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PRELIMINARY STUDY ON THE MAGNETIC SUSCEPTIBILITY OF SEDIMENTS IN CAVE C6-1 OF DAK NONG UNESCO GLOBAL GEOPARK

Luu Thi Phuong Lan[a], Le Xuan Hung[b*], Ellwood Beresford Brooks[d], Nguyen Chien Thang[a], Nguyen Thanh Dung[a], Dao Van Quyen[a], Nguyen Ha Thanh[a], Nguyen Thi Mai[a], Nguyen Trung Minh[c], La The Phuc[c]

[a]*Institute of Geophysics, Vietnam Academy of Sciences and Technology, Hanoi, Vietnam*
[b]*The Faculty of Literature and History, Dalat University, Lam Dong, Vietnam*
[c]*Vietnam National Museum of Nature, Vietnam Academy of Science and Technology, Hanoi, Vietnam*
[d]*Department of Geology and Geophysics, Louisiana State University, Louisiana, USA*
[*]*Corresponding author: Email: hunglx@dlu.edu.vn*

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Abstract

The magnetic susceptibility (MS) of cave sediments has become a proxy for the paleoclimate. The magnetic properties of the sediments formed outside the cave are influenced by the weather. The sediments are later brought into the cave by various means and deposited. Thus, the MS in the stratigraphic column of cave sediments carries information about the weather when the sediments formed. The stratigraphic column at cave C6-1 has been investigated in several archaeological studies. In this study, 185 soil samples were collected to a depth of 184 cm at a sampling interval of about 1 cm. MS measurements were carried out by the Department of Geomagnetism at the Institute of Geophysics of the Vietnam Academy of Science and Technology. The MS results can be divided into eight magnetic zones, C6.1-1 to C6.1-8, of which C6.1-1, C6.1-3, C6.1-5, and C6.1-7 correspond to cold dry weather, and C6.1-2, C6.1-4, C6.1-6, and C6.1-8 correspond to warmer weather. Multi-Taper Method (MTM) analysis of the MS data shows three significant cycle ranges with MTM confidence levels above 95%. Using the carbon-14 radiocarbon dating method, we determined ages for three weather cycles of 562, 375, and 281 years. From 6,768 to 6,954 years BP, there was a sudden accumulation rate of sediment in the section that was 5 to 30 times higher than in other periods.

Keywords: Cave C6-1; Dak Nong Geopark; Magnetic susceptibility; Paleoclimate; Volcanic caves.

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1. INTRODUCTION

In recent decades, the study of magnetic susceptibility (MS) of cave sediments has allowed researchers around the world to prove that the changes in MS values are caused by changes in climate (temperature and humidity) (Ellwood et al., 2001, 2004, 1988, 1996). This is proven by the evidence of cave sediments that formed outside the cave in the open-air soiland in direct contact with bacteria in the environment. Weather is an environmental factor that directly affects the magnetic properties of sediment through bacterial activity. The signs of external cavernous MS of the sediment continued to be preserved during the formation process inside the cave. The stratigraphic column of the sediments now preserves the residue of the climate, through the value of MS, these sediments are the source of the MS data set. Changes in MS values and increasing or decreasing trends in MS are the basis for comparing sections of sedimentary layers that have similar ages. This increase and decrease in MS values also indicate trends in paleoclimatology.

In conjunction with a group of scientists from the United States, the study of climate-related MS of cave sediments has been conducted for many years in Vietnam (Lưu et al., 2009, 2010; Luu & Nguyen, 2015). Lưu et al. (2009) found the Younger Dryas cycle and other hot and cold climate periods from MS data at Con Moong cave (Thanh Hoa Province).

Cave C6-1 belongs to the volcanic cave system of Dak Nong UNESCO Global Geopark and was formed during the eruption and solidification of basalt lava. The sediments in the cultural layer of cave C6-1 have a very large range of particle size. The sediments are mostly coarse crumb, except for a few rocks of vesicular basalt that fell from the ceiling. The rest are mainly materials created by toolmaking, including stone cores, tools, flakes, and chips (with basalt as the main component, but also siltstone, quartzite, and quartz), ceramic fragments, fragments of animal bones and teeth, and mollusk shell fragments. The fine-grained sediment has sand, clay powder containing mollusk shell fragments, coal ash, and bone fragments of all kinds (La, Tachihara, et al., 2018). The sediments of the cultural layer are of anthropogenic origin; the prehistoric cave dwellers brought these items into the cave. The items are mainly raw materials purposefully brought into the cave to make tools, remnants of plants, animals, and mollusks that were food items, and foreign substances such as mud that were inadvertently carried in. Minor secondary sources include seepage from the ceiling to the cave floor and dust floating into the cave. This paper introduces the MS data obtained from a stratigraphic column in volcanic cave C6-1 in Dak Nong Global Geopark. Through the documentation, we will introduce the initial MS results obtained from the stratigraphic column in the C6-1 volcanic cave, MS cycles, and related weather cycles.

