Origin of magnetic particles in speleothems: a review

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Abstract. Soil erosion poses a significant threat to global socio-economic development and environmental conservation. Particularly, karst regions are grappling with severe erosion issues. Recent researches have shown that the concentration and particles of magnetic minerals in cave stalagmites can reflect past soil erosion. This paper summarizes the sources of magnetic mineral particles in stalagmites and the process of their entry into stalagmites, providing basic information for the study of soil erosion in karst areas. The main carrier of magnetism in stalagmites is magnetite. It is mainly derived from the soil overlying the caves. These magnetic minerals migrate from soils and weathered rocks to cave environments mainly by water infiltration, storm water runoff and flooding.

1. Introduction

Soil erosion poses a significant challenge for global socio-economic development and environmental protection efforts. It is projected that soil erosion from global runoff will be more severe than previously anticipated over the next 50 years [1]. Karst regions, in particular, are facing this critical situation, amplifying the need for a comprehensive understanding of the characteristics and patterns of soil erosion within these areas. Owing to the disturbances caused by natural factors and human activities, surface vegetation is destroyed and soil is eroded, which in turn leads to reduced soil productivity and even degradation, and ultimately leads to the occurrence of karst rock desertification. Therefore, understanding the characteristics and patterns of soil erosion in the region is crucial for identifying their underlying mechanisms and predicting future trends.

Speleothems, defined as secondary mineral deposits formed in karst caves, are excellent recorders of soil processes, regional and global environmental and climatic evolution during their growth period [2-4]. With the intensive investigations of stalagmite paleoclimate, cave monitoring and model simulation, some new insights have been gained into the response mechanisms of proxies in stalagmites to the environment. It has been found that stalagmite carbon isotopes ($\delta^{13}C$) are closely linked to the regional environment and can respond sensitively to fluctuations in local climatic environments, including precipitation, vegetation and surface soils, and can record regional land coverage changes, changes in karst hydrological conditions. The effects of human activities on karst ecosystems and surface vegetation can also be quickly reflected in the $\delta^{13}C$ of dissolved inorganic carbon from cave drips. In addition to the traditional indicator of $\delta^{13}C$, recent studies have highlighted the role of speleothem magnetization as a valuable tool in investigating soil erosion, as magnetic mineral particles in stalagmites originate directly from the soil overlying the cave. The transportation of magnetic minerals from soil and regolith to the spelean environment is predominantly facilitated by multiple factors such as water percolation, storm runoff, and floodings [5]. This hydrodynamics, conveying magnetic particles through intricate pathways that culminate in their deposition within cave systems. The magnetic signal embedded in speleothems, originating from these transported minerals, serves as a dynamic recorder of hydrodynamic changes, and most importantly, providing a valuable recorder of soil erosion. The magnetic signal in speleothems may thus act as a sensitive indicator of soil erosion events over time. Numerous studies have shown that the use of stalagmite magnetization can be used to reconstruct the past soil erosion and its associated pedological evolution [6]. Essentially, the study of soil erosion through stalagmite magnetization is a novel way of understanding the intricate interactions between environmental processes and geological formations.

In this study, we comprehensively outline the origin of magnetic particles in stalagmites and reveal the process by which magnetic minerals move from soil to karst systems. By thoroughly investigating the types and sources of magnetic minerals and their mechanisms of entry into stalagmites, this study not only enhances our understanding of soil dynamics in karst landscapes, but also serves as a basis for interpreting regional climate and environmental changes.

2. Magnetic minerals in speleothems

Speleothems contain a considerable amount of magnetic minerals associated with the detrital components originate

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from the soils and rocks above a cave system (Fig. 1). The magnetic properties of cave sediments are largely determined by a range of characteristic minerals, including magnetite, maghemite, hematite, and goethite [7-9]. For example, through detailed analysis of magnetic components analysis using the remanent curves and/or the plot of median acquisition field versus dispersion parameter, Shi et al. (2022) found that the bulk of the magnetic minerals in the stalagmites are of detrital/pedogenetic origin [10]. Further investigation of the magnetic composition revealed the presence of detrital hematite in stalagmites, evidenced by the stable magnetic directions after thermal demagnetization up to 700 °C [11]. Electron microscope observations have shown clear evidence of surface texture changes in ferrimagnetic grains, indicating migration and weathering such as shrinkage cracks and etch pits [12]. These detrital magnetic minerals were released from their parent rock by physical weathering, and then transported by runoff. Subsequently, secondary pedogenic iron minerals were formed in the overlying soils by inorganic precipitation, or possibly mediated by dissimilatory iron reducing bacteria.

