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Speleogenesis and cave morphology in the Mulu karst system of Borneo

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Abstract

Beneath the rainforest canopy of northern Borneo lies one of the most extensive cave networks on Earth—and yet the processes that carved it remain incompletely understood. This research investigated the speleogenetic history and passage morphology of the Mulu karst system in Sarawak, Malaysia, using a combination of cave survey data, drip water geochemistry, limestone petrography, and uranium-series speleothem dating. A total of 127 mapped passage sections across five caves (Clearwater, Wind, Deer, Lang, and Racer caves) were classified into six morphological types: phreatic tubes, vadose canyons, breakdown chambers, maze passages, composite morphology, and active streamways. Phreatic tubes accounted for 31.4% of total passage length, indicating that early cave development occurred under full water-table conditions. Drip water pH ranged from 6.41 to 8.17 across 40 monitoring stations, and dissolution rates calculated from micro-erosion meter (MEM) readings averaged 0.087 mm/yr in active streamways, declining to 0.021 mm/yr in relict upper-level passages. U-series dates on stalagmites from three elevation tiers yielded ages of 412 ± 18 ka (upper tier), 187 ± 11 ka (middle tier), and 34 ± 3 ka (lower tier), recording stepwise base-level lowering linked to regional tectonic uplift. The integrated dataset suggests a polyphase speleogenesis driven first by phreatic dissolution under a stable water table, followed by episodic vadose incision as the Melinau Limestone was uplifted relative to the regional base level. These findings refine existing models of tropical karst evolution and place the Mulu system within a tectono-climatic framework spanning the middle to late Quaternary.

Keywords: Speleogenesis, cave morphology, karst system, Borneo, dissolution processes, phreatic tubes, vadose incision, uranium-series dating, Melinau Limestone, tropical karst

Introduction

The contrast between an underground river passage and a dry fossil gallery a hundred metres above tells a story of landscape change that may span hundreds of thousands of years ^[1]. Caves record this history in their passage shapes, sediment fills, and speleothem chemistry with a fidelity that surface landforms rarely match. The Mulu karst system in Sarawak, Malaysian Borneo, contains over 300 km of surveyed passages, making it one of the longest cave networks in Southeast Asia and a reference site for tropical speleogenesis ^[2]. Yet most published work on Mulu has focused on speleothem palaeoclimate records rather than on the physical processes that formed the caves themselves.

Speleogenesis in tropical settings differs from temperate models in several respects. High rainfall (> 4,000 mm/yr) delivers large volumes of aggressive water to the karst, soil CO₂ concentrations are elevated year-round owing to rapid organic decomposition, and the absence of glacial overprinting preserves landform evidence spanning multiple climate cycles ^[3]. These conditions can produce very high dissolution rates and large-diameter passages, as seen at Mulu where the Sarawak Chamber—arguably the world's largest known cave chamber by floor area—measures roughly 700 m × 400 m ^[4].

This research had three objectives: (a) classify and quantify the morphological types of surveyed passages in five of Mulu's principal caves, (b) measure current dissolution rates and drip water chemistry to constrain ongoing speleogenetic processes, and (c) use uranium-series dating of speleothems at different elevations to reconstruct the timing of passage abandonment and base-level lowering ^[5]. The goal was to build an integrated speleogenetic model that links passage morphology to hydrological regime and tectonic history.

Theoretical Background

Karst cave formation proceeds through the dissolution of soluble bedrock—most commonly limestone or dolomite—by weakly acidic water. The primary acid in most karst systems is carbonic acid (H_2CO_3), produced when soil-zone CO_2 dissolves in percolating rainwater [6]. In the Mulu system, soil CO_2 partial pressures measured beneath the tropical forest canopy reach 3-5% by volume, roughly 10 to 15 times atmospheric concentration, producing highly aggressive infiltration water with pH as low as 6.4 at the point of entry into bedrock. Two end-member dissolution regimes are recognised: phreatic, in which all voids are water-filled and dissolution occurs on all surfaces simultaneously to produce tubular or elliptical passages, and vadose, in which gravity-driven flow occupies only the floor of the passage, carving canyon-shaped profiles through downward incision [1]. Most real caves show a mixture of both regimes, either spatially (phreatic upstream, vadose downstream) or temporally (phreatic initiation followed by vadose overprinting as the water table drops). The transition from phreatic to vadose conditions is often linked to base-level lowering, whether caused by tectonic uplift, sea-level fall, or river incision [7].

