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An Assessment of Geological Formation of The Rakwana-Pannila Mountain of Sri Lanka

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ABSTRCT

The Rakwana mountain range, situated along the northern margin of the Sinharaja rainforest, a UNESCO World Heritage Site, represents a significant geodiversity hotspot. Recent excavations of alluvial deposits within the Sabaragamuwa Basin have led to the identification of cave systems within the crystalline limestone (marble) formations of the Pannila Mountain region, locally referred to as 'Pannila Hunugala.' The primary cave structure extends approximately 550 meters in length with an entrance height of 350 cm, of which 60 cm is submerged in water. The cave exhibits distinct secondary mineralogical features, including stalagmites and stalactites reaching heights of 2.5 meters, which are hypothesized to have formed through the re-crystallization of pre-existing Precambrian basement rocks within the Highland Complex. Speleothem volumetric analysis was conducted to estimate the deposition rates of calcium carbonate. The speleogenetic processes within these caves are largely driven by chemical weathering of the crystalline limestone, wherein dissolution and precipitation cycles contribute to the formation of speleothems. Regional geological mapping suggests that this crystalline limestone sequence extends beyond Pannila Hunugala to other significant karstic formations, including Samanalawewa and Handagiriya caves. These findings enhance the understanding of the geochemical evolution of karst systems in the region and underscore the role of subterranean processes in the broader geomorphological framework of Sri Lanka.

Article information | Key Words: Sinharaja Forest, Crystalline Limestone, Paleontology, Pleistocene Geology, Sri Lanka

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INTRODUCTION

The geological history of Sri Lanka provides crucial insights into its palaeo-biodiversity and evolutionary significance. Geological evidence suggests that Sri Lanka was once part of the supercontinent Gondwanaland during the Middle Jurassic epoch and subsequently began its separation from the Indian subcontinent during the Late Jurassic as an independent landmass (Cooray, 1994; Kröner et al., 1991). This tectonic shift played a fundamental role in shaping the island's geological and ecological landscape. During the Early Miocene era, Sri Lanka continued its south-eastern drift, contributing to the formation of the Cauvery Basin, where substantial lime mud deposits accumulated in an oceanic basement, indicating a significant marine influence on its geological development (Katupotha, 2013).

Throughout the Quaternary period, geostatic changes facilitated the emergence of a land bridge between Sri Lanka and the Indian subcontinent, enabling faunal and floral exchanges between the two regions (Voris, 2000). This intermittent land connectivity and subsequent disconnection have had profound evolutionary consequences, leading to speciation through isolation. Fossil evidence from different parts of the island supports the existence of extinct flora and fauna, underscoring the role of geological transformations in shaping biodiversity.

Paleontological studies of sediments and rock formations offer critical insights into the ancient climatic conditions and the organisms that once inhabited Sri Lanka. Such studies are instrumental in reconstructing past biodiversity, ecological interactions, and environmental adaptations. Furthermore, paleo-biodiversity research extends beyond biological evolution to encompass human evolutionary patterns, including the development of prehistoric tools, hunting and gathering strategies, cultural beliefs, and environmental interactions. The integration of geological and paleontological data thus serves as a powerful framework for unraveling the intricate history of life on the island and its evolutionary trajectories.

1.1 Geology of Sri Lanka

The geological history of Sri Lanka is deeply intertwined with the evolution of East Gondwana, a supercontinental assembly that included Antarctica, Australia, India, Madagascar, Mozambique, and Tanzania (e.g., Powell et al., 1988; Kröner, 1991; Yoshida et al., 1992; Jacobs et al., 1998; Dissanayake and Chandrajith, 1999). Sri Lanka, positioned at the heart of these ancient continental fragments, played a crucial role as a geological bridge facilitating the correlation between the geological records of Antarctica and East Africa. This unique positioning has resulted in the presence of striking geological, geochronological, and geotectonic similarities between Sri Lanka and its neighboring Gondwanan counterparts.

Over the last two decades, Sri Lanka has garnered increasing attention within the geoscientific community. This has led to significant advancements in understanding its geological framework, including refinements in the nomenclature of rock units, redefinition of geological boundaries, and reassessment of the timing of major metamorphic and tectonic events. Notably, the Proterozoic basement of Sri Lanka provides an exceptional window into the lower continental crust, exposing extensive metamorphic rock sequences that have been fundamental in reconstructing the tectono-metamorphic evolution of East Gondwana.

