THE STONE BOOK*

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Abstract. The aesthetic value of a wild and/or tourist cave is well known everywhere. Anyway, presently only few people are aware that caves are the most important natural laboratories, in which it is possible to complete studies and researches that, in some cases, would be impossible in any other place. The caves are normally characterized by low energy and by the absence, or at least scarcity, of perturbing factors characterizing the external environments. Therefore, natural cavities may be regarded as perfect accumulation traps, preserving all the materials falling inside them. In the last half century the importance of cave deposits grew enormously in the field of paleo-environmental and paleoclimatological studies, often allowing to reconstruct the chronology of the events a given environment underwent. From this point of view speleothems are by far the most important cave deposits, because their layered structure is always chronologically ordered and several techniques allow for an easy absolute dating of even a single event. Moreover, all these events may sometimes be restricted to a single year interval (or even less) on the basis of the speleothem growth layers. The speleothem's layered structure makes reasonable to consider each of them a "stone book", where each growing layer corresponds to a "page" of a multidisciplinary encyclopaedia. We are still unable to extract most of the information recorded by them. But in the near future, when we will be able to read all the pages of these "stone books", their scientific importance will grow exponentially.

Key words: Cave deposits, speleothems, applied & theoretical research, paleoenvironmental archives.

INTRODUCTION

Caves are underground environments characterized by a constant total absence of light and often have minimum variations of most environmental parameters (temperature, relative humidity, etc.) and low to very low energy (physical, chemical and biological) flows. The rock walls that separate them from the outside world minimize, or even eliminate completely in some cases, the influence that the external climatic and/or other environmental variations can have on the cave's interior. To summarize the situation, a natural cave is generally a very stable environment, a perfect "accumulation trap" that conserves everything it collects over time (Fig. 1). These characteristics are exploited by most scientific researchers interested in cave environments.

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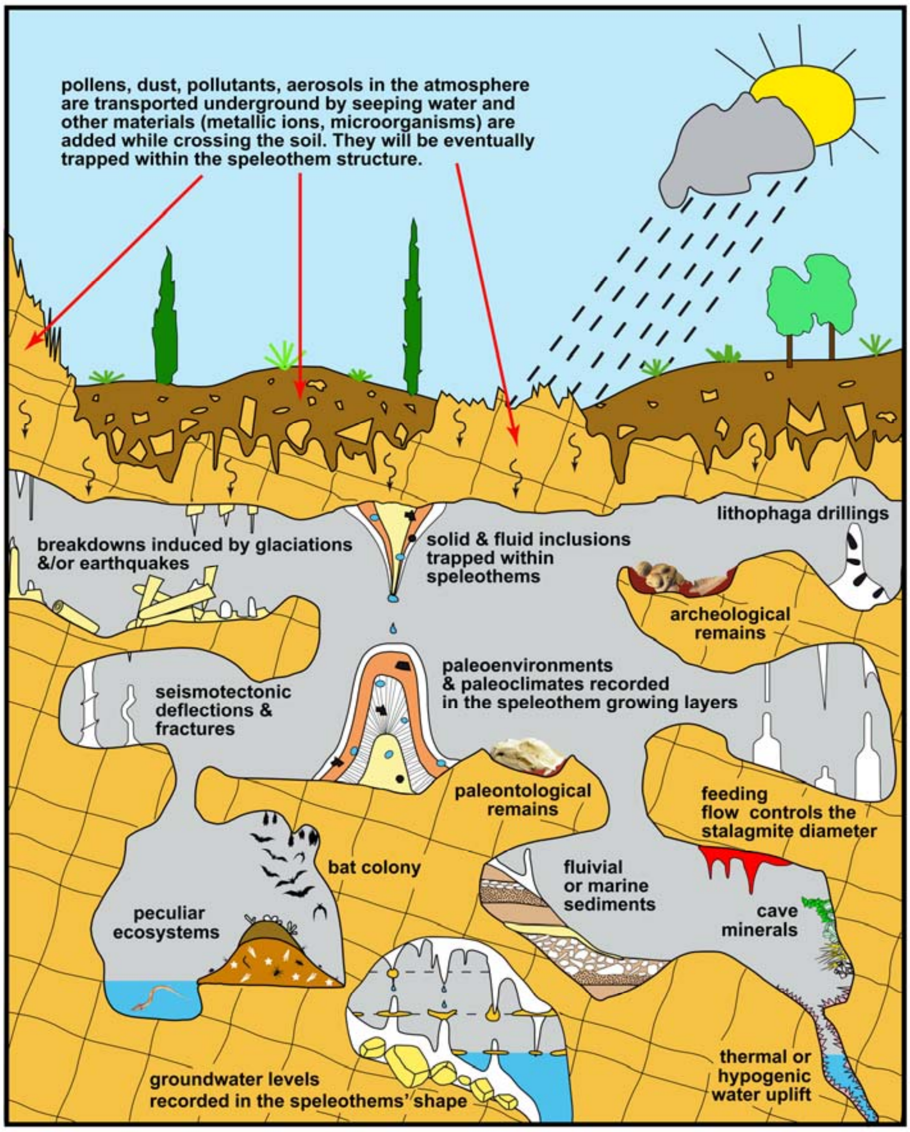

Fig. 1. Sketch of a cave and of the paleoenvironmental data possibly trapped inside.

Within caves it is therefore possible to complete studies that, in some cases, would be impossible in any other place, while others are easier and simpler when carried out in the underground environment. When thinking of a scientific discipline that can take advantage of the cave environment, the first that comes to mind is geology. However, this identification of a cave's scientific interest for geology is limiting, contrary to what one would suppose; other fields have the same scientific interest if not even more.

It would be impossible to give a complete list of all types of research that are effectively being carried out in caves. Here it is sufficient to outline some of the most important ones (Table 1).

Table 1

Main pure and applied sciences interested in cave environments (after Forti, 2009)

Discipline		**Fields of interest**
Archeology		remains, graffiti, rock-paintings
Social Sciences		history, theology, folklore,
Biology		adaptation strategies, microbiology, chemioautothropic environments, astrobiology
Physics		meteorology, climatology
Engineering		large voids, oil deposits, show caves
Medicine		speleotherapy, physiology, psychology, new medicines
Geology	Geomorphology	karst, speleogenesis, paleoenvironmental reconstruction
	Geochemistry	stable isotopes, absolute dating
	Geophysics	earth tides, seismology
	Hydrogeology	karst aquifers
	Mineralogy	cave minerals, low enthalpy processes
	Paleontology	lairs, sedimentation traps
	Sedimentology	clastic sediments, speleothems
	Stratigraphy	stratigraphic sequences
	Structural Geology	structural elements, neotectonics
	Volcanology	lava flow morphologies, deep volcanic structure

ARCHAEOLOGY

Caves have represented an environment of fundamental importance to man for an extremely long period and the use of caves as temporary or permanent homes is still cultivated in some places today (FORTI, 2009). Primitive man has used caves for many different reasons: homes, cemeteries, temples, mines (TANKERSLEY, 1996). Caves form a formidable and often unique archive where it's possible to find evidence particularly relative to the Paleolithic period and also of older or more recent eras. The sacred caves that maintain the most fascinating and important vestiges of prehistoric man with their rock paintings couldn't have been preserved so perfectly in their delicate state until today if cave environments hadn't protected them, not only against atmospheric agents but also from human vandalism.

SOCIAL SCIENCES

Theology should be deeply interested in caves. In fact, the cavern environment has been fundamental for most religions. Some of the most important events in the recent human history are directly linked to caves. For example, caves provided saltpeter for the U.S. war of independence, which was a key in defeating the

English army, while the Cuban revolution had the possibility to grow and to become successful thanks to the caves in La Sierra de los Organos (NUÑEZ JIMENEZ, 1987).

But caves have an even greater importance in the study of the folklore of local populations. Rapa Nui Island is probably one of the best examples. The lives of the inhabitants, since the beginning of their history up to the present, is strictly related to ceremonies performed inside caves. Nowadays, anthropologists have the target of defining the recently developed extra-national aggregations (new tribes) of cavers, caving reunions, and/or associations.

PALEONTOLOGY

A great quantity of animal remains have often been found in caves (GUNN, 2004). Therefore, it was possible to reconstruct a detailed paleo-environment that otherwise would have remained unknown. These remains are either of animals that utilized caves as lairs or of prey animals. Surely the most famous large predator was the cave bear, *Ursus spelaeus*, which shared caves with cavemen, the latter being probably responsible for its extinction. Moreover, the micro-mammals provide a highly precise reconstruction of surface climate variations. Similar studies can also be undertaken with pollen trapped in the same sediments or in speleothems.

BIOLOGY

The cave environment is, in general, hostile to life. Consequently, caves are not highly populated and the animals found there have adapted to the extreme conditions present underground through loss of pigmentation, loss of sight organs, and the lengthening of sensorial organs. Other adaptations include a reproductive strategy, that only provides a small number of fully developed new individuals (CULVER, 1982). Biologists are therefore extremely interested in caves in general and in the study of evolutionary steps induced by the cave environment in particular. Presently, the most advanced cave research is microbiology. It involves the study of some peculiar and important microorganisms, like those related to the sulfur cycle, which give rise to chemioautotrophic ecosystems inside hypogene caves (SARBU *et al*., 1996).