2. OVERVIEW OF THE RESEARCH LOCATION

2.1. Geological features in the study area

Dak Nong UNESCO Global Geopark covers an area of 4,760 km² stretching across five districts: Krong No, Cu Jut, Dak Mil, Dak Song, Dak Glong, and the city of Gia Nghia in Dak Nong Province. In the geopark area, geologists have discovered (and located on the map) 50 volcanic caves (Figure 1) of which 12 contain traces of prehistoric people (La, Lương, Phạm, Bùi, et al., 2020; La, Lương, Phạm, Phạm, et al., 2020).

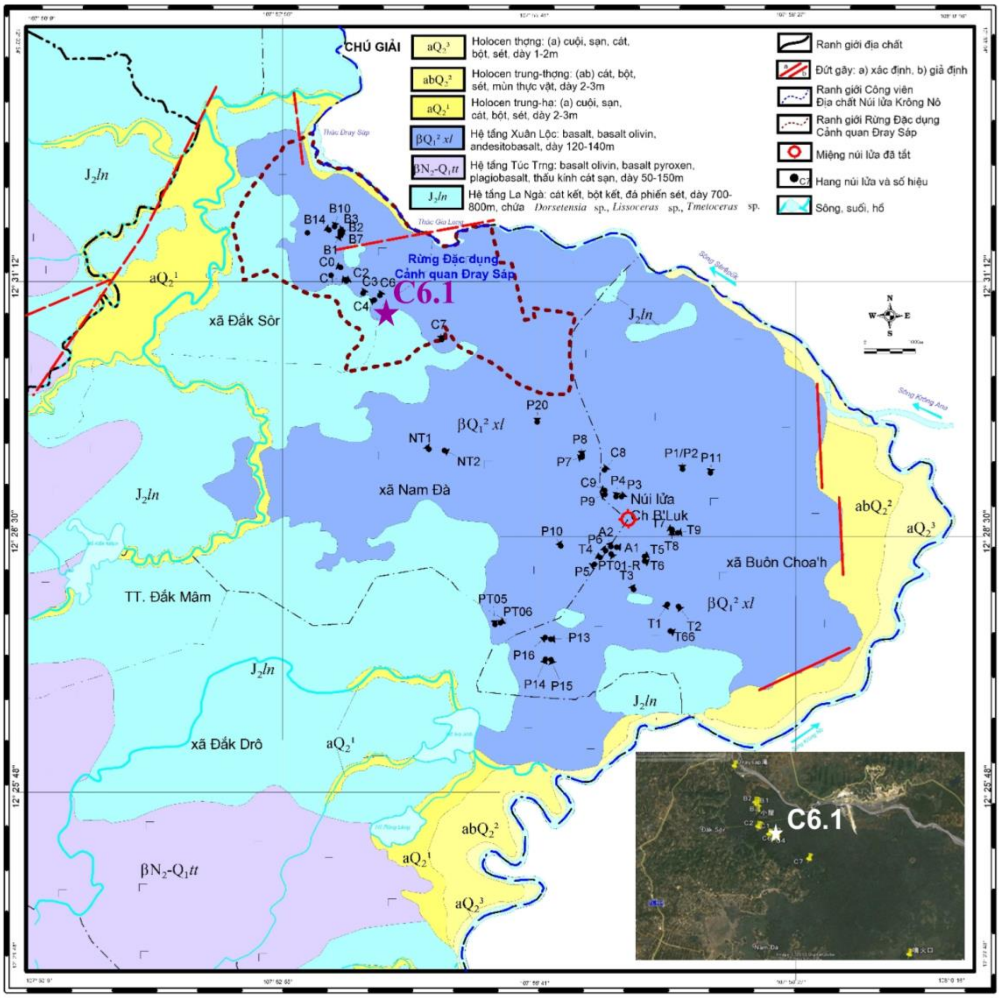


Figure 1. Location map of cave C6-1 at Krong No (Dak Nong)

Source: La, Lương, Phạm, Bùi, et al. (2020).

The geological formations exposed on the surfaces of the caves in Dak Nong Global Geopark are relatively simple and include the La Nga, Xuan Loc, and Tuc Trung formations. The La Nga formation (J_2ln) is spread across a large area in the west and is exposed in some small areas of the cave. This formation is mainly composed of terrigenous sediments. The second formation is the Xuan Loc formation (β/Q_1^2xl), which is widely distributed in the central area (Figure 1) and is mainly composed of basalt. Quaternary formations are distributed in a fairly wide area along rivers and streams in the southeast and most northern parts of the cave area. They are mainly composed of gravel, sand, and clay of alluvial origin, about 5 to 6 meters thick. The sediments form levels I and II of the Serepok River basin at an elevation of 3 to 10 meters. In addition, basalt belonging to the Tuc Trung formation (βN_2-Q_1*tt*) is present on the western and southwestern edges (Nguyễn, 1989). The system of volcanic caves is distributed in the Xuan Loc formation.

