and anthropogenic signal of the cave deposits.

2. Study Area

2.1. Maronia Cave

The Maronia Cave is located at the Koufoplati hill (3 km NW of the Maronia village) (Figure 1). It has an elongated shape in N - W direction, with a total length of 350 m and width ranging from 15 m to 50 m. The main entrance of the cave is located 150 m above mean sea level (Figure 2a). The Maronia Cave developed in a relatively thin layer of eroded Nummulitic limestones of Middle Eocene age (Melfos et al., 2005; Pavlides et al., 2008). The limestones are strongly fissured and fractured, slightly inclined towards the west and contain several species of fossilized foraminifera, algae, corals, sea urchins, bivalves and bryozoan (Vaxevanopoulos and Melfos, 2010). Detailed study of the cave based on the morphological features and microthermometric analyses on calcite spars documents that the speleogenetic processes are closely related with thermal ascending fluids (Vaxevanopoulos & Melfos, 2010). Epigenetic processes resulting to sediment accumulation control the subsequent evolution of the Maronia Cave.

During the last six years, numerous findings from the Maronia Cave have been excavated from the Ephorate of Paleoanthropology and Speleology of Northern Greece. The excavation of new profiles in the entrance of the cave brought to light important data concerning the use of the cave during the prehistoric and historic years. Traces of the oldest habitation are dating this phase back to early copper age II. After a long period with no evident anthropogenic use of the cave, the second occupation phase is observed, dating to the 7^{th} century A.D. Another big gap occurred in the following centuries ending up with the last habitation level in the end of the 12^{th} beginning of the 13^{th} century A.D. (Panti and Miteletsis, 2008).

2.2. Mikro Eptamilon Cave

The Mikro Eptamilon Cave is located at the foothills of the southern-eastern part of Mount Menikio (Serres Prefecture, northern Greece) (Figure 1) and belongs to a broader cave complex that is developed in Paleozoic marbles. The cave consists of lenticular in cross section corridors following the strata of the marbles that suggest the epi-phreatic origin of the cave. At the entrance of the Mikro Eptamilon Cave, which revealed during the works of marble exploitation in 1965, a naturally deposited sequence of clastic sediments alternating with chemical deposits approximately 200 cm thick, is lying uncomfortably on the bedrock marbles (Figure 2b).

