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Microbialite Complexification at the Limits: Morphological Complexity as an Adaptive Biosignature in Cenote Azul, Mexico

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Microbialites are prime astrobiology targets: they have continuously colonized Earth's surface since the Archean, preserving an uninterrupted record of microbial life. Their diverse depositional settings serve as analogs for both ancient and modern aqueous systems, including potential Martian environments, where karst-like landforms suggest analogous microbialite-forming habitats. This work investigated morphological complexity as a biosignature in modern freshwater microbialites from Cenote Azul, Mexico, one of the Yucatán Peninsula's many karstic sinkholes. We analyzed a depth transect (5–50 m) of hand-collected microbialite samples, correlating their morphological complexity with biomass content, estimated via total PLFA concentration. Morphological complexity was quantified using 3D photogrammetric reconstructions, computing the local point-wise dimensions across a scale-informative range. Results showed that as biomass declines sharply with depth, tracking the exponential attenuation of light, morphological complexity increases. Deeper microbialites (≥40 m) develop highly organized, blade-like, upward-oriented structures with spatially heterogeneous roughness, preferentially aligned toward incident light. This is not random roughening, but structured heterogeneity: roughness maxima clustered on upward-facing, better-illuminated surfaces, while shaded regions remained smoother. We interpret this as an adaptive structural response to energy limitation where phototrophic communities migrate towards better-illuminated surfaces, driving the emergence of morphologies that maximize functional exposure to scarce light, trading biomass for structure. In this framework, microbialites are not just archives of life, they are dynamic systems that record environmental stress in their very form. This has direct implications for life detection: in planetary settings where molecular or isotopic signals may be degraded, morphology, if quantified and contextualized, can serve as a robust, observable signature of biological organization.