The compact basalt and the local river and stream pebbles were preferred by prehistoric people as raw materials for making tools for survival. Weathered clay and kaolin clay are the raw materials that prehistoric people used to make pottery.

2.2. Some cave features related to archaeological sites

Typical of the craters of this region is Chu B'Luk volcano (at 601 meters above sea level and with a throat depth of about 63 meters) in Buon Choah commune, Krong No district. The caves here are directly related to the eruptions of the Chu B'Luk volcano (Xuan Loc formation) and are scattered around the crater in the communes of Dak Sor, Nam Da, Dak Ro, and Buon Choah in Krong No district, Dak Nong Province (Figure 1). Most of the volcanic caves with traces of prehistoric man have a secondary-type cave entrance. The front of the cave entrance is often cluttered with basalt rocks as a result of cave collapse.

In the history of human habitation, limestone caves are considered the ideal home for prehistoric humans. In Vietnam, the earliest fossil remains of *Homo erectus* were discovered in caves at Tham Hai and Tham Khuyen, which date back to about 0.5 million years ago. The most common inhabitants of limestone caves were people of the Neolithic period. Nearly 200 cave relics exist, distributed mainly in the north and north-central regions of Vietnam (Lê et al., 2018).

The detailed survey results of 21 out of 50 Krong No caves show that most of the caves are over 200 meters in length and have open entrances preventing suffocation. This is a favorable prerequisite for prehistoric humans to choose as a permanent residence. Of the 12 caves containing cultural relics of prehistoric people, two excavated caves belong to the "C" cave system. The relics found here indicate places of residence, burials, toolmaking workshops, and temporary hunting camps (Lê et al., 2018; Nguyễn, La, & Lê, 2018, Nguyễn et al., 2017). These findings and studies have provided perspectives for new research in volcanic cave archaeology and anthropology in recent years in Vietnam(La, Lương, Phạm, Bùi, et al., 2020; La, Nguyễn, et al., 2018; K. S. Nguyễn, Lê, Nguyễn, et al., 2019; K. S. Nguyễn et al., 2018; K. S. Nguyễn, Lê, et al., 2020; K. S. Nguyễn, Nguyễn, Lê, et al., 2020; K. S. Nguyễn, Nguyễn, Nguyễn, et al., 2020; L. C. Nguyễn, 2018; L. C. Nguyễn, 2020; Nguyễn et al., 2021), etc.

The typical feature of caves with traces of prehistoric inhabitants is the cave entrance. It is often of the secondary type: easy to climb up and down, wide and airy inside, having high ceilings, enough light, and facing mainly the south and southwest. Caves often have many entrances and branches so as to be "hard to attack, easy to defend." The caves here are often near a source of water. The rivers and streams all flow to the Serepok River, where there is not only an abundant source of stones for toolmaking but also rich aquatic food resources and, especially, a source of drinking water for cave dwellers.

3. RESEARCH METHODS

3.1. MS of cave sediments

MS is one of the methods to assess paleoclimatic variation from sedimentary deposits in caves. This method operates on the principle of measuring the MS of sediments deposited in caves by depth in the intact stratigraphic column.

All materials become magnetized when placed in a magnetic field, and MS is a measure of the strength of this magnetism within a sample. In a geoarchaeological context, MS is considered an indicator of iron mineral concentration. Essentially, all mineral grains are susceptible to magnetization in the presence of an external magnetic field. MS is a function of the concentration and composition (mineralogy and grain morphology) of the magnetizable material in a sample (minerals, particle size, and shape).

The magnetic matter present in cave sediments includes not only ferromagnetic minerals that can form residual magnetism, but also any compounds containing Fe^{2+}, Fe^{3+} or Mn^{2+} ions, compounds with odd numbers of electrons, and paramagnetic and diamagnetic substances. The paramagnetic component can make up a large proportion of the material, but it plays an insignificant role because its MS has a very low value. In contrast, magnetite and maghemite minerals play an important role. Although they account for a small percentage, their MS values are very strong.

MS (χ) is defined as the ratio of the induced moment (M_i) to the intensity of the applied magnetic field (H_j) when the field is of low intensity $M = \chi_{ij} H_j$.

MS levels measured in cave sediments are mainly due to maghemite and magnetite generated in soil by bacterial activity and introduced into the cave by many sources, including soil erosion, human activity, animals, and wind (Ellwood et al., 1997; Maher, 1998; Tite & Linington, 1975). These climate-affected sediments are then deposited and preserved in caves.

