

A Geomorphological Study on The Micro Karst Landform Diversity of a Limestone Cave: A Case Study of Waulpane Cave, Ratnapura District

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Abstract: Karsts are the result of complex interactions between geology, climate, hydrology, and biological factors over long periods of time. These landscapes comprise a variety of surface and subterranean landforms formed primarily through the dissolution of soluble rocks, especially limestone. The dissolution process creates unique surface features and intricate networks of underground cavities, while the deposition of calcium carbonate (CaCO_3) forms secondary mineral deposits known as speleothems. Sri Lanka is home to several limestone caves, with the Waulpane limestone cave in the Ratnapura District being one of the most significant. This study focuses on identifying the diversity and distribution of micro karst landforms within the Waulpane cave. Both primary and secondary sources were used in the study; primary sources included direct observations, interviews, and sample collections, while secondary sources, such as literary materials, provided additional context and information. Research findings revealed a variety of speleothems such as stalactites, stalagmites, drapery-like formations, and karren features present on the walls, ceiling, and floor of the cave. These formations vary widely in size and morphology. Some stalactites resemble bulbs, cones, leaves, and pillars, while others take shapes akin to pencils, wall lamps, arches, hourglasses, and flower petals. Most of these features are concentrated in the central part of the cave, where environmental conditions are most favourable for their development. The formation of these features is influenced by several interrelated factors, including the calcium carbonate-rich spring water, local climate, topography, vegetation cover, hydrological patterns, and the spatial distribution of limestone.

Keywords: Karst, Dissolution process, Limestone cave, Depositional process, Micro karst landforms

I. Introduction

The Earth's surface consists of land and water, with the solid outer layer known as the lithosphere, continuously reshaped by natural forces such as wind and water. These dynamic processes give rise to a range of landforms, including coastal, oceanic, aeolian, mountain, glacial, fluvial, and karst types. Among these, karst landscapes are notable for their unique origin and morphology, formed through the dissolution of soluble rocks like limestone.

Karst terrains are distinguished by features such as caves, sinkholes, and underground drainage systems, shaped primarily by water and climatic influences. Often referred to as 'living landscapes,' these environments exhibit unique hydrological and geomorphological characteristics resulting from the interaction of rock solubility and environmental processes. This study specifically focuses on micro-scale karst features within tropical limestone caves, where continuous geological activity produces intricate subterranean formations that remain relatively underexplored.

According to Ford and Williams (1989), karst landscapes are defined as "terrain with distinctive hydrology and landforms that arise from a combination of high rock solubility and well-developed secondary (fracture) porosity. Such areas are characterized by sinking streams, caves, enclosed depressions, fluted rock outcrops, and large springs." These features highlight the complexity and diversity of karst systems across both surface and subsurface environments.

Karst landforms are generally classified into two main categories: surface and subterranean. Surface landforms tend to be larger and primarily erosional, shaped by the gradual removal of material over time. In contrast, subterranean landforms such as those found within caves can be either erosional or depositional in nature, often varying significantly in size and structure. These underground features include formations like stalactites, stalagmites, and flowstones, which develop under specific hydrological and geochemical conditions.

This study investigates the largely understudied micro-scale karst landforms found within tropical limestone caves, with a focus on Waulpane Cave in Sri Lanka. While karst research has traditionally emphasised macro and meso-scale features, micro and nano-scale karst formations, particularly those within subterranean environments have received comparatively limited scholarly attention. These smaller-scale features, including speleothems and other fine formations offer valuable insights into geological, hydrological, and climatic processes. By addressing this gap, the study contributes to a more nuanced understanding of karst development in tropical regions.

Waulpane Cave serves as an ideal case study due to its distinctive geological setting and multidisciplinary significance. Situated in Sri Lanka's Sabaragamuwa Province, this limestone cave is notable for its ancient calcareous deposits, a calcium-rich

underground spring, and remarkable biodiversity. Of particular importance is its considerable geological, archaeological, paleontological, anthropological, and biological value. Unlike many other karst sites dominated by large-scale features, Waulpane is characterised primarily by micro-scale formations, making it especially relevant to the aims of this research.

The study aims to explore several key research questions related to the micro karst landforms within Waulpane Cave. It investigates the specific types of micro-scale features present in the cave and examines why these formations are more prevalent than macro-scale features. Additionally, the research seeks to identify the geological and environmental factors that contribute to the development of these micro formations. A further objective is to analyse the spatial distribution of speleothems within the cave, providing insights into the processes that influence their formation and arrangement.

By identifying and analysing the diversity of micro karst landforms in Waulpane Cave, this research aims to enhance understanding of subterranean karst processes in tropical limestone environments and contribute to the broader discourse on cave geomorphology.

Empirical Review

Karst landforms are a significant yet often undervalued element of geo-diversity, reflecting the complex interactions between surface water and groundwater. These landforms are an integral part of the rich geo-diversity of our planet and are highly valued for their natural, cultural, scientific, recreational, socio-economic, and aesthetic significance. These landscapes are recognized not only for their geological and geomorphological significance but also for their roles across diverse scientific fields, including Geology, Geomorphology, and Speleology but also in disciplines such as Hydrology, Hydrogeology, Paleontology, Paleoclimatology, Pedology, Biology, Botany, Zoology, Mycology, Entomology, Biospeleology, Archaeology, and Physical Anthropology. This interdisciplinary importance highlights the multifaceted value of karst systems and their features such as caves and speleothems.

Seminal works such as *Karst Hydrology and Geomorphology* by Derek Ford and Paul Williams (1989) and *Karst Geomorphology* by Professor J.N. Jennings (1971) have provided foundational insights into karst processes and landform development. Ford and Williams offer a comprehensive analysis of karst topography, with a particular emphasis on hydrology and geomorphology. Their work addresses topics including the geological structure of karst rocks, the physics and chemistry of dissolution processes, global dissolution rates, karst water resources, hydrological systems, cave development, and both dissolutional and depositional landforms. Jennings complements this perspective with a detailed discussion of geological structure and climatic influences shaping karst terrains. His book explores the nature of karst, karst processes, surface and subterranean landforms, and the historical geomorphology of karst landscapes.

More recent geomorphological texts, such as *Fundamentals of Geomorphology* by Richard John Huggett (2007), have examined a wide range of landforms and landscapes on the Earth's surface, including karst systems. This work addresses both macro and micro-scale karst features, along with the processes involved in their formation. Region-specific studies, such as *Karst and Caves of Southeast Alaska* by Priscilla Schulte and Karalynn Crocker (1998), offer detailed accounts of karst development in Southeast Alaska. Their research explores the geological, biological, archaeological, paleontological, and geographical significance of these landscapes, both regionally and in a broader global context.

Several journal articles have documented karst development across diverse geographical regions. For example, *Caves of New Jersey* by Richard F. Dalton (1976), *Geologic and Hydrologic Controls on Karst and Cave Development in Belize* by Thomas E. Miller (1996), *The Limestone Caves and Caverns of Ohio* by George W. White (1926), and *Limestone Caves in the Sigatoka Valley, Viti Levu, Fiji* by Dick Watling and John C. Pernetta offer detailed accounts of karst topography and limestone caves in their respective regions. Additionally, the research article *Origin and Morphology of Limestone Caves* by Arthur N. Palmer provides valuable insights into karst topography and its characteristics in the United States, incorporating advanced techniques and methods. However, these too prioritize broader-scale features, underscoring a persistent research gap at micro and nano-scale karst formations.

Within Sri Lanka, research on karst landscapes remains relatively limited. Nonetheless, several scholars have explored karst landforms in regions such as Matale, Nalanda, Habarana, Kandy, Badulla, Welimada, and Maskeliya. Notably, the work of S. N. Wikramaratne and Malcolm Jancen on the Streeepura Cave provides significant contributions to understanding cave biogeochemistry, speleothem formation, and cave ecology. Their studies document the distribution of vegetation, the formation processes of stalactites and stalagmites, and the characteristics of pool deposits and sub-aqueous formations. They also examine the presence of microorganisms and other cave-dwelling organisms, as well as the production of gases such as CO₂, CH₄, and H₂S within the cavern environment.

Similarly, W.S. Weliange and Jayasingha Pathmakumara in their work of *Speleothems in Gneissic Caves of Sri Lanka* (2010), investigate speleothem diversity in gneissic caves, providing detailed morphological analyses that enhance the understanding of non-limestone cave systems. Their research includes studies conducted in caves such as Kosgala Wavul Lena in Kehelawitagama, Streeepura Lena in Kuruwita, and Yahal Lena in Nikawalamulla. They examine a range of speleothems, including stalactites,

stalagmites, flowstone, curtains, ridges, and rim pool-like structures, focusing on their morphology, colour variations, and depositional contexts.

Despite these valuable contributions, limestone caves such as Waulpane remain underexplored, particularly with regard to their abundance of micro-scale karst landforms shaped by distinct hydrological conditions, such as calcium-rich springs. This persistent gap in research on tropical micro karst systems underscores the need for targeted investigations into the genesis, spatial distribution, and environmental controls of small-scale karst features.

Interdisciplinary perspectives further emphasize the broader relevance of micro karst studies. Micro speleothems, for example, serve as valuable indicators for paleoclimate reconstruction and host specialized ecosystems, linking geological processes with biological and climatic research. Yet, these aspects remain underrepresented in current literature, particularly in tropical karst environments.

