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LITTORAL DRIPSTONE AND FLOWSTONE — NON-SPELEAN CARBONATE SECONDARY DEPOSITS

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ABSTRACT
Speleothem-like dripstone and flowstone deposits can form in the non-spelean environments of marine notches on tropical carbonate coastlines. Hereby termed "littoral dripstone" and "littoral flowstone" to distinguish them from genuine cave deposits, they reflect the basic speleothem types: draperies, stalactites, stalagmites, and columns. Nevertheless, these formations lack the luster and crystallinity of cave analogues, and are not nearly as well-developed, dense, and massive. They are composed of layered microcrystalline aragonite and calcite, are generally highly porous, and invariably overlie dissolutional and bioerosional karren.
Because true speleothems, often found in the remnants of solution voids breached by coastal erosion, are also commonly present in the modern littoral environments on tropical carbonate islands, they could be confused with littoral dripstone and flowstone deposits. The distinction between the two is crucial, because the true speleothems are indicators of karst cave paleoenvironments, while littoral dripstone and flowstone are contemporary parts of the modern coastal landscape.

Key words: speleothem, marine notch, littoral cave, secondary deposits, aragonite, calcite

Introduction

Dripstone and flowstone are secondary cave deposits, precipitated from solution as water respectively drips from, or flows over, cave roofs, walls, and floors (Jennings, 1985). Although most generic terms applied to spelean deposits have now been largely abandoned in favor of the universal term "speleothem" (White, 1976), the terms "dripstone" and "flowstone" have retained their utility and remain in use (White, 1988). While speleothems include all secondary chemical deposits formed in caves, dripstone and flowstone comprise only those speleothems formed by dripping or flowing vadose water (Jennings, 1985). Arguably the most common supracate-

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gories of speleothems, dripstone and flowstone significantly exclude subaqueous forms (e.g. rimstone pools) and erratics (e.g. helictites), but include all the quintessential speleothems such as stalactites, stalagmites, columns, and draperies (Bull, 1983). Usually composed of calcite, they are precipitated from vadose water, which, carrying a high load of dissolved $CaCO_3$, enters a cave from fissures and pores in the surrounding rock. Inside the cave, this water attains equilibrium with the partial pressure of CO_2 in the local atmosphere by CO_2 outgassing. This results in an elevated pH and precipitation of calcite (Dreybrodt, 1988).

Because the formation of dripstone and flowstone requires an enclosed, humid atmosphere, and generally does not occur under normal surface atmospheric conditions, where it is limited by evaporative processes (Hill & Forti, 1997), their presence in non-cave settings is good evidence of former caves. For example, flowstone deposits on a limestone boulder can indicate that the boulder was once part of a cave that had collapsed. In coastal areas, the presence of stalactites is often a factor in discerning between littoral caves and true karst caves and has also been identified as one of the features enabling the distinction between marine (bioerosional) notches and breached solution cavities (Mylroie & Carew, 1991). While no doubts are being raised regarding the validity of these field tests and the logic behind them, there exist speleothem-like dripstone and flowstone that form in the open environments of marine notches, littoral caves, and sea cliffs on tropical coasts. If not carefully examined and recognized as not being true speleothems, these deposits can cause misinterpretation of wave cut or bioeroded landforms as remnants of solution cavities.

As Mylroie and Carew (1991) have pointed out, only well-developed, dense, layered calcite speleothems can be considered evidence of karst caves. Working in the Bahamas, they noticed that "lumpy porous stalactitic features" do develop in outside conditions, and report them to be readily separable from true cave stalactites based on visual observations. The purpose of this study, carried out on the island of Tinian in the Mariana Islands, is to document the existence of such features in the Pacific, describe their morphology and depositional environments, elucidate the basic differences and similarities between them and true speleothems, and set the basis for future in-depth research.

In addition, we propose the terms "littoral dripstone" and "littoral flowstone" to refer to these deposits. The adjective identifies them as vadose precipitates forming in coastal settings, and clearly distinguishes them from archetypal and genuine dripstone and flowstone that form inside caves.