Caves and deep rock shelters are ideal for MS studies of the paleoclimate because the sediments are not altered by post-depositional bacterial activity due to their isolation in caves, an environment that is not favorable for the growth of bacteria. Thus, the cave sediments record climate changes through variations in the rate and intensity of MS formation that occurred outside the caves.

The advantage of the MS method is that the sample is measured in mass form; therefore, it is easy and fast, with a high level of accuracy. Because of its ability to sample densely and continuously, MS allows the recovery of highl resolution weather cycles, even inplaces that have no evidence of spores and pollen or archaeologycal sites.

The sediments deposited in cave C6-1 mainly originated outside the cave and were affected by changes in climate that altered the magnetic properties of their minerals. After the sediments were transported into the cave by humans, animals, wind, rain, etc., they were deposited and preserved in the stratigraphic column. The sediments were not altered by bacterial activity after deposition due to the absence of sunsight in the cave. They recorded the climate as a result of variations in the rate and intensity of sediment formations. Cave sediments are therefore ideal for MS studies of paleoclimatology.

3.2. Sampling, preliminary processing, measurements, and results

3.2.1. Sampling process

The research area is located in Nam Tan village, Nam Da commune, Krong No district (Dak Nong). Cave C6-1 has coordinates of 12º30'47.6" N and 107º54'06.2" E and is at an elevation of 346 meters above sea level. Cultural relics are mostly found at the main cave entrance, whose width and height are 15.0 meters and 3.2 meters, respectively. The entrance of the cave is flat, wide, airy, full of light, and slopes slightly inward. The arch structure is quite stable, and it is easy to enter and leave the cave (Lê et al., 2018; K. S. Nguyễn et al., 2020).

The cultural layer of cave C6-1 is intact with a thickness of 1.84 meters. Based on the texture and color of the sediments in the stratigraphic column, we divide the cultural layer into eight layers, numbered in order from top to bottom (Figure 2). Many organic samples were taken from the cultural level and dated using the C^{14} radiocarbon dating method at the Radiocarbon Laboratory of the RAS Institute of Geography (Russia) and the IGAN Laboratory of the Center for Applied Isotope Research at the University of Georgia (USA). The radiocarbon results show that the cave was occupied from 6,954 to 5,391 years BP.

A total of 185 MS samples were taken from the archaeological excavation pit along the east wall of the cave, from the earliest layer (the original cave floor) to the latest (the current cave floor) (Figure 2). High sample density (1 cm/sample) serves the purpose of studying the change of MS over time. The sample order is graded from 0 at the bottom of the excavation pit (the original cave floor) to 1.84 meters (the current cave floor). Sampling according to the section of archaeological excavations helps define the radioactive isotope of carbon (C^{14}) and the cultural relics of the prehistoric inhabitants. To avoid interference, samples are mainly taken of soil, avoiding nonmagnetic materials such as snail shells, mussels, animal bones, tree roots, charcoal, etc.

L1: Brown and dark-brown soil, porous soil texture, much laterite gravel.

L2: Gray and white soil; soft, smooth, porous texture with many shells.

L3: Red-brown soil mixed with laterite lumps; this layer is porous.

L4: Dark-gray, fine, soft soil containing ash, many mollusks, interspersed with sparse kaolin particles.

L5: Gray-brown soil with much kaolin, little weathered rock, and red-brown weathered basalt, with burnt soil, loess, with nonporous texture.

L6: Soil mixed with weathered basalt, kaolin, and solid dark-gray soil. However, kaolin and basalt do not form a seam.

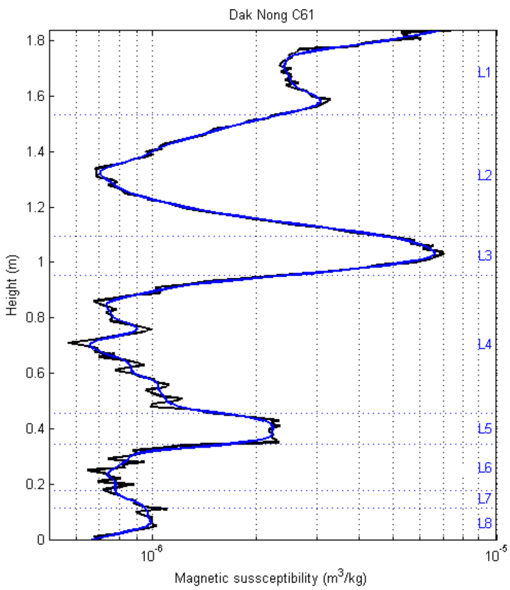
L7: Divided into two layers: the upper layer is dark gray like L8; the lower layer is a weathered basalt rock seam mixed with some kaolin.

L8: Dark-gray soil mixed with kaolin, white weathered basalt of nonporous texture mixed with coal ash.