In summary, while existing research provides extensive insights into karst geomorphology, it predominantly focuses on macro and meso-scale features within temperate zones or non-tropical settings. The limited focus on tropical micro-scale karst features, especially in caves like Waulpane, leaves a significant knowledge gap. This study aims to bridge this gap by investigating the formation processes, diversity, and spatial distribution of micro karst landforms, thereby advancing understanding of tropical karst systems in both geological and interdisciplinary contexts.

II. Literature Review

The term *karst* originates from pre-Indo-European roots and has evolved through various linguistic forms (Ford & Williams, 1989). It appears in German as *karst*, derived from the Indo-European word *kar*, meaning 'rock'. The Italian equivalent is *carso*, while the Slovenian term *kras* (or *krš*) refers to 'bare stony ground' (Huggett, 2007).

As defined by Ford and Williams (1989), 'Karst is the term used to describe a special style of landscape containing caves and extensive underground water systems that is developed on especially soluble rocks such as limestone, marble, and gypsum'. In the field of geomorphology, karst is a terrain in which soluble rocks are altered above and below ground by the dissolving action of water and that bears distinctive characteristics of relief and drainage (Jennings, 1971). Other definitions highlight karst as a distinctive terrain created by erosion of a soluble rock where the topography and landforms are a consequence of efficient underground drainage. Its characteristic features therefore include disrupted surface drainage, closed depressions, dry valleys and caves (Figure 1). In essence, karst is not simply a geological formation, but a dynamic system shaped by the interaction of lithology, hydrology, and climatic factors over long temporal scales.

Karsts are often described as 'living landscapes' due to their dynamic evolution driven by the prolonged interaction of climatic, topographic, hydrological, biological, and edaphic (soil-related) factors. They are primarily formed by chemical weathering of rock, rather than mechanical weathering. Karst topography and limestone caves, or solutional caves, are dramatic examples of the effects of acidic groundwater on soluble bedrock. While most solution caves are found in limestone, they can also occur less frequently in other carbonates such as dolomite ($\text{CaMg}(\text{CO}_3)_2$), calcite (CaCO_3), gypsum, marble, halite, dolostone, salt, and chalk. In some cases, even clastic rocks with soluble cements are susceptible to karstification. The defining condition for the formation of such landscapes is the solubility of the bedrock, which determines the extent and complexity of karst development (Huggett, 2007).

The origins of limestone and its transformation into karst landscapes are closely tied to both biological and geological processes. Early life forms in the oceans, dating back approximately 3.8 billion years, were single-celled organisms known as cyanobacteria. These blue-green algae produced their own food through photosynthesis and, in the process, released oxygen, significantly contributing to the oxygenation of Earth's atmosphere. Over geological timescales, the biochemical activity of such organisms facilitated the precipitation and accumulation of carbonate sediments, eventually leading to the formation of dolomitic limestone and other carbonate rocks. These sedimentary layers were later uplifted and exposed at the surface through tectonic activity. In contrast to the biological genesis of the host rock, most karst landforms are shaped by the inorganic chemical process of dissolution. Weak carbonic acid formed when rainwater or snowmelt absorbs atmospheric and soil-derived carbon dioxide, percolates through the ground and reacts with calcium carbonate (CaCO_3) in limestone. This mildly acidic solution gradually dissolves the rock, enlarging joints and bedding planes and eventually forming subterranean voids and drainage systems. Over time, the permeable and soluble limestone is eroded by this carbonic water. As the water penetrates the underlying depths of sediments, the limestone is gradually eroded due to the reaction between the weak carbonic acid in rainwater and the chemicals in the rock. Large hollow cavities are formed in the rock due to this process. These features, resulting from the dissolution process, are known as karst topography (Figure 2).

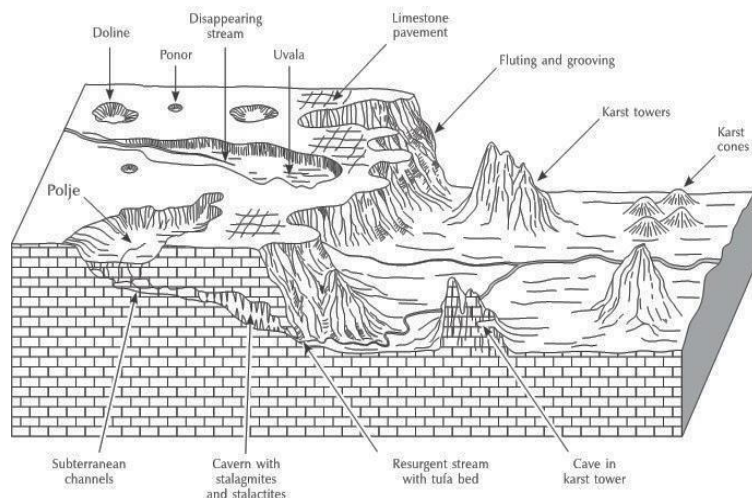


Figure 1: Diagram of the karst landscape

Source: Adapted from Huggett (2007)

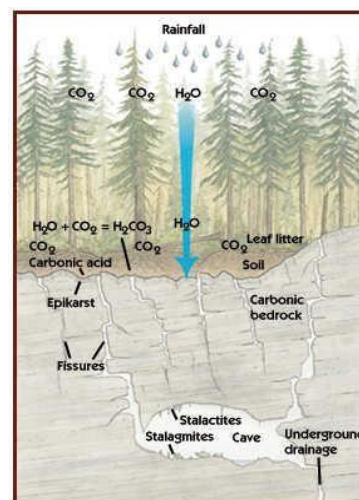
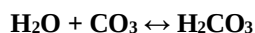


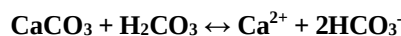
Figure 2: The carbon dioxide cascade in the forested karst environment

Source: Adapted from Stokes et al. (n.d.)

Carbonic acid (H_2CO_3) is naturally formed when carbon dioxide (CO_2) from the atmosphere dissolves in rainwater.



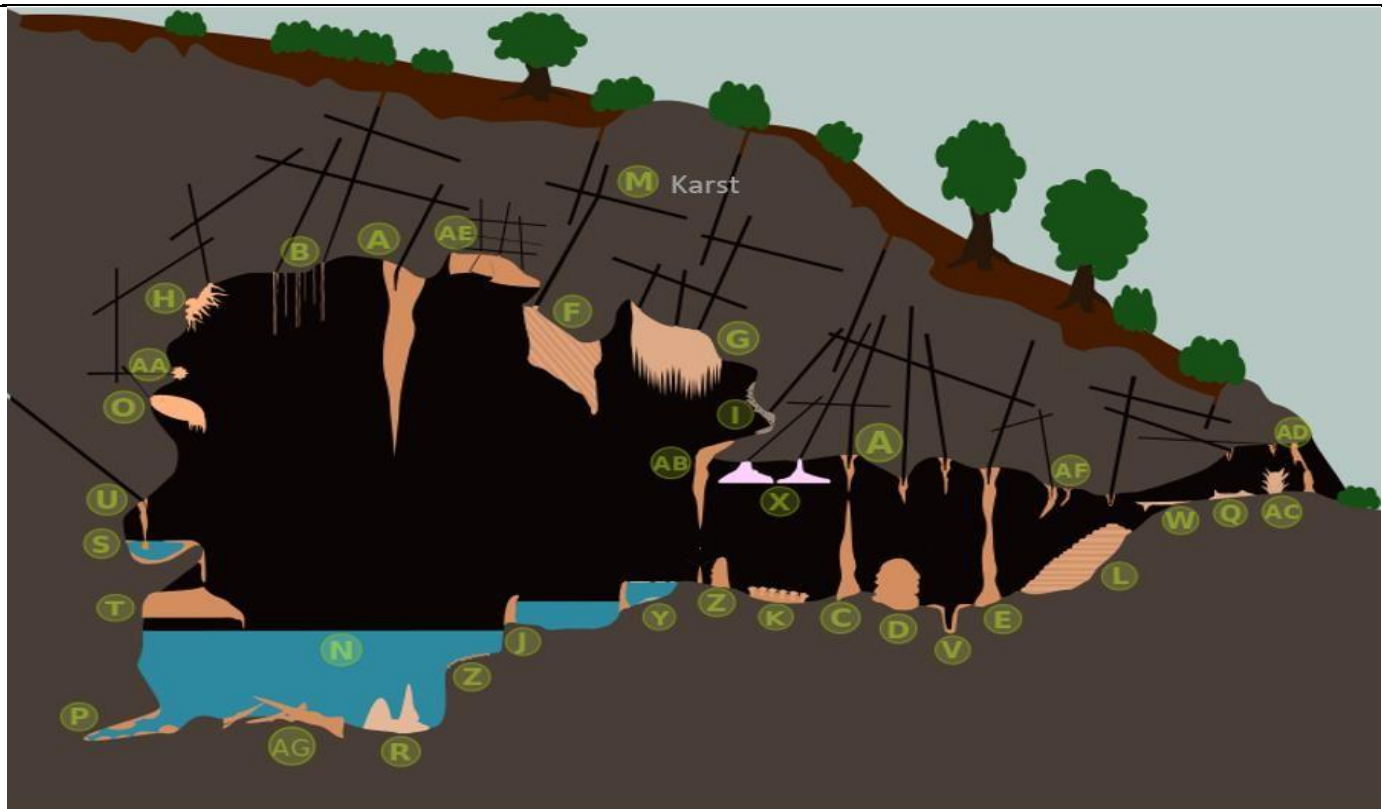
When solid calcium carbonate (CaCO_3) comes into contact with carbonic acid (H_2CO_3), it dissolves, producing calcium ions (Ca^{2+}) and bicarbonate ions (HCO_3^-) in solution.