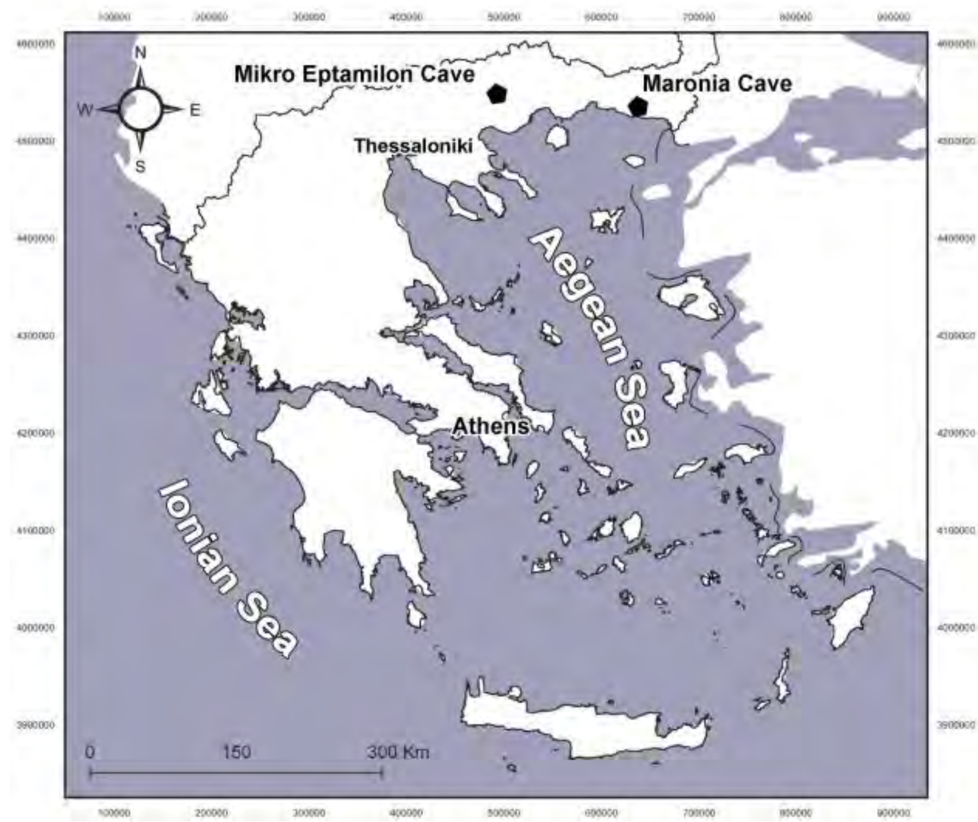

Figure 1 - Location map of the Maronia Cave and the Mikro Eptamilon Cave.