The lithological and structural heterogeneity of Sri Lanka has necessitated a rigorous classification of its geological units. Based on isotopic, geochronological, geochemical, and petrological constraints, four distinct crustal units have been delineated, each bearing crucial implications for understanding the high-grade metamorphic processes and crustal evolution of the region (e.g., Kröner et al., 1991; Cooray, 1994; Milisenda et al., 1994). These units provide valuable insights into the processes of crustal formation, reworking, and stabilization that have shaped Sri Lanka's geological history within the context of Gondwanan tectonics.

The study of Sri Lanka's geological framework is thus imperative for broader reconstructions of supercontinental cycles, particularly in deciphering the Proterozoic to Cambrian geodynamic evolution of East Gondwana. Continued multidisciplinary research integrating geochronology, petrology, and structural geology will further refine our understanding of the complex tectonic history embedded within the Sri Lankan crust and its relevance to global geological processes.

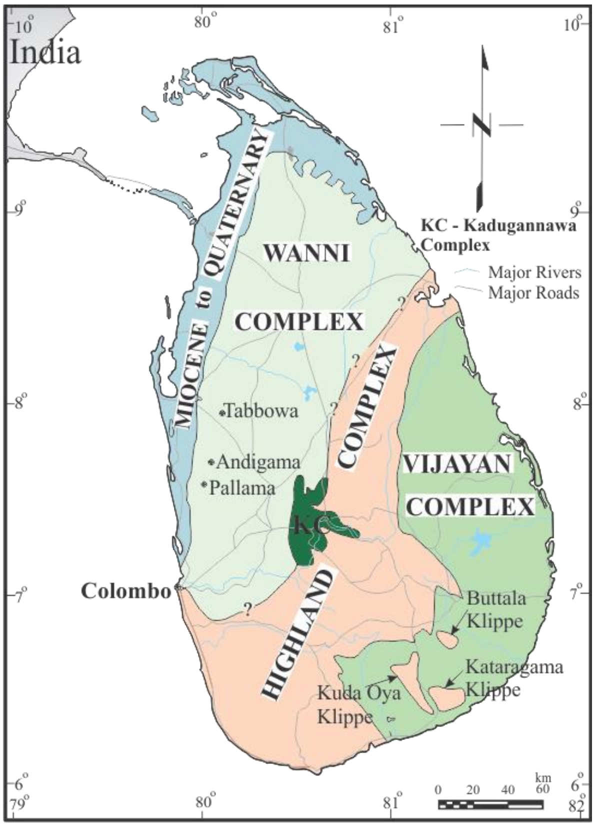

Figure 01: Simplified Geology map of Sri Lanka showing all major lithotectonic Unit, (After Cooray, 1994) and the location of Pannila Cave.

(1). Highland Complex (HC)

(2). Vijayan Complex (VC)

(3). Wanni Complex (WC) and

(4). Kadugannawa Complex (KC)

The HC consists mainly of inter-bedded-metapelites, quartzites, marbles, metabasites and charnockites. Calc-silicate gneisses, sapphirine-bearing granulites, cordierite-bearing gneisses and corundum-bearing gneisses are exposed in minor quantities. The VC exposed in eastern Sri Lanka consists of meta-igneous gneisses of tonalitic to leucogranitic composition. Rocks of the KC are seen in the cores of the six doubly plunging synforms, which were named as *'Arenas'* by Vitanage (1972). The dominant rocks of the KC and WC are hornblende-biotite gneisses, granitic, granodioritic and tonalitic associations. Some granulites are exposed in the southern part of VC near Buttala and Kataragama. They comprise rocks similar to those of HC and are interpreted as tectonic nappes namely; Buttala klippe, Kuda Oya klippe and Kataragama klippe (Fig 1).