Figure 2. Section for MS samples collected from cave C6-1, Krong No (Dak Nong)

3.2.2. Pre-treatment, measurements, and results

The whole process of preparing and measuring the MS samples was conducted at the Geomagnetic Department of the Institute of Geophysics, Vietnam Academy of Science and Technology. The samples were dried naturally at room temperature, and then sieved through copper sieves with a grid spacing of 1 mm to remove plant roots, snail and bone fragments, and carbonate particles. Sieves made of nonmagnetic copper were used to ensure that no additional error is introduced into the samples. MS was determined relative to mass. The average mass of each sample was determined from three measurements. Each sample was measured three times with a Kappabridge MFK1-B magnetic susceptibility meter manufactured by AGICO (Czech Republic). The MS values of the 185 samples are shown in Figure 3.



L1: Brown and dark-brown soil, porous soil texture, much laterite gravel.

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L8: Dark-gray soil, mixed with kaolin, white weathered basalt of nonporous texture mixed with coal ash.

Figure 3. Magnetic susceptibility versus height from the original cave floor

4. RESULTS

4.1. Time series analysis

Time series analysis of the data is performed on the initial data χ for the sample of the entire cross-section. Essentially, the samples are equally divided and initially assumed that the distances are even and relatively linear to time. That is, Δx is proportional to Δt. Therefore, analysis methods can be used variously. This assumption is often incorrect, as variations in the sediment deposition velocity or other factors result in more errors in the graph spectrum and spectral peaks (lower energy) are less defined.

After the raw data was obtained, the spectral intensities of the dataset were collected using Multi-Taper Method (MTM). The proportion of statistically significant peaks (at 90, 95, and 99% confidence limit) in the resulting spectra was determined using the MTM(Ghil et al., 2002), calculated using the SSA-MTM toolkit (Dettinger et al., 1995). MTM are capable of dealing with datasets with high-frequency characteristics. The approach taken is as follows: (1) collect samples at short regular intervals in the field, (2) apply confidence limits to the MTM data, and (3) establish a standard model using bar logs that can then be compared with the period χ as a check for the constancy of the sediment deposition rate and for sediment discontinuities. These three factors provide a rigorous and reliable assessment of time series datasets.

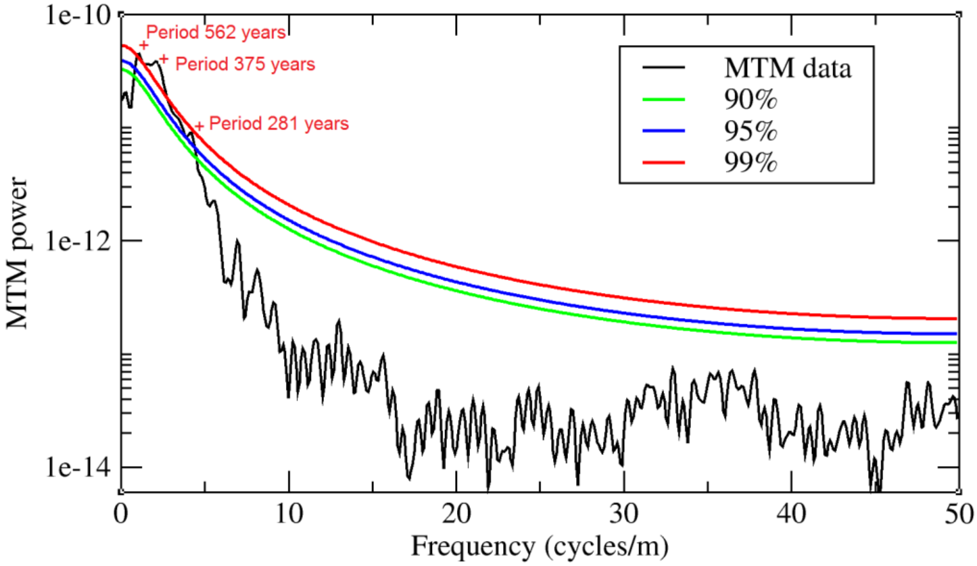

Figure 4. Results of time series analysis by the MTM

MS data, processed by the data smoothing technique (blue line in Figure 3), were used in MTM calculations. The results of the time series analysis are presented in Figure 4, where three major peaks are identified. By extrapolating the age range from the absolute age data obtained at the section, the study period of the section is found to be about 2,200 years (from 4,857 to 7,104 years BP). From this, we determine that the three MS cycles correspond to three overlapping weather cycles of 562, 375, and 281 years and that these three cycles have a high confidence level of 95% (Figure 4).

4.2. Magnetic zones division

To clarify the MS variability, we represent MS value: $\delta_{MS} = (MS_{measure} - MS_{standard})/MS_{standard}$, with $MS_{standard} = 4.5 \times 10^{-7}$ m^3/kg being the average MS value of about 5,200 samples collected in caves of relative age around the world. In Figure 5, the black line represents the raw δ_{MS}, and the blue line represents the δ_{MS} processed by the data smoothing technique.