Furthermore, the environmental conditions within most cave systems, including factors such as temperature, humidity, pH, and Eh (redox potential), are not conducive to the natural formation of magnetite and hematite. Despite the ongoing discussion about the pH range required for the stability of magnetite [13], the Eh values of dripwater within the majority of karst environments exceed the conditions essential for magnetite stabilization. In contrast, the pH of dripwater in caves, typically ranging from 7 to 8 [14], can facilitate the oxidation of magnetite or the inversion of maghemite to hematite at normal room temperature. Additionally, there is a possibility of goethite precipitation occurring within the caves. Goethite can directly form from any source of iron through solution and accumulate at the expense of hematite and maghemite under relatively damp conditions [14]. The complex combination of these cave environmental factors precludes the formation of specific magnetic minerals, primarily magnetite, that occur naturally in caves. Therefore, it is likely that the magnetite in stalagmites is derived from the surface environment, primarily from the soil (Fig. 1).

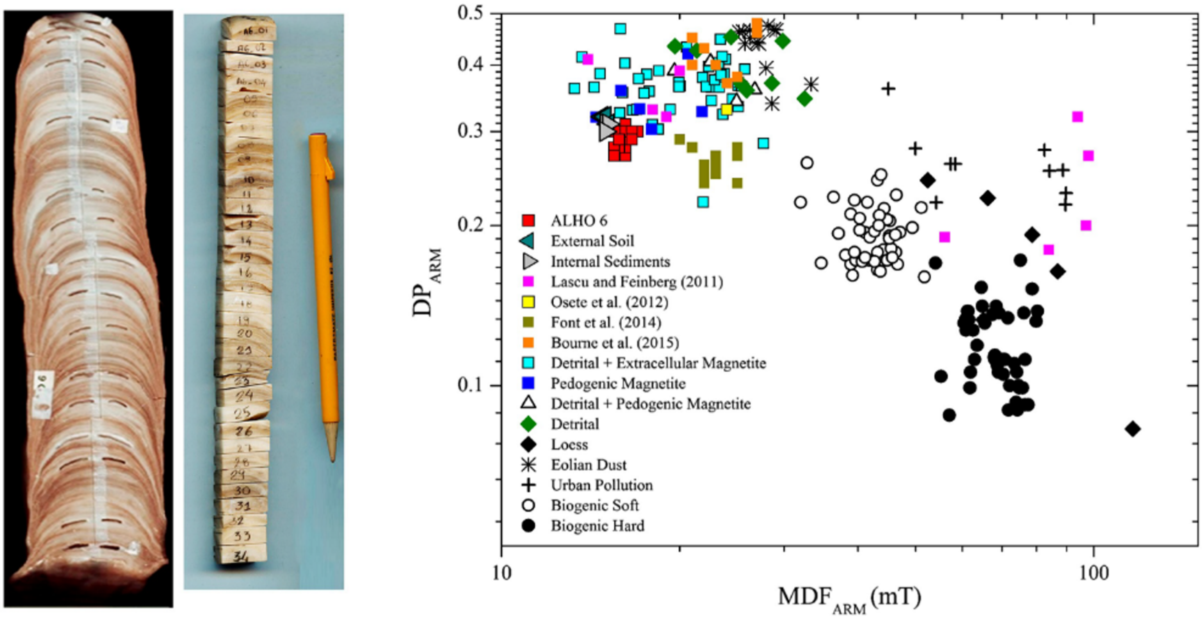

Fig. 1. (left): Half-split photo of stalagmite and samples for analysis measurements. (right): ARM parameters (DP: dispersion parameter and MDF: median destructive field) for magnetite and maghemite in different environments and results for other stalagmites. (Figure are modify from [5])

3. The input of magnetic minerals into speleothems

The dimensions of ferrimagnetic particles residing within stalagmites typically span a spectrum, predominantly clustering within the relatively modest range of 0.1-15 μm. However, interspersed among this majority are sporadic occurrences of larger particles that transcend the centenary threshold, occasionally reaching diameters in excess of 100 μm [12,15]. This variation in size distribution illustrates the complexity and diversity of the ferromagnetic component of the stalagmite matrix, and hints at the hydrodynamic strength of the geological processes. Typically, fine-grained magnetic minerals are steadily fed into the cave environment in suspension under stable climatic conditions, while episodic pulses occur during storms and floods. In contrast, large-grained magnetic minerals and some insoluble residues, such as zircon [16-17], are mainly carried into groundwater by storms and floods. Of course, vegetation and soil types, surface topography and aquifer structure all influence the production and transportation of magnetic minerals. When the climate is humid, the soil has a higher effective moisture content with flourishing vegetation, and soil formation is strong, producing more soil-forming magnetite. Hydrodynamics are stronger at this time, resulting in more magnetic particles entering the stalagmite. However, due to the complexity of the fissures in the carbonate rocks overlying the caves, the pipes may have acted as a filter for the particles if they passed through the bedrock for a longer period of time, which may have resulted in some of the magnetic particles being retained in the pipes. And when the climate is dry, the vegetation is scarce, the root system is weak in fixing the soil, and the karst area is very prone to erosion, leading to a large amount of detrital material into the karst system, and the content of magnetic minerals in the stalagmites increases. Ultimately, these particles are deposited on speleothem surfaces and would be immediately encapsulated by the precipitation of new layers of calcite from the water film covering the speleothem [18] (Fig. 2).