Isotopic data from HC shows prolonged crustal history. Supracrustal rocks of the central high-grade belt of HC were derived from early Proterozoic to late Archaean source terranes (3.2 - 2.4 Ga) and were probably deposited some ~2 - 2.4 Ga ago in a Proterozoic basement, which is now believed to be the host for the present-day stratigraphic succession (Crowford 1969; Crowford and Oliver 1969; Hölzl et al. 1994; Kröner et al. 1987; Milisenda et al. 1988). The rocks from VC, WC and KC, which are predominantly of granitoids, yield relatively younger deposition ages at ~1.1Ga ago (Milisenda et al. 1988). This implies that igneous activity had occurred after the deposition of supra crustal rocks of HC, but prior to fabric-forming events since their tectonic layering is parallel to that of supra crustal rocks (Hölzl et al. 1991, 1994; Kröner and Jaeckel 1994). The HC and WC were separated from each other until at least 750 Ma ago. They must have come together, perhaps during WC thrusting over HC, prior to peak granulite facies metamorphism (Kröner and Jaeckel 1994). The boundary between HC and WC is an isotopic boundary based on large-scale sample grids and, as such, not recognizable in the field (Milisenda et al. 1988; Milisenda 1991). The absence of field evidences at the boundary of WC and HC provided that high-grade fabric-forming events may have been destroyed the possible pre-peak metamorphic tectonism (Kröner et al. 1991).

The source terrane for the Wanni supracrustal association remains controversial and is unlikely to be present in Sri Lanka. Although HC and WC are characterized by different primary sedimentary and magmatic ages, it appears that both segments have been affected by a common peak metamorphism of Pan-African age. The timing of peak metamorphism was estimated to be ~610-~550 Ma old. No significant Pb loss occurred in the time record between 1900 Ma (the end of the deposition of supracrustal rocks of HC) and 600 Ma ago (Bauer, et al., 1991; Hölzl et al., 1991, 1994; Kröner et al., 1991; Kröner and Williams, 1993). Taking into account similarities in geology, geotectonics and geochronology in the other Gondwana fragments, the rocks of the HC show a link with the Pan-African Mozambique belt (Kriegsman 1991; Kröner et al.1991; Powell et al. 1988; Dissanayake and Chandrajith 1999). The HC and WC were together thrust over the VC with a top to the eastward vergence at about 580-550 Ma, under upper amphibolite facies conditions (Kleinschrodt 1994).

The rocks of the Wanni Complex (WC) have undergone upper amphibolite to granulite facies metamorphism. Subsequent exhumation of these lower crustal rocks was not accompanied by tectonic activity, allowing all deformation fabrics to be preserved during the slow cooling process. During the Jurassic period, the Sri Lankan basement experienced crustal extension (Powell et al., 1988), leading to the deposition of Jurassic sediments, which are now preserved in three isolated occurrences—Tabbowa, Andigama, and Pallama—in northwestern Sri Lanka (Cooray, 1984; Vithanage, 1985). Following the initial breakup of Gondwana, Sri Lanka drifted alongside India. In the Miocene period, the formation of the Cauvery Basin separated Sri Lanka from India. This basin was subsequently filled with a thick cover of limestone, which now extends across the northwestern coastal strip of Sri Lanka and southeastern India (Vithanage, 1985). The northwestern region of Sri Lanka is composed of Mesozoic (Jurassic—Tabbowa beds; Andigama-Pallama beds), Tertiary (Miocene—Jaffna limestone; Minihagalkanda beds), and Quaternary (Pleistocene—Ratnapura beds) sedimentary formations, many of which are fossiliferous (Cooray, 1984).

Limestone caves are formed through the recrystallization of limestone bedrock during the chemical weathering process. These unique geological formations can be found in various locations, including Nitre Cave (near Rangala), Ravana’s Cave (near Ella), Maturata (near Padiyapelella), Wellawaya, Hakgala, Isthripura (near Welimada), Padanwela (near Wilson’s Bungalow), Handagiriella (near Balangoda), Patanagedara (near Laggala), Kudawa (near Gilimale), Norton Bridge, Wavulpane, and Pannila. Notably, the Pannila cave is located at coordinates 6°28'52.10"N, 80°32'23.04"E, with an elevation of 920 meters. These caves hold significant geological and environmental value, contributing to the region's natural heritage

MATERIALS AND METHODS

Speleothems, secondary mineral deposits found in limestone caves, provide valuable insights into past climatic and environmental conditions. Among these formations, stalagmites and stalactites are particularly significant due to their ability to record geochemical signatures over time. The study of speleothem dimensions is crucial for understanding their growth patterns, volume, and potential paleoenvironmental implications.

In this study, the dimensions of speleothems were measured to determine their volume, focusing on stalagmites and stalactites. Measurements were conducted using a caliper for diameter assessment and a 10m measuring tape for height determination. The diameters were recorded at the base, at points of notable width changes, and near the tip of the speleothem. Additionally, the condition of the stalactites was evaluated, with distinctions made between undisturbed formations—characterized by fragile, translucent calcite with euhedral crystal terminations—and those showing signs of breakage, indicated by thick calcite layers lacking crystal terminations.