Study area

Tinian, a tropical carbonate island, lies in the western Pacific Ocean, at 15°N latitude and 145°W longitude. It is the second largest (105 km^2) island in the Commonwealth of the Northern Mariana Islands, located 160 kilometers north-northwest of Guam (Fig. 1). Tinian is somewhat rhomboid in shape, approximately 19 km long, and up to 10 km wide. The island's relief is subtle, with a maximum ele-

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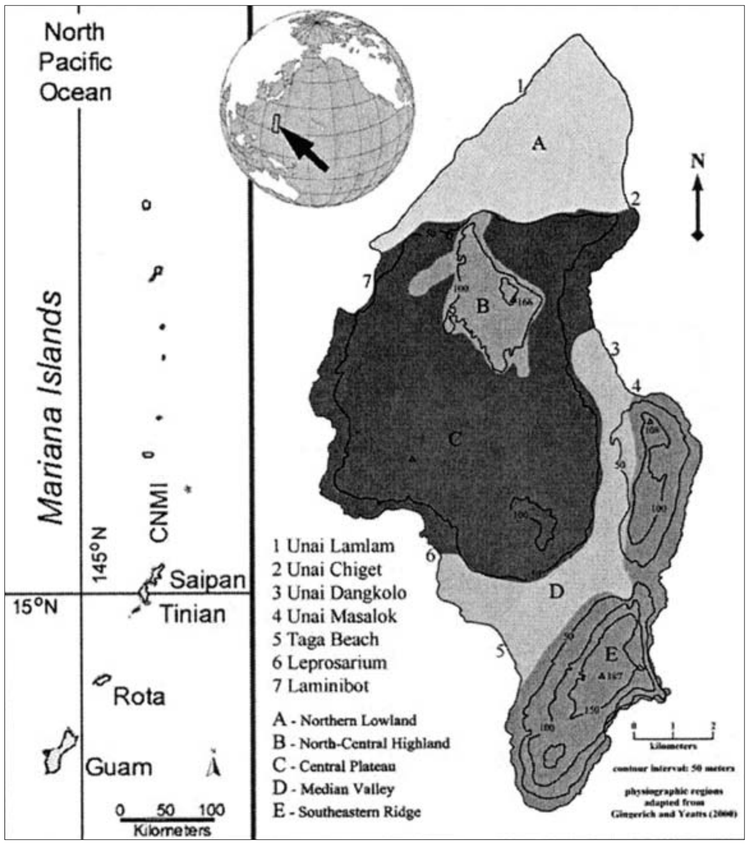

Fig. 1. Location and simplified physiographic map of Tinian, showing sites mentioned in text.

vation of 187 m, but not monotonous. Intricate systems of horizontal and tilted plateaus and terraces dominate the land surface, forming five physiographic regions (Fig. 1). They are separated by steep, rocky scarps, which also make up most of the coastline. About two percent of the island's exposed land surface is volcanic rock. The rest is covered by early Miocene Tagpochau Limestone and Pliocene to Pleistocene Mariana Limestone, composed of mostly coralline and algal lithologies. The principal geologic reference for Tinian is the US Army report by Doan *et al.* (1960), which includes a 1:25,000 scale geologic map.

The climate of Tinian is uniformly warm and humid, with a mean annual temperature of 27°C and a relative humidity range from 60 to 100%. The annual rainfall averages 200 cm/year and exhibits marked seasonality. Approximately 50% of this precipitation occurs during the wet season (July through October) and only about 10% falls during the dry season (February through April). Trade winds are dominant throughout the year, and annual variations in insolation and illumination are slight. Tinian has no perennial streams and its vegetation is dominated by thick shrub brush

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and limestone forests. The mean tide range is about 45 cm and spring tide range is about 52 cm. Both swell and waves generated by local winds generally come from the east, with the roughest seas occurring between November and February.

Rationale, methods and sampling locations

Karst features of Tinian were systematically investigated and surveyed in June and December 2002 (Stafford, in prep.; Stafford et al., 2003). During fieldwork, special attention was paid to coastal areas, where a large number of caves are exposed in coastal cliffs. Many of these are flank margin caves – dissolutional voids that form in the discharging margin of the freshwater lens on carbonate islands (Mylroie & Carew, 1990). Although hypogenic (forming without direct connections to the land surface or the ocean), these caves are commonly breached by collapse and erosion. The resultant morphologies are normally easily recognizable as breached flank margin caves, but can, in certain cases, be difficult to distinguish from fossil marine notches. Some of the scarp reentrants in the Bahamas, previously thought to be marine notches, have been recognized as remnants of flank margin caves (Mylroie & Carew, 1991). Flank margin caves can occasionally be difficult to distinguish from littoral caves, as well, particularly in places where erosion and collapse have destroyed all but a fraction of original morphology. Distinction between karst (solution) caves and littoral caves is important, because the latter are wave-eroded landforms rather than karst features, and their formation is independent of groundwater hydrology.