The dissolution process is often accompanied by several additional factors. Elevated levels of carbon dioxide in the soil produced through root respiration, microbial activity, and the decomposition of organic matter enhance the acidity of percolating water, thereby accelerating the dissolution of soluble bedrock. The collapse of overlying soil and bedrock further facilitates this process by increasing the exposure of fresh rock surfaces. Additionally, the transport of insoluble debris through subterranean channels can modify hydrological pathways and contribute to the enlargement and evolution of karst features.

Karst features can develop in a range of rock types, not solely limestone, as long as soluble components are present. A limestone cave or cavern is a natural underground cavity formed through the dissolution of bedrock and can range from just a few metres to many kilometres in length and depth. Over time, the persistent percolation of mildly acidic water along bedding planes, faults, and joints enhances the chemical weathering of limestone, leading to the progressive enlargement of cavities and fissures throughout the cave system. This dissolution process contributes to the development of a variety of macro and meso-scale landforms. Karst landscapes are typically characterized by underground features such as caves, as well as a variety of surface features. Surface karst features include swallow holes (sinkholes), dolines, uvalas, poljes, gorges, dry valleys, limestone pavements, clints, grikes, cockpits, tower karst, and springs. The size of these features can vary greatly, ranging from small-scale structures measuring just a few millimetres or centimetres to large-scale landforms hundreds of metres across (Ford and Williams, 2007).

Another type of landform that develops within caverns through solutional processes is the speleothem, a secondary mineral deposit formed by the precipitation of minerals from dripping or flowing water. Common types of speleothems include stalactites, stalagmites, columns (or pillars), soda straws, flowstones, draperies, helictites, and cave popcorn. Speleothems are crystalline deposits that typically occur on the ceilings, walls, and floors of caves (Figure 3). Their composition is largely determined by the mineralogy of the host rock, most often limestone, and the chemistry of percolating groundwater. The rate and morphology of speleothem growth are influenced by several environmental factors, including temperature, rainfall, the concentration of carbon dioxide in the soil, and the rate of organic decay. These factors affect the acidity of the water; more acidic water, rich in carbonic acid, can dissolve greater amounts of minerals and facilitate faster speleothem formation. Speleothems can also exist on very small scales, including micro and nano-scale formations. Small-scale limestone sculptures, known as karren, include linear channels or grooves (Huggett, 2007). Despite their scientific value, micro-speleothems remain understudied, particularly in tropical karst systems, where their formation dynamics may differ significantly from temperate counterparts. As such, they represent a critical yet overlooked component of cave geomorphology deserving of further investigation.



A - Stalactite	L - Sinter terrace	W - Flowstone
B - Soda straws	M - Karst	X - Trays
C - Stalagmites	N - Body of water	Y - Calcite rafts
D - Coned stalagmite	O - Shield	Z - Cave popcorn or coralloids
E - Stalagnate or column	P - Cave clouds	AA - Frostworks
F - Drapery	Q - Cave pearls	AB - Flowstone
G - Drapery	R - Tower cones	AC - Splattermite
H - Helictites	S - Shelfstones	AD - Speleoseismites
I - Moonmilk	T - Baldacchino canopy	AE - Boxworks
J - Sinter pool, rimstone	U - Bottlebrush stalactite	AF - Oriented stalactite
K - Calcite crystals	V - Conulite	AG - Collapsed rubble

Figure 3: Types of speleothems

Source: <https://en.wikipedia.org/wiki/Speleothem> (2017)

Karst topography is globally distributed, occurring across a wide range of latitudes and elevations. It is estimated that karst landscapes cover approximately 20% of the Earth's dry, ice-free land surface and roughly 20-25% of the global population depends largely or entirely on groundwater sourced from karst aquifers (Figure 4; Ford and Williams, 2007). This widespread dependence underscores the importance of understanding karst systems, particularly the subsurface processes that govern groundwater flow and storage. Such global relevance highlights the need for site-specific investigations, especially in under-researched tropical karst environments, where geomorphological and hydrological dynamics may diverge from temperate models commonly represented in the literature.

Caves are distributed globally, with notable concentrations in countries such as France, Italy, Australia, the United Kingdom, and the United States. Among them, Mammoth Cave in Kentucky stands as the world's longest known cave system. Carlsbad Caverns in New Mexico contains the largest known subterranean chamber, while Gouffre Berger near Grenoble, France holds the distinction of being the deepest cave explored to date. According to the National Speleological Society of America, more than

100,000 caves have been documented worldwide, reflecting the widespread occurrence of karst processes. Prominent examples include Kartchner Caverns (USA), Cango Caves (South Africa), Harrison's Cave (Barbados), Dongzhong Cave (China), Fantasy Cave (New Zealand), Phong Nha Cave (Vietnam), Barton Creek Cave (Belize), Škocjan Caves (Slovenia), Deer Cave (Malaysia), and Onondaga Cave (USA). The global distribution and morphological diversity of these caves underscore the geomorphic complexity of karst systems and their importance as natural archives of climatic, hydrological, and ecological histories.

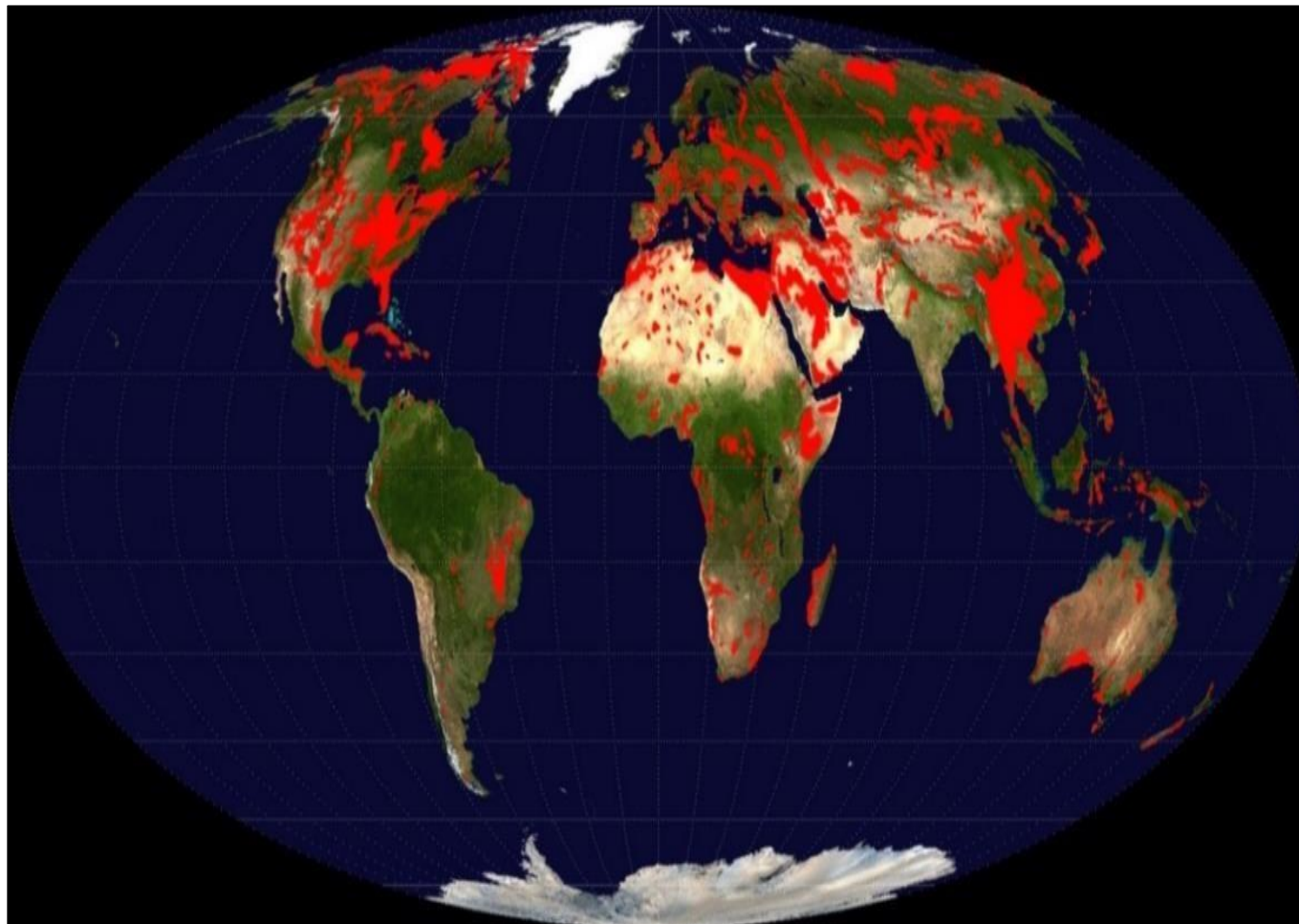


Figure 4: Global distribution of major outcrops of carbonate rocks (mainly limestone except evaporites)

Source: <https://en.wikipedia.org/wiki/Karst> (2017)

Several limestone caves have been identified in Sri Lanka, predominantly within the Sabaragamuwa, Uva, and Central Provinces. Research indicates that caves located in the wet zone exhibit a greater propensity for speleothem development compared to those in the dry zone, owing to higher levels of moisture and biological activity. These solutional caves, often formed within limestone or marble bands, can attain vertical dimensions ranging from approximately 10 to 20 feet (3 to 6 m). The distribution and morphological characteristics of these caves reflect the influence of climatic zonation and lithological variability on karst development in the Sri Lankan context (Cooray, 1984).