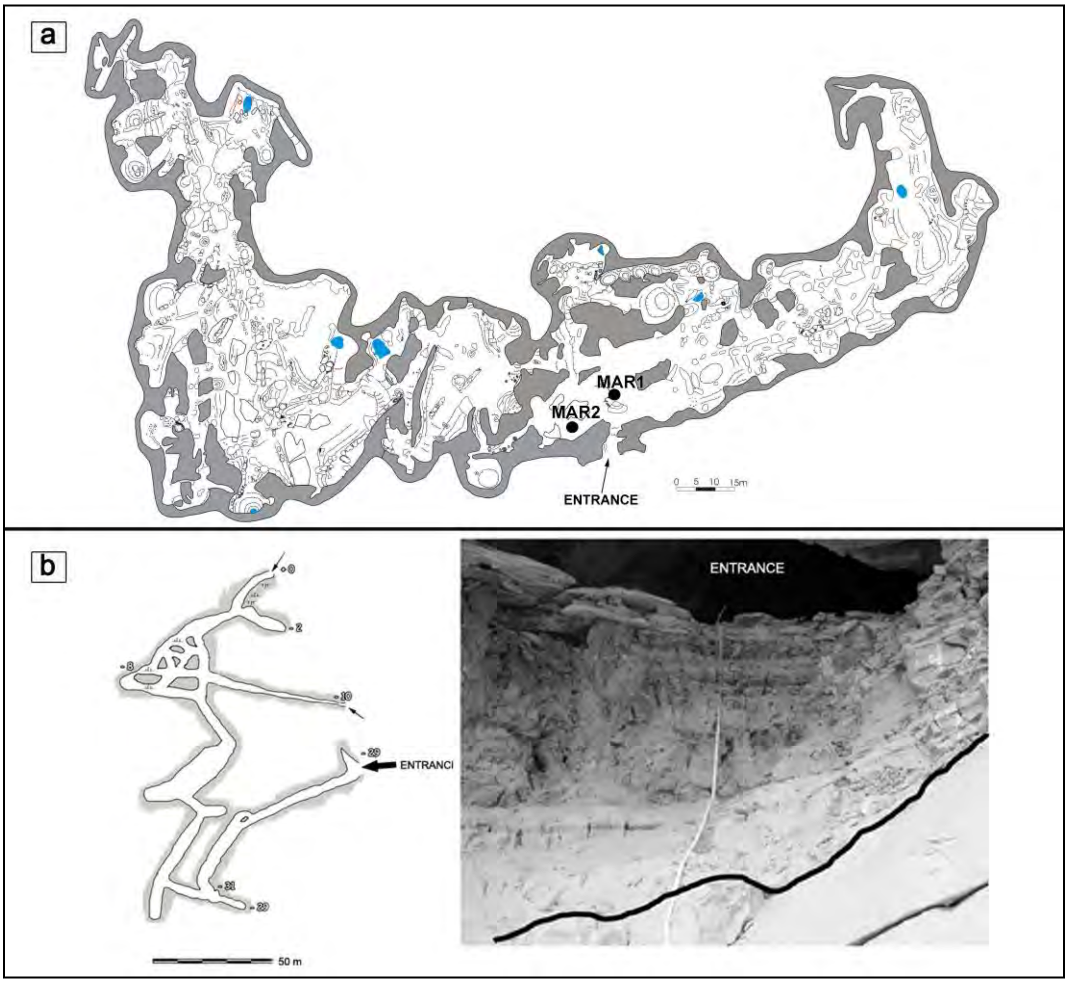

Figure 2 - Plan view of (a) the Maronia Cave with location of the studied vibracores MAR1 and MAR2 (from Pavlides et al., 2008) and (b) the Mikro Eptamilon Cave (in detail the studied sedimentary sequence at the entrance of the cave) (from Pechlivanidou et al., 2011).

3. Methodology

Magnetic susceptibility is a measure of the ease, which a material can be magnetised. The volume susceptibility is defined by the relation κ=M/H, where M is the acquired magnetisation when a uniform magnetic field (H) is applied. In SI units both M and H are expressed in A/m consequently k is dimensionless. Mass specific susceptibility χ is defined as: $\chi = \kappa/\rho$ where ρ is the density and has m^3/Kg units in SI.

Volume magnetic susceptibility (κ_{lf}) was measured on clastic and chemogenic sediments from the Maronia Cave using a Bartington MS2E meter (resolution: 2 $x10^{-6}$ SI on 0.1 range). Two vibracores, 80 cm and 90 cm respectively, retrieved from the interior of the cave (Figure 2a). The cores were split in half and surface measurements performed continuously with a step of 2.5 cm.

At the Mikro Eptamilon Cave, bulk sampling was performed continuously throughout the sedimentary sequence at the entrance of the cave (Figure 2b). Samples were packed in plastic boxes (2 x 2 x 1.6 cm^3), weighted and mass magnetic susceptibility was measured both at low (0.465 kHz ± 1%) and high (4.65 kHz ± 1%) frequency with a Bartington MS2B dual frequency sensor. The dual frequency enabled the estimation of the frequency dependent magnetic susceptibility (χ_{fd}) which indicates the presence of ferrimagnetic grains close to the superparamagnetic stable single domain (SP) transition (Evans and Heller, 2003). Moreover, the variation of the magnetic susceptibility with temperature was estimated for selected samples, using the Bartington furnace in free air.

4. Results

4.1. Maronia Cave

Magnetic susceptibility shows a great variability across the studied cores from the Maronia Cave. Figure 3 shows the downcore variations of κ_{lf} for MAR1 and MAR2. κ_{lf} values are significantly low for the upper 20 cm of MAR1, ranging from $21*10^{-6}$SI to $45*10^{-6}$SI. Between 20 - 65 cm, magnetic susceptibility values increase to $211.3*10^{-6}$SI, while are decreasing until the depth of 80 cm to $7.5*10^{-6}$SI. From 80 cm to the end of MAR1, magnetic susceptibility increases again reaching the value of $348.8*10^{-6}$SI (Figure 3).

