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DEFINITION AND PROCESS-BASED CLASSIFICATION OF CAVES

OPREDELITEV IN KLASIFIKACIJA JAM NA PODLAGI PROCESOV

Georgios LAZARIDIS[1]

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Georgios Lazaridis: Definition and process-based classification of caves

A new definition of the term "cave" enables its linking to recognised cave formation processes, its coverage of the known cave types, its differentiation from porosity and contiguous spaces, and its applicability within a continuum of sizes, as well as ensuring avoidance of explorational bias. Despite its scientific basis, the proposed definition remains straightforward enough to be used by cavers and by non-specialists. Guided by this definition, a proposed hierarchical classification scheme, which is also process-based, combines the known cave types. The hierarchy is based upon five levels of classification, wherein the first two levels define the major cave categories. Further branching encompasses variation in cave development settings and in agents of cave formation. Discussion of various pre-existing classifications and definitions reveals the non-static nature of such schemes, which tend to evolve in response to the progress of cave research. The key is in increases in cave census data and improved communication by and between scientists about previously and newly discovered caves.

Keywords: cave definition, cave classification, speleogenesis.

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Georgios Lazaridis: Opredelitev in klasifikacija jam na podlagi procesov

Nova opredelitev pojma jama omogoča povezavo s prepoznanimi procesi nastajanja jam, to, da zajema znane jamske tipe, da se razlikujejo na podlagi poroznosti in sosednjih prostorov ter uporabnost v okviru proučevanja velikosti, poleg tega preprečuje pristranskost v raziskovanju. Kljub znanstveni podlagi je predlagana opredelitev dovolj preprosta, da je uporabna tako jamarjem kot nestrokovnjakom. Na podlagi te opredelitve predlagana hierarhična klasifikacijska shema, ki prav tako temelji na procesu, združuje znane tipe jam. Hierarhija temelji na petih ravneh klasifikacije, pri čemer prvi dve ravni opredeljujeta glavne kategorije jam. Nadaljnje razvrstitve temeljijo na razlikah v okolju nastanka jam in dejavnikih nastanka jam. Razprava o različnih že uveljavljenih klasifikacijah in opredelitvah razkriva nestatičnost takšnih shem, ki se razvijajo glede na napredek pri raziskovanju jam. Ključni so večji nabor podatkov o jamah, sporočanje znanstvenikov in izboljšana komunikacija med znanstveniki o predhodno in na novo odkritih jamah.

Ključne besede: definicija jame, klasifikacija jam, speleogeneza.

[1] Aristotle University of Thessaloniki, School of Geology, 54124, Thessaloniki, Greece, e-mail, ORCID: geolaz@geo.auth.gr, https://orcid.org/0000-0002-4926-2357

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1. INTRODUCTION

Whereas use of the term "cave studies" is understood internationally, underlying use and understanding of the term "cave" continues to hinge upon a conventional but arbitrary limiting constraint of human size. For example, according to the most-used definition of the International Union of Speleology (UIS, Union Internationale de Spéléologie), a cave is considered as being "… *any natural, underground cavity, large enough to be entered by man*" (Bögli, 1980). This definition is not genetic and uses (arbitrary) human-size as a measure of caves. It is broadly applied because most related information comes only from accessible parts of caves (Ford & Williams, 2007). However, openings of smaller size may be parts of what is termed cave and share the same characteristics as they are both formed under the same formation conditions. This is the reason for the existence of more specific definitions for some process-based groups of caves, such as karst (in particular hypergene) caves, where, for example, Ford and Williams (2007) define cave as "*an opening enlarged by dissolution to a diameter sufficient for 'break-through' kinetic rates to apply if the hydrodynamic setting will permit them*". In other scientific fields such as biology various cave definitions are adopted. For example, White and Culver (2005) define cave as "*a cavity, at least part of which is in constant darkness, with turbulent water flow and with eyeless, depigmented species present*". An ecological definition of caves is the following: "*A cave is a natural or artificial cavity in rock in which large-scale scalar phenomena are actually or potentially ecologically significant. These phenomena include the presence of surfaces (which may be at rock-air, rock-water and/or water-air interfaces) available for utilization by mesofauna and/or macrofauna. Usually, though not invariably, they also include the presence and effects of fluid flow (air currents, streams, springs or tidal flow) and they also commonly have accumulations of bulk substrates such as guano, vegetable debris, talus and sediments. There is also potential for access and utilization by flying animals (bats, birds and insects) and by terrestrial and aquatic animals that are unable, because of their size, to utilize mesocaverns or smaller voids*." (Moseley, 2009). Furthermore, a definition introduced by White (1988) successfully emphasizes how subjective it could be to define "cave" and the arbitrary use of human-size; "*a natural opening in the Earth, large enough to admit a human being, and which some human beings choose to call a cave.*" Various legal definitions of "a cave" for monitoring purposes are provided by Weigand et al. (2022).

Mylroie (2019) provides the most recent discussion of the subject and addresses several issues around the current definition of caves, such as what is a cave and what is in and around of that; temporal and spatial aspects; and classification. Most importantly he points out that it is time for cave scientists better to communicate the "cave" term with those who have no direct association with caves. The potential opportunity to study extraterrestrial caves is the motivation for meeting such a need. He defines a cave by using an answering process of the following five questions "*1. How did the void form? 2. How big is it? 3. How long has it lasted? 4. What does it contain? 5. How does it connect to exterior space?*". These have to be answered in order to access the function of the cave to the extraterrestrial landscape and how life may have utilized the cave (Mylroie, 2019). Beyond this he discusses various problems and prerequisites.