Beyond stalagmites and stalactites, other formations such as small curtains were also examined, with length, width, and height measurements recorded due to their distinct morphology. Any anomalous formations were noted, and appropriate measurements were taken to ensure comprehensive data collection. To quantify the volume of calcite within the speleothems, calculations were performed using equations derived from the volume formula of a truncated cone. The selected equation, as determined by James U.L. Baldini (2001), provided an optimal balance between accuracy and practicality in speleothem volume estimation. This methodological approach allows for precise volumetric assessments of speleothems, contributing to broader research on cave mineralogy and paleoclimate reconstruction.

$$\text{Volume} = \mathbf{[}1/3\,\pi\,(h_1)(R^2\text{base} + R_1^2 + R_{base}R_1\,)\mathbf{]} + \mathbf{[}\,1/3\,\pi(h_2 - h_1)(R_1^2 + R_2^2 + R_1R_2\mathbf{]} + [1/3\,\pi\,(h_{total} - h_2)R_2^2\mathbf{]} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where: h_1 = height from base to first radius measurement (cm)

h_2 = height from base to second radius measurement(cm)

R_{base} = radius at the base of speleothem (cm)

Volume $=\pi r^2\, h$ (h =Average Height / 10)

$$R_1^2, R_2^2, R_3^2, R_4^2 \ldots\ldots\ldots\ldots\ldots Rn^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where $R_1^2, R_2^2, R_3^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots Rn^2$(Average radius of stalagmite and stalactites)

(Table 01, 02, 03 show the Results & calculations at the end)

The measurements of the stalagmite and stalactites was shown in tables 1, 2 and 3. According to the second equation (2) average of stalagmite formation dated, table 01 as 13576.92ybp, Table 02 as 14923.07ybp and table 03 as 9923.07ybp.

The results shows that stalagmite and stalactites formation in Pannila limestone cave have been commenced approximately late Pleistocene & Holocene period. According to our measurements the deviation of average formation section of Stalagmite & Stalactites belongs to 32000 ± 50 ybp, 22500 ± 50 ypb, 7500 ± 50 ypb, 175± 50 ypb. The relationship between caves and marble in Sri Lanka is very complex. A few are developed entirely in marble but most are not. 'Pannila Hunugala' is a part of the basement marble bed in the Highland Complex of Sri Lanka which is belongs to the Precambrian age. It is postulated that the same marble bed is extended to the marble beds located at the Samanalawewa, and Rakwana. The action of chemical weathering occurred in the recent times makes it secondary features like stalagmite and stalactite (Fig 2).