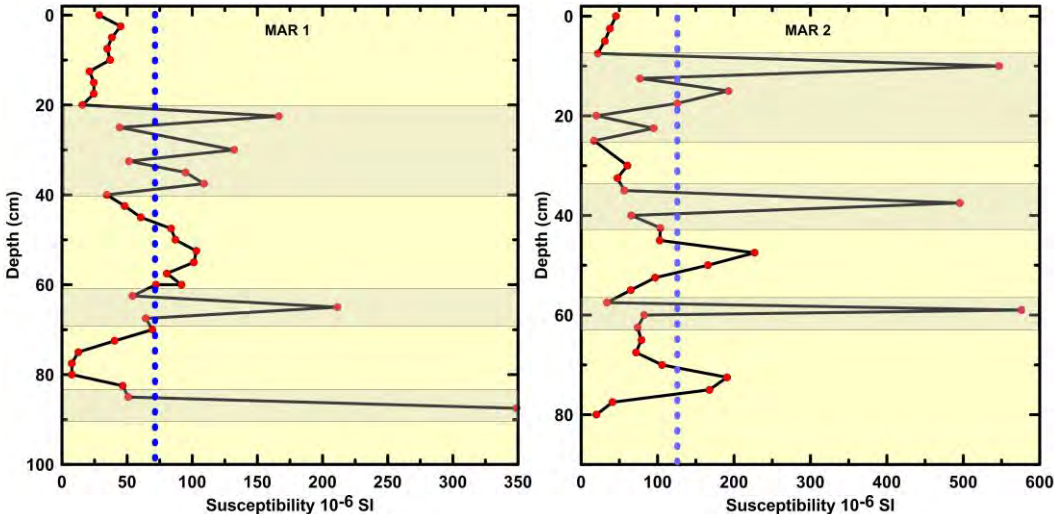

Figure 3 - Downcore variations of magnetic susceptibility (κ_{lf}) for MAR1 and MAR2, from the Maronia Cave. Grey zones indicate the enhanced layers, while blue line corresponds to the mean values for each core.

A similar trend in the magnetic susceptibility depicted for MAR2 (Figure 3). κ_{lf} values ranging from 21.7*10-6SI to 45.6*10-6SI at the upper part of the core until the depth of 7.5 cm. From 7.5 cm to 20 cm, magnetic susceptibility values are significantly higher with a maximum value of 547.7*10-6SI, while from 20 cm to 35 cm, are decreasing, reaching a minimum value of 17*10-6SI. From 35 cm to 75 cm, there is a distinct downcore increase in κlf and maximum values are detected at 37.7 cm, 50 cm, 59 cm and 72.5 cm. An exception occurs between 52.5 - 57.5 cm depth, where κlf values are gradually decreasing to 33.8*10-6SI. From 75 cm to the end of MAR2, κlf decreases reaching a value of 19.9*10-6SI.

4.2. Mikro Eptamilon Cave

Magnetic analysis of sediment samples derived from the sedimentary sequence at the Mikro Eptamlon Cave is shown on Figure 4. Both the magnetic susceptibility (χ_{lf}) and the frequency dependent susceptibility (χ_{fd}) show distinct variations with depth. Increased magnetic susceptibility values observed between 85 cm and 165 cm depth, showing a maximum value of $80.5*10^{-8}$ m^3/Kg at 100 cm depth. The upper and the lower part of the sequence depicts rather small magnetic susceptibility values, ranging between 7.8 - 22.8 $*10^{-8}$ m^3/Kg. Frequency magnetic susceptibility

(χ_{fd}) shows a more complicated trend across the studied sequence. χ_{lf} values are generally increasing until the depth of 138 cm, from 138 cm to 100 cm are decreasing and from 100 cm to the upper part of the sequence are increasing again. Maximum χ_{fd} values (> 14%) depicted at 26 cm, 48 cm, 50 cm, 135 cm, 145 cm and 190 cm, depth. The two pick values (~ 30%) observed at 15 cm and 138 cm depth, are considered as erroneous measurements since they do not seem realistic (Dearing, et al., 1996), hence are excluded for further interpretation.

Additionally, the variation of magnetic susceptibility with temperature was studied in selected samples. In Figure 5 the heating curve of the sample located at 100cm depth (showing the maximum susceptibility value Fig.4a) is displayed. A clear susceptibility drop near 585^0C is observed, suggesting the existence of nearly stoichiometric magnetite. The drop of susceptibility in the range of 300^0C is interpreted as the conversion of metastable cubic maghemite to weakly magnetic rhombohedral hematite (Deng et al., 2005). Moreover, Liu et al. (2005) further showed that this susceptibility decrease results from the inversion of fine-grained maghemite to hematite. Such a susceptibility drop is more prominent for paleosol samples and is consistent with the idea that paleosol contains more fine-grained pedogenic maghemite grains.