In such problematic cases, the presence of speleothems is often used as an indicator of dissolutional origin (as opposed to wave erosion and/or bioerosion) for voids in question. Therefore, the occurrence of speleothem-like deposits in several places on the Tinian coast where overall geomorphology clearly indicates a marine notch (rather than a breached cave) prompted additional inquiries into the nature of these deposits. Four sites where speleothem-like formations occur in indubitable non-karst cave settings were selected for the study, surveyed and photodocumented. They include marine notches at Unai Lamlam, Unai Chiget, Unai Dangkolo, and Unai Masalok (Fig. 1). Secondary deposits were carefully examined, and fifteen samples were removed using a hammer and a chisel and were kept for future analyses. Marine notches and littoral caves at three additional sites, Taga Beach, the historic Leprosarium site, and Laminibot (Fig. 1), were inspected and found to contain no speleothem-like features. Because many of the sampling locations are exposed to nearly constant high surf, much of the work could only be carried out during low tides, while exercising extreme caution.

X-Ray Diffraction (XRD) analyses were carried out on a Bruker AXS MX-Labo powder diffractometer with Cu radiation at 40 kV and 20 mA. Powdered samples mounted on glass slides were rotated at 60 rpm and radiation counts were measured at stepped diffraction angles of $0.02^{o}2q$ from 2.02 to 70.00 degrees. Peak characteristics were analyzed using MacDiff 4.2.5 software.

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Result

Depositional environments

Most of the coastline of Tinian is comprised of rocky scarps of Plio-Pleistocene Mariana Limestone. A prominent sea-level notch has been incised at the base of the scarps and is associated with a narrow bench. In places where the ocean is not in direct contact with the tall, nearly vertical coastal cliffs, the coast is dominated by large, angular blocks, broken loose from the steep cliffs above; low terraces of extremely rough, solution-pitted emergent limestone; wide constructional algal benches and rimmed pools; and littoral caves and fractures, widened by wave erosion. There are a few well-developed beaches that are protected by fringing reefs, and several small beaches within rocky coves. The latter belong to at least three genetic types, exemplified respectively by Unai Chiget, developed by the lateral retreat of a fault scarp; Unai Masalok, which appears to have formed by erosion and collapse of flank margin caves (as in the caletas of Back *et al.* 1984); and coves shaped by sea erosion concentrated within structural zones of weakness. Marine notches associated with these coves are the typical depositional environments of non-spelean dripstone and flowstone on the Tinian coast, while marine notches in coastal cliffs elsewhere generally lack similar deposits.

Unai Chiget (Fig. 2) is a prominent slot-like inlet on the northeast coast of Tinian, formed by the lateral retreat of a fault scarp. It contains a shallow fringing reef, bound on the south side by a 30-m tall fault scarp, on the north side by a 4-m tall coastal terrace, and on the ocean-facing side by an algal ridge under near-constant impact by intense surf. The reef is less than 2 m deep, and shallows inland

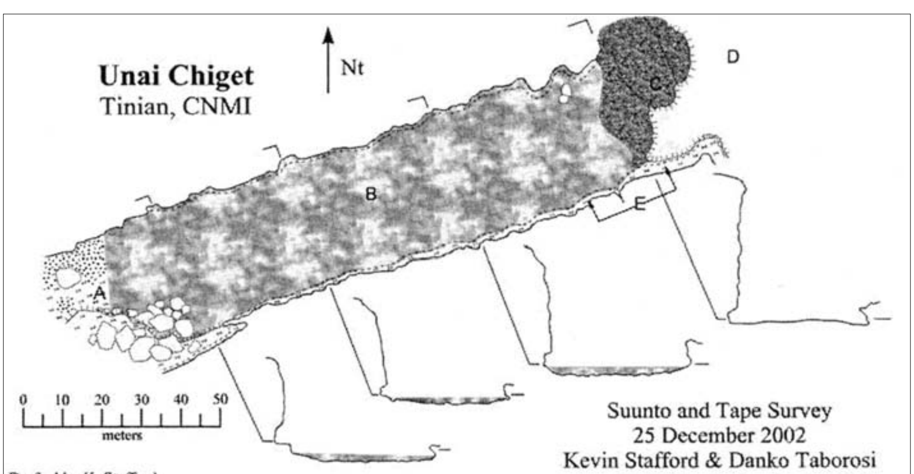

Fig. 2. Plan and selected profiles of Unai Chiget inlet. A – beach, B – fringing coral reef, C – algal ridge, D – ocean, E – segment of the marine notch where speleothem-like deposits occur.