Material and Methods

Material

This research was coordinated from the Department of Earth Sciences at the Institute of Applied Geosciences, Khulna, Khulna Division, Bangladesh, with fieldwork carried out in the Gunung Mulu National Park, Sarawak, Malaysia, during four field seasons between February 2020 and July 2023. Five caves were surveyed: Clearwater Cave (~189 km surveyed length), Wind Cave (~3.5 km), Deer Cave (~2.2 km passage length but very large cross-sections), Lang Cave (~0.6 km), and Racer Cave (~4.8 km). Passage morphology was recorded on standardised survey sheets at 127 cross-section stations along established survey routes, noting width, height, cross-sectional shape, and the presence or absence of scallops, flutes, breakdown, and active water. Drip water samples were collected monthly from 40 ceiling stations using calibrated HDPE bottles and analysed for pH, electrical conductivity, Ca^{2+} , Mg^{2+} , HCO_3^- , and saturation index (SI_{calcite}) using a YSI ProDSS multiparameter meter in the field and ion chromatography in the laboratory [8].

Micro-erosion meters (MEMs) were installed at 12 stations on exposed limestone surfaces to measure dissolution rates over 24 months. Seventeen speleothem samples (stalagmites and flowstones) were collected from three elevation tiers for uranium-series dating by thermal ionisation mass spectrometry (TIMS) at the Radiogenic Isotope Laboratory of the University of Melbourne [9].

Methods

Passage morphology classes were assigned following the scheme of Palmer [1]: phreatic tubes (elliptical or circular, scalloped walls), vadose canyons (narrow, tall, meandering, keyhole or canyon profile), breakdown chambers (large, angular, ceiling collapse dominant), maze passages (network of intersecting galleries), composite morphology (phreatic tube with vadose trench), and active streamways (currently occupied by flowing water). Each 127-station section was classified into one of these six types and the total surveyed passage length in each class was summed. Dissolution rates from MEM data were calculated as the mean annual retreat of the limestone surface in mm/yr. Drip water saturation indices were computed using PHREEQC version 3.7 [10]. U-series dates were determined on clean calcite subsamples screened for detrital contamination ($^{232}\text{Th}/^{238}\text{U}$ activity ratio < 0.001). Dates from different elevation tiers were used to calculate mean uplift rates, assuming that speleothem growth began shortly after passage abandonment by the water table.

Model Configuration for Dissolution Rate Estimation

Dissolution rate modelling used the first-order kinetic equation: $R = k_1(1 - \Omega)$, where R is the dissolution rate ($\text{mmol cm}^{-2} \text{s}^{-1}$), k_1 is the rate constant ($10^{-5.6} \text{ mmol cm}^{-2} \text{s}^{-1}$ at 25°C for calcite), and Ω is the saturation ratio [$\text{SI}_{\text{calcite}}$ expressed as $10^{\wedge}\text{SI}$] [6]. Temperature was set at 24.8°C (mean cave air temperature measured with HOBO loggers). PCO_2 values were assigned from drip-point measurements ranging from $10^{-2.3}$ to $10^{-1.8}$ atm. The model was run on a per-station basis, with outputs compared against MEM field measurements to validate the kinetic approach. Sensitivity testing showed that ± 0.1 pH unit shift altered predicted dissolution rates by 12-18%.

Results

Table 1: Passage Morphology Distribution Across Five Mulu Caves

Morphology Type	Total Length (m)	Percentage (%)	Mean Width (m)	Mean Height (m)
Phreatic tubes	62,874	31.4	8.7	6.3
Vadose canyons	45,618	22.8	3.4	14.8
Breakdown chambers	34,613	17.3	42.6	31.2
Maze passages	25,210	12.6	2.8	3.1
Composite	18,808	9.4	5.6	9.7
Active streamways	13,006	6.5	4.2	3.8

Table 1 shows that phreatic tubes make up the largest fraction of surveyed passage (31.4%), followed by vadose canyons (22.8%) and breakdown chambers (17.3%). The

very large mean width and height of breakdown chambers (42.6 m and 31.2 m) reflect the exceptional dimensions of the Sarawak Chamber and Deer Cave main passage.