PHYSICS

It is perhaps one of the first sciences to become interested in caves. In fact, in the 1600's there is already a first document published about underground meteorology. At the moment, papers on cave meteorology and climatology have a noticeable theoretic importance (BADINO, 1995, 2000). Above all, detailed studies on underground meteorology are of fundamental importance in the planning, implementing, and managing of tourist caves (CIGNA *et al.*, 2000).

ENGINEERING

Engineering: Engineers are interested in caves for theoretical but mostly practical reasons. Caves allow engineers to verify some of their theories on “empty spaces.” One of the main engineering problems in fact, is relative to the design and excavation of large underground chambers used for many purposes. Excavation of large empty spaces inside a rock mass creates the problem of pressure discharge along the wall and vault. However, caves contain chambers of absolutely enormous dimensions; Sarawak Chamber in Borneo is the largest natural underground span in the world and has dimensions of about 600×400×80 m. Therefore, it’s evident how the study of such structures can be of great help and save a large amount of money. Lastly, engineering has to be considered in the complex field of planning, implementing, and managing show caves. The economic importance of the cave tourism is relevant on a worldwide scale. It provides direct and/or indirect income for 150 million people, especially in still developing Countries (CIGNA & FORTI, 1988).

MEDICINE

The search for natural medicines, like epsomite in the prehistoric age, was one of the motivations for man to explore caves. The materials people looked for in many other cases had more to do with magic than with medical science (stalagmite powder, prehistoric animal bones, moonmilk, etc.). The therapeutic use of thermal caves is very ancient, so much so, that there is a specific term for these particular activities: speleotherapy (TARDY, 1989). In more recent times, East European countries have begun to make widespread use of non-thermal caves in order to cure allergies and infections of the respiratory tract.

Interesting studies that began in the early 1960’s involved temporal space isolation experiments taking place inside caves. The results demonstrated that in the absence of temporal-space reference, the vital body rhythm tends to progressively slow down passing from a daily frequency toward one based on a double cycle (48 h).

One of the last medical disciplines to mention is pharmacology, halfway between medicine and biochemistry. During the last couple of decades, some research groups have begun to make specific investigations in cave environments with the intention of identifying both the active ingredients to use in new medicines, and the organisms that can carry those ingredients inside our body in a selective manner.

GEOLOGY

Practically all the branches of geology extract useful and often exclusive information from the cave world. Stratigraphy can easily take advantage of the vertical caves which go down for more than 2100 meters deep inside geological formations. Structural geology uses caves as a powerful tool to obtain a detailed definition of the structural fabric of an area because speleogenetic mechanisms normally use the already existent discontinuities to develop galleries (JAKUCS, 1977).

Sediments left by cave rivers are often protected and remain unaltered for very long periods of time. It is then possible to carry out sedimentological studies that corresponding surface deposits can't always guarantee. Caves offer vast potentials for mineralogical research, since there are many minerogenetic processes potentially active in caves. Sometimes caves host also minerals exclusive to their environment (HILL & FORTI, 1997). During the last 10 years, calcium carbonate speleothems have revealed to be the best natural archive for the paleo-environmental and paleoclimatic reconstruction of the recent Quaternary, thereby, in some cases, permitting weather resolutions in the order of a solar year.

Geomorphology even has its own specific sector for studying processes, peculiar forms and agents that develop inside the caves (FORD & WILLIAMS, 2007). Geochemists are interested in the study of the chemistry and isotopic composition of speleothems in order to reconstruct environmental conditions at the time of their development, and also to date them.

Geophysicists utilize caves in passive ways, as ideal places for measurements and experiments and in active ways by studying the response of the cave system to physical actions. In the first case, the underground environment appears ideal to investigate physical phenomena that are very subtle when compared to the background noise coming from other natural or anthropogenic processes. One example is the research on earth tides, as it's very difficult to measure the induced gravity variations unless they are recorded inside a cave.

Recent interest in another geophysical field involving caves is seismology and paleoseismology (QUINIF, 1998). It's been verified that caves can be among the most powerful natural registers of seismic waves, especially for relatively high energy events which cause both breakdown and/or deflections on stalagmites' growth axes.

Hydrogeology is certainly the field that shows most interest in caves. Karst aquifers are of great importance as drinking water supplies throughout the world, representing more than 30% of the available drinking water (FORTI, 2009). The peculiarity of karst aquifers derives from their extreme heterogeneity. Fortunately, advanced technologies for the study and safeguard of the karst aquifers have been developing in the last few years. These results would absolutely not have been possible without the regular and constant speleological activity inside caves.

Finally, volcanologists can investigate the morphology and the evolution of lava flows by analyzing lava tubes, magma chambers and other deep volcanic structures.

SPELEOTHEMS: THE LARGEST NATURAL ARCHIVE

It is well known that the most important aesthetic value of a cave is represented by its speleothems. But only a few are aware that they are the most detailed natural archive of our planet (BORSATO & FORTI, 2005). This because all what occurs in a given area is accurately recorded inside the cave formations developed within the caves of that area (Fig. 1).

Therefore, in the last few decades, speleothems became the strongest tool for paleoclimatic and paleoenvironmental reconstructions worldwide (FAIRCHILD & BAKER, 2012), due to the fact that caves, and consequently speleothems, are spread everywhere.

Today speleothems are the most detailed archive for the Quaternary (ONAC & FORTI 2011, FORTI & ONAC, 2014) being sensitive proxies for climate, environment, earthquakes etc., supplying also an easy method for their absolute dating.

The majority of the information is recorded within the speleothem growth layers: environmental data are obtained through high resolution analyses of their morphology, texture, chemical and/or isotopic composition.

Moreover, the speleothem's layered structure allows for an automatic definition of the relative chronology of the observed environmental events (BORSATO & FORTI, 2005): this because the upper layer must always be younger than the lower one.

Even if it is normal that a single layer corresponds to one year, it is impossible to transform directly a relative chronology into an absolute only on the base of the growth layers due to several perturbing factors. The most important of them may be summarized as:

- Stop in the speleothem grow
- Dissolution/corrosion of the speleothem surface
- Diagenesis of the speleothem structure
- Non-annual banding.

The first three of these events may be easily evidenced by a detailed study of the inner structure of the speleothem, but the last one (non-annual banding) cannot be detected.

In general, a frequency of banding higher than annual may be induced by the regimen of seeping water feeding the speleothem: in fact if the speleothem dries up completely, when feeding is restored a new layer forms above the former one. Therefore it is possible that single layers may even correspond to a single rain event (Fig. 2A).

If annual multi-banding may be common, the total absence of layering is extremely rare: in fact, to achieve this effect a absolutely constant composition of the feeding water must be maintained over time: this was the case of the cave pearl (Fig. 2C) grown deep inside the Reforma Mine (Mexico) where the totality of the feeding water came from condensation processes thus its composition was always the same over a very long span of time (FORTI, 2004a).

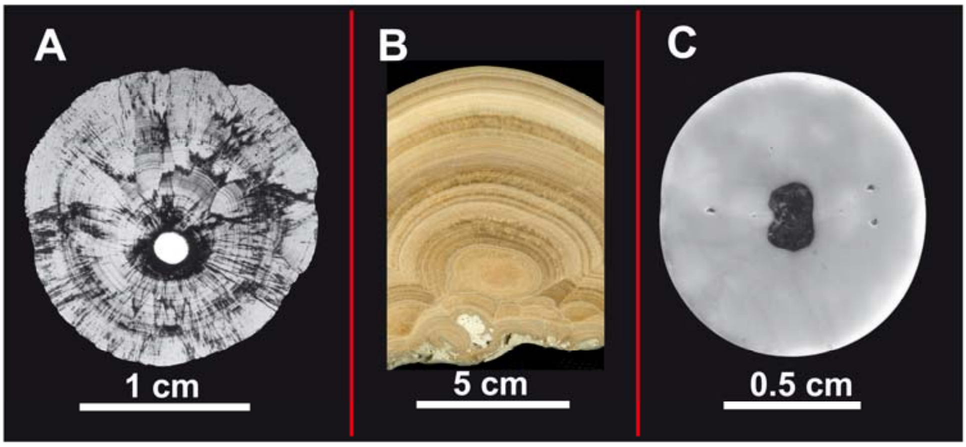

Fig. 2. A) Over 400 calcite layers developed in ~20 years around a nylon thread left inside the Acquafredda gypsum cave, Bologna, Italy; B) Yearly layers of a thick calcite flowstone of Re Tiberio Cave, Italy; C) A ~50-year old aragonite cave pearl developed within an abandoned mine in the Quatro Cienegas (Mexico) completely lacking an internal banding (Photo by P. Forti).

Different methods are available to transform the relative chronology of a speleothem into an absolute one: among them may be cited:

- Paleomagnetism
- C14
- 230Th/234U
- Electron Spin Resonance
- Luminescence.