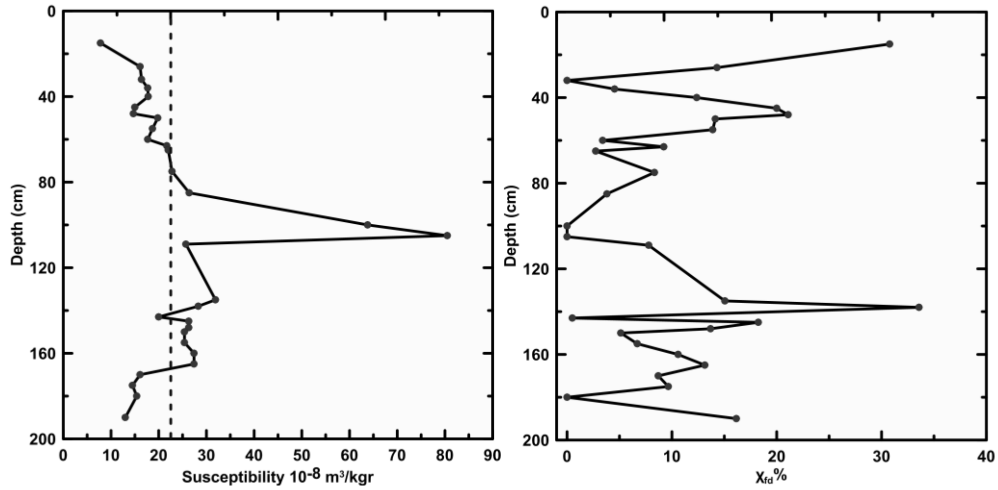

Figure 4 - Magnetic susceptibility (χ_{lf}) and frequency dependent susceptibility (χ_{fd}) variations with depth, recorded from the sedimentary sequence at the Mikro Eptamilon Cave (location is shown in Fig. 2b).

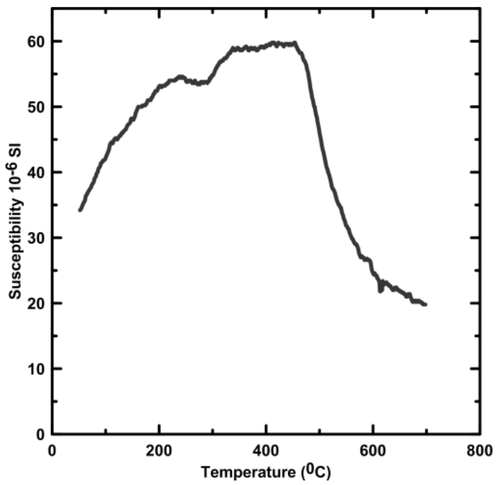

Figure 5 - Variation of the magnetic susceptibility with temperature.

5. Discussion

As it is well known, magnetic susceptibility shows enhanced values in the buried archaeological human occupation layers. As it is reported by several authors (e.g. Dalan 2006, 2008) this enhancement is due to an increase in fine grained magnetite or maghemite.

Similar behaviour it is observed in the case of Maronia Cave. The variation of the magnetic susceptibility across the two cores from this cave records the anthropogenic influence on these sediments. Three evident picks are observed in both cores and they exhibit a clear correlation (Figure 3, grey zones). These enhanced layers are related with the human occupation that took place inside the cave. Archaeological findings confirm the existence of different occupation levels dating from Neolithic period until 13th century A.D. Several authors have been led to similar conclusions in archaeological trenches. Aidona et al., (2001) reported that enhanced values of magnetic susceptibility could correlate with the habitation layer of the studied settlement, indicating that magnetic susceptibility measurements are capable of distinguishing the archaeological layers of the site from those where the complex was abandoned and provide additional evidence for the occupation periods of the complex. Additionally, Dalan (2008) identified a buried archaic soil layer by its correlation with high values of susceptibility. Sediments depicting lower magnetic susceptibility values were not influenced by human activities in the Maronia Cave and have likely been deposited under infiltration and fluvial processes.