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where it ends at a small carbonate sand beach. On the south side, the inlet contains a particularly prominent marine notch (Fig. 3). The notch has a semi-circular profile, 2.2 to 2.5 m and 1.2 to 2.4 m in vertical and horizontal dimensions respectively. It is defined by a flat to slightly inclined floor continuous with the intertidal algal bench; a back wall with a horizontal ridge located roughly half way between the roofs and the notch floors; and a flat to inclined roof. Although located in northeast Tinian,

Fig. 3. Unai Chiget. Note the prominent marine notch and the algal ridge (breaking waves). Person for scale.

where rough seas frequently impact the coast, most of the length of the marine notch is unexposed to waves, because it extends at approximately a right angle to the coastline. Additionally, most of it is protected by a well-developed *Porolithon* algal ridge that breaks the waves (Fig. 2). Approaching the algal ridge seaward, the exposure to surf greatly increases, and the parts of the notch adjacent to the ridge are constantly hit by large waves. Further along the cliff, where any protection by a fringing algal reef is lacking, the surf is even more forceful. Speleothem-like secondary deposits are present in the roof and the back wall of the marine notch, but only in the immediate vicinity of the algal ridge. They are found exclusively in the notch segment extending from 3 m seaward of the algal ridge to 17 m inland from the algal ridge, an area regularly, but indirectly, splashed by waves (indicated in Fig. 2). The deposits are lacking elsewhere, both in the seaward parts of the notch, where the wave impact is more direct, and in the inland parts, which are not wetted by waves except during storm events.

At Unai Masalok (Fig. 4), on the southeast coast of Tinian, the existence of a narrow fringing reef partially protects the coast from surf. A series of adjacent coves, separated by narrow rocky headlands, is formed by a locally-recessed coastal scarp.

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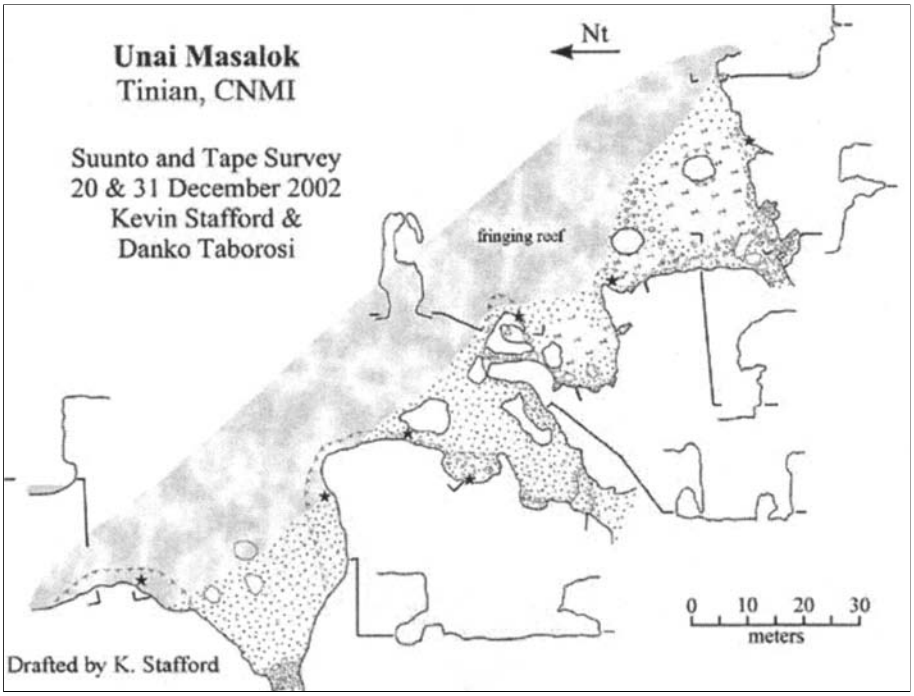

Fig. 4. Plan and selected profiles of Unai Masalok. Stars indicate the sites of speleothem-like deposits.