Each of these methods have specific limits and/or operational problems. From the theoretical point of view the most sensitive method is the one based on luminescence, which is induced by the presence of humic and fulvic acids trapped within the speleothems. Their concentration is controlled by the soil bacterial activity, which, in turn depends on the temperature and the solar radiation.

When luminescence is activated by UV or better laser sources, it is possible to obtain the concentration of fulvic and humic acids in each layer by measuring the relative intensity of their emission. Thus, it is possible to reconstruct in detail the chronology of the speleothem by means of solar cycles and the mean annual temperatures.

The theoretical sensitivity of this method allows for dating within 24 hours, but in reality, there are many factors which practically do not allow such degree of precision over long time intervals (SHOPOV *et al*., 1996, SHOPOV, 2005).

SPELEOTHEM SHAPE AND PALEO-RECONSTRUCTION

Sometimes just the presence of “normal” speleothems testifies that the cave underwent a sudden variation of some environmental parameters. This is the case of the presence below sea level of submerged gravitative formations (e.g. stalactites and stalagmites) and/or the presence of lithophaga drillings over vadose speleothems. The detailed study of their inner structure (with the possible presence of hiatuses and/or layers of submarine deposition) in several caves along a seashore, may allow to define in detail the evolution of the sea level in a given area (ANTONIOLI *et al*., 2004, ANTONIOLI 2005).

Moreover, a sudden variation of the external and/or internal shape of common speleothems sometimes can be a proxie of climatic changes in the area in which they developed.

A classic example is given by the sudden changes in the stalagmite diameter (Fig. 3), which is controlled by a single factor: the amount of feeding water (FRANKE, 1965). If the diameter variation occurs in all the stalagmites of a cave (or, even better, of several nearby cavities), this general phenomenon may easily been related to variation of rainfall occurring in that area and therefore to a climate change.

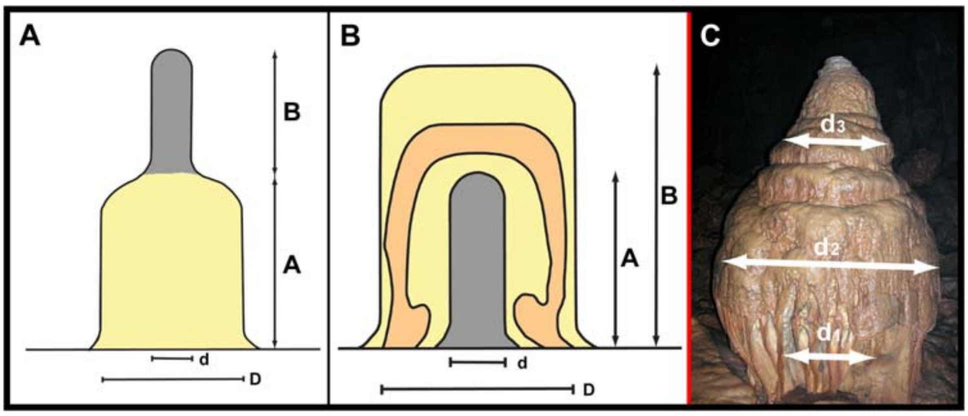

Fig. 3. Effect of sudden increase (A) or decrease (B) of feeding water on the stalagmite diameter; C) Stalagmite in Impossible Cave (Trieste, Italy) showing clear evidences of variation in water supply (Photo by P. Forti).

Sharp alternations of thin clay-silt layers overgrowing calcite layers within a speleothem may be produced by soil denudation, and consequent strong erosion, induced by different natural and/or anthropogenic causes. But if the phenomenon interests the whole karst area and there is always a clear discontinuity between the calcite layer below and the silt layer, while the deposition of calcite restarted progressively over the silt it strongly suggests that the strong erosion occurred just at the beginning of an interglacial. An example of such phenomenon is given by the “telescopic” stalactites of Postojna cave (JAKUCS, 1977).

SPELEOTHEMS AND EARTHQUAKES

Speleothems may record strong earthquakes occurred in the last million year, allowing also the evaluation of their magnitude, thus representing the best tool for a correct evaluation of the seismic hazard of non historical erthquakes. All these data may be extracted from broken speleothems and still standing stalagmites (FORTI & POSTPISCHL, 1984).

It has been proved that, if a statistical analyses filter out local perturbing factors, then within a still standing stalagmite structure, sudden changes in the verticality of the stalagmite's growth axis and/or sharp variations in the texture, color and chemical composition in its layered structure can be the consequence of a seismic shock, while peculiar breakages of stalactites and stalagmites (Fig. 4) can be induced by the resonance effect of seismic waves on their crystalline structure.

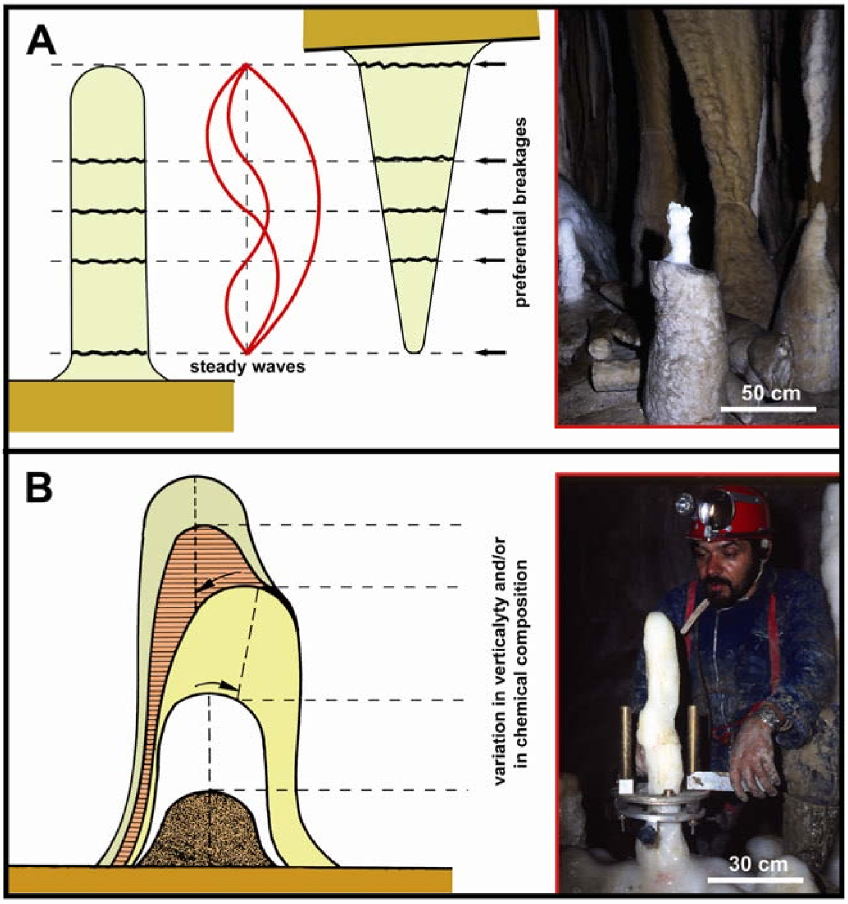

Fig. 4. A) Resonance-induced breakdowns of speleothems caused by strong earthquakes (Grotta dei Cervi, Pietrasecca, Italy); B) Earthquake induced tilting of a still standing stalagmite (Frasassi Cave, Italy) (Photo P. Forti).

Such studies are of practical value as they supply seismic information on the cave area over the last 600,000–800,000 years (FORTI, 2001, 2004b). Therefore, they enhance the evaluation of the seismic risk that otherwise would have to be calculated on a historical period that is absolutely insufficient if compared to geologic time.

SPELEOTHEMS AND GLACIATIONS

During ice ages some caves were filled by ice tongues, which caused specific breakages of the eventually present speleothems (KEMPE *et al*., 2009). Some of these breakages are absolutely peculiar (Fig. 5 left) and can be summarized as:

1. Missing ceiling formation of older generation
2. Sheared-off stalactites and draperies later deposited on top of floor speleothems
3. Broken stalagmites
4. Cracked conical stalagmites
5. Tilted and leaning stalagmites
6. Moraine-like piles of floor flowstone.