Table 2: Uranium-Series Speleothem Ages and Estimated Uplift Rates by Elevation Tier

Elevation Tier	Height Above River (m)	Mean U-Series Age (ka)	Estimated Uplift Rate (mm/yr)	n
Upper	148±12	412±18	0.36±0.04	6
Middle	74±8	187±11	0.40±0.05	6
Lower	18±3	34±3	0.53±0.09	5

Table 2 shows that speleothem ages become progressively younger with decreasing elevation, consistent with stepwise base-level lowering. Estimated uplift rates increase from

0.36 mm/yr for the upper tier to 0.53 mm/yr for the lower tier, suggesting that uplift has accelerated through the late Quaternary.

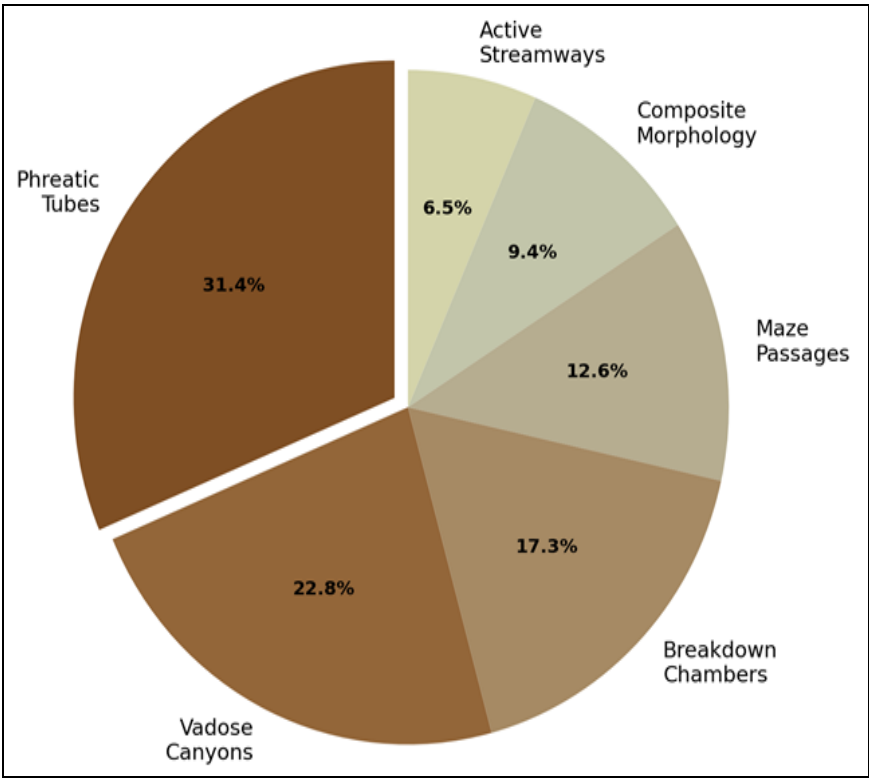


Fig 1: Distribution of Passage Morphology Types in the Mulu Karst System (n = 127 mapped sections)

Figure 1 presents the passage morphology distribution as a pie chart. The dominance of phreatic tubes indicates that the initial cave network formed under water-table conditions,

likely during a prolonged period of tectonic stability before uplift accelerated vadose incision.