III. Methodology

The limestone cavern at Waulpane is located in the Kumburugamuwa Grama Niladhari Division, within the Kolonna Divisional Secretariat of Ratnapura District in Sabaragamuwa Province. Situated at an elevation of 278 m above sea level on the eastern slopes of the Bulutota Rakwana Mountain Range, it lies northwest of Embilipitiya and approximately 14 km from Palledbedda. The approximate coordinates of Waulpane are 6°25.5' N latitude and 80°43.8' E longitude (Figure 5). The name 'Waulpane' meaning 'cave of bats', likely originates from the enormous bat population inhabiting the cavern, estimated at around 800,000 individuals. Located within a tropical rainforest covering nearly 30 acres (12.1 hectares), the Waulpane Cave is surrounded by dense vegetation, with trees reaching heights of up to 100 feet (30.4 metres). This forest hosts a rich diversity of species, including several endemic flora and fauna. Birds, mammals, lizards, butterflies, fish, reptiles, herbal plants, and wild rice species are among the many forms of biodiversity found in the Waulpane area.

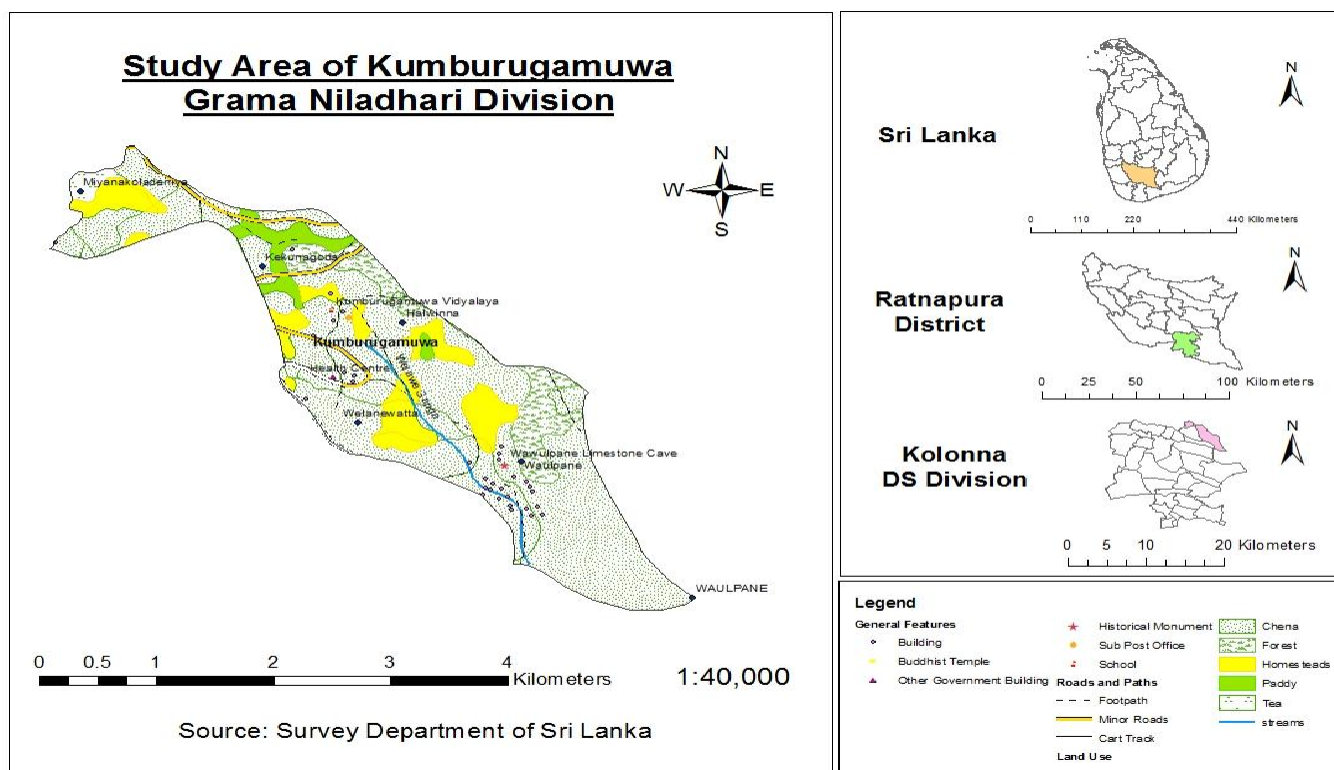


Figure 5: Study area - Kumburugamuwa Grama Niladhari Division

Source: Created using 1 : 50,000 Digital Data, Survey Department of Sri Lanka

Given the objectives of this study, the research site was defined as the Waulpane limestone cave and its immediate surroundings. A purposive sampling approach was adopted to select data collection sites within the cave, targeting areas that exhibited significant speleothem development, active hydrological features (e.g., brackish water spring and waterfall), and diverse micro-environments. Sampling locations were selected to represent both high-humidity zones near water bodies and drier, more stable interior sections, enabling spatial comparisons of geomorphological and hydrological characteristics.

Data collection incorporated both primary and secondary sources. Secondary data were obtained through a comprehensive review of relevant literature, including published books, academic research reports, institutional publications, maps, and online articles. Cartographic and spatial resources such as metric maps, GIS data, and Google Earth imagery were analysed to contextualise the regional geomorphology and land cover.

Primary data were collected through a combination of direct observation, informal interviews, and sampling. Unstructured in-depth interviews were conducted with villagers, the Grama Niladhari (village officer), and academic experts to gather information about the cave's historical significance, ecological characteristics, and perceived changes over time. Observational methods were employed to document morphological and hydrological features, while photographic records supported spatial interpretation and descriptive analysis.

Environmental sampling included the collection of water, soil, and rock specimens from various parts of the cave for laboratory analysis. Water samples were tested for pH, temperature, electrical conductivity, turbidity, dissolved oxygen, and total dissolved solids. Water hardness was assessed using the EDTA titration method, following standard protocols. Speleothem dimensions, length, width, and height were measured using measuring tapes, while surface morphology was recorded through high-resolution photography and field sketches. All samples were selected randomly, as no specific statistical sampling method was employed. For data analysis, a combination of methods and techniques was employed. Quantitative methods, including both basic and advanced statistical techniques, were applied where appropriate. The findings were primarily presented through photographs, maps, and descriptive narratives depending on the context.

IV. Results and Discussion

This study sought to investigate the types, distribution, and environmental conditions influencing the formation of karst landforms within the Waulpane limestone cave. The findings reveal that micro-scale karst features dominate the cave system, particularly speleothems such as stalactites, stalagmites, and karren. These features vary significantly in shape, size, and spatial distribution, reflecting the interplay between local geological, hydrological, and climatic factors. Macro-scale landforms such as the cave

chamber itself and the surface sinkholes are limited in number and extent, likely due to the restricted presence of limestone and relatively low calcium carbonate concentrations in the spring water feeding the system. The data also indicate that the most visually and structurally complex micro karst features are concentrated in the central portion of the cave, where environmental conditions such as moisture, temperature, and water chemistry are most favourable. The sections below provide a detailed account of these observations, categorised by landform type, scale, and morphological characteristics, and further explore the nature of the distribution of karst landforms, the factors influencing their formation, and the diversity of micro karst land forms within Waulpane Cave.

The nature of the distribution of karst landforms

According to geological research, the Waulpane Cave is estimated to be approximately 500 million years old, with its rock formations dating back to the Precambrian era. It is considered the oldest and largest limestone cave in Sri Lanka and potentially one of the oldest known caves in the world. Geologists estimate that the limestone deposit in the area spans approximately 20 square miles (Weerasekara, 2001). The main cave is aligned in an east-west direction and is situated southeast of Waulpane village, within a drop valley carved by the Hulwini Dola stream, which is partially obstructed by the cave itself. In addition to the primary chamber, the cave system comprises approximately 12 subsidiary caves of varying sizes, located both within and around the main cavern.

The main chamber of the Waulpane Cave extends approximately 150 feet (45.7 m) in length. The primary entrance measures about 12 feet (3.6 m) in height and 11 feet (3.3 m) in width (Figure 6). Adjacent to this is a smaller entrance on the right, separated by a limestone column with a diameter of approximately 5 to 6 feet (1.5 to 1.8 m). To the left of the main entrance lies an upper opening, which is both wider and nearly twice as tall, while the lower entrance is comparatively narrower. The Hulwini Dola enters the cave through this lower entrance at an elevation of approximately 900 feet (274.3 m) above mean sea level. After flowing through the subterranean passage for nearly a quarter of a mile, the stream reemerges at an elevation of about 800 feet (243.8 m) above mean sea level.

The height of the cave varies along its length, averaging approximately 108 feet (32.9 m). Near the entrance, the vertical height is around 51.8 feet (15.8 m), increasing to approximately 55.4 feet (16.9 m) towards the end of the cave. The exit doorway is situated at the far end of the cavern and measures about 13 feet (3.9 m) in height, although it is partially obstructed by a large broken limestone block. Notably, the cave roof above the exit slopes upward, resulting in a higher internal ceiling in that section. The Hulwini Dola flows out through an opening to the right of the main exit, where the roof has collapsed over time due to natural processes. According to observations by Sir Arthur C. Clarke, the stream once flowed at a significantly higher elevation than it does at present. He attributed the gradual lowering of its course to ongoing weathering and erosion, a process for which physical evidence remains visible within the cave environment.