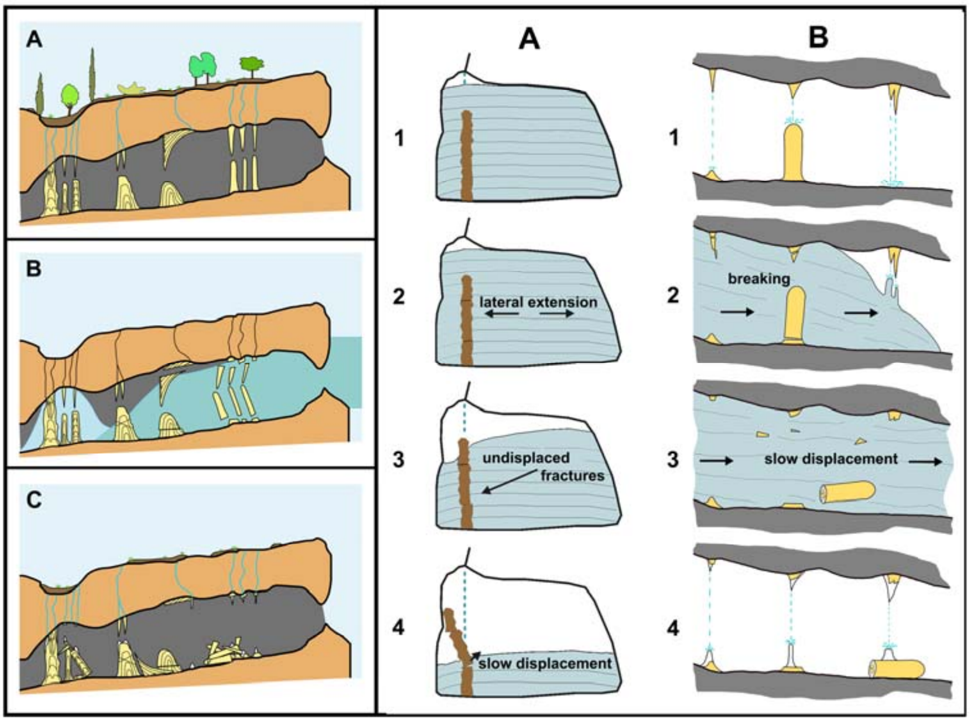

Fig. 5. Left: peculiar speleothem breakages induced by glaciation: A) speleothems grow during an interglacial; B) ice tongue freezing inside the cave causes speleothem breakages; C: at the beginning of a new interglacial broken speleothems accumulate on the cave floor while a new generation of speleothems starts growing. Right: breakages which cannot be the consequence of an earthquake: (A) as a consequence of the lateral expansion of an underground glacier upon a stalagmite and (B) of the ice tongue movement (from KEMPE 2005, modified).

In a region potentially interested by glaciations, if all breakdowns occurred in the same period the local perturbing factors are avoided, thus the presence of such peculiar breakages is the direct consequence of an ice tongue slowly moving inside the cave itself.

One of the main problems in using such a technique is that we must be sure that they were induced by ice and not by an earthquake.

It is often easy to discriminate the effects of these two different phenomena (FORTI, 2009): in fact ice tongues may justify displacements of broken speleothems that cannot be the consequence of seismic events: A) the presence of broken speleothems piled up in an unstable equilibrium or B) their displacement not induced by gravity (Fig. 5 right).

CAVE MINERALS AND PALEO-RECONSTRUCTIONS

Until the end of last century only speleothems made of calcite and/or aragonite have been used to obtain paleo-climatic and paleo-environmental information (FRISIA *et al.*, 2003). This because often their deposition is enhanced by different environmental and climatic conditions: normally aragonite prevails in hot and arid climates, where evaporation is the prevailing mechanism of deposition, while calcite is the preferred mineral when the climate is cooler and more humid, thus CO_2 diffusion becomes the prevailing phenomenon.

In many cases a climatic change may also induce the diagenesis of the already deposited mineral causing the transformation of aragonite into calcite or the reverse.

Only very recently scientists started to consider other cave minerals as possible proxy for paleoclimatic studies. The first studies evidenced that some of them may be sensitive proxies of the environmental changes occurred within a karst environment.

CRYSTAL SIZE AND PALEOENVIRONMENT

The cavern environment rarely allows the development of very big crystals, this because specific boundary conditions are requested for their development, which may be summarized as: very low supersaturation, stable groundwater level and constant geochemical parameters over a long time interval. These conditions are hard to be obtained inside meteoric caves, while thermal caves are surely more suitable.

In fact, most of the occurrences of big crystals in caves are related to the development of phreatic calcite from thermal water, even if other minerals (halite, barite, fluorite) have also been reported (HILL & FORTI, 1997). Anyway, most of the time, the single parameter which has been taken into account was the temperature of their formation, and nothing more.

Actually, probably the best example of the relationships existing between big crystals and paleoenvironment were recently supplied by the study of the giant gypsum crystals of Cueva de los Cristales (Naica Mine, Mexico). Their genetic mechanism was totally new (Fig. 6), being driven by the extremely low difference in solubility between gypsum and anhydrite at a rather constant temperature (just below 58°C), which was maintained practically unaltered for over 250.000 years (GARCIA RUIZ *et al*., 2007).

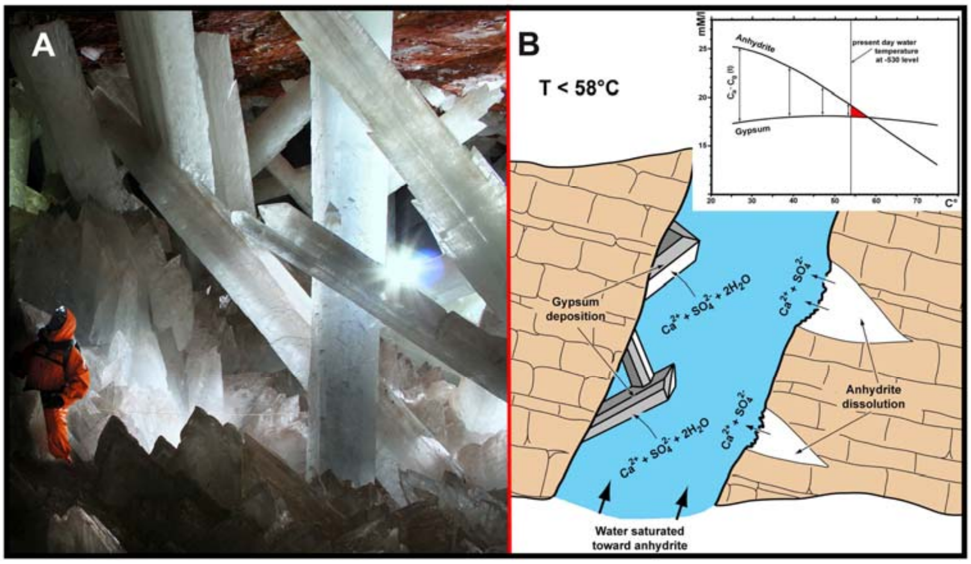

Fig. 6. A) Giant gypsum crystals in Cueva da los Cristales, Naica (Mexico) and (B) The mechanism by which they develop.

GYPSUM *VS.* CALCITE IN GYPSUM CAVES

The first cave mineral, beside calcite and aragonite, utilized for climatic and paleo-climatic studies was gypsum: this because within the gypsum caves often secondary deposits of these two minerals coexist and it was demonstrated that their relative abundance is a sensitive proxy of the local climate. This is because the competition in the development of these two minerals is strictly controlled by temperature and by the amount of dissolved CO_2 (MALTSEV, 1999): calcite prevails in humid temperate climates while gypsum prevails in hot arid climates. It has therefore been possible to detect climate changes occurred within a given area hosting gypsum caves just by analyzing the variations in the relative abundance of these two minerals (CALAFORRA *et al*., 2008).

But gypsum caves are widespread practically all around the globe and therefore it is possible, at least theoretically, to use the relationships existing between gypsum and calcite speleothems in these caves as proxy for paleoclimatic analyses for the whole planet (Fig. 7).