Based on the fluctuation of δ_{MS} data, we divide the magnetic regions of this data set using the principle that an inflection point will exist (i.e., the second derivative will be 0) for each region of the data. Figure 5 shows the division of the magnetic zones for the studied section at the C6-1 volcanic cave in Krong No. In the figure, we can see a difference between cold dry regions and warmer, wetter regions. The four cold dry zones are C6.1-1, C6.1-3, C6.1-5, and C6. 1-7 (shown in blue), and the four warmer, wetter ones are C6.1-2, C6.1-4, C6.1-6, and C6.1-8 (shown in red). The cold dry zone of C6.1-5 is subdivided to show more detail. There was a short period when the weather became warmer (C6.1-5-2) between the two colder and drier periods: C6.1-5-1 and C6.1-5-3.

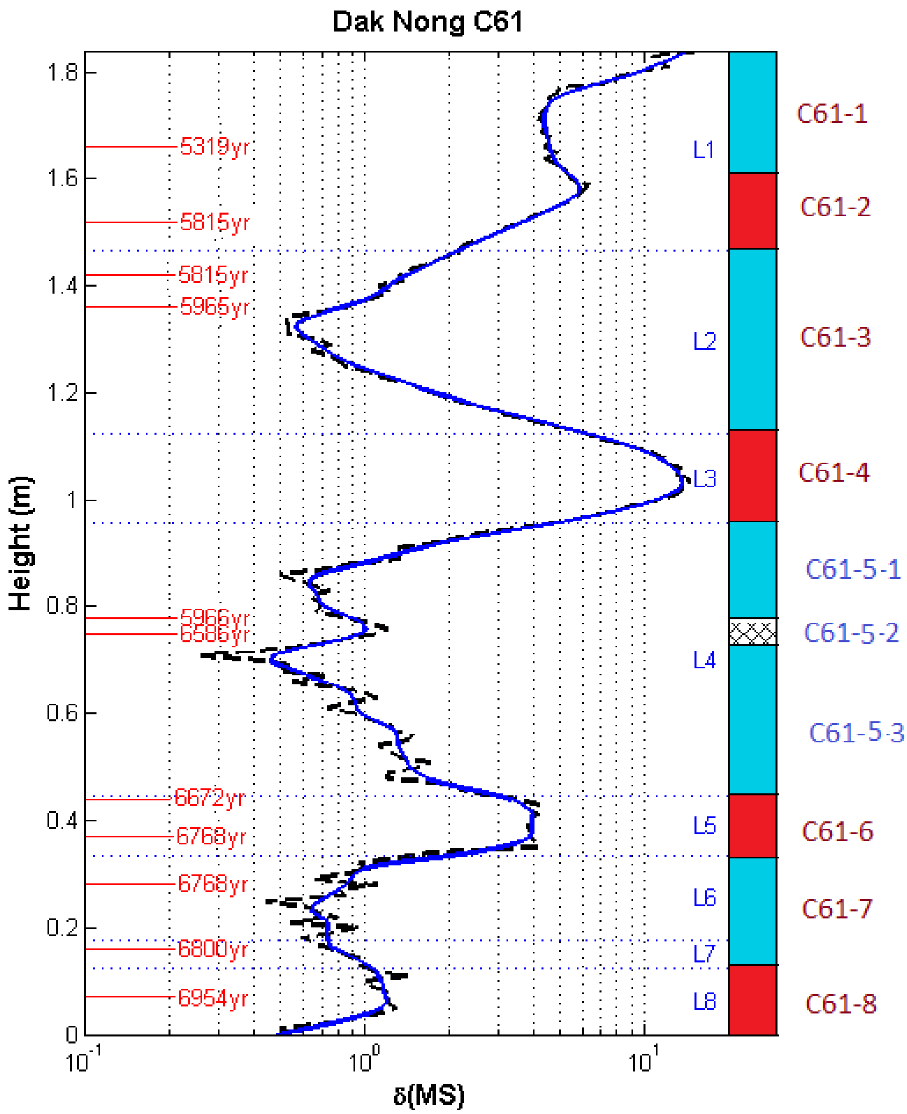

Figure 5. Division of magnetic zones in volcanic cave C6-1

4.3. Thermomagnetic susceptibility measurements

Seven samples with different MS values, C61-2, C61-36, C61-87, C61-105, C61-135, C61-160, and C61-182, were analyzed for thermomagnetic susceptibility magnitude at the Department of Geology and Geophysics of Louisiana State University (USA) to determine the composition of the magnetic minerals in the rocks (Figure 6).