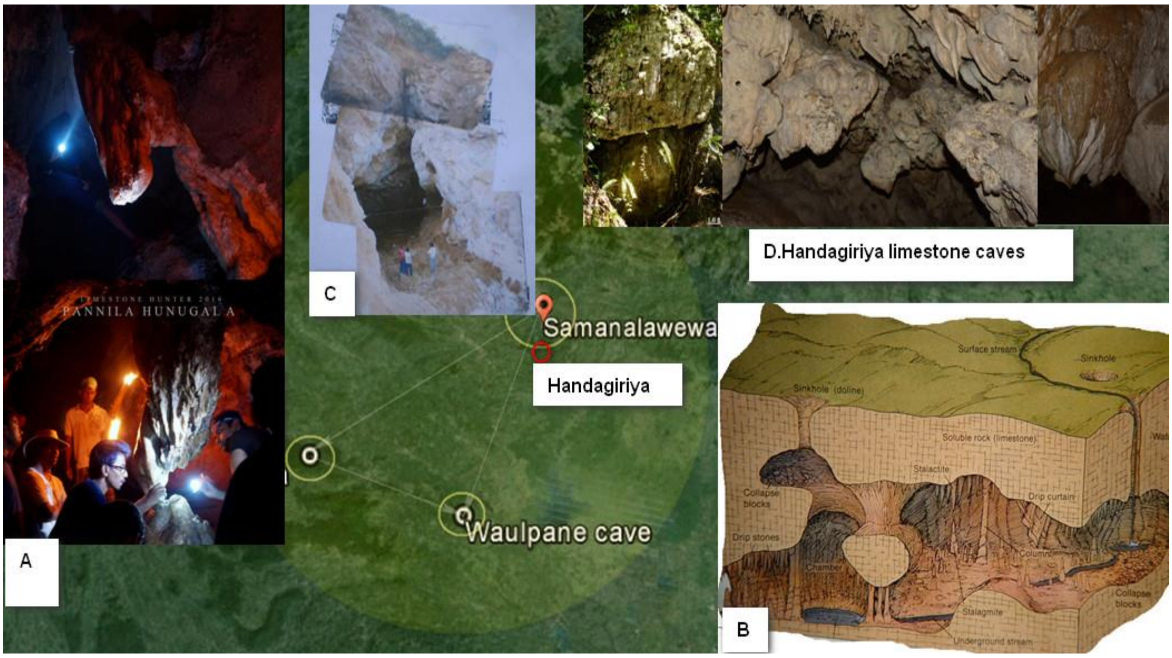

Figure 02: Distribution of limestone Caves in studied Area (a) PannilaHunugala (Sinharaja heritage site), (b). Model for action of chemical weathering formations of limestone cave. (c). Cavity of right bank at river level in Samanalawewa, (d) Handagiriya(Balangoda).

In order to penetrate into the fractures of the limestone rock, the rainwater, acidulated by atmospheric and soil carbon-dioxide (CO2), dissolves it and carries off the calcium carbonate until it finally emerges on the roof of the cave. The drop of water suspended on the roof of the cave is exposed to environmental conditions, such as greater ventilation, alterations in temperature, pH, and CO2 pressure. These environmental conditions create chemical instability through the liberation of the CO2 into the cave and the consequent precipitation of part of the dissolved carbonate. The drop of water hangs on the roof until it reaches the volume and weight necessary to overcome surface tension and fall. Hanging on the roof of the cave and exposed to environmental conditions of the interior's cave, the surface of the drop develops the first crystals of calcite; these, organizing themselves during the period in which the drop is still in contact with the roof, form an initial crystalline ring which will serve as a base for a future stalactite. Drop by drop, a hollow tubular stalactite grows in a downward direction. The drop, when it at last falls, carries with it a solution of carbonate which slowly forms a succession of layers on the floor immediately below, and which becomes a stalagmite.

The opposing growth of stalactites and stalagmites might finally result in the union of the two, to form a column. Fig: 03: (A) and (B) show examples of stalactites and stalagmites, respectively, whereas (C) A flowstone illustrates a after column, formed by the union of a stalactite with a stalagmite. Speleothems take various forms, depending on whether the water drips, seeps, condenses, flows, or ponds. Many speleothems are named for their resemblance to man-made or natural objects. Types of speleothems include Dripstone, Stalactites, Soda straws, Helictites, Flowstone, Speleogens (Fig 03)

Figure 03: Real Speleothems: (A) Stalactites - (B) Stalagmites- (C) Flowstone of the Pannila Hunugala, Image: Aravinda Ravibhanu©2016

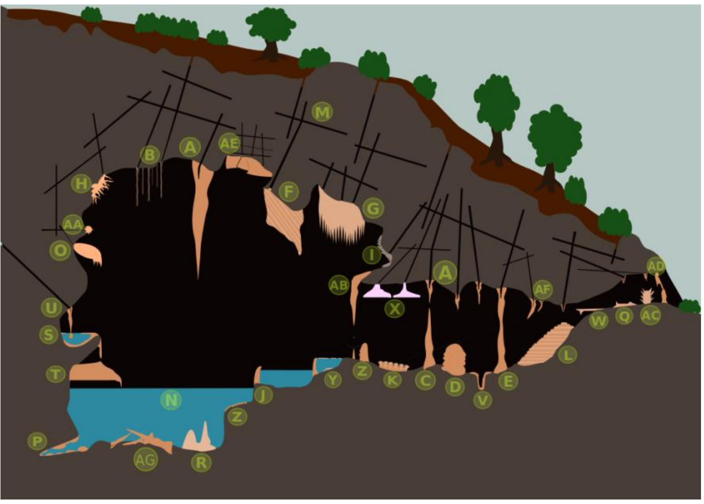

Figure 04 : *A — Stalactite *B — Soda straws *C — Stalagmites *D — Coned stalagmite *E — Stalagnate or column *F — (de:Sinterfahne) *G — Drapery *H — Helictites*I — Moonmilk *J — Sinter pool, rimstone *K — Calcite crystals *L — Sinter terrace *M — Karst *N — Body of water *O — Shield *P — Cave clouds *Q — Cave pearls *R — Tower cones *S — Shelfstones *T — Baldacchino canopy *U— Bottlebrush stalactite *V — Conulite *W — Flowstone, the sand underneath is gone *X — Trays *Y — Calcite rafts *Z — Coralloids *AA — Frostworks *AB — Flowstone *AC — Splattermite *AD — Speleoseismites *AE — Boxworks *AF —Oriented stalactite *

