博士（地球環境科学）　ダンコ　タボロシ

学位論文題名

Environmental and biologic controls of vadose carbonate precipitation-Evidence from stalactites outside and inside caves

（鍾乳石の形成における鍾乳洞環境および
生物の影響―石灰洞内外の鍾乳石）

学位論文内容の要旨

While most carbonates form subaqueously, their precipitation also occurs in vadose settings, notably karst caves, where stalactites are the typical products. Stalactites are deposited by a chemical abiotic process driven by CO_2 degassing from dripping water. Inhibited by evaporation, their growth is believed limited to enclosed, humid atmosphere of caves. For this reason, stalactites observed at the land surface, where they are most commonly seen plastered to tropical cliffs, have been widely considered evidence of former caves, partly destroyed by erosion and collapse.

During the course of this study, however, scrutiny of 600 petrologic thin sections and 300 SEM samples and X-Ray Diffraction analyses of 211 stalactite specimens from limestone cliffs and other land surface settings from the Mariana Islands, Ryūkyū Islands, Thailand, Viet Nam, Indonesia, and the Caribbean have revealed ample evidence that such vadose carbonates (namely stalactites) are not limited to caves and can form at the land surface, in which case they represent new, previously unstudied sedimentary features distinct from speleothems.

Although initiated by the same fundamental mechanism as most speleothems (i.e., precipitation from dripping vadose groundwater), the land surface stalactites are vastly divergent from their cave analogues. Centimeter to tens of meters in scale, they are generally friable and porous, and exhibit somewhat irregular macromorphology. Crooked, bulbous, elongate, and pendant-like forms are common and their growth axis is often deflected from the vertical. Their outside surfaces feel pasty or powdery due to covering by biofilms and thicker organic coatings. A wide array of biota is associated with them and includes bacteria, cyanobacteria, eukaryotic algae, mosses, higher plants, and invertebrates. Composed almost exclusively of encrusted, amorphous, or laminated microcrystalline $CaCO_3$, these deposits lack the sparry calcite typical of speleothems. Occurring in a bewildering array of fabrics, they are suggestive of calcareous tufa and are herby defined as its unique subaerial category and termed *stalactitic tufa*. They can contain various inclusions, such as plant and other organic material, calcified cyanobacterial filaments and other microbial structures, eolian particles, arthropod and insect

fragments, and within the littoral realm, foraminiferal tests, diatom frustules, and skeletal grains of marine origin. Most importantly, in addition to microcrystalline calcite, they often contain aragonite, which indicates active growth.

The numerous variations in morphology, mineralogy, petrology, and other idiosyncrasies distinguishing stalactitic tufa from normal cave stalactites are imparted upon these sediments by the unique climatic and biologic properties of their epigean settings. In order to establish links between their petrology and specific environmental conditions, series of long-term microclimate observations were combined with stalactite sampling and analyses in selected caves in Guam, Mariana Islands, and Krabi, Thailand. Temperature, humidity and light intensity were monitored by data loggers and photosynthetically active radiation and air current patterns evaluated by spot measurements. It transpired that microclimatic regimes dramatically change along transects from cave entrances to cave interiors, with the general pattern characterized by pronounced diurnal and seasonal oscillations in the entrance area, their gradual buffering toward the interior of the cave, and nearly constant conditions at the back. Following microclimate measurements, actively growing stalactites were sampled along the same transects and found to be morphologically highly variable. Their overall appearance, porosity, crystal size and fabric are directly related to each sample's position in a cave and its local microclimate. Stalactites growing at the very entrance are porous microcrystalline and organic-rich bioconstructional deposits, dominated by encrusted fabrics initiated by macrophyte and microbial structures to the point were certain specimens are comprised entirely of calcified cyanobacterial filament networks and, as such, representing the first known fully subaerial bioherms. Entering the twilight zone, as temperature and humidity oscillations attenuate, illumination declines and relative humidity increases, the stalactites become progressively denser and more organized. Encrusted fabrics give rise to amorphous and layered microcrystalline fabrics, with progressively less evidence of microbial involvement in their precipitation. Further into the caves, where light no longer penetrates, microclimates stabilize, and temperature and humidity attain near-constant levels, the crystal size gradually increases and deposits become increasingly dominated by regularly arranged sparry calcite. Thus, microclimatic and biologic gradients are closely reflected by properties of the precipitates, which, range from stalactitic tufa in the microclimatically most variable parts of the caves to normal speleothems in the cave's environmentally stable interiors.