All of the heating curves have a peak at about 225-250ºC, which is predicted to be broken goethite, and all samples have a significant decrease in magnetism from 550ºC to ~580ºC, representing the existence of maghemite and very little hematite. We believe that the main magnetic mineral in this section is maghemite.

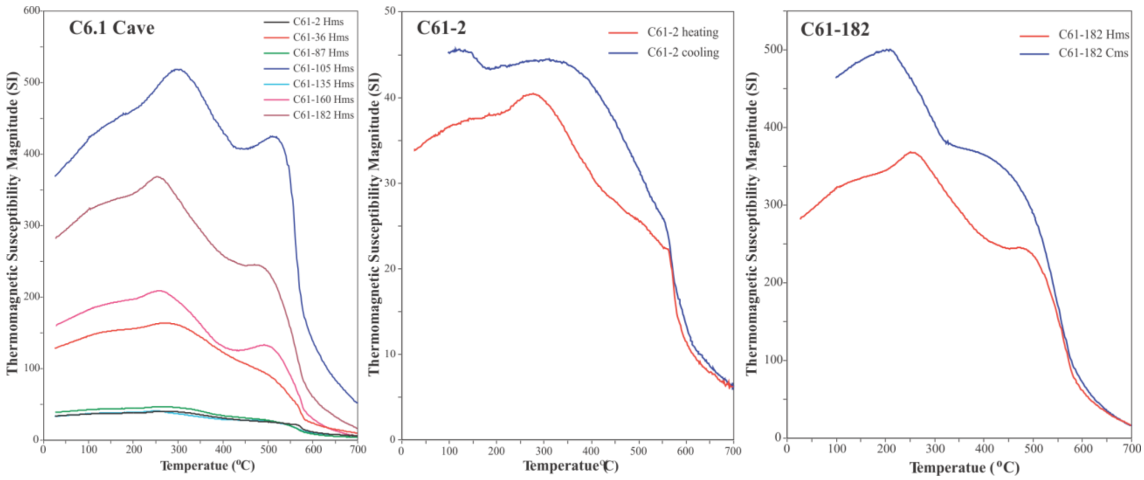

Figure 6. Thermal Kappa curves of seven samples: C61-2, C61-36, C61-87, C61-105, C61-135, C61-160, C61-182

4.4. The sediment accumulation rate (SAR)

Based on 11 isosotope Carbon data ^{14}C measured at the section (Table 1) (Nguyen, Le, Pham, La, & Nguyen (2020), we plot isosotope Carbon ages versus depth Here we only use 11 value C^{14} data (in total 13 values C^{14}) because 2 scattered points (with square icon in figure 7) with insitu distribution are considered to be errors.

Table 1. Age expression by depth (cm)

Depth (cm)	Age (Years BP)
16	5,391
32	5,815
43	5,815
56	5,965
63	5,966
99	6,686
126	6,672
138	6,768
154	6,768
175	6,800
183	6,954

Source: (Nguyễn, Lê, et al., 2020).

Figure 7 shows the change of SARs in the section. Six Lines of Correlation (LOC)s are drawn through the stippled dots, and the resulting calculated SAR is given. The results of SARs show in Table 2.

Table 2. Sediment Accumulation Rate (SAR) Data

Periods	Year (BP)	SAR (cm/1000 years)
LOC1	5,391 – 5,815	38
LOC2	5,815 – 5,965	205
LOC3	5,965 – 6,586	58
LOC4	6,586 – 6,772	226
LOC5	6,772 – 6,800	1113
LOC6	6,800 – 6,954	52