The coves contain small carbonate sand beaches, several large boulders, and beachrock deposits. A prominent sea level notch is incised at the base of the rocky scarp (Fig. 5). In the inland portion of the coves, the notch is partially to completely covered by upward sloping beach sand. Elsewhere, the notch roof and the back wall contain conspicuous speleothem-like formations, most shaped as draperies (Fig. 6), but also as stalactites and irregular patches. Interestingly, the deposits occur on the flanks of the rocky scarps separating the coves where wave splashing is intermittent, but are absent in the headlands directly exposed to waves, as well as the inland portions that are not regularly wetted by waves (as indicated in Fig. 4). Within one of the coves, an adjunct cave contains prominent flowstone deposits, clearly superimposed on the ubiquitous bioerosional and dissolutional karren (Fig. 7).

Further north from Masalok, a similar cove and a long beach at Unai Dangkolo also exhibit speleothem-like secondary deposits, located in the roof, back wall, and floor of the local marine notch. The notch at Unai Lamlam, on the northwest side of the island, contains comparable, but considerably fewer, deposits.

It must be noted that true cave speleothems are also a common feature of the littoral landscape on Tinian. Unlike the speleothem-like deposits discussed in this paper, the real speleothems are not a contemporary part of the coastal environment, but a remnant of former caves. Although the two are often found in immediate vicin-

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Fig. 5. Marine notch at Unai Masalok. Dark material are secondary deposits of littoral flowstone. Person for scale.

Fig. 6. Marine notch at Unai Masalok and its prominent "draperies" of littoral flowstone. Hammer for scale.

ity of each other, this is only due to imposition of coastal processes on pre-existing karst features. This occurs when coastal scarp retreat breaches flank margin caves and incorporates them into the modern coastline. Marine notches, bioerosional karren, and other wave or bioeroded landforms thus encroach on karst caves. Masalok

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Fig. 7. Extremely hard and dense flowstone on the walls of a shelter cave at Unai Masalok. Although it may have developed in sealed conditions (created by closing up of the cave by beach sand), it is nevertheless a young deposit prominently superimposed on bioerosional karren. Hammer for scale.

is an excellent site to appreciate this phenomenon. Its coves have formed by breaching of flank margin caves, and the modern marine notch is incised in what was once a wall of a cave.
The result is contemporary littoral speleothem-like formations being deposited in the seaward portions of the coves, but true cave speleothems still present in more landward positions.

Exterior morphology of the deposits

The speleothem-like deposits found in marine notches on Tinian are morphologically varied. Their overall forms reflect the basic speleothem types and include formations shaped like draperies, stalactites, stalagmites, and columns; also common are irregular patch-like deposits. Despite exhibiting a speleothem-like form, littoral dripstone and flowstone formations are not genuine speleothems and should not be referred to as stalactites, stalagmites, etc. They are rudimentary versions of cave analogues, lacking their luster and crystallinity, and are not as well-developed, dense, and massive; hence, any speleothem terms applied to these non-spelean deposits should be included in quotation marks to distinguish them from genuine cave deposits.

"Draperies" are rather common. Not thin and wavy as draperies found in caves, they are similarly shaped linear deposits vertically extending along walls of marine notches (Fig. 8). Often appearing as stalactites plastered onto rock walls, they cover antecedent karren and bioerosional scars, and are thus easily identifiable as secondary deposits that formed in open, non-spelean conditions (Fig. 9). They can be very prominent in marine notches, where they typically occur as a series of vertical deposits lining the back walls, with their black color in stark contrast with the bedrock (Fig. 10). Also common are "stalactites", which hang from the roofs of

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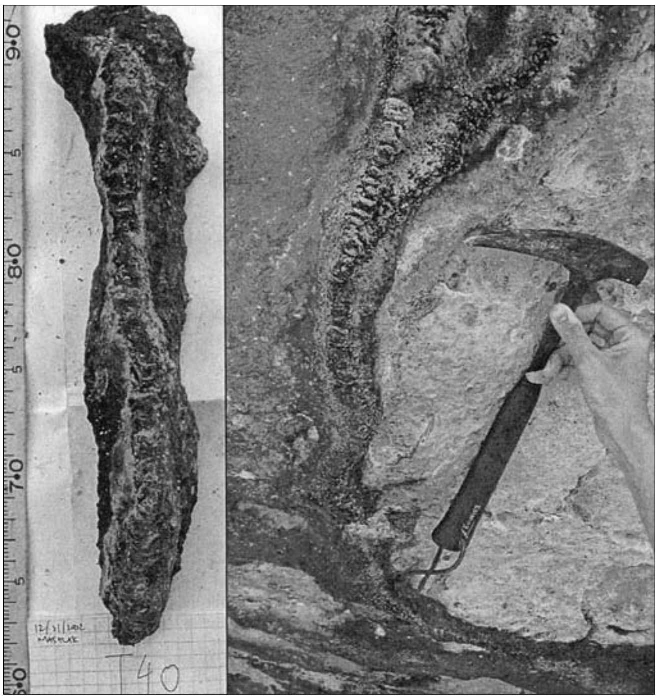

Fig. 8. Littoral flowstone "drapery" from a marine notch at Unai Masalok. Scale in centimeters.