In conclusion, it has been demonstrated that stalactitic carbonates can form outside of caves and in a far winder range of microclimatic conditions than previously thought. They all originate from the same fundamental mechanism: inorganic precipitation of solid $CaCO_3$ from saturated karst water. However, in areas outside of caves, a plethora of inter-related processes, ranging from inorganic precipitation to active biomineralization, profoundly affects or even drives carbonate precipitation, producing unique, previously unrecognized biosedimentary rocks. The relative contribution of each process depends on specific environmental conditions and is reflected in identifiable microfabrics. Since morphologic and petrologic properties of stalactites can be directly related to specific environmental parameters of their depositional settings, they have a potential use in paleoenvironmental interpretation.

学位論文審査の要旨

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炭酸塩堆積物は多くの場合水中で形成されるが，カルスト洞穴に顕著に発達する鍾乳石のように，沈積は地下水面上の空気にさらされる場所でも生じる．いわゆる鍾乳石は，滴下する水が蒸発する過程における化学的な非生物プロセスによって形成される．鍾乳石は閉塞的かつ湿潤な洞穴環境に限って発達すると考えられている．このため，熱帯地域の崖では普通に分布する地表面上の鍾乳石は，過去のカルスト洞穴が破壊されて露出したとされている．

この研究では，マリアナ諸島，琉球列島，タイ，ベトナム，インドネシアおよびカリブ海において洞穴内外から採取した鍾乳石について，600 個の薄片試料精密観察，300 個の試料の走査型電子顕微鏡観察ならびに 211 個の X 線回折分析を行った結果，地下水面上で発達する炭酸塩堆積物（鍾乳石）の発達は洞穴内に限られるのではなく，地表面で生じうる多くの証拠を得た．これらの堆積物はいわゆる洞穴内二次生成物（いわゆる鍾乳石）とは明らかに異なる、本研究の試料は，これまで研究されたことのない堆積構造を持つとともに、形態的、鉱物学的、岩石学的に変化に富む。起源に関しては、洞穴内の鍾乳石と基本的に同様のメカニズムであるが、主として地表面での生物による諸プロセスによる。それらのプロセスの相対的な関与の度合いは、形成場所の環境によっており、鍾乳石の微細構造に反映されていることが確かめられた。

この研究の重要な点は，マリアナ諸島ならびにタイの石灰洞において洞穴内外の観測地点を系統的に設定し、微気象・環境要素（気温、湿度、照度、気流）の長期自動観測を行い，併せて対応する位置の鍾乳石の各種分析を系統的に行ったことにある。その結果、鍾乳石の見かけの形態、空隙度、結晶の大きさ、および組織は洞穴内（試料採取）の位置、すなわちそれぞれの場所での微気象・環境要素と直接に関わることが明らかになった。微気象・環境要素が日変化、季節変化する洞穴口では、多孔質かつ有機質な生物起源の“鍾乳石”が、形成される。湿度、温度ともに変動幅が小さくなり、光量が減る場所では、“鍾乳石”は急速に密度を増す。外殻の組織は非晶質かつ層状の微細結晶構造を示し、微生物の影響は急激に減少する。微気象・環境要素が安定する、光が届かない洞穴内では、結晶は徐々に大きくなり規則的な配列のスパー状のカルサイトになる。このように、“鍾乳石”は断続することのない一連の沈積作用を示しており、それらの微細構造の変化は連続的であること、 “鍾乳石”の多様性は、微気象および微生物の変化に関わる環境条件の関数であることが明らかになった。

以上のように，この研究は，第一に世界の主要な熱帯カルスト地域において鍾乳石の形態観察、試料採取を行い、室内では基本的な内部構造の分析、記載を系統的に行って、従来考えられたことさえなかった微生物起源の“鍾乳石”の存在を明らかにした。第二このような“鍾乳石”の形成は洞穴内外の微気象・光環境によっていることを、現地における微気象・環境要素の観測によって裏付けることに成功した。審査員一同はこれらの成果を高く評価し，また研究者として誠実かつ熱心であり，大学院課程における研鑽や取得単位なども併せ申請者が博士（地球環境科学）の学位を受けるのに十分な資格を有するものと判定した.