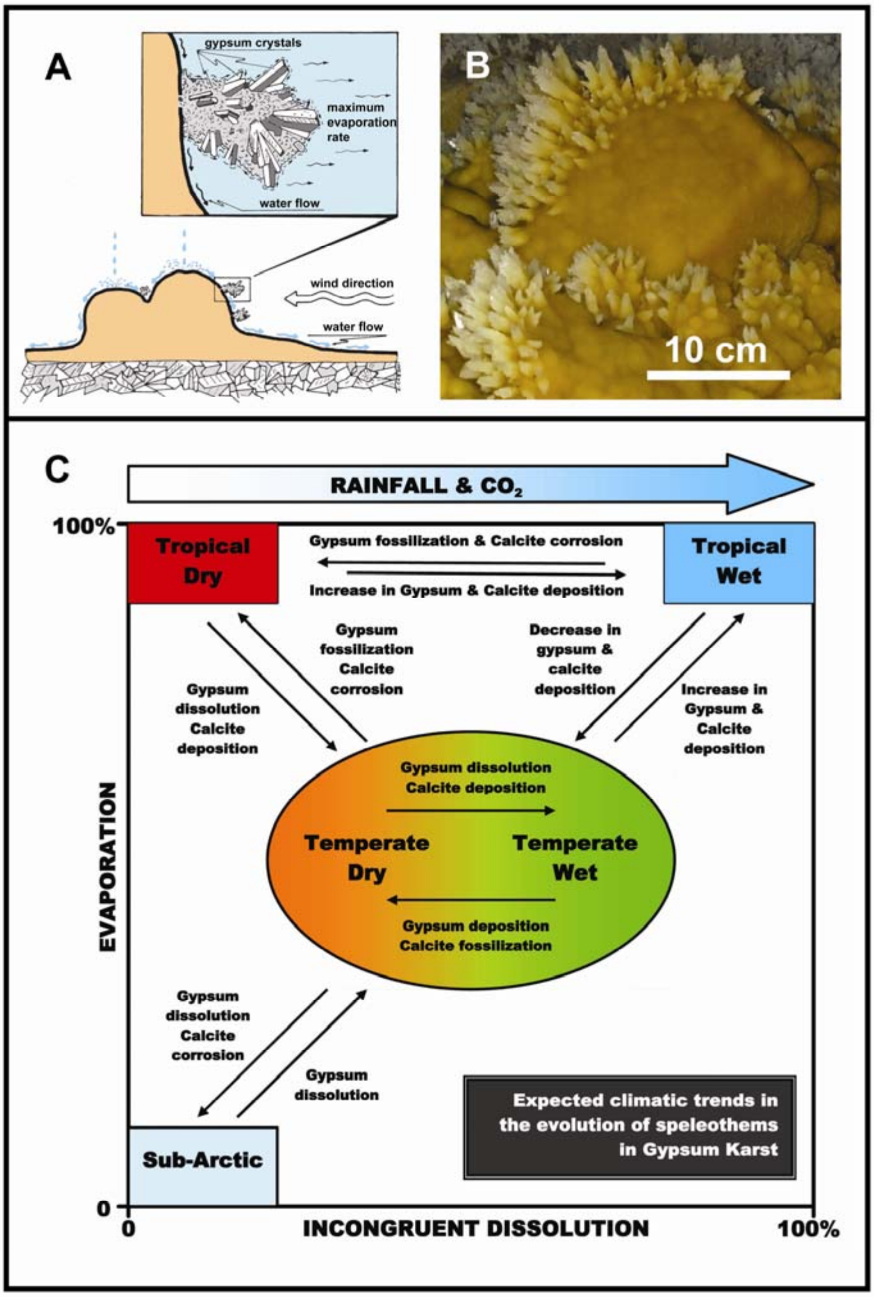

Fig. 7. A) Sketch displaying the simultaneous genesis of calcite and gypsum speleothems within gypsum caves; B) Gypsum flowers growing over an active calcite flowstone in Basino gypsum cave, Italy (Photo: Piero Lucci); C) Climatic induced effects on the calcite/gypsum speleothems within gypsum cavities (after ONAC & FORTI, 2011).

GYPSUM *VS.* ARAGONITE AND GROUNDWATER LEVEL FLUCTUATIONS

This peculiar relationship was observed inside the thermal aquifer of Naica, which gave rise to several caves at different elevation most of which filled by the giant gypsum crystals. Among the gypsum crystal bearing caves the Cueva de la Espadas is the most elevated and the single in which an alternation of gypsum and aragonite was detected within some "pseudo-stalagmites" grown in the lowermost passage.

The study evidenced that when the cave was completely filled by thermal water only large gypsum crystals developed, but when the groundwater lowering allowed air to enter just in the upper part of the cave the CO_2 diffusion into the solution induced the deposition of aragonite, while gypsum immediately stopped its growth. Later the ground water raised refilling the cave and a new generation of gypsum crystals started developing. From 57 ky BP the groundwater level fluctuated 3 times and finally some 7000 yr BP it left definitively the cave thus allowing the inlet of meteoric water which deposited a thin crusts of calcite (Fig. 8) (GÁZQUEZ *et al*., 2013).

The evolution of the pseudo-stalagmites ended at the beginning of the last century, when mining works dried the cave which was in turn interested by the inlet of mud thus allowing the evolution of a final thin layer of silt covering the pseudo-stalagmites

DOLOMITE CRUSTS WITHIN GYPSUM CAVES AND GLOBAL CHANGE

Dolomite proved to be a sensitive and fast proxy of the microclimatic variations induced by Global Change in the gypsum caves near Bologna (Fig. 9). In fact, it suddenly appeared on the gypsum walls of the Spipola cave as thin white crusts extruded from the inter-crystalline planes after an exceptional long drought period (FORTI *et al*., 2004c). These crusts were rapidly re-dissolved when the normal dripping was re-established within the cave. In the following years only another drought was so prolonged to cause a similar phenomenon.

In fact, only prolonged drought periods allow lowering dramatically the relative humidity of the cave atmosphere and consequently to bring its gypsum walls to a total dryness. These boundary conditions induce the capillary rise and total evaporation of the waters trapped within the gypsum inter-crystalline planes, thus allowing the deposition of dolomite.

CALCITE/ARAGONITE *VS.* OPAL AND RAIN PATTERNS

In peculiar cavern environment rain patterns may influence the kind of mineral deposited by seeping water: it is the case of some of the volcanic caves in Jeju Island (Korea), which are extremely well decorated with huge calcite-aragonite speleothems (WOO *et al*., 2000). This peculiarity is induced by the fact that the lava beds are buried by a thin calcareous layer made by broken shells (microcoquina) covered by a thick soil.

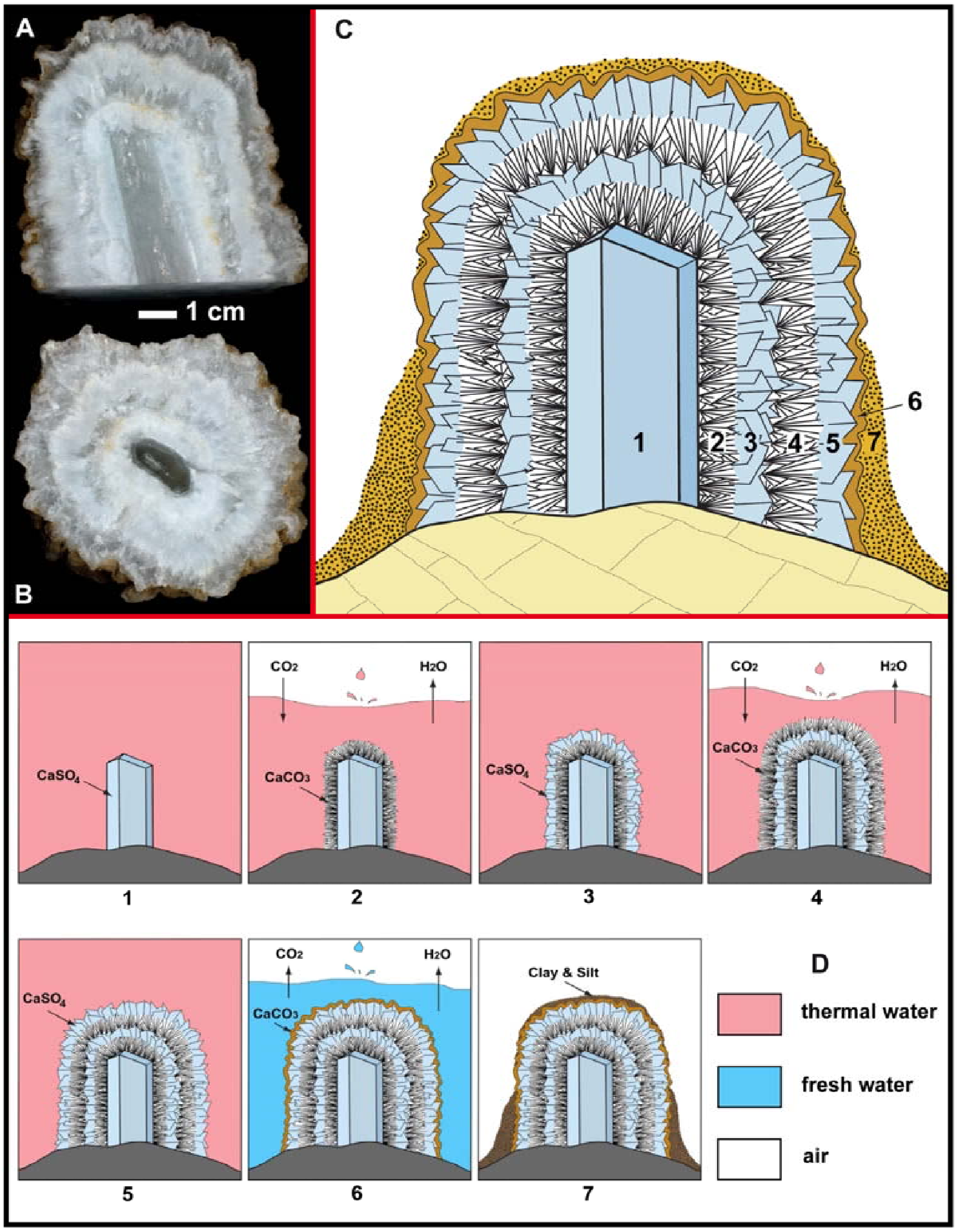

Fig. 8. Cueva de las Espadas (Mexico): polished vertical (A) and horizontal (B) sections of a subaqueous pseudo-stalagmite and its graphical reconstruction with alternation of gypsum (1, 3, 5), aragonite (2, 4), calcite (6), and silt (7) and their relationships (D) with past groundwater level fluctuations (after FORTI *et al*., 2008).

Fig. 9. Spipola gypsum cave (Bologna, Italy): A) dolomite moonmilk developed over the gypsum walls during an exceptional drought and a SEM image of a dolomite crystal.

In the past, rainfalls were relatively scarce and distributed over the whole year, therefore the seepage through the microcoquina layer was slow enough to allow a complete saturation with respect to $CaCO_3$. Given these boundary conditions, when dripping occurred within the volcanic caves the CO_2 degassing and evaporation caused the development of "normal" stalactites, stalagmites and columns, the inner structure of which was characterized by an alternation of calcite and aragonite layers.