The first question to be answered relates to the process(es) of cave formation, widely known as speleogenesis. This parameter is used in this paper to define "cave" and classify processes and consequently caves according to studies that exist in the various speleogenetic disciplines.

Motivation to propose the new classification scheme presented here was provided by the need to communicate the subject to speleology students via an analytical classification that would introduce them to cave research. Available information is combined into a classification scheme of various levels. Cave definition and cave classification are presented and discussed in the next two sections.

2. METHODS

Criteria such as speleogenesis, size, location and content are considered for the definition of "cave". To evaluate the potential advantages of the proposed definition various specifications introduced by Curl (1964), are used. It is compared with widely used definitions that already exist (Table 1 and in text references).

Speleogenesis is considered the classifying factor for the classification scheme. Classic and recent works that identify and describe cave type variations in different setting and lithology are used (e.g., Ford & Ewers, 1978; Bögli, 1980; Audra & Palmer, 2011; Kempe, 2012; Bella & Gaál, 2013; Klimchouk, 2017; Oberender & Plan, 2018;

Gradziński et al., 2018; Mylroie, 2019). Cave types that share common speleogenesis are grouped together. The groups are based on the predominant process of speleogenesis and composite categories are introduced in order to include exceptions regarding this criterion. The results are organized in different levels of classification in tree diagrams. Categories become more detailed as the classification level increases.

3. DEFINING CAVE

As mentioned above, many studies use human-size as a limiting metric for caves, commonly by excluding any smaller voids (e.g., Davies, 1960). The work of Curl (1964) is especially significant for two reasons. First, he describes the cave as a space, not as an object. This important distinction emphasizes the need to define its boundaries. Secondly, he recognized the various problems that result when human-size is used to help constrain cave definitions. He solved this problem by introducing (and defining) a human-sized module on the basis of which caves can be defined. Applying this module, he defined "proper caves". He also discussed the entrances as boundaries, and the cave content that can bound or fill the space, depending upon the perspective of the researcher. Before providing the definition proposed here, it is appropriate to examine the questions set for the exploration of caves in space (Mylroie, 2019). The first question for a scientist concerns the formation process. Subsequent questions relate to sizes, the age, the content, and its connection to the exterior. Thus, following this aspect, any definition should incorporate this information. Another issue about definitions is that when more specific ones are proposed (e.g., for karst caves), they cannot be applied to other process-based cave types.

Attempting to provide a definition that will include most, if not all, possible cases, the following new definition is formulated:

Cave is called every non-artificial potentially empty underground space in solid matter that can be formed by constructional and destructional geological and biological processes (such as corrosion, erosion/weathering, deposition, tectonics, mass movement, deformation, animal activities or a combination of them) if the same process is capable of creating openings large enough to be entered by humans.

Caves are not necessarily air-filled; they can be filled partially or totally with matter in any state. The cave-forming process is called speleogenesis. A discussion of the definition and possible issues follow.

Most of the proposed definitions consider caves as naturally formed and exclude human-made structures. This is not absolute. Curl (1964) suggests that this is optional. Parise et al., (2013) and Mylroie (2019) include artificial cavities within the category caves. The definition proposed above uses the expression "non-artificial" to exclude any voids created by humans. Such voids could be tunnels, basements, mines, tombs, etc., which could have conditions, such as climate, similar to the cave environment, or include processes common in caves, such as speleothem deposition. Most artificial types of underground voids, such as tunnels, tombs and basements, are commonly not called a cave, except of mines. Thus, they are not included in the current definition.

Subsequently the cave is described as an "underground potentially empty space in solid matter". This part of the definition locates the cave below surface and most importantly defines the limits of the void. The space is defined as potentially empty because it can be found totally or partially filled with any state of matter (i.e., sediments, water, air or other gases, lava, etc.). The formation is defined as being in solid matter, to avoid the inclusion of void formation in liquid matter. Cases of voids in the liquid state are described as bubbles. Only if the liquid changes to the solid state might a space be formed that can be called a cave instead of a bubble. For example, after solidification, original bubbles in lava become caves in volcanic rock. In the gaseous state, voids cannot be formed at all.

The known processes that support formation of such potentially empty spaces are summarized as constructional or destructional geological and biological processes. This prerequisite makes the definition broad and genetic. In contrast to previous genetic definitions, the inclusion of all the processes (excluding human activity) in this definition allows the term "cave" to be applied within each of the various process-based groups, i.e., not only to karst caves. This consideration enhances the descriptive utility of the definition and allows its use across a spectrum of speleogenetic studies.

The qualifying phrase "*if the same process is capable of creating openings large enough to be entered by humans*" is added as the key factor to differentiate caves from porosity and contiguous spaces. Essentially it allows that potentially empty spaces be regarded as caves if they are formed by the same process or processes that elsewhere form potentially empty spaces large enough to be entered

Table 1: Specifications for various cave definitions, introduced by Curl (1964) and presented with modifications and additions. The term 'proper' corresponds to human size as a module.