Underground streams could potentially serve as a significant source of magnetic minerals found in flowstone. Particles that are washed down from sinkholes could eventually enter underground streams. In the steady flow of normal conditions, these particles might be suspended and delicately deposit along the flow directions of the underground streams, gradually contributing to the evolving matrix of magnetic minerals within the flowstone formations. And in the case of storms and floods, there is also backwash from the stream water. Thus, in the events of storms and floods, magnetic particles could potentially become integrated into the flowstones as the stream back flushes the cave passages. Alternatively, they might also be deposited on the surfaces of flowstones during the calm stages following a flood. And when floodwaters overflowed the stalagmites in the lower parts of the cave, some of the detrital material may have been retained on the stalagmite surfaces, resulting in a flood layer of unusually high magnetic signals in the stalagmites. In addition, pool water in caves may have been one of the inputs of magnetic minerals to secondary carbonate deposits in caves. Dripping water collects in pools at low points on the cave floor, allowing the detrital material it carries to settle in the pools and form stable deposits.

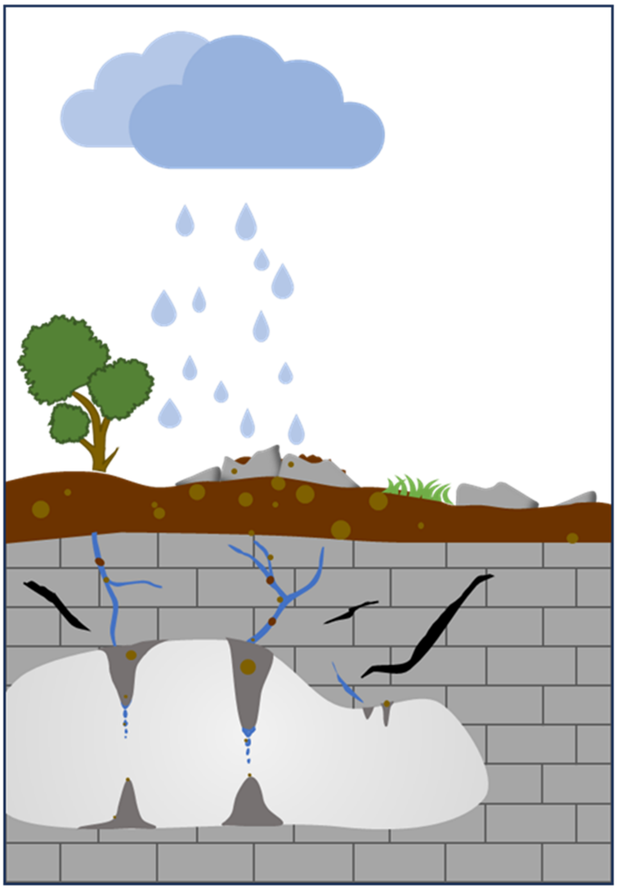

Fig. 2. Concept sketch for the input of magnetic particles into speleothea system

Some research also indicates that aeolian dust may contribute to the introduction of magnetic minerals in stalagmites [19]. During periods of drought, when vegetation is sparse and soils are loose, it provides a source of dusty material for aeolian dust formation, and magnetic mineral particles from basic detritus transported by the wind increase. Greater wind intensity results in the transportation of more magnetic minerals from detritus, leading to an increase in magnetic input. Even if the cave has only a small opening, the cave has ventilation. Especially in winter, cave ventilation is enhanced. This facilitates the wind to carry to the detrital material into the cave, which in turn settles on the stalagmite surface. The opening of the caves to tourism has led to a significant increase in the amount of detritus carried in by the wind.

4. Conclusion

The use of speleothem magnetization as a tool for studying soil erosion is widespread and growing. Progressive advances in the understanding of magnetic signal in speleothems have propelled speleothem magnetization as one of the most efficient methods to reconstruct precipitation, and ultimately soil erosion. This paper aims to offer a comprehensive overview of the origin and occurrence of magnetic particles within speleothems, shedding light on their role as invaluable recorders of environmental processes.

Nodoubtly, the amount, composition and grain size of the magnetic mineral assemblage in speleothems are strongly dependent on geological, hydroclimatic, pedological processes. These factors collectively contribute to the distinctive characteristics of magnetic minerals within speleothems, thus reflecting environmental changes over time. Therefore, for soil and water conservation in karst areas, on the one hand, it is necessary to carry out soil and water conservation projects in small watersheds and strengthen soil monitoring, and on the other hand, it is necessary to carry out environmental protection projects in large areas. It is also important to standardize land-use patterns based on the characteristics of karst areas, which are characterized by thin soils, susceptibility to erosion and limited soil water storage capacity.

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