The Waulpane limestone cave features the second-longest brackish internal waterfall in Asia, known as *Waulpane Ella*. Located at the centre of the cavern, this subterranean waterfall stands approximately 150 feet (45.7 m) in height. The water cascades onto a prominent limestone pillar, which has been rounded and smoothed over centuries due to persistent hydraulic action. The waterfall is fed by a stream originating from the adjacent hillside, which enters the cave through a sinkhole in the limestone roof. This sinkhole, wide enough for a person to pass through, allows the water to descend in a series of three distinct steps. The stream is brackish and rich in calcium carbonate (CaCO_3), a characteristic that significantly contributes to the development of speleothems and other internal karst landforms within the cave (Figure 7).



Figure 6: Entrance of the Waulpane cave

Source: Unknown, retrieved from the internet (n.d.)



Figure 7: Waulpane Falls and the sinkhole where the stream enters to form the waterfall

Source: Field survey (2017)

The general morphology of the Waulpane Cave can be categorised into three distinct zones: the front area, the middle area, and the rear (or behind) area. In the front section, situated around the cave's entrance, surfaces are coated with secondary carbonate deposits formed through successive layering of calcium carbonate incrustations. Some of these deposits extend downward as stalactites; however, their growth appears to have ceased. The limestone walls in the front area appear relatively older and show

signs of significant weathering, with some rock masses appearing close to collapse (Figure 8). The apparent stagnation of speleothem development in this section may be attributed to slope dynamics. The direction of subterranean water flow, an essential factor in speleothem formation is guided by the cave's internal gradient. The steep inclination in this area likely causes water to flow rapidly through the front section, reducing the conditions required for sustained mineral deposition and thereby inhibiting further landform development.

The central section of the cavern contains a diverse array of karst landforms, including numerous stalactites, stalagmites of varying morphologies, and cave pools, some of the most visually and geomorphologically significant features of the site (Figure 9). Several smaller subsidiary caves are also located in this zone, with vertical openings extending between 39.3 and 47.2 feet (12 and 14.4 m). The high concentration of karst features in this area is primarily attributed to sustained subterranean water flow, which promotes both the dissolution and subsequent deposition processes essential to speleothem development. This section represents the most geomorphologically dynamic part of the cave, with a dense distribution of karst formations. Additionally, numerous broken stalactites and stalagmites are found scattered across the cave floor, some measuring up to 16 feet (4.9 m) in length and 6 feet (1.8 m) in width, suggesting either past structural collapses or mechanical disturbances, both natural and anthropogenic in origin.

The rear section of the cave also contains a notable concentration of karst landforms, though its geomorphological characteristics suggest substantial alteration over time. Field observations indicate that this area has undergone significant morphological change, likely driven by fluvial overflow from nearby surface waterways. It is hypothesised that the rear portion of the cave was once more expansive, with subsequent erosional and depositional processes contributing to its partial collapse or infill. Evidence supporting this includes the presence of numerous broken stalactites located approximately 49.2 feet (15 m) beyond the rear entrance. These fragments exhibit considerable variability in size, ranging from as small as 5-11 centimetres to nearly 9 metres in height. Despite the apparent degradation and structural change, the outer cave walls in this section remain adorned with visually and scientifically significant speleothem formations (Figure 10), underscoring the persistence of karst processes even in more environmentally exposed or disturbed zones.

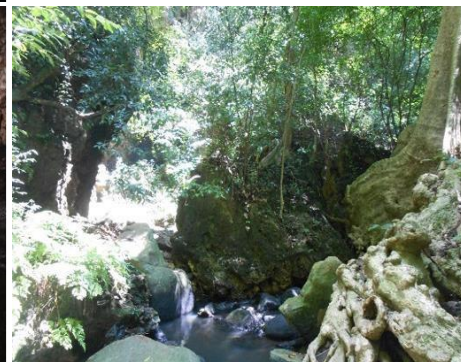


Figure 8: Front area of the cave

Figure 9: Middle area of the cave

Figure 10: Rear area of the cave

Source: Field survey (2017); Unknown, retrieved from the internet (n.d.)

Factors Influencing the Formation of Karst Landforms

The primary factor influencing the formation of these karst landforms is the calcium-laden water spring, locally referred to as 'kiwul diya ulpatha' (Figure 11). This spring discharges water with elevated concentrations of calcium carbonate (CaCO_3) and iron hydroxide, both of which are critical agents in speleogenetic processes. Hydrological measurements vary across sources, with

some estimates indicating a discharge rate of approximately 26 litres per second, while others suggest a slightly lower flow rate of around 20 litres per second (0.7083 cubic feet per second). Regardless of this variation, the spring is reported to maintain a steady flow throughout the year, including during the dry season. Anecdotal evidence from local residents further suggested that the water flow velocity is higher in the dry season compared to the rainy season. This persistent and mineral-laden water supply plays a vital role in both the dissolution of limestone and the precipitation of secondary mineral formations within the cave.

The spring exhibits a distinct yellowish hue, attributed to the presence of mineral compounds such as iron hydroxide and other dissolved substances. These compounds have also imparted a yellow to rust-orange coloration to the surrounding substrate, including rocks and soil in the immediate vicinity. Local communities and some researchers believe that the spring water possesses therapeutic properties, particularly in treating skin ailments, a claim that has received some scientific attention, though further empirical validation is needed. The spring emerges as a shallow stream and flows for approximately 250 feet (76.2 m) before descending into a sinkhole known as *Aadaraya*, where it forms the Waulpane waterfall. Located on the northwestern margin of the sinkhole, the spring measures approximately 16.7 feet (5.1 m) in length and maintains a relatively consistent width throughout its course. It is hypothesised that the spring originates from a separate karst system, where it dissolves calcium carbonate (CaCO_3), contributing to the formation of karst landforms in the Waulpane cave.



Figure 11: Calcium-laden water spring

Source: Field survey (2017)

A study conducted by Perera in 1970 revealed that the streams surrounding the cave, such as Halwini Dola and Katukumbura Dola, contain high concentrations of chemical compounds (Table 1).

Table 1: Dissolved materials in waterways; Source: Adapted from Perera (1970)

Dissolved materials in Halwini dola		Dissolved materials in Katukumbura dola	
pH value	7.3	pH value	7.6
Iron	0.2 ppm	Iron	0.4 ppm
Chloride	9 ppm	Chloride	12 ppm
Sulphate	2 ppm	Sulphate	7 ppm
Calcium carbonate	20 ppm	Calcium carbonate	288 ppm

Field survey analyses revealed a notably high concentration of dissolved chemical compounds in the brackish spring water. The total hardness was measured at 309 parts per million (ppm), a value significantly higher than those reported in previous measurements. Total hardness refers to the combined concentration of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions, present in the water. According to standard classification, water with a CaCO_3 concentration exceeding 180 ppm is considered to exhibit very high hardness. The elevated hardness of the Waulpane spring water suggests a substantial presence of carbonate and other mineral constituents, consistent with the observed speleogenetic activity. Furthermore, the richness in chemical compounds is perceptible even through sensory indicators, such as taste, underscoring the mineral-laden nature of the water and its potential role in the formation and development of karst features within the cave system.

Previously, the spring entered the cave through a separate sinkhole, which has since become buried beneath accumulated sediments, leaving only a shallow depression. This geomorphological shift has resulted in a complete redirection of the water flow, leading to the desiccation of the former waterway. Such hydrological alterations are of particular significance in karst studies, as they directly influence the formation, evolution, and spatial distribution of karst landforms. Understanding these changes provides valuable insight into the dynamic processes governing subterranean landscape development and highlights the sensitivity of karst systems to even minor environmental alterations.

According to the villagers, numerous pristine white stalactites and stalagmites are visible on the cave ceiling near areas of active water flow. They also mentioned that ropes are required to descend into the hole to explore these pristine karst formations. These formations are visible even from inside the cavern. The widespread presence of these perfect structures underscores the importance of the calcium-laden water spring, as the distribution of karst features is notably concentrated on the cavern ceiling near both the previous and current sinkholes, where CaCO_3 -rich water is abundant. This pattern strongly suggests that the continued deposition of calcium carbonate is influenced by the hydrological inputs from these karstic sources. Consequently, speleothem growth appears more abundant along one side of the cave, where water chemistry and flow dynamics create optimal conditions for secondary mineral formation.

In addition to the calcium-rich spring, several environmental and geological factors have significantly influenced the development of karst landforms within the Waulpane Cave. These include the local climate, topography, vegetation cover, hydrological regime, limestone distribution, and soil composition. The cave is situated beneath a tropical forest canopy, which contributes to a thick overburden of soil and dense vegetation. Many of the trees above the cave reach heights exceeding 100 feet (30.4 m), and their continuous leaf fall enriches the soil with organic matter. As this leaf litter decomposes, it releases carbon dioxide, which combines with soil moisture to form weak carbonic acid, a key agent in the chemical weathering of limestone. This process enhances dissolution, thereby accelerating the formation of karst features.

Moreover, the root systems of large trees exert mechanical pressure on the bedrock, generating cracks and fissures that increase the permeability of the limestone. These fractures facilitate the infiltration of water, further promoting both dissolution and speleothem deposition within the subterranean environment. Collectively, the interplay between biotic and abiotic factors, particularly the synergistic effects of soil chemistry, vegetation, and hydrology plays a crucial role in shaping the morphology and distribution of karst features inside the cave.