	Limits	Explorer	Module	Entrances	Purpose
present work	solid state	human	proper or smaller	not required	see text
Ford & Williams, 2007	soluble rock	water	dimensions for turbulent flow	unspecified	speleogenesis
White & Culver, 2005	not specified but apparently rock	size of leaving organisms	dimensions for turbulent flow	unspecified	biological research
White, 1988	rock	human	proper	unspecified	descriptive
UIS, Bögli 1980; Bates & Jackson, 1987	rock	human	proper	proper	descriptive
Woodward, 1961	rock and fill	water	freely flowing water	not required	speleogenesis
Curl, 1960	rock, fill and water	human	proper or smaller	proper	statistical theory of evolution
Howard, 1960	solid rock	unspecified	apparently small	not required	descriptive
Davies, 1960; 1964	solution surface	unspecified	larger than "primitive tubes"	unspecified	speleogenesis
Bretz, 1956	rock and fill	human	proper	unspecified	descriptive
Cullingford, 1953	rock and fill	human	proper	unspecified	descriptive

by humans. Thus, although a human module remains as an intrinsic part of the definition, it finally conforms to the idea of Curl (1964) and embraces caves along a continuum of sizes. This refinement allows the definition to be used legitimately in deriving statistics of cave evolution and speleogenesis.

Another crucial issue related to cave definitions is the question of explorational bias (Mylroie, 2019). For example, is a lava tube transmitting fluid lava a cave or not? According to the proposed definition, this can be regarded as a cave because, potentially, the same processes can creates empty spaces in the solid state. With regard to entrances, this definition, as opposed to the classical ones, also allows inclusion of entrance-less caves, again potentially removing some of the scope for explorational bias.

A schematic definition of caves is provided in Figure 1, which takes into account the issues discussed.

Several specifications for cave definitions (Curl, 1964) are summarized in Table 1. The potential advan-

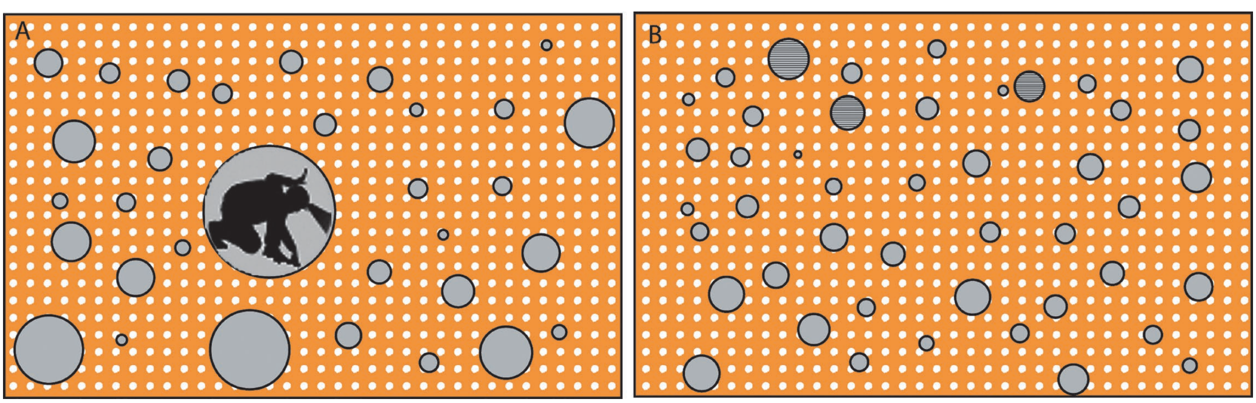

Figure 1: Schematic summary of caves as defined in this paper. White and grey circles represent voids formed by different processes. The colored background represents solid matter. A) Voids related to two processes are represented; the white ones are small inaccessible voids such as inter-granular porosity, formed by processes that cannot normally create voids large enough for human entry; the grey ones represent caves that are defined by the human size but also smaller voids that are also caves because they are formed by the same process. In this way explorational bias and human size limitations are avoided, and the definition is based on the process. B) This figure represents an area where caves large enough for human entry have not yet been found. The grey circles can nevertheless be described as caves because they are formed by the same process(es) that formed the grey circles in figure A. Thus, these are considered to be caves according to the proposed definition because they are formed by a process (or processes) that generally can create spaces large enough for human entry. Any cave-filling material that obscures exploration (as illustrated by the grey circles with horizontal lines) is irrelevant, because even though inaccessible to humans, the filled cavities are formed by a process that creates caves. This consideration also avoids explorational bias.

tages of the proposed definition are readily recognizable. In most cases the 'limits' of the space (cave) is defined by the rock and maybe the filling. In the present work the term 'solid state' is used to include all rocks, but also to acknowledge other possibilities, such as caves existing within metallic asteroids in space (Mylroie, 2019). As in almost all the general definitions of cave, the 'Explorer' is (necessarily) the average human. In the proposed definition the 'Module', however, is proper or smaller, in contrast to most definitions that use the arbitrary human size as a limiting measure. There are no stipulations about 'Entrance' parameters. In most definitions these are not specified, or is the entrance is required to be at least of human size (called a 'proper entrance' by Curl, 1964). The 'Purpose' parameter is discussed above within the analysis of the definition's parts. In conclusion, it is intended that the present definition covers the totality of the usages that previous definitions have included.