Fig. 9. Littoral flowstone deposits in a marine notch at Unai Dangkolo. Tape reel is 14.5 cm in diameter.

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marine notches. They lack the elegant, smooth and linear appearance of cave stalactites, and are often contorted, bulbous and craggy (Fig. 11). Despite the irregularities, they retain the vertical, hanging aspect of stalactites, and are a few centimeters to 30 cm long. Their length does not greatly exceed their width, and no soda straw-like or

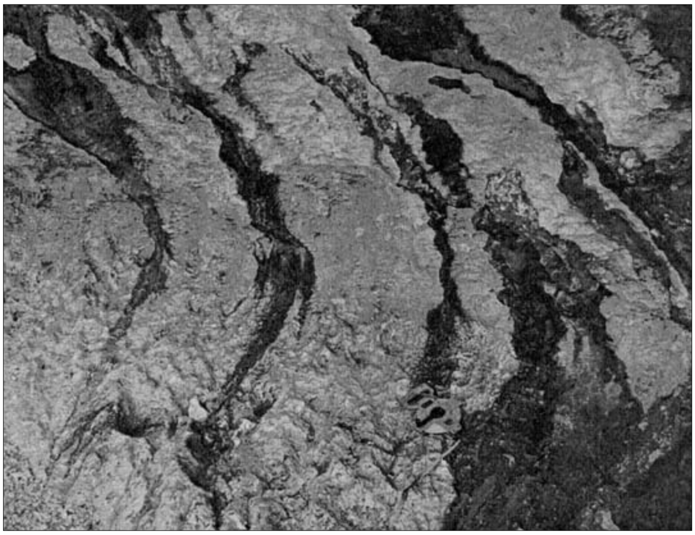

Fig. 10. Littoral flowstone deposits in a marine notch at Unai Dangkolo. Note the color contrast between the secondary deposits and bedrock. Tape reel is 14.5 cm in diameter.

Fig. 11. Littoral dripstone "stalactite" from Unai Chiget. Note the bulbous and irregular appearance. Protrusion in bottom right is the active (dripping) end. Scale in centimeters.

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thin specimens have been encountered. “Stalagmites” are uncommon, and occur on marine notch floors in locations well protected from wave action. They are not cylindrical like exemplary cave stalagmites, but instead are wide-based, short and conical (Fig. 12). Columnar formations, which are quite rare, have also been documented. They join the roofs and floors of the thinnest (inland) portions of marine notches (Fig. 13).

Fig. 12. “Stalagmites” at the base of marine notch just south of Unai Dangkolo. Their surface is wet and light green in color, apparently due to algal covering. The “stalactites” above are actively dripping. Tape reel is 14.5 cm in diameter.

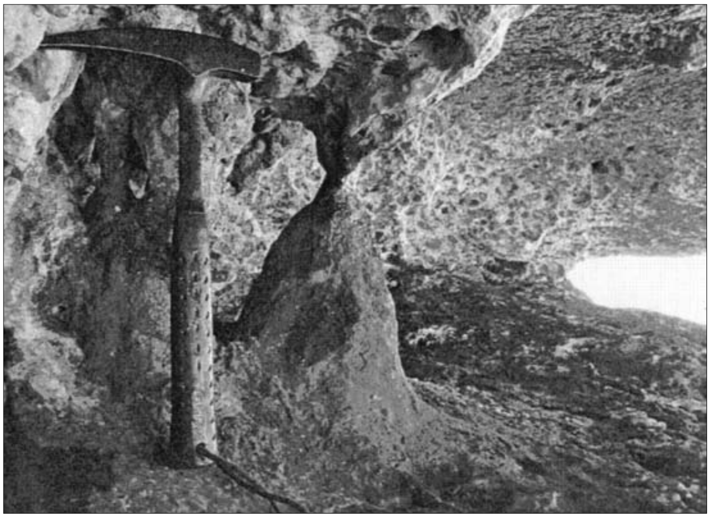

Fig. 13. A “column” connecting the roof and floor of a marine notch at the south end of Unai Dangkolo. Hammer for scale.