Diversity of Micro Karst Landforms in Waulpane Cave

The Waulpane Cave safeguards an impressive array of stunning and artistically captivating stalactites and stalagmites, which have made the cave renowned. In addition to these formations, the cave also safeguards several other types of karst landforms, such as columns, as well as various micro-scale karstic features, all of which can be observed within the cave premises. The stalactites in particular are noteworthy for their abundance and morphological variety. These impressive stalactites, hanging downward from the cave roof, include several distinct types, such as:

- Bulbous stalactites (bulb-shaped or circular in form)
- Scattered stalactites (widely dispersed)
- Joint-scattered stalactites (dispersed but interconnected)
- Flat stalactites (not elongated, appearing more horizontal)
- Pillar-shaped stalactites (linear and elongated)
- Leafy stalactites (cultured like an umbrella)
- Cone-shaped stalactites (resembling a cone)

At the cave entrance, a variety of limestone formations of unique and visually striking shapes and sizes can be observed. These features predominantly exhibit circular or leaf-like morphologies and are hanging from the ceiling of the portico (or porch) fronting the main entrance. The circular, bulbous stalactites resemble partially opened flower buds, while the leafy forms cluster together in umbrella-like arrangements, evoking the appearance of parasols. These formations display a brownish-white hue, with the lighter-coloured stalactites likely representing more recent growth. Additionally, on the left side of the entrance, large wavy formations known as draperies, a type of flowstone descend from the cave walls, formed by thin sheets of mineral deposits. Collectively, these diverse speleothems characterise the ceiling and upper walls of the entrance zone (Figure 12). However, many of these features appear aged and structurally compromised, with some showing signs of impending collapse.



1 - Ceiling of the portico in front of the main entrance

2 - Leafy stalactites clustered like an umbrella

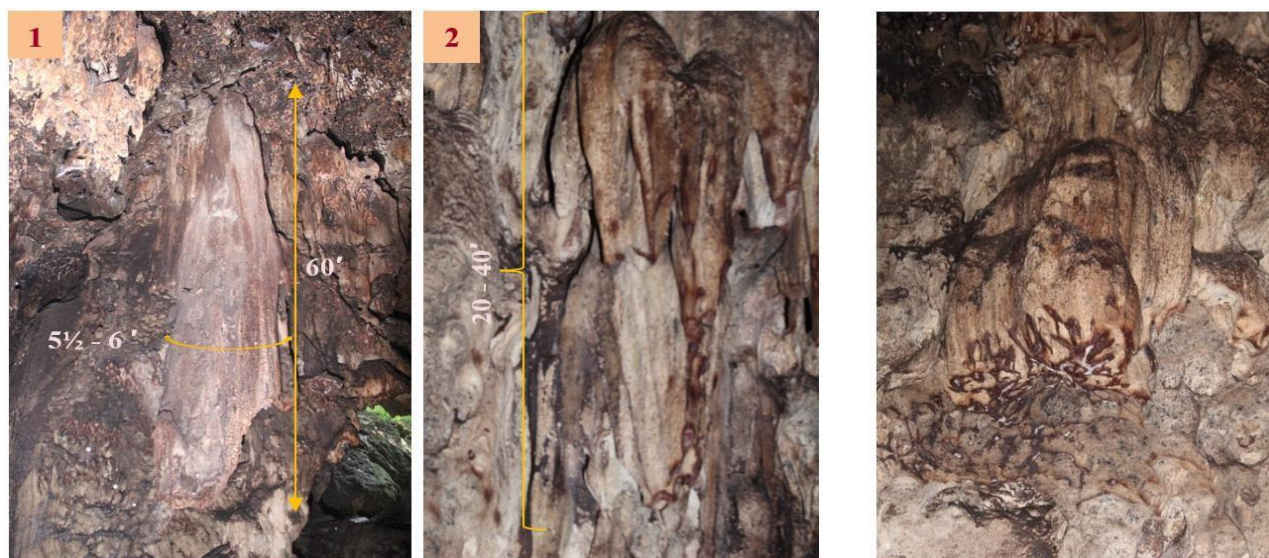
3 - Flowstone hanging down from the wall (Draperies)

4 - Circular bulbous stalactites

Figure 12: Landforms in front of the entrance

Source: Field survey (2017); Unknown, retrieved from the internet (n.d.)

On the right side near the main entrance, approximately 10 feet (3 m) away, a large stalactite hangs from the wall. This stalactite is brown in colour, nearly 60 feet (18.2 m) in height, and $5\frac{1}{2}$ to 6 feet (1.7 to 1.8 m) in circumference (Figure 13). Surrounding it are four or five other stalactites, which although dispersed, appear to be structurally interconnected. These formations range in height from 20 to 40 feet (6 to 12 m). In addition to these, there are other stalactites with irregular shapes scattered among the larger ones (Figure 13). On the left side of the entrance, about 8 feet (2.4 m) away, another notable cluster of stalactites is present. These are bulbous stalactites, clustered together in a manner resembling small wall lamps, extending approximately 5 feet (1.5 m) towards the cave floor (Figure 14).



1 - Huge stalactite

2 - Cluster of stalactites

Figure 13: Stalactites near the main entrance

Source: Field survey (2017)

Figure 14:

Elongated bulbous stalactites

Source: Field survey (2017)

Several large, well-formed stalactites are located near the waterfall, which cascades onto a smooth limestone pillar that hosts a variety of speleothem types. Some of these formations are still actively growing and exhibit shield-like morphologies. With the continuous flow of mineral-rich water over centuries, these small, cone-shaped stalactites are expected to develop into more extensive, elongated structures. On the pillar directly beneath the waterfall, several massive stalactites, measuring between 15 and 20 feet (4.5 and 6 m) in height are clustered and appear to have merged into compound formations (Figure 15). The ceiling area in front of the waterfall is also adorned with joint-scattered stalactites. These linear, elongated features range from approximately 7, 10 to 15 feet (2.1, 3 to 4.5 m) in length (Figure 15).

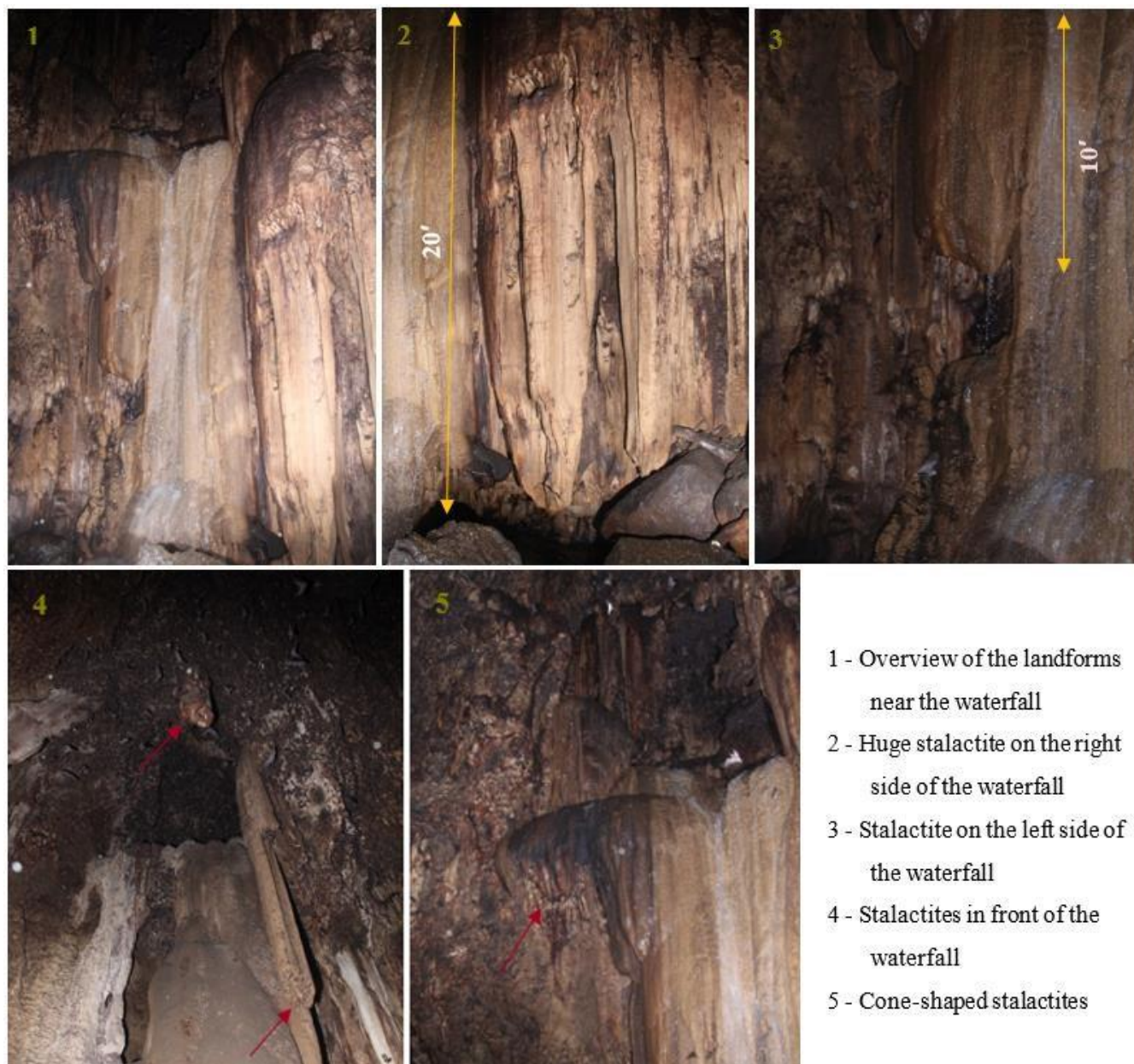


Figure 15: Stalactites near the waterfall

Source: Field survey (2017)

The ceiling of the entire cave exhibits a broadly hemispherical shape, from which an array of solidified stalactites descends in diverse and distinctive forms. These include bulbous, scattered, leafy, flat, and pillar-shaped structures of varying sizes, many of these formations resemble shields in appearance. The ceiling is structured into multiple levels that resemble balconies, and within these balcony-like platforms, deep cavities have formed, creating small cave-like pockets. These cavities serve as roosting habitats for bats (Figure 16). Every inch of these formations reflects centuries of gradual geological development. The stalactites are predominantly brown, with some displaying yellowish-brown tones due to mineral variations.