4. PROCESS-BASED CLASSIFICATION OF CAVES

Variations in cave morphology, location, total area, deposits, etc. are results of variation in speleogenetic processes and settings, offering the possibility of cave classification relying on different internal characteristics and external factors (e.g., Ford & Williams, 2007). Some of these characteristics are the size, the cave pattern in ground plan, the meso-morphology such as passage geometry, the hydrological setting of speleogenesis and the cave deposits. External factors are related to lithology, topography, climate, and geomorphological and hydrological cycles. All these classifications may be useful for addressing different problems in a variety of cave and karst studies contexts. Furthermore, some of them can be related to speleogenesis, whereas others cannot. However, it is notable that internal and external factors are not necessarily separated from and independent of each other.

Several classification schemes based on numerous criteria can be found among the scientific publications of the last two centuries (e.g., Virlet, 1835; Kraus, 1894; Trimmel, 1968; Bögli 1980; White & Culver, 2005; Striebel, 2005; Klimchouk, 2006; Ford & Williams, 2007; Oberender & Plan, 2013; 2018; Bella & Gaál, 2013; Mylroie, 2019). Because a process-based cave definition is proposed herein, there is a related need to recognize, gather, and map all the various processes involved in the formation of caves. The classification scheme presented in figures 2–4 is assembled by considering the speleogenesis as the classifying factor, and combining aspects from previous publications that relate to various cave types. Difficulties arise when discussing morphologies, because there are a number of contrasting interpretations among researchers. For example, the speleogenesis of maze caves (Palmer, 2000), has been part of a long-lasting discussion. Caves with multiple loops, included in the second and third stages of the four-stage model (Ford, 1971; Ford & Ewers, 1978) are attributed by Audra and Palmer (2011) to development under epiphreatic conditions. Thus, reflecting the understanding that genetic processes impact the subsequent cave morphology, speleogenetic criteria were used. The proposed classification aims to employ and understanding of speleogenetic processes to inform the establishment of solid categories that will accommodate the various morphologies. In a few exceptions, the categories may directly be considered morphogenetic (e.g., pyroducts); these have been included in the classification scheme (Figures 2–4), because some identifiable variations in the processes might exist.

The proposed classification is driven by distinctions within the mechanics and dynamics that are involved in the processes, as in other geomorphological sub-disciplines (including fluvial, aeolian, glacial, groundwater, etc.).

Five levels of classification emerged during development of the proposed scheme (Figures 2–4) with the aim of classifying caves along with processes of speleogenesis. Thus, the cave groups represent either integrated caves and cave systems or parts of them. For example, hypergene caves consisted of a vadose part connected to the water table, and conduits within the phreatic and epiphreatic zones are scrutinized independently at higher levels of classification. The first classification level is based upon the distinction between constructional caves, when the space pre-exists and the boundary is formed later, and destructional caves, where the boundary already exists and the space is created within (Mylroie, 2019).

The fundamental cave types are included in the second classification level, which is based on the main processes of cave formation. Although, the predominant process defines the cave groups of the classification scheme, it is worth mentioning that multiple processes can act simultaneously. If a dominant process cannot be recognized, they are grouped as "composite caves" (Figure 2). The second level of classification is further divided into subgroups due to variations in the conditions and setting of the formational processes. The classification scheme is

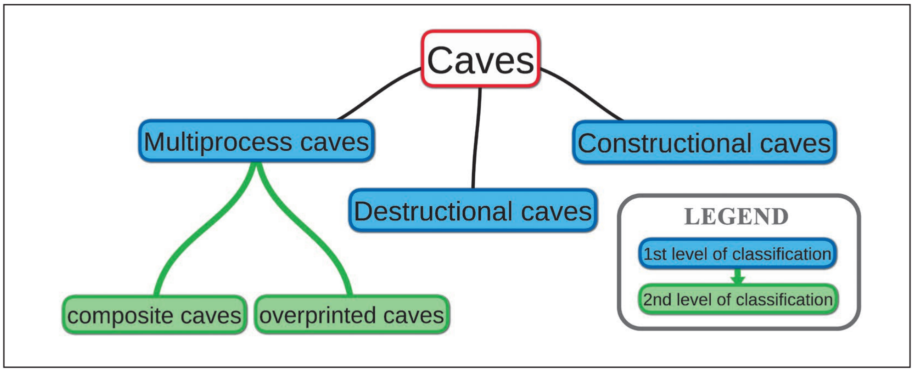

Figure 2: Division of cave forming processes into three major cave groups. Constructional, destructional and multi-process caves. Groups are explained in the text.

paired with short descriptions and some comments that are intended to clarify the distinction followed.

A. CONSTRUCTIONAL CAVES (FIGURES 2 & 3)

These caves are formed concurrently with the formation of the host rock.

1. Synsedimentary caves: they are formed in clastic and chemical sediments by depositional processes.
   a. Progradational caves: they are formed by the progradation of the steeply sloping surfaces of travertine terraces/masses (Gradziński et al., 2018). As defined by Pentecost (2005), no distinction is made between travertine and tufa. They are further divided into the most common type of caves, formed in waterfall sites, and those that are developed as travertine bridges in narrow valleys when several prerequisites are met (Bayari, 2002).
   b. Aggradational caves: these are formed by the aggradation of travertine in artesian springs (Gradziński et al., 2018).
   c. Talus caves: this type is found when caves are formed among large boulders. The boulders may originate in several ways (Bella & Gaál, 2013) and the caves can be further divided, mainly into morphological subtypes (Halliday, 2006a) that are not described separately here.