Later the rain pattern varied towards an increase in the number and intensity of the rainfalls and this variation caused the diagenesis of most of the aragonite and the transformation of a large part of calcite within the speleothems to opal (Fig. 10). This occurred because, the increase of velocity avoided the possibility to saturate the solution with calcium carbonate while crossing the thin microcoquina layer. Therefore, acidic water undersaturated with respect to calcium carbonate reached the volcanic caves where aragonite and calcite were corroded, while opal was simultaneously deposited.

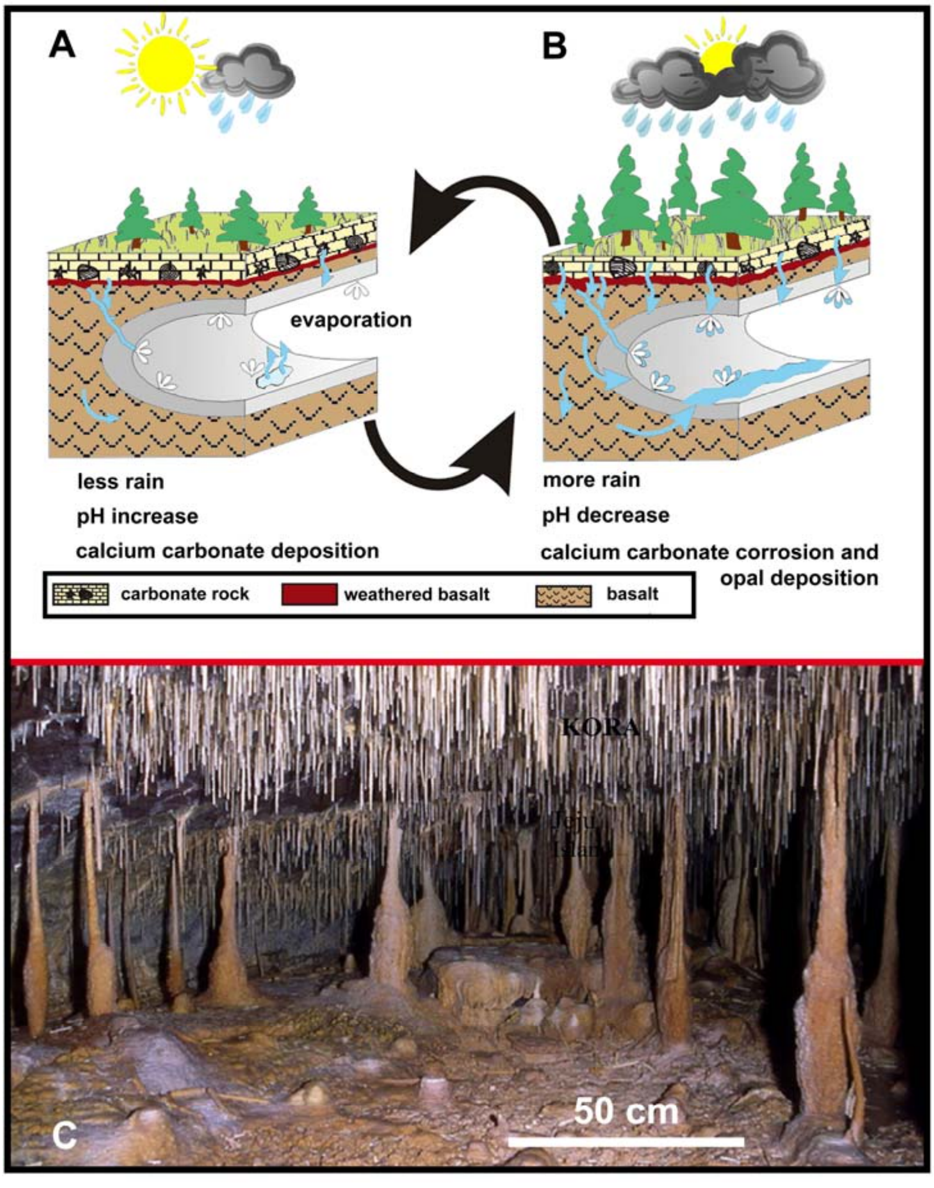

Fig. 10. A) Large calcite speleothems inside a lava tube of Jeju Island, Korea (Photo by K.S. Woo); B-C) Mechanisms by which calcite speleothems are replaced by opal inside lava tube of Jeju Island, Korea (after Woo *et al*., 2000, modified).

GYPSUM *VS.* SULFUR AND PALEO-ENVIRONMENT

Gypsum is the normal product of the oxidation of H_2S within limestone caves, but sometimes large sulfur speleothems with a gypsum nucleus develop (FORTI & MOCCHIUTTI, 2004). Sulfur cannot be deposited directly over the limestone because the reaction between H_2SO_4 and $CaCO_3$ maintain the pH of the solutions close to the neutrality, in a range in which the S-oxidant bacteria, bringing S^{2-} to S^{6+} are active, while those transforming S^{2-} to S^0 can't work, needing a strongly acidic environment.

Only when the condensation of H_2S occurs over an already formed gypsum speleothem, thus avoiding a direct contact with limestone, the oxidized solution cannot be buffered and its pH rapidly lowers, thus allowing the specific bacteria responsible for the deposition of sulphur to become active, while all the others stop working (Fig. 11).

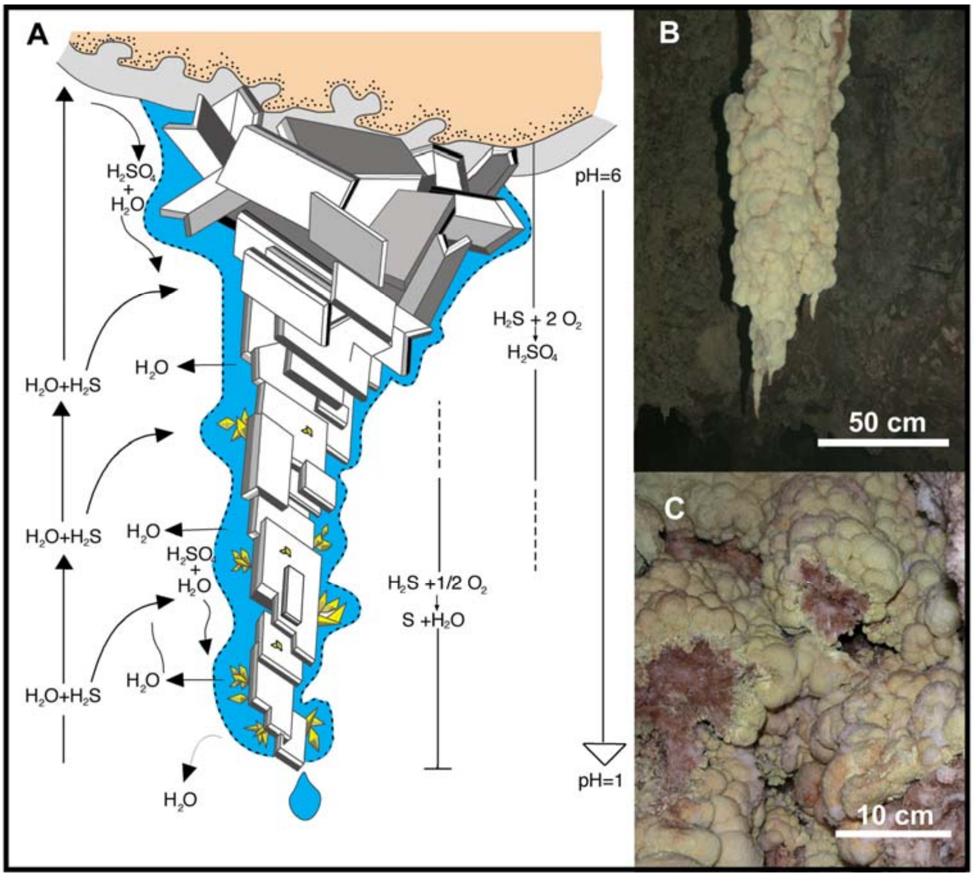

Fig. 11. Genetic sketch (A) of a sulfur stalactite (B) growing over a gypsum core (C) in Cala Fetente Cave (Italy) (modified after FORTI & MOCCHIUTTI, 2004).

The presence of a sulfur deposit inside a cave is the consequence of uncommon boundary conditions which may be summarized as follows:

1. Very high H_2S concentration
2. Very fast condensation
3. Very low pH.

This normally occurs just very close to the upwelling of the connate/thermal waters and therefore the presence of sulfur deposits within a limestone cave may be considered an evidence of closeness to (paleo-) rising of H_2S-rich waters.

CAVE MINERALS AND HUMAN IMPACT

Human impact on caves is well known and documented worldwide: speleothem intentional breakages, or disfigurement with paintings and/or graffiti, occurred since the humankind started visiting caves and increased with time.

The development of new cave minerals induced by human activities in caves are not commonly studied, but they exist and probably are much more diffuse than thought until present.