CONCLUSIONS

Caves are remarkable geological formations shaped by complex environmental and geological processes, including chemical weathering and erosion, as exemplified by the Rakwana Pannaila Marble Cave. While the formation and deposition within caves follow fundamental geological principles, they also provide essential ecological habitats. The study of cave ecosystems, including their unique fauna and ecological interactions, remains an important area for further research. By utilizing baseline data, future investigations can enhance our understanding of cave biodiversity, geological history, and environmental influences on these subterranean systems.

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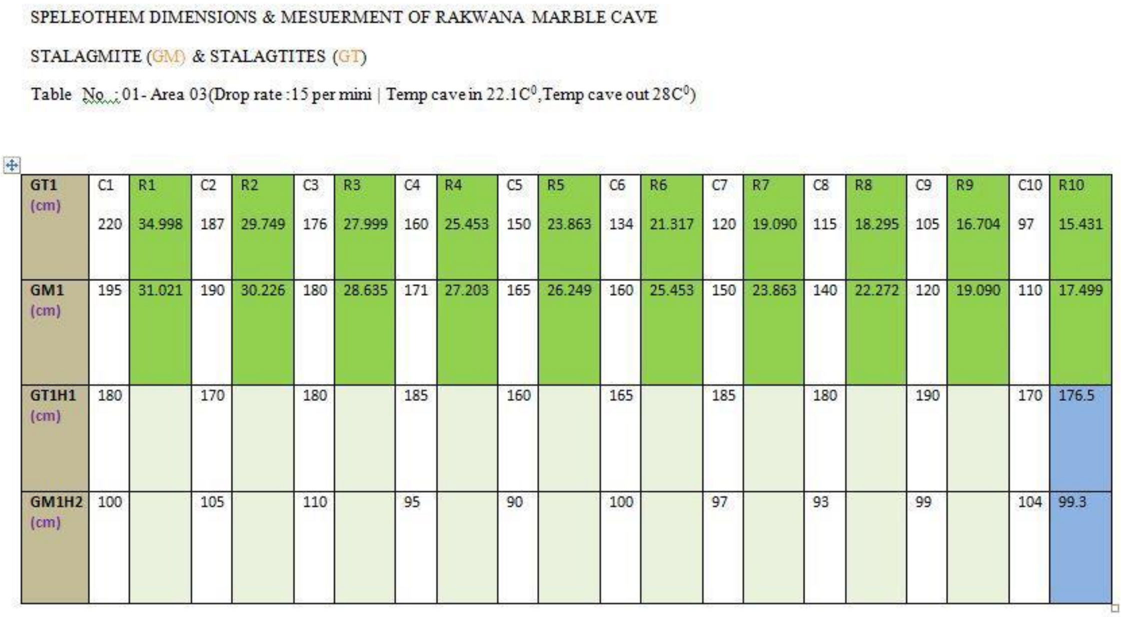
APPENDIX