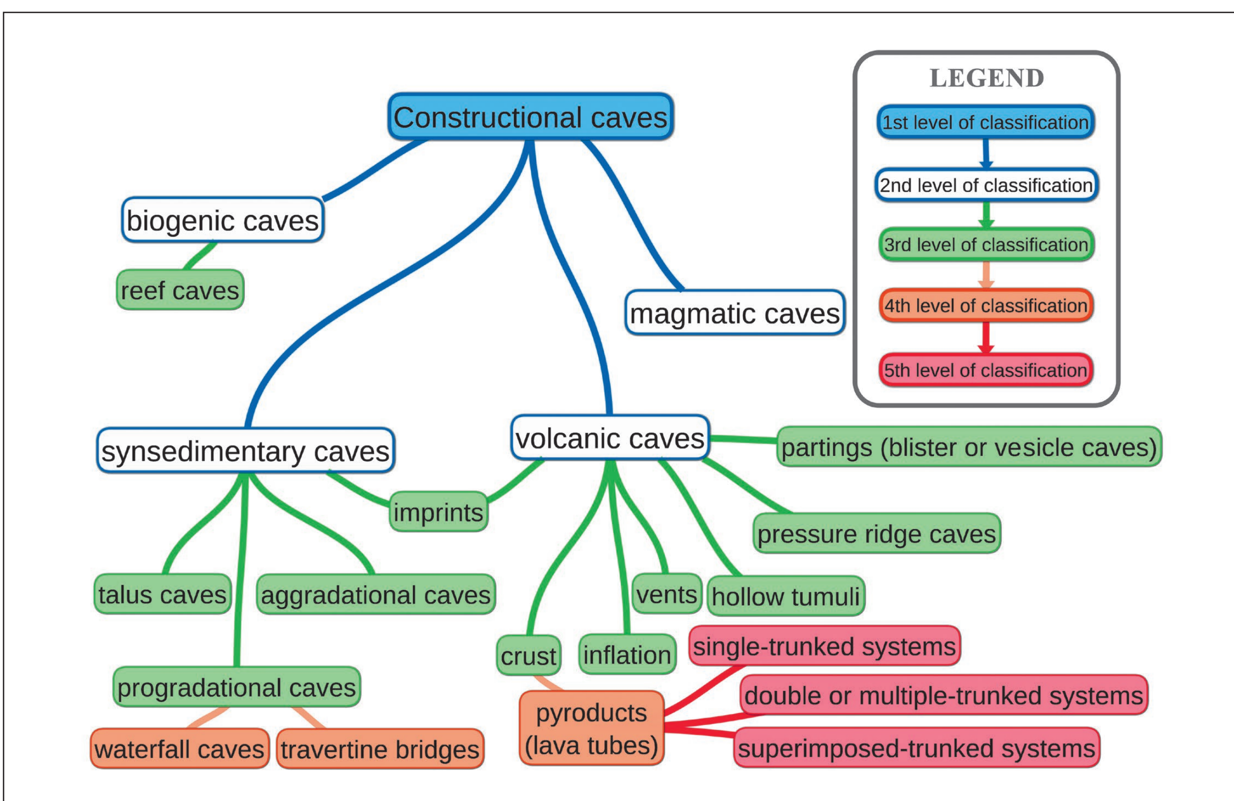

Figure 3: Classification of constructional caves. The second level represents the major groups, and higher levels are due to variations in conditions and settings.

d. Imprints: caves formed when travertine or lava encloses an organism that disintegrates over time, leaving an empty space. Tree trunks are a common example (Gradziński et al., 2018). Removal time of the organic matter differs in such cases but according to the proposed definition both types are caves, because potentially empty space is created with the deposition of lava or travertine. However, it is a good example of the temporal aspects as discussed by Mylroie (2019).

2. Biogenic caves: these are formed by organisms such as coral-reef builders (e.g., Trimmel, 1968; Bögli, 1980). Biogenic caves can also be destructional as mentioned below.
3. Volcanic caves: they are developed in rocks originating from low-viscosity lavas due to factors including lava flow volumes and velocities, unequal cooling, degassing and deformation by lateral forces (Kempe, 2012).
   a. Pyroducts: caves formed by flowing lava, either due to inflation of older beds or by crust formation of the outer bed. Both processes form similar morphologies that are further differentiated morphologically and possibly genetically into three categories of increasing complexity: single-; double- or multiple-trunked and superimposed-trunked systems.
   b. Vents: mainly sub-vertical caves in volcanoes that are formed when the lava vent is not refilled.
   c. Hollow tumuli: caves formed inside low-profile hills in the volcanic-flow landscape (tumuli) due to still-fluid lava draining away from inside the mounds.
   d. Pressure ridge caves: low and wide caves that are formed by lateral pressure of solidified lava beds while the underlying bed is moving.
   e. Partings: these are formed when vesicles are developed due to degassing during lava cooling.

B. DESTRUCTIONAL CAVES (FIGURES 2 & 4)

These caves are formed in a pre-existing host rock.