Mellite ($Al_2[C_6(COO)_6]\cdot 18H_2O$) is a very rare organic mineral which was firstly discovered within Romanelli cave (Apulia, Italy) (Fig. 12A), where it gave rise to a yellow macrocrystalline flowstone developed just over a fireplace where our ancestors cooked their foods in contact with a red soil layer (GARAVELLI & QUAGLIARELLA, 1974).

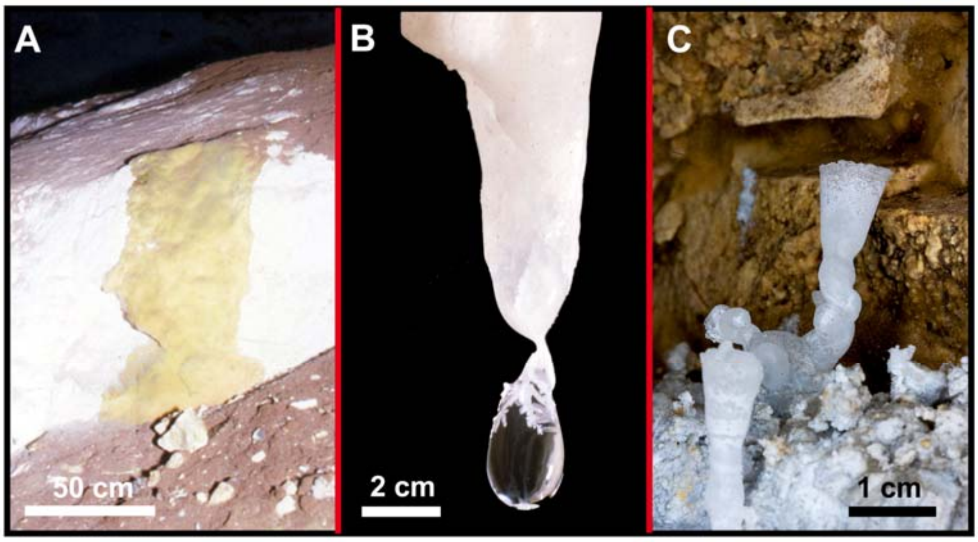

Fig. 12. A) Grotta Romanelli (Apulia, Italy): yellow crust of Mellite; B) Castellana Cave (Apulia, Italy): aragonite helictites grown over a monocrystalline calcite stalactite; C) carbidimites developing over exhausted carbide (Photo by C. Iacovone).

The transformation of a wild cave into a show cave may induce environmental parameters changes even to cause the deposition of new minerals (CIGNA & FORTI, 1989). This was the case of the Castellana Grotte (Apulia, Italy), where a small bunch of aragonite helictites developed just from the tip of a calcite mono-crystalline stalactite (Fig. 12B). Their growth started immediately after a strong light was placed some 100 cm below the stalactite tip as a consequence of the tremendous variation induced in the local microclimate (from 16 to 30°C and from no air movement to over 1 m/s of vertical wind).

Finally, in many wild cavities, explored by cavers in the last decades, the use to abandon the exhausted carbide inside the cave allowed the evolution of a totally new speleothem type (Fig. 12C): the carbidimites (BROUGHTON, 1971) the development of which was induced by the reaction of the $Ca(OH)_2$ present in the exhausted carbide powder with the CO_2-rich condensing water.

It is pretty sure that many other minerogenetic mechanisms exists, which can be activated by human impact in caves, therefore it would be important to study them in the near future.

SOLID AND FLUID INCLUSIONS IN GYPSUM CRYSTALS AND PALEO-ENVIRONMENTS

All speleothems, while growing, incorporate in their structure several kinds of "solid impurities" (trace & or diagenetic minerals, dust, pollens, spores, micro-organisms…) or gas and water (small bubbles coming from the "mother solution" feeding the speleothem). Pollen (BASTIN & GEWELT, 1986) and fluid inclusions (MCGARRY *et al*., 2004) have been utilized since the second part of the last century for paleoclimatic and paleo-environmental analyses.

The first time in which solid inclusions within cave minerals, beside calcite and aragonite, have been used as paleoenvironmental proxies was in the first decade of the third millennium, when the inclusions of the giant gypsum crystal of Naica (Mexico) were analyzed (PANIERI *et al.*, 2008).

Fluid inclusions were fundamental to state that the temperature of the aquifer feeding the Naica crystal was maintained practically stable for an extremely long interval of time, thus allowing the development of such big crystals (GAROFALO *et al*., 2009).

Moreover, plenty of well-preserved pollen were extracted from these inlcusions and the presence among them of *Quercus garryana*, *Lithocarpus densiflora, Taxus, Plantago, Poaceae* and *Lycopodium*, put in evidence that about 35.000 B.P. the Naica climate was very similar to the actual one in San Francisco (some 1500 km of the desert of Naica) (GAROFALO *et al*., 2009).

ASTROBIOLOGY: THE LAST FRONTIER

This rather new science was interested in caves since the beginning (BOSTON *et al*., 2001; GÁZQUEZ *et al*., 2014; GARCIA-SANCHEZ *et al*., 2015): this because some of the underground environments (specifically volcanic, but also thermal caves) may be very similar to extraterrestrial environments. In this respect a few years ago a search started to possibly find still living organisms within the fluid inclusions of the Naica giant gypsum crystals and the DNA studies over the cultured biomass evidenced some 30 new for science microorganisms, trapped within the fluid inclusions for a period between 10 to 50.000 y BP (ESPINO *et al*., 2018). This result seems to be very important for the future research of possible survived extremophiles in the Mars soil.

CONCLUSIONS

At the end of this short and surely incomplete overview on the paleo-environmental data stored within the cave formations, it is possible to state that in the last few years speleothems proved to be among the most interesting, long lasting and detailed geological-environmental archives, but many are the cave minerogenetic environments which we are still unable to use for paleoenvironmental reconstruction. By sure the most complex is the guano digestion which induces the development of hundreds of different minerals, all of which characterized by strict stability boundaries, thus suitable to be utilized as proxy for paleoenvironmental reconstruction.

But, even if we can understand the processes ruling the development of a speleothem as a whole, or of its single growth layer, the detection limits of the present day available instruments and/or techniques do not allow obtaining all the information stored within them.

Considering speleothems true “stone books”, we must admit that, despite the great achievements of the last decades, presently we are able to “read” only the “titles” of the main”chapters”, but we can understand only a few pages of most of them.

In the near future, when we will be able to read and fully understand these “stone books”, the importance of speleothems will enormously increase.

This means that cave environments will become more and more important for exciting research in plenty of scientific fields, while their importance in terms of renewable resources will be greatly enhanced.

To ensure the adequate preservation of caves and karst for future generations it is necessary that the speleological community voluntarily exercises worldwide control, and in some cases prohibitions, on the activities to be performed in caves to ensure their preservation. In particular, scientific oversampling must be avoided. This cautious approach should be the main target of the whole speleological scientific community in the near future.

REFERENCES

ANTONIOLI, F., *Variazione del livello del mare nell’ultimo semiciclo glaciale ottenute da speleotemi in grotte sommerse di aree costiere italiane*. Studi Trentini di Scienze Naturali v Acta Geologica **80**(2003), 2005.

ANTONIOLI, F., BARD, E., POTTER, E.K., SILENZI, S., IMPROTA, S., *215-ka history of sea-level oscillations from marine and continental layers in Argentarola Cave speleothems (Italy)*. Global Planet. Change **43**: 57–78, 2004.

BADINO, G., *Fisica del clima sotterraneo.* Memorie dell'Istituto Italiano di Speleologia, **7**, 136 p, 1995.

BADINO, G. (ed.), *Proceedings of "Vth Int. Workshop on Glacier Caves and cryokarst in polar and high mountain regions"*. Courmayeur 2000, Italy, Nimbus, **23–24**, 2002.

BASTIN, B., GEWELT, M., *Analyse pollinique et datation ^{14}C des concrétions stalagmitiques Holocenes. Apports complementaires des deaux methods.* Geographie Physique et Quaternaire, **40**, 185–196, 1986.

BORSATO, A, FORTI, P., *Ricostruzioni paleoclimatiche e paleoambientali da concrezioni di grotta.* Studi Trentini di Scienze Naturali v Acta Geologica **80**(2003), 55–63,2005.

BOSTON, P.J., SPILDE, M.N., NORTHUP, D.E., MELIM, L.A., SOROKA, D.S., KLEINA, L.G., LAVOIE, K.H., HOSE, L.D., MALLORY, L.M., DAHM, C.N., CROSSEY, L.J. & SCHELBLE, R.T., *Cave biosignature suites: microbes, minerals and Mars*. Astrobiological Journal (**1)** 25–55, 2001.

BROUGHTON, P.L., *Additional data on the carbidimite formations.* National Speleological society Bulletin 33(3), 123–125,1971.

CALAFORRA, J.M., FORTI, P. & FERNANDEZ-CORTÈS, A., *The speleothems in gypsum caves and their paleoclimatological significance*. Environmental Geology **53 (5)**, 1099–1105, 2008.