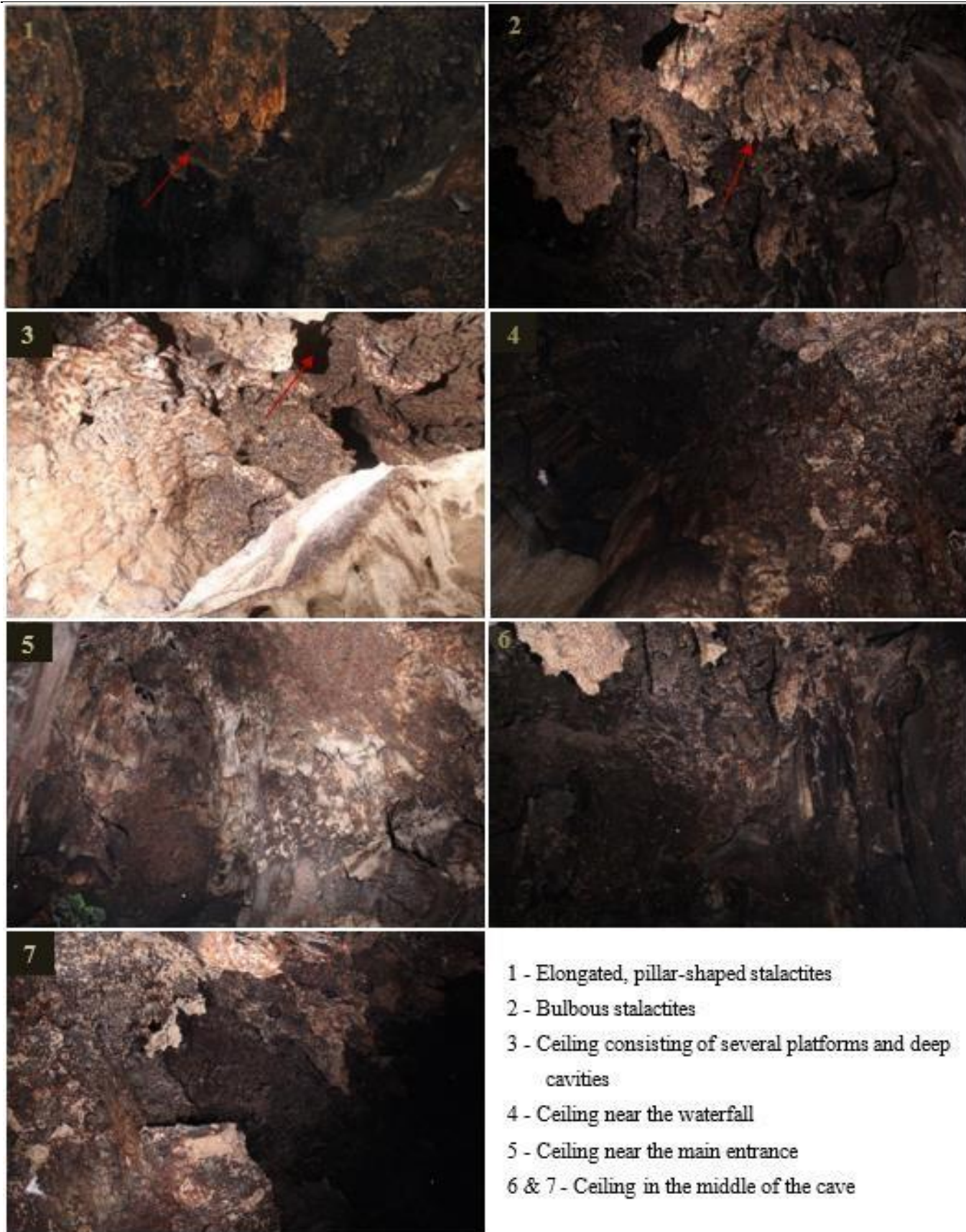


Figure 16: Ceiling of the cave

Source: Field survey (2017); Unknown, retrieved from the internet (n.d.)

Another notable feature of the stalactites can be observed at the far end of the cave, where tiny crystals of calcium carbonate (CaCO_3) mark the earliest stage in the formation of soda straws and stalactites. These crystals form when water droplets seep through cracks in the rock and carbon dioxide (CO_2) escapes into the air, leaving behind a deposit of calcite. With each droplet, a thin ring of calcite is left behind (Figure 17). Over time, as water continues to drip from the same point, a delicate stalactite straw begins to form. These formations are particularly significant in karst studies, as they indicate the earliest phase in the evolution of more complex speleothems.

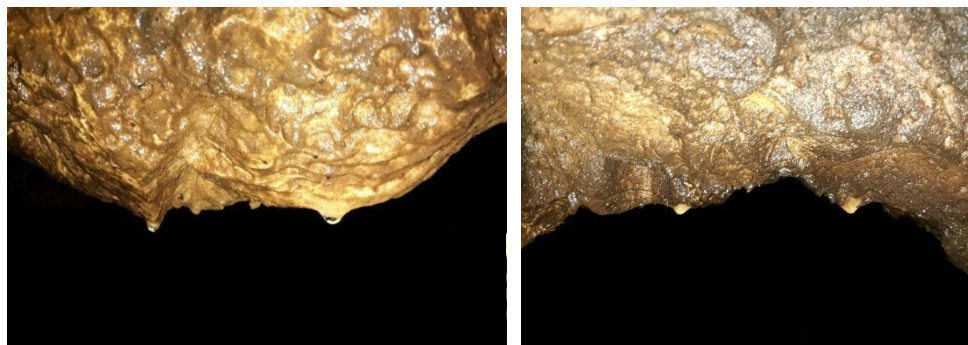


Figure 17: Tiny crystals made of
 CaCO_3
Source: Field survey (2017)

Despite the abundance of stalactites within the cave, stalagmites are notably absent from the cave floor. This absence may be attributed to the dynamic hydrological conditions within the cave, particularly the velocity and turbulence of the stream that flows through the cave, which likely disrupts their formation. The continuous force of moving water, combined with the impact of floating tree trunks and tumbling rock boulders, may have eroded or destroyed any developing stalagmites. Evidence of this can be seen in the form of broken fragments of stalagmites, along with other limestone boulders, large tree trunks, and rock debris, scattered across the cave floor.

In addition, several small-scale karst formations can be observed on the cave wall near the roof, which resemble stalagmites, despite their elevated position hundreds of feet above ground level. These formations, measuring approximately 4 to 5 feet (1.2 to 1.5 m) in length, appear to be actively growing. They are located in front of the current waterfall, in the area where a previous waterfall is believed to have once flowed. The presence of these features suggests past vertical water flow in this section of the cave. Among them, one of the larger formations is distinctly dark brown, while another exhibits a yellowish-brown hue (Figure 18), likely reflecting variations in mineral content or flow dynamics over time.

Another small-sized column (pillar) can be observed on the left side of the main entrance. This feature, which measures approximately 3 to 4 feet (0.9 to 1.2 m) in height, has formed against the cave wall and bears a striking resemblance to a buttress in structure (Figure 19). The upper section of the column is coated with successive layers of calcium carbonate, which display intricate patterns resembling flower petals or small leaves (Figure 19).



1 - Larger feature

2 - Smaller feature

Figure 18: Stalagmite-like landforms

Source: Field survey (2017)

Figure 19: Small-sized column

Source: Field survey (2017)

Another column-like landform is found high on the walls in front of the waterfall. Unlike typical columns formed by the vertical union of a stalactite and a stalagmite, this particular feature appears to have originated from the erosion or breakage of a drapery formation. What remains is a slender, pencil-like structure, that reveals its internal stratification, distinct layers of mineral deposits in varying hues accumulated over time. Similarly, a few other columns and column-like features can be observed elsewhere within the cave. One such formation located directly in front of the waterfall beside the previously mentioned structure, exhibits a whitish-brown coloration. Another example, near the main entrance, is more robust and displays a yellowish-brown hue, its surface adorned with bulbous stalactites (Figure 20).

Another notable micro-scale karst feature can be observed on the left side of the main entrance, located near the ground on the cave wall. This formation, measuring approximately 6 to 7 inches (15.2 to 17.7 cm) in height (Figure 21), closely resembles an hourglass or sand clock. Its morphology includes two rounded bulbous ends connected by a narrow, thin middle section, forming a vertically aligned, symmetrical structure. Multiple such formations are interconnected, with small apertures or voids appearing between them. These cavities are likely to be progressively filled by calcium carbonate (CaCO_3) precipitates over time, contributing to the lateral growth of the cave wall. Upon further examination, it is evident that these features are still growing, as indicated by the newer, whitish portions of the formation. This dynamic development highlights the ongoing geochemical and morphological processes shaping the cave interior.