1. Weathering/erosion caves: in this category weathering and erosion are the dominant cave formation processes. Various processes and lithologies are involved. Nine subtypes are recognized:
   a. Wave-cut caves: these are formed by the erosional action of waves on the host rock.
   b. Fluvial caves: their formation is related to the effects of fluvial erosion. Three subtypes are included: riverbank erosion caves by laterally directed fluvial erosion; waterfall erosion caves by backward-directed erosion of bedrock below and behind waterfalls; and fluvial channel erosion caves that are formed by erosion cutting into the channel floor (Bögli, 1980; Kempe & Werner, 2003; Bella & Gaál, 2013).
   c. Eolian caves: these are formed by abrasive erosion related to winds.
   d. Suffosional/piping caves: open spaces are formed by the slow or catastrophic removal of matrix and clasts due to seepage and waterflow.
   e. Frost weathering caves: processes of rock breakage related to freezing conditions are responsible for their formation (Oberender & Plan, 2015).
   f. Salt weathering caves: they are formed by rock disintegration related to intergranular salt crystallization.
   g. Mudflow caves: these are formed on slopes of mud volcanoes due to mud outflow between dried indurate crust (Bella & Gaál, 2013).
   h. Exfoliation caves: caves formed along fissures due to exfoliation of rocks.
   i. Tree moulds: this type includes cavities created by mechanical removal of petrified wood buried in sediments (Bella & Gaál, 2007).
2. Karst caves: the main cave-forming agent is rock dissolution.
   a. Hypergene caves: these caves are formed by meteoric water that generally moves downwards and laterally towards a spring or spings. The term hypergene has been proposed by Dublyansky (2014), better to describe what has commonly been called "epigene" in speleological studies, for a number of reasons well established by the author. Hypergene caves are divided into categories according to the four-stage model of Ford and Ewers (Ford & Ewers 1978; Ford & Williams, 2007) and the model of Audra and Palmer (2011), who also used the term "*per ascendum*", which is restricted to development of hypergene caves related to "water-table rise". The term "*per descendum*" is used here as the opposite of *per ascendum*, and it relates to caves/passages developed as a result of "water-table drop". The "epiphreatic caves with loops" group is also added according to the model of Audra and Palmer (2011) and interprets differently part of the four-state model. The rest groups and their interpretations can be found in both models.
      i. Vadose caves: they are developed in the vadose hydrological zone where water moves downwards; include three subtypes: the basic vadose caves that are formed in rocks when the water table is initially deep; the drawdown caves that are formed in rocks with initially shallow water table which drops down as breakthrough advances; invasion caves formed by streams that invade preexisting drawdown systems.
      ii. Phreatic caves: they are formed in the phreatic hydrologic zone.

iii. Epiphreatic caves with loops: formed in the epiphreatic zone.
iv. Base level caves: they are formed along the water table.
v. Multistage systems: these are composite cave systems with complex evolutionary history that result in the occurrence and succession of several processes that create the above-mentioned hypergene cave types. They are divided into those that follow a rising or dropping base-level; per ascendum and per descendum speleogenesis, respectively. It is worth noting that both terms are defined by base-level changes and not by the direction of water movement (ascending or descending).

b. Hypogene caves: the recharge of these caves comes from underlying hydrostratigraphic units and is independent of the adjacent surface; the fluids have a distant, estranged or deep source. In dominantly vertical parts of these systems the overall water movement is upwards. Classification of hypogene caves follows Klimchouk (2017).
i. Artesian hypogene caves: they are formed in confined multi-story aquifer systems by their hydraulic communication.
ii. Endogenous hypogene caves: the process is based on upwelling flow in, and from deep zones of fluid-geodynamic influence. Volcanogenic degassing and other non-volcanogenic volatiles (cold degassing; see Klimchouk, 2017) can influence the process and thus, are used as further division.
iii. Combined artesian and endogenous caves: when fluids of deep origin (basinal/basement) ascent through cross-formational discontinuities can interact with the regime of artesian hypogene speleogenesis and this results in the formation of caves.
iv. Hypogene caves inside open and incised aquifers: they are formed in a relatively shallow environment and result in the formation of two cave-types. Sulfuric acid speleogenesis (SAS) hypogene caves are formed close at the water table by water rich in hydrogen sulfide that is oxidized to sulfuric acid (Klimchouk, 2017). The second type are coastal hypogene caves, which are formed in the mixing zone between fresh water and sea water (Klimchouk, 2017; Mylroie & Mylroie, 2017).

3. Mass-movement and deformation caves of mechanical origin.
a. Crevices: these are formed as narrow rectilinear caves by mass-movement. They can form single passages or passage networks (Halliday, 2006b; Self & Farrant, 2013).
b. Falling-out caves: formed by the displacement or removal of blocks due to gravity.
c. Caves related to volumetric changes: are formed in some evaporites/diapirs due to the effects of hydration and deformation (Bella & Gaál, 2013, Gorbunova, 1978; Reinboth, 1997; Calaforra & Pulido-Bosch, 1999; Kendall & Warren, 1987; Vendeville & Jackson, 1992).
d. Collapse shafts: these are formed due to ceiling collapse of underground caves. Realistically, almost all cave types discussed here can include collapse shafts. To allow their formation a pre-existing void is needed below the incipient shaft. If that void is inaccessible and cannot be studied (explorational bias), the shaft cannot be attributed as part of a particular cave system. Thus, mass-movement remains the driving process and that explains the need for additional classification levels. Otherwise, such special cases will remain unclassified or included erroneously in broader categories based on more-general criteria such as lithology. Even though recognition of this category allows an explorational bias to be introduced, there is no bias related to the specific cave-forming processes that are the basis of this scheme.