CIGNA, A., CUCCHI F., FORTI, P., *Engineering problems in developing and managing show caves.* J. Nepal Geol. Soc., **22**, 85–94, 2000.

CIGNA, A., FORTI P., *Environmental impact assessment of a tourist cave.* International Symposium Cave Tourism, Postojna, November 1988, 23–38, 1989.

CULVER, D.C., *Cave life evolution and ecology.* Harvard University press, 189 p, 1982.

ESPINO, A., BERALDI-CAMPESI, H., AMADOR-LEMUS, P., BELTRÁN, H.I., BORGNE, S. LE, *Bacterial diversity associated with mineral substrates and hot springs from caves and tunnels of the Naica Underground.* International Journal of Speleology **47(2)**, 213–227, 2018.

FAIRCHILD, I.J., BAKER, A., *Speleothem science. From process to past environments*. Oxford, Wiley-Blackwell, 432 p, 2012.

FORD, D.C., WILLIAMS, P.W., *Karst Geomorphology and Hydrology.* John Wiley & Sons, Chichester, 562 p, 2007.

FORTI, P., *Seismotectonic and paleoseismic studies from speleothems: the state of the art.* Geologia Belgica **4(3–4)**, 175–185, 2001.

FORTI, P., *Aragonite cave pearls of Reforma Mine.* in BADINO, G., BERNABEI T., DE VIVO T., GIULIVO, I., SAVINO, G. (eds.), *Under the desert: the mysterious waters of Cuatro Ciénégas.* Tintoretto, Treviso, 236–241, 2004a.

FORTI, P., *Paleotectonics from speleothems.* in GUNN J. (ed.), *Encyclopedia of Caves and Cave Sciences*, 565–566, 2004b.

FORTI, P., *State of the art in the speleological sciences.* Proc. XV° Int. Spel. Congr. Kerrville Texas, **1**, 26–31,2009

FORTI, P., DE MARIA, D., ROSSI, A., *The last mineralogical finding in the caves of the "Gessi Bolognesi" natural Park: the secondary dolomite.* Memorie Istituto Italiano di Speleologia **16**, 87–94, 2004.

FORTI, P., GALLI,E., ROSSI, A., *Il sistema Gesso-Calcite-Aragonite: nuovi dati dalle concrezioni del Livello -590 della Miniera di Naica (Messico).* Congresso Nazionale di Speleologia, Iglesias 2007, Memorie Istituto Italiano di Speleologia, **21**, 139–149, 2008.

FORTI, P., MOCCHIUTTI, A., *Le condizioni ambientali che permettono l'evoluzione di speleotemi di zolfo in cavità ipogeniche: nuovi dati dalle grotte di Capo Palinuro (Salerno, Italia)*. Grotte d'Italia **4**, 39–48, 2004.

FORTI, P., ONAC, B., *Caves and Mineral deposits* Zeitschrift für Geomorphologie, **60**, Supplement. **X**, 55–101, 2014.

FORTI, P., POSTPISCHL, D., *Seismotectonic and paleoseismic analyses using karst sediments.* Marine Geology **55**, 145–161, 1984.

FRANKE, H.W., 1965 *The theory behind stalagmite shapes*. Studies in Speleology 1(2–3), 89–95.

FRISIA, S., BORSATO, A., SOMOGYL, A., SUSINI, J., *Aragonite to calcite transformation in speleothems (Grotte de Clamouse, France): environment, fabrics and carbonate geochemistry.* Journal of Sedimentary Research **72(5)**, 697–699, 2003.

GARAVELLI, C.L., QUAGLIARELLA, A.F., *Mellite di Grotta Romanelli (Otranto).* Periodico di Mineralogia, **43(1**), 39–49, 1974.

GAROFALO, P. S., FRICKER, M., GÜNTHER, D., FORTI, P., MERCURI, A.M., LORETI, M., CAPACCIONI, B., *Climatic control on the formation of gigantic gypsum crystals within hypogenic caves (Naica mine, Mexico)?* Earth & Planetary Science Letters **289(3/4)**, 560–569, 2009.

GARCÍA-RUIZ, J.M., VILLASUSO, R., AYOPA, C., CANALS, A. & OTÁLORA, F., *The formation of natural gypsum megacrystals in Naica, Mexico*. Geology **35**: 327–330, 2007.

GARCÍA-SÁNCHEZ, A.M., MILLER ,A.Z., PEREIRA, M.F., GÁZQUEZ, F., MARTÍNEZ-FRÍAS, J., CALAFORRA, J.M., FORTI, P., TOULKERIDIS, T., SÁIZ-JIMÉNEZ, C., *Searching for traces of life in underexplored lava tubes from Galápagos Islands (Ecuador): a little bit of Mars on Earth.* European Astrobiology Network Association, EANA 2015, Abstracts. Noordwijk, Netherlands, 2015.

GÁZQUEZ, F., CALAFORRA, J. M, STÖLL H., SANNA, L., FORTI, P., LAURITZEN, S.-E., DELGADO-HUERTAS, A., RULL, F., MARTÍNEZ-FRÍAS, J., *Isotope and trace element evolution of the Naica aquifer (Chihuahua,Mexico) over the past 60,000yr revealed by speleothems.* Quaternary Research **80**, 510–521, 2013.

GÁZQUEZ, F., RULL, F., CALAFORRA, J. M., VENEGAS, G., MANRIQUE, J.A., SANZ, A., MEDINA, J., CATALÁ-ESPÍ, A., SANSANO, A., NAVARRO, R., FORTI, P., DE WAELE, J., MARTÍNEZ-FRÍAS, J., *Caracterización mineralógica y geoquímica de minerales hidratados de ambientes subterráneos: implicaciones para la exploración planetaria.* Estudios Geológicos **70(2)**, 2014, e009. doi: http://dx.doi.org/10.3989/egeol.41688.314.

GUNN, J. (ed), *Encyclopedia of caves and karst science.* Fitzroy, New York, 902 p, 2004.

HILL, C.A., FORTI, P., *Cave Minerals of the World.* Nat. Spel. Soc., Huntsville, 464 p, 1997.

JAKUCS, L., *Morphogenetics in karst landforms.* Higler, Bristol, 284 p, 1977.

KEMPE, S., BAUER, I., DIRKS, H., *Glacial cave ice as the cause of widespread destruction of interglacial and interstadial speleothem generation in Central Europe*. In WHITE, W.B. (ed): *Proceedings 15th International Congress of Speleology*, Kerrville (TX), **2**, 1026–1031, 2009.

MALTSEV, V.A., *The influence of seasonal changes of cave microclimate upon the genesis of gypsum formations in caves*. The NSS Bulletin **52**, 99–103, 1990.

MCGARRY, S., BAR-MATTHEWS, M., MATTHEWS, A, VAKS, A., SCHILMAN, B., AYALON, A., *Constraints on hydrological and paleotemperature variations in the eastern Mediterranean region in the last 140 ka given by the dD values of speleothem fluid inclusion.* Quaternary Science Reviews, **23**, 901–918, 2004.

NUÑEZ JIMENEZ, A., *Geografia y Espeleologia en Revolucion.* CENFAR, La Habana, 190 p, 1987.

ONAC, B., FORTI, P., *State of the art and challenges in cave minerals studies.* Studia UBB Geologia **56** (1), 33–42, 2011.

PANIERI, G., FORTI, P., GASPAROTTO, G., SOLIANI, L., *Studio delle inclusioni solide presenti nei cristalli di gesso della Grotta delle Spade (Naica, Messico).* Congresso Nazionale di Speleologia Iglesias 2007, Memorie Istituto Italiano di Speleologia **21**, 150–158, 2008.

QUINIF, Y. (ed), *Karst & Tectonics*. Speleochronos, hors serie, 199 p, 1998.

SARBU, S.M., KANE, T.C., KINKLE, B.K., *A chemoautotrophically based groundwater ecosystem*. Science **272**, 1953–1955, 1996.

SHOPOV, Y.Y., TSANKOV, L., GEORGIEV, L.N., DAMYANOVA, A., DAMYANOV, Y., FORD, D.C., YONGE, C.J., MACDONALD, W., KROUSE, H.P.R., *Speleothems as Natural Climatic Stations with Annual to Daily Resolution.* Extended abstracts of Int. Conference on "Climatic Change – the Karst Record", Bergen, Norway. Karst Waters Institute Special Publication 2, p. 150–151, 1996.

SHOPOV, Y.Y., *Luminescence of Speleothems* Studi Trentini di Scienze Naturali, Acta Geologica **80**, 2005

TANKERSLEY, K.H., *Prehistoric salt mining in the Mammoth Cave System*. In CARSTENS K. & WATSON P.J. (eds.) *Of caves and shell mounds in west-central Kentucky*. Tuscaloosa, University of Alabama Press, 33–39, 1996.

TARDY, J., *Speleoklima and therapy höhlenklima und therapie*, Budapest, 118 p., 1989.

WOO K., S., CHOI, D.W., KIM, R., KIM ,J. K., *The origin of the speleothems in Dangcheomul Cave, Jeju Island, Korea*. Journal of the Geological Society of Korea, **36 (4)**, 411–434, 2000.

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