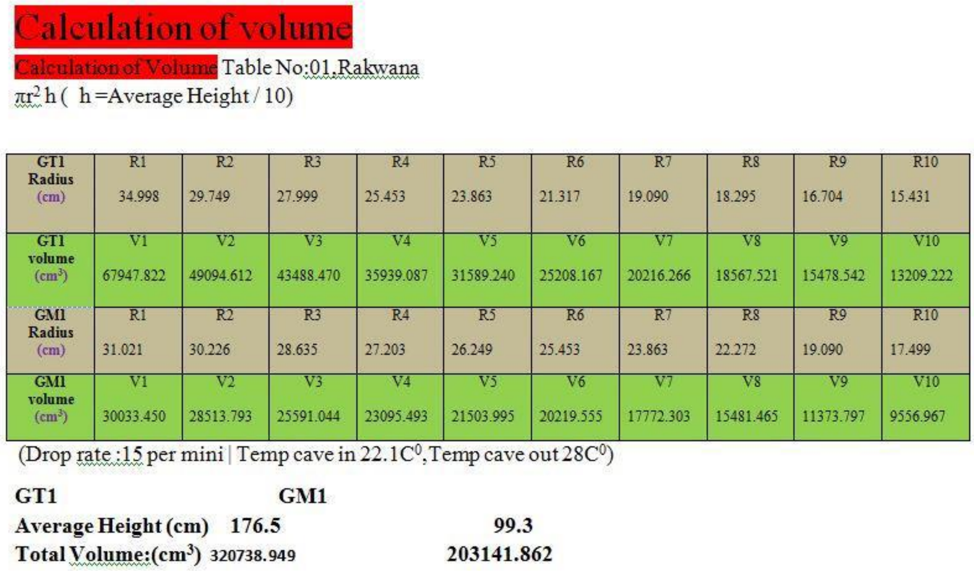


SPELEOTHEM DIMENSIONS & MESUERMENT OF RAKWANA MARBLE CAVE

STALAGMITE (GM) & STALAGTITES (GT)

Table No.: 01- Area 03(Drop rate :15 per mini | Temp cave in 22.1C^0,Temp cave out 28C^0)

	C1	R1	C2	R2	C3	R3	C4	R4	C5	R5	C6	R6	C7	R7	C8	R8	C9	R9	C10	R10
GT1 (cm)	220	34.998	187	29.749	176	27.999	160	25.453	150	23.863	134	21.317	120	19.090	115	18.295	105	16.704	97	15.431
GM1 (cm)	195	31.021	190	30.226	180	28.635	171	27.203	165	26.249	160	25.453	150	23.863	140	22.272	120	19.090	110	17.499
GT1H1 (cm)	180		170		180		185		160		165		185		180		190		170	176.5
GM1H2 (cm)	100		105		110		95		90		100		97		93		99		104	99.3



Calculation of volume

Calculation of Volume Table No:01,Rakwana

πr^2 h (h =Average Height / 10)

GT1 Radius (cm)	R1 34.998	R2 29.749	R3 27.999	R4 25.453	R5 23.863	R6 21.317	R7 19.090	R8 18.295	R9 16.704	R10 15.431
GT1 volume (cm^3)	V1 67947.822	V2 49094.612	V3 43488.470	V4 35939.087	V5 31589.240	V6 25208.167	V7 20216.266	V8 18567.521	V9 15478.542	V10 13209.222
GM1 Radius (cm)	R1 31.021	R2 30.226	R3 28.635	R4 27.203	R5 26.249	R6 25.453	R7 23.863	R8 22.272	R9 19.090	R10 17.499
GM1 volume (cm^3)	V1 30033.450	V2 28513.793	V3 25591.044	V4 23095.493	V5 21503.995	V6 20219.555	V7 17772.303	V8 15481.465	V9 11373.797	V10 9556.967

(Drop rate :15 per mini | Temp cave in 22.1C^0,Temp cave out 28C^0)

	GT1	GM1
Average Height (cm)	**176.5**	**99.3**
Total Volume:(cm^3)	**320738.949**	**203141.862**

Table No : 02 -Area 03(Drop rate : 7ml per mini | Temp cave in 22C^0,Temp cave out 28C^0)

GT2 (cm)	C1 175	R1 27.840	C2 180	R2 28.635	C3 175	R3 27.840	C4 170	R4 27.044	C5 156	R5 24.817	C6 141	R6 22.431	C7 128	R7 20.363	C8 100	R8 15.908	C9 80	R9 12.727	C10 70	R10 11.136
GM2																				
GT2H1 (cm)	212		200		190		185		180		205		193		187		190		198	194.0
GM2H2																				

Calculation of Volume Table No:02,Rakwana

$\pi r^2 h$ (h =Average Height / 10)