4. Tectogene caves (Bella & Gaál, 2013 and references therein): these are formed as a result of tectonic activity and deformation.
a. Fault caves: they are formed in an extensional geodynamic regime along faults and fissures.
b. Fold caves: they are formed due to unequal deformation of adjacent rock beds during the tectonic activity that produces folds.
5. Pyrogenic caves: these spaces are created by the burning-out of coal or organic material (i.e., Dubljanskij & Andrejčuk, 1989; Bella & Gaál, 2013). It is notable that the development process corresponds to chemical removal, and they should not be confused with the pyroducts mentioned above in the volcanic caves section.
6. Ghost-rock karstification: this type of cave is formed when various types of altered rock are developed locally within a rock bed or succession during early stages of diagenesis. Caves may then be formed by later removal of susceptible material from the zone of altered rock (Quinif, 2010; Dubois et al., 2014).
7. Glacier caves: formed by the melting of ice and the related "erosional" effects of meltwater in glaciers.
8. Magmatic caves: these geode-like cavities of various sizes are most commonly found in plutonic rocks (Dubljanskij & Andrejčuk, 1989; Bella & Gaál, 2013).
9. Biogenic caves: these are voids that are excavated by animals (e.g., Lundquist & Varnedoe, 2006).

C. MULTIPROCESS CAVES (Figure 2)

This group accommodates caves that owe their origins to multiple processes.

1. Composite caves: two or more processes acted simultaneously to develop two or more caves that are subsequently interconnected.
2. Overprinted caves: pre-existing caves of a specific type are affected and transformed by the action of processes differing from those that formed the original voids.

Depending on which question is addressed, all the classifications available in the literature can be used at least in part. Some of the main differences between them are discussed below.

The classification of Bögli (1980) defines primary and secondary caves, following earlier works by Kraus (1894; as cited by Oberender & Plan, 2018 and Trimmel, 1968). Subdivisions of exogenous and endogenous types are recognized in the secondary caves. Their division depends upon the dominant cave-forming agent. This classification can provide information about the speleogenesis and the processes involved, but without subtypes. Furthermore, the scheme does not include categories that were recognized and defined later, such as hypogene caves. Despite its broad applicability it was not adopted by English-speaking researchers until recently (Oberender & Plan, 2018), when caves were classified as constructional and destructional by Mylroie (2019). These latter terms can be considered synonymous with primary and secondary, respectively.

The scheme of White and Culver (2005) includes only the major cave types. Caves developed by dissolution are further divided by lithology and then by water chemistry. However, based in some cases on recent ideas, such as the definition of hypogene caves, hydrological criteria dominate over geochemical ones. Nevertheless, water chemistry is also important in speleogenesis and especially in the case of karst caves. For example, there are hypogene caves formed by carbonic acid in carbonates, by hydrolysis of gypsum, by sulfuric acid speleogenesis, by mixing corrosion, etc. This classification considers various geochemical controls in the karst speleogenetic processes.

The scheme of White (1988) divides caves according to chemical and mechanical processes. Klimchouk (2006) gives the following cave types: solution, volcanic, glacier, crevice, littoral, piping, and erosion. Both suggestions include only major divisions. Striebel (2005) proposed a classification based on lithology and cave-forming processes (Oberender & Plan, 2018). Palmer (2007) also used lithology and morphogenetic criteria for classification. Lithology seems to be significant for many classifications but there are processes that are not restricted to specific rock types (Oberender & Plan, 2018).

Mylroie (2019) divides caves into constructional and destructional. This aspect is also adopted here. He also includes artificial caves in the context. In the proposed classification scheme, it can be observed that biogenic caves can be both constructional and destructional features. Human-made underground voids also fit within these two formation options and one can consider them part of the wider grouping of biogenic caves, even though they are excluded from the proposed cave definition.

A classification of non-dissolution caves is provided by Bella and Gaál (2013); it is a process-based scheme with 56 subtypes that may be genetic or morphological. In some cases, cave types, such as boulder caves (e.g., glacial, in lava flows, seismotectonic, rockslide boulder caves, boulder exfoliation caves) or collapsed caves (e.g., collapsed pit craters, suffosion collapse shafts), are included within several processes. In the proposed classification scheme, boulder and collapsed caves are considered as synsedimentary and categorized under the mass-movement subtype, respectively. Some other subtypes, such as the tafoni, are considered to be morphological forms, and they are included in the proposed scheme mainly within the salt weathering group. In addition, this cave morphotype has been explained by many processes, which complicate usage of the term. Tectogene caves are not included among those related to deformation because they are caused by endogenous forces rather than the exogenous ones that form mass-movement and other deformation caves.

Many of the caves classified can be subject to changes by the predominant cave-forming agent. For example, mature karst cave systems may go through substantial modifications due to erosion (Klimchouk, 2006). In such cases, a genetic classification may fail to classify it adequately. To remedy this shortfall, the multiprocess group, as a major type, and multi-stage hypergene subtypes have been added to the classification scheme within the fourth level of classification. Many other examples of overprinted processes and composite caves can be recognized.

Ghost-rock karstification is another complex process that is defined as a cave group at the first classification level. They are differentiated from karst and mechanical/weathering caves because their formation combines aspects of both processes in two successive stages of chemical alteration and material removal. A new perspective relates both (dissolution and weathering/erosion) with the endogenous processes of hypogene speleogenesis (Klimchouk, 2017). Considering all these factors, ghost-rock karstification is connected provisionally with both categories in Figure 4.