The variation of the magnetic susceptibility in the sedimentary sequence from the Mikro Eptamilon Cave exhibits a different behavior. All χ values are much lower than the ones from the Maronia Cave as it is shown from the comparison of their mean values (Figures 3, 4). So, it is evident that the sediments deposited in the Mikro Eptamilon Cave are natural and they are not affected by any anthropogenic influence. This is also confirmed by the lack of any archaeological remains in the cave. The observed variability in the magnetic susceptibility (Figure 4) is likely due to changes of the paleoflow inside the Mikro Eptamilon Cave, primarily controlled by climate alterations. During periods of increased flow a larger amount of magnetic minerals is transferred and deposited inside the cave, resulting in higher magnetic susceptibility values. In contrast, during periods of low flow conditions the depositional energy was not capable enough to carry a significant amount of ferrimagnetic minerals (e.g. magnetite). In addition, the presence of rather small magnetic grains (SP grains) at the upper and the lower part of the studied section obtained from χ_{fd} values (Figure 4), indicates low energy conditions. The detected variability in both the magnetic susceptibility and the frequency dependent magnetic susceptibility is also consistent with detailed grain size analysis (Pechlivanidou, et al., 2011) that further support possible changes of the paleoflow.

Moreover, the increased magnetic susceptibility values are considered to indicate warmer paleoclimatic conditions between 85 cm - 105 cm depth, while magnetic susceptibility lows indicate cooler climatic conditions at the upper and the lower parts of the studied sequence. Ellwood et al., (1996) and Šroubek et al., (2001) have also proposed paleoclimatic reconstructions on cave sites from the Mediterranean region based on magnetic susceptibility variations. These variations were attributed to the growth of extremely fine- grained magnetite and/or maghemite formed by pedogenic processes during warm and humid climatic periods and redeposition into the cave sites. As it is known, the magnetic behavior of many minerals varies with temperature. All magnetic minerals have a temperature point (Curie temperature) above which they become paramagnetic. So, when the magnetic susceptibility is recorded continuously with the increase of the temperature (the so-called thermomagnetic experiment) it is possible to detect from the shape of the temperature–susceptibility curves the presence of magnetic minerals which are present.

In figure 5 such a variation of the magnetic susceptibility with temperature is shown. The shape of the curve and especially the decrease observed around 300°C indicates the presence of maghemite. The above indication further reinforces the suggestion of warmer climatic conditions since the formation of maghemite is possibly due to effects of pedogenetic processes on sediments washed into the Mikro Eptamilon Cave area.

6. Conclusions

Environmental magnetism techniques used in the present study proved to be a useful tool for detecting the paleoenvironmental conditions under which sediment deposition took place inside the two studied caves. Both the natural and anthropogenic signal of the cave deposits was detected based on magnetic susceptibility measurements. In the case of the Maronia Cave three different occupation levels were well distinguished from the magnetic susceptibility data, while in the Mikro Eptamilon Cave, the variation of the magnetic parameters were correlated with changes of the paleoflow controlled by paleoclimatic alterations.

In order to complete and reinforce our preliminary results further magnetic analyses are required, such as the estimation of remanence parameters. The most important issue for the continuation of this kind of research is the dating of the sediments with independent dating techniques (e.g. U/Th, 14C dating techniques). Being able to correlate magnetic variations with marine oxygen isotope stages as well as with archaeological data, will lead us to safer conclusions regarding the past environmental changes imprinted on cave sediments.

7. Acknowledgments

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