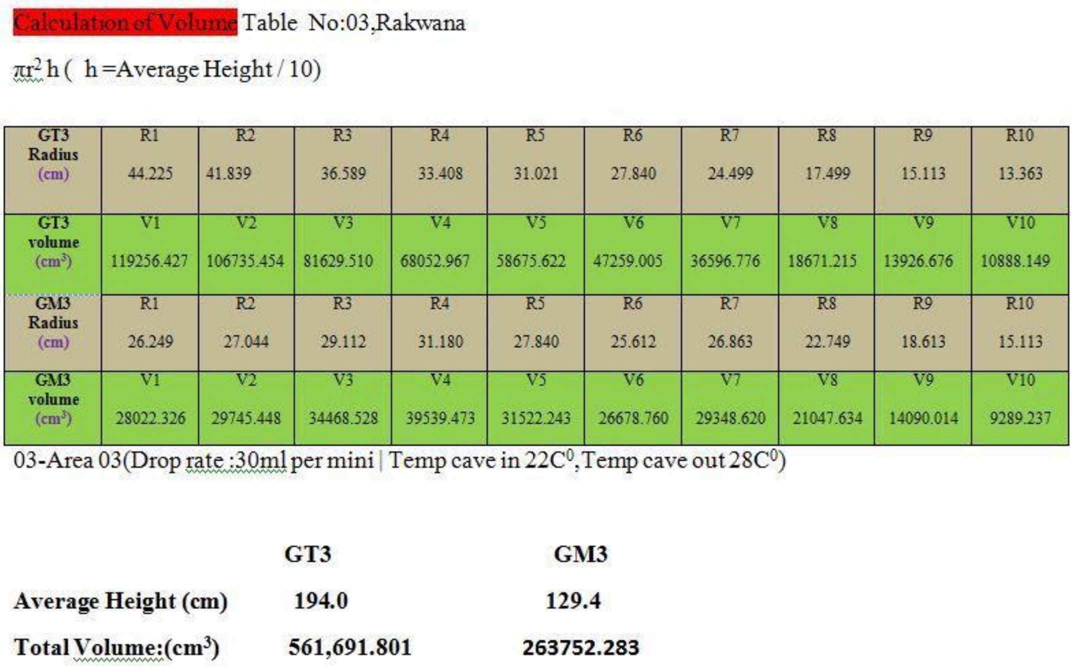
GT2 Radius (cm)	R1 27.840	R2 28.635	R3 27.840	R4 27.044	R5 24.817	R6 22.431	R7 20.363	R8 15.908	R9 12.727	R10 11.136
GT2 volume (cm^3)	V1 47259.005	V2 49996.602	V3 47259.005	V4 44595.185	V5 37553.003	V6 30679.154	V7 25283.060	V8 15430.403	V9 9876.389	V10 7561.441
GM2 Radius (cm)	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
GM2 volume (cm^3)	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10

02-Area 03(Drop rate :25ml per mini | Temp cave in 22C^0,Temp cave out 28C^0)

	GT2	**GM2**
Average Height (cm)	**194.0**	
Total Volume(cm^3)	**315493.247**	

Table No : 03-Area 03(Drop rate :30ml per mini | Temp cave in 22C^0,Temp cave out 28C^0)

GT3 (cm)	C1 278	R1 44.225	C2 263	R2 41.839	C3 230	R3 36.589	C4 210	R4 33.408	C5 195	R5 31.021	C6 175	R6 27.840	C7 154	R7 24.499	C8 110	R8 17.499	C9 95	R9 15.113	C10 84	R10 13.363
GM3 (cm)	165	26.249	170	27.044	183	29.112	196	31.180	175	27.840	161	25.612	150	23.863	143	22.749	117	18.613	95	15.113
GT3H1 (cm)	227		220		203		196		184		190		200		210		217		180	
GM3H2 (cm)	150		145		136		138		130		128		123		119		115		110	129.4



Calculation of Volume Table No:03,Rakwana

$\pi r^2 h$ (h =Average Height / 10)

GT3 Radius (cm)	R1 44.225	R2 41.839	R3 36.589	R4 33.408	R5 31.021	R6 27.840	R7 24.499	R8 17.499	R9 15.113	R10 13.363
GT3 volume (cm^3)	V1 119256.427	V2 106735.454	V3 81629.510	V4 68052.967	V5 58675.622	V6 47259.005	V7 36596.776	V8 18671.215	V9 13926.676	V10 10888.149
GM3 Radius (cm)	R1 26.249	R2 27.044	R3 29.112	R4 31.180	R5 27.840	R6 25.612	R7 26.863	R8 22.749	R9 18.613	R10 15.113
GM3 volume (cm^3)	V1 28022.326	V2 29745.448	V3 34468.528	V4 39539.473	V5 31522.243	V6 26678.760	V7 29348.620	V8 21047.634	V9 14090.014	V10 9289.237

03-Area 03(Drop rate :30ml per mini | Temp cave in 22C^0,Temp cave out 28C^0)

	GT3	**GM3**
Average Height (cm)	**194.0**	**129.4**
Total Volume:(cm^3)	**561,691.801**	**263752.283**

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