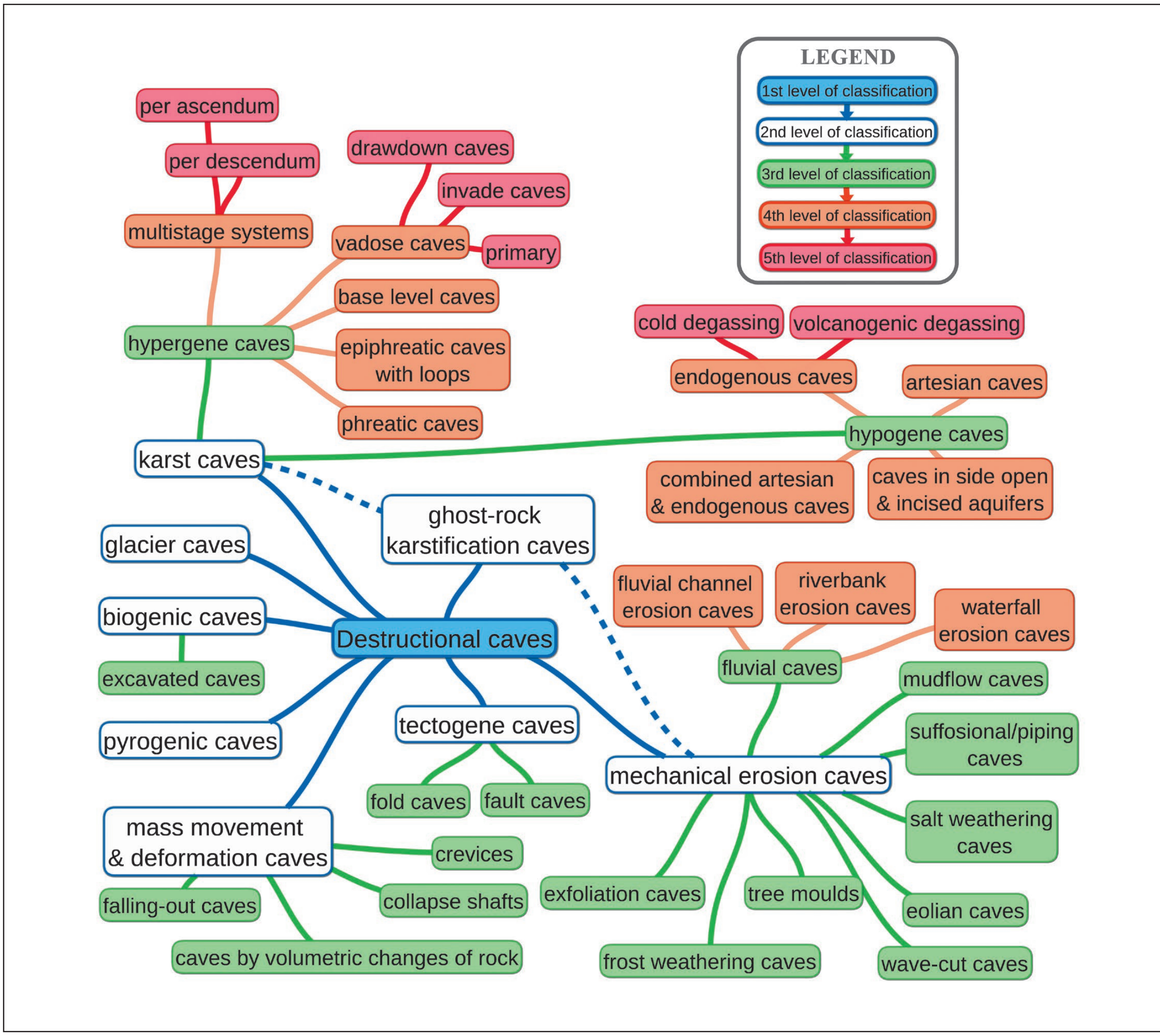

Figure 4: Major groups of destructional caves (2nd level of classification) and their process-based clusters indicate variations of conditions and setting. The upper right corner is the legend for the classification levels. For group descriptions see text.

5. CONCLUSIONS

The new cave definition proposed herein has the main advantages that:

- it is linked to the cave formation processes,
- it covers the known cave types,
- it uses (typical) human size to differentiate from porosity and contiguous spaces,
- it applies also in a continuum of sizes even smaller than human dimensions and
- it is independent of explorational bias.

These characteristics of the cave definition allow it to be applied on descriptive purposes, speleogenetic studies, and statistical analysis. Apart from its scientific ground, it remains simple enough to be used by cavers and non-specialists.

The classification scheme is analytical and combines aspects of the most widely used grouping systems that have been developed to date. Grouping of the basic processes are encompasses depositional, mechanical and chemical rock destruction categories. Settings and specific formational agents provide the additional branches of the classification.

Thus, the process-based classification scheme recognizes 3 main groups with 12 main branches. These are the first two levels of the classification, referencing all the known major processes that create caves. The next three levels of the classification add details that summarize current knowledge derived from speleogenetic studies into a state-of-the-art scheme with 51 endmembers.

A comparison of the various classifications that have been proposed previously in relevant publications reveals that such schemes are inevitably non-static in character. They tend to change in response to the progress of research, more detailed cave census data and improved communication by and between scientists on aspects of previously and newly discovered caves.

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