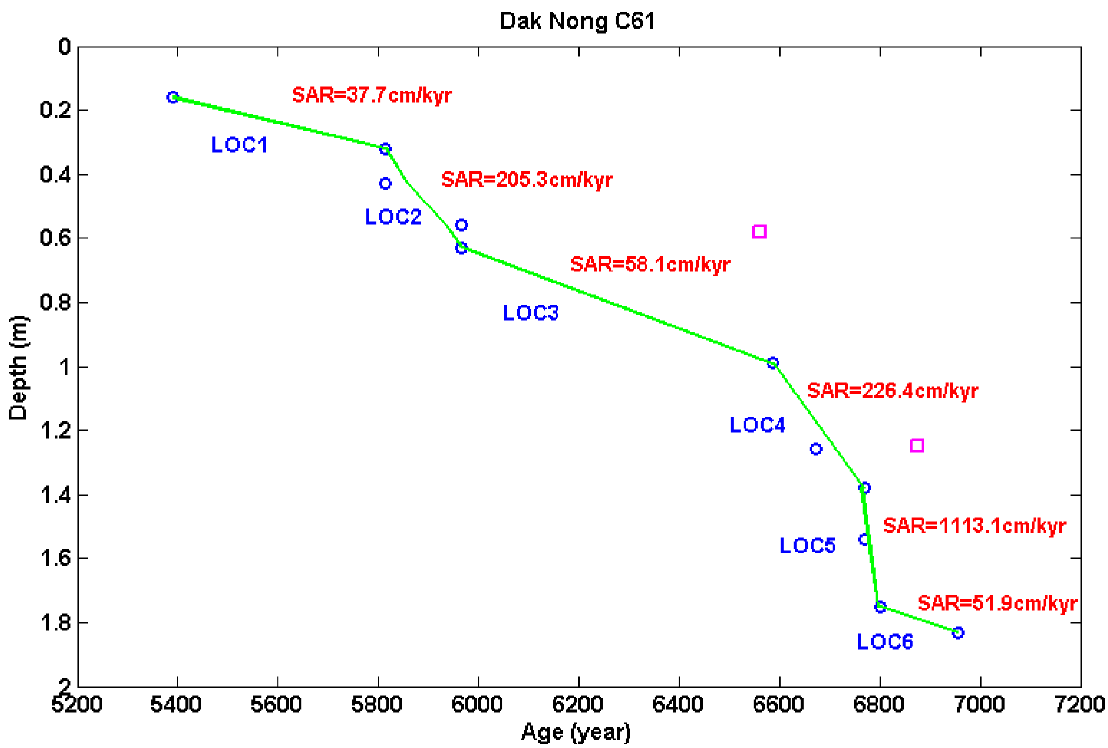

Figure 7. Variation in SAR over time

Fifure 7 show that: in LOC 5 (from 6,768 to 6,954 years BP the sediment accumulation rate increased 5 times (LOC1: 5,815 - 5,965 years BP) to 30 times (LOC 4: 6,568 - 6,768 years BP) compared to other periods (in the BP period) (Table 2).We can explain this based on the increase of rain: increased rain increases the adesion of mud tract in by humans and animals. Moreover, when the rain increases, the amaut of wind also increases, leading to an increase the dust brought in to the cave.

4.5. Prehistoric inhabitants in the previous environment and climate

Cave C6-1 has many favorable factors for continuous habitation by prehistoric people. The cave has a relatively large area, its floor is flat, its doors are wide and facing southwest (this direction receives a lot of light in the afternoon), and a water source is nearby. Cave C6-1 has a fairly stable ceiling, which is an important condition for human habitation. As evidence, the cultural layer in the cave is 1.84 meters thick and contains many fire stoves and food remains. Cave C6-1 is the archaeological site with the thickest stratigraphic column known in the Central Highlands (Nguyễn, Lê, et al., 2020).

Excavation documents show that from an early stage, humans have hunted many large animals such as rhinoceros, bison, wild boar, and deer and have caught and gathered mollusks (snails, clams, and mussels), worms, and crustaceans in the surrounding rivers, streams, and swamps. Later, the hunting targets were usually smaller species, such as monkeys, iguanas, weasels, musk deer, etc. However, the mollusks are almost unchanged, but there are fewer species than in the previous period (A. T. Nguyễn et al., 2019; Nguyễn, Lê, et al., 2020).

Changes in stone toolmaking techniques and the types of tools, the emergence of ceramics and bronze objects, and the change in the composition of terrestrial and aquatic animals, and mollusks that humans hunted and collected show that these changes were adaptations to climate change and the surrounding environment (T. M. H. Nguyễn, 2018). Similarly, the results of the paleomagnetic analysis also show that the cave C6-1 resident community from 7,200 to 4,800 years BP witnessed alternating changes in climate and environment.

5. CONCLUSION

The study of the MS on 185 samples (with a sampling interval of about 1 cm) with the total section depth of 1.84 meters, there were archaeological studies at cave C6-1 allowing us to divide the MS results at cave C6-1 Dak Nong into eight zones. Four zones, C6.1-1, C6.1-3, C6.1-5, and C6.1-7, correspond to periods of cold dry weather, and the others, C6.1-2, C6.1-4, C6.1-6, and C6.1-8, correspond to warmer weather. MTM analysis of the MS data shows three significant cycle ranges with confidence levels above 95%. Using the data set collected with the radiocarbon dating method (C^{14}), we determined three weather cycles of 562, 375, and 281 years. In studying the section of the period from 6,768 to 6,954 years BP, we found a sudden, high sediment accumulation rate 5 to 30 times higher than in the other periods.

In summary, approaching the archaeological research of the Krong No volcanic caves with various modern scientific methods and with peer assistance has improved information on relics and artifacts. Research results of 185 MS samples in cave C6-1 sediment show the change of paleoclimate, impacts and adaptations in the living activities of prehistoric inhabitants in cave C6-1 between the period of 7,104 and 4,857 years BP. The value of the information and documents obtained in cave C6-1 is also an accurate reference for other archaeological sites in the Central Highlands that we have not had the chance to analyze and study.

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