1 - Pencil-like formation 2 - Whitish-brown column 3 - Column near main entrance

Figure 20: Column-like features in the cave

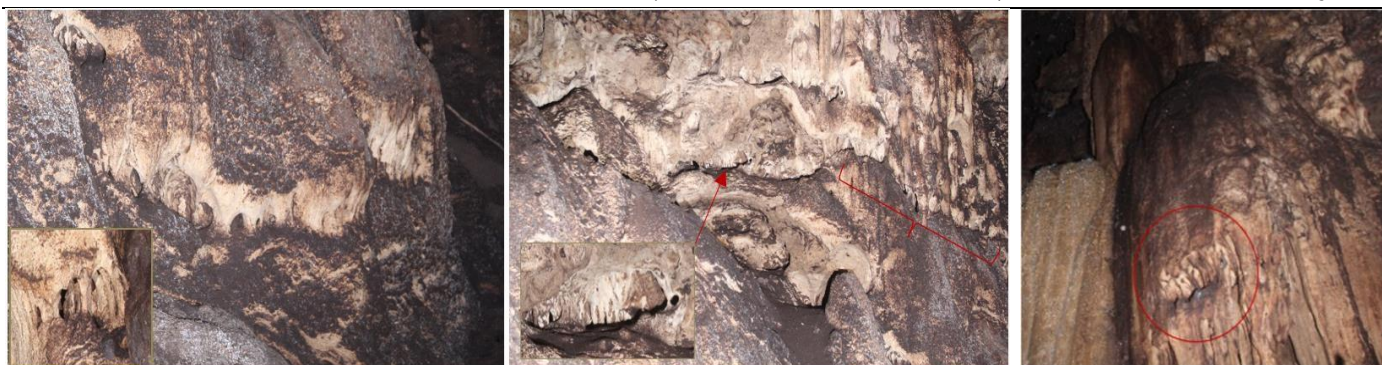
Source: Field survey (2017)



Figure 21: Hourglass-like feature

Source: Field survey (2017)

Another distinctive set of features found across the cave walls comprises micro-scale formations, typically measuring only a few centimetres in size. These are particularly noticeable on the pillar beneath the waterfall, as well as in various other sections of the cave. While their formation process, precipitation of calcium carbonate (CaCO_3)-laden water is similar to previously described features, some exhibit unique morphologies resembling pointed or ogival arches, reminiscent of Gothic architectural motifs. Unlike the rounded hourglass-shaped features, these are more angular and linear in appearance, although they are still actively developing. Small cavities can often be observed between these micro-karst structures (Figure 22), suggesting ongoing depositional activity.



Micro karst landforms resembling pointed arches in Gothic architecture on the wall near the main entrance

Micro karst landforms near the waterfall resembling the recurved petals of bluebell flowers

Figure 22: Micro karst landforms formed on the cave walls

Source: Field survey (2017)

The colour palette of these landforms ranges from white and cream to yellow, pink, and brown, indicating variations in mineral composition and stages of development. Pillars and columns of precipitated calcareous substances are abundant, particularly on the left side of the cave, where balconies carved from the stone extend and disappear into the earth. These formations continue to evolve under the influence of persistent hydrological processes associated with the stream and the subterranean waterfall, underscoring the dynamic nature of speleogenetic activity within the cave system.

V. Conclusion

Karst is a significant yet often undervalued component of geo-diversity, referring to the array of landforms created by the action of natural water on soluble rocks. It is typically formed through the dissolution of bedrock, most commonly limestone, resulting in a network of enlarged joints and cavities through which water flows. When these cavities grow large enough, they develop into caves. Additionally, karst landscapes exhibit a variety of distinctive surface features, along with secondary mineral deposits found within caves. These deposits, known as speleothems, form through the solutional and depositional processes involving calcium carbonate (CaCO_3).

Beyond their geological importance, karst and limestone environments are of significant ecological, scientific, and recreational value. Globally, karst topography occurs across a broad range of latitudes and altitudes, and Sri Lanka is no exception. The island hosts several notable limestone cave systems, particularly within the Sabaragamuwa, Uva, and Central Provinces. Notable examples include the caves at Kudawe, Pannila, Waulpane, Padiyapelella, Sthreepura, and Ravana Lena. Among these, the Waulpane Cave, situated in Palledbedda in the Ratnapura District, is especially distinguished for its unique geological features and substantial contribution to Sri Lanka's geo-diversity.

The Waulpane Cave contains a vast array of visually striking and artistically captivating formations, including numerous stalactites, stalagmites, shield and drapery-like features, as well as other macro karst elements such as the limestone cave itself and sinkholes. Despite the presence of these prominent features, research indicates that the cave is predominantly characterised by micro-scale karst landforms, with relatively fewer meso and macro-scale formations. Among the various speleothems, secondary mineral deposits formed through calcium carbonate precipitation, stalactites are the most commonly observed within the cave. The limestone cave itself and the adjacent sinkhole are the only large-scale karst landforms observable on the cave premises, a limitation likely attributable to the relatively restricted extent of limestone deposits in the surrounding geological setting.

While some macro karst landforms can extend over several kilometres, the brackish spring water that contributes to the formation of these features, lacks the necessary discharge volume and calcium carbonate (CaCO_3) concentration to support the development of meso-scale features. Instead, only speleothems and karren have developed from this spring. Environmental factors including climate, topography, vegetation cover, and local hydrological patterns play a significant role in shaping micro karst landforms but remain insufficient to facilitate the formation of meso or macro-scale features. This limitation arises because large-scale karst formations typically develop through prolonged dissolution of limestone, rather than from a purely depositional process. This cave is primarily composed of micro karst landforms, such as speleothems on the walls and ceilings and karren on both the walls and the ground. These features vary in size and exhibit diverse morphologies, including bulbous, conical, leafy, and pillar-like stalactites, as well as pencil-shaped, lamp-like, ogival, hourglass, and petal-like forms. Most of these formations are concentrated in the central part of the cave, where conditions are particularly favourable for their development.

Several challenges and obstacles were encountered during the course of this research. Access to the site was hindered by poor infrastructure and limited transportation facilities. Additionally, the lack of adequate field equipment and proper lighting created

further difficulties during data collection. Conditions within the cave itself posed significant challenges, including the presence of insects, mites (ticks), and accumulations of bat guano. The absence of natural light and the resulting darkness further complicated exploration. Moreover, navigating the cave interior was made difficult by the slippery and uneven ground, particularly in certain sections where surface stability was compromised.

Likewise, understanding the dynamics of micro karst features, particularly their formation processes and environmental dependencies, is essential for informed cave management and conservation planning. The fragile nature of many speleothems, especially those in active growth stages, makes them highly susceptible to anthropogenic disturbances such as tourism, pollution, and structural damage. Additionally, shifts in climatic conditions such as variations in rainfall, temperature, and humidity may alter the hydrological regimes that govern mineral deposition within the cave. By documenting the spatial distribution and morphological variability of micro karst features in Waulpane, this study highlights specific formations that are potentially vulnerable to such stressors. These insights can inform the development of targeted preservation strategies, such as controlled access zones, visitor education programmes, and continuous environmental monitoring. Ultimately, linking speleothem morphology and cave micro-environments to conservation priorities ensures that scientific knowledge contributes directly to the sustainable stewardship of this geo-diverse habitat.

VI. Recommendations

To support future research and ensure the sustainable management of karst environments, several key recommendations can be made. First, improving field equipment and infrastructure is essential for enhancing accessibility and facilitating efficient data collection. The development of reliable transportation routes to and from the site would also enable safer and more consistent access for researchers and conservation personnel.

Equally important is the need to raise public awareness about the multifaceted value of such sites, not only in terms of their natural and geological significance but also their cultural, scientific, recreational, socio-economic, and aesthetic contributions. This can be achieved through targeted education programmes and widespread dissemination of information via mass media platforms. Moreover, formal recognition of the site as a nationally protected area or even a UNESCO World Heritage Site could offer critical legal and institutional support for its long-term preservation.

Preserving the integrity of fragile karst features in Waulpane, particularly speleothems, requires careful and deliberate conservation efforts to ensure their protection for both scientific study and public enjoyment. Many of these formations are actively growing and highly sensitive to disturbance. Human activities pose significant threats, including physical contact, improper specimen collection, and the erosion of cave sediments, which may hold geological or archaeological importance. Disturbance of cave-dwelling species such as bats and the irresponsible disposal of waste further endanger the delicate ecosystem. Historical accounts from local villagers also reveal past practices such as lime extraction and bat hunting, which have likely contributed to the degradation of both biological and geological elements within the cave.

Even minimal interference such as contact with natural skin oils can disrupt the speleothem formation process by preventing the deposition of calcium carbonate. As these features take thousands of years to develop and are incredibly fragile, preserving them in their natural state is imperative. Any disturbance, no matter how minor, can harm their delicate formation process and hinder their natural development. Strict protection measures, including controlled access zones and clear visitor guidelines, are recommended to ensure that these irreplaceable formations remain undisturbed and continue to evolve naturally.

As the Native American leader Chief Seattle once said, *"The Earth does not belong to us; we belong to the Earth. Take only memories, leave nothing but footprints"*. This timeless message underscores the ethical responsibility we hold as stewards of nature and the best way to preserve the gifts given by Mother Nature for future generations. We do not inherit the Earth from our ancestors but rather borrow it from future generations. It is our duty to protect these natural wonders so that their beauty, scientific value, and ecological integrity endure for those yet to come.

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