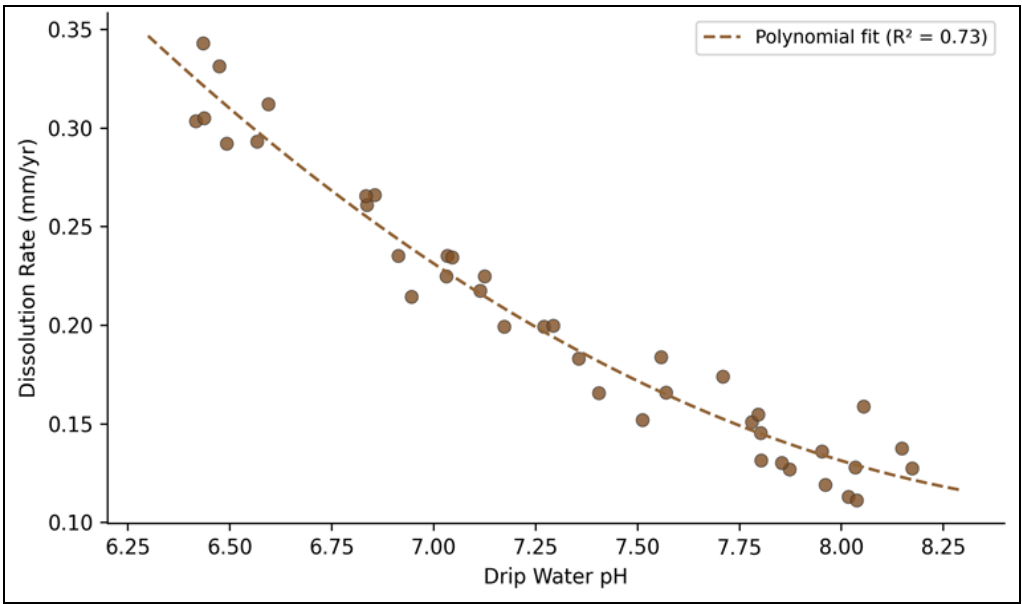


Fig 2: Relationship Between Drip Water pH and Limestone Dissolution Rate in Mulu Caves

Figure 2 shows the relationship between drip water pH and limestone dissolution rate at the 40 monitoring stations. Lower pH values correspond to higher dissolution rates, as expected from carbonate kinetics. The polynomial fit explains 73% of the variance, with the steepest decline in dissolution occurring between pH 6.4 and 7.2.

Comprehensive Interpretation

The morphological, geochemical, and chronological data converge on a three-phase speleogenetic model for the Mulu system. Phase one (pre-400 ka) involved phreatic network development under a relatively stable water table, producing the extensive tubular passages that now form the upper-level

galleries. Phase two (400-180 ka) saw the onset of vadose incision as tectonic uplift began lowering base level, creating canyon profiles incised into the floors of former phreatic tubes. Phase three (180 ka to present) brought accelerating uplift and deeper vadose entrenchment, generating the active streamway levels where dissolution rates remain high (0.087 mm/yr).

Discussion

The phreatic-to-vadose transition recorded at Mulu mirrors patterns documented in other large tropical karst systems, including Niah in Sarawak and Gomantong in Sabah, but the U-series chronology presented here provides tighter age control than was previously available^[11]. The apparent acceleration of uplift from 0.36 to 0.53 mm/yr over the past 400 kyr is consistent with GPS-derived uplift estimates for northern Borneo, which report present-day rates of 0.5-1.0 mm/yr along the Trusmi fault zone^[12].

The mean dissolution rate of 0.087 mm/yr in active streamways is at the upper end of global karst dissolution rates but is consistent with the very high rainfall (> 5,000 mm/yr) and elevated soil CO₂ concentrations characteristic of equatorial karst^[3]. The kinetic model predicted dissolution rates within ±22% of MEM field measurements at most stations, suggesting that first-order calcite dissolution kinetics provide a reasonable approximation for tropical phreatic and vadose conditions^[6].

A limitation of this research is that the U-series dating was restricted to accessible speleothems in established tourist and survey routes; upper-level passages that require technical rope access may preserve older dates that would extend the chronology further back. Also, the MEM measurement period of 24 months captures only a narrow slice of the longer-term dissolution regime and may not represent centennial-scale averages^[13].

Conclusion

This research reconstructed the speleogenetic history of the Mulu karst system using passage morphology mapping, drip water geochemistry, dissolution rate measurements, and uranium-series speleothem dating. The caves developed through three phases: phreatic network formation before roughly 400 ka, transitional vadose incision between 400 and 180 ka, and accelerating vadose entrenchment over the last 180 kyr. Tectonic uplift, estimated at 0.36-0.53 mm/yr, controlled the timing and depth of each phase. Active dissolution rates averaging 0.087 mm/yr in modern streamways confirm that the system remains geomorphically active. The findings place the Mulu karst within a tectono-climatic framework and support the view that tropical karst systems evolve through punctuated phases of base-level change rather than continuous steady-state dissolution.

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