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The most common littoral dripstone formations, however, are not shaped as any particular speleothems; they take the form of irregular, flat patches attached to notch roofs. Several centimeters thick, they are usually covered by small knobs reminiscent of cave coral (Fig. 14). Despite being coralliform, these secondary deposits are easily distinguished from the actual coral fossils (primary deposits) often comprising the limestone bedrock in the tropics (Fig. 15).

Surface textures of littoral dripstone and flowstone formations include the above mentioned knobby, coralliform exteriors most common in patch-like deposits and "draperies" (Fig. 16); relatively smooth surfaces that are regularly found in "draperies", "stalactites", "stalagmites" and "columns"; irregular, bumpy and somewhat botryoidal crusty surfaces found in large, bulbous "stalactites" (Fig. 11); and rarely, rippled textures (Fig. 17).

Fig. 14. A coralliform patch deposit from the roof of the marine notch at the north end of Unai Dangkolo. In situ, the knobby surface was oriented downward. Note the sharp contact with the bedrock. Scale in centimeters.

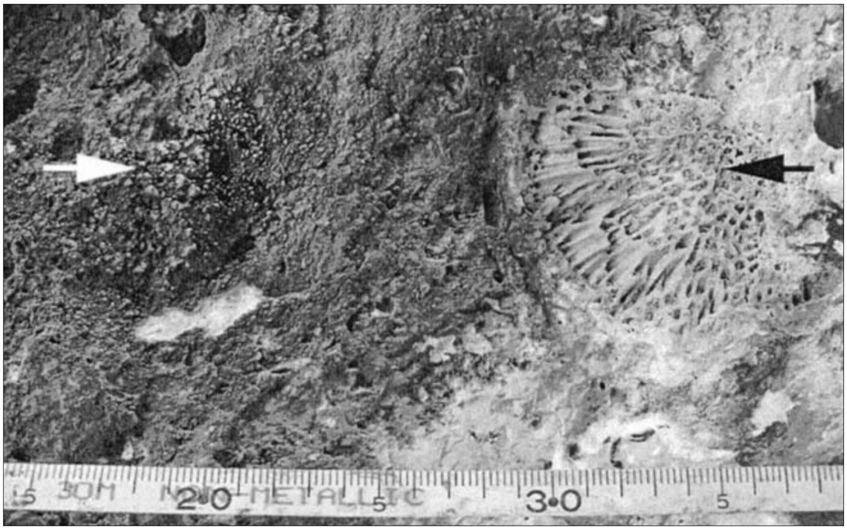

Fig. 15. Roof of the marine notch at the north end of Unai Dangkolo. White arrow indicates a coralliform secondary deposit; black arrow indicates a scleractinian coral fossil. Scale in centimeters.

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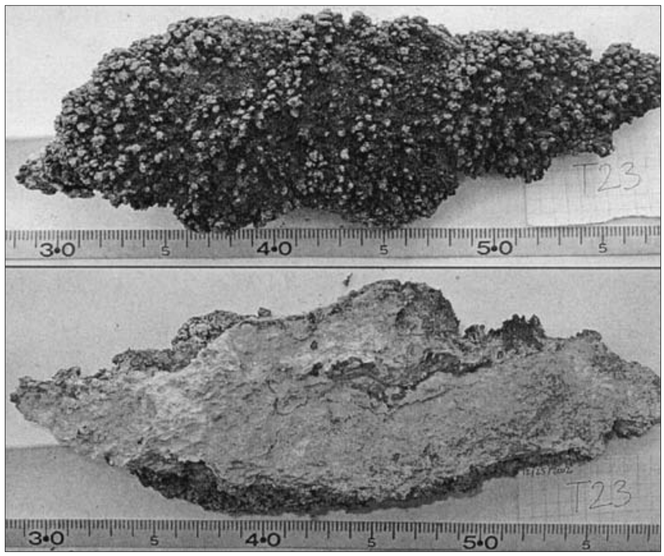

Fig. 16. An elongate littoral dripstone patch from the roof of the marine notch at Unai Chiget. Top photo shows the knobby outer surface reminiscent of cave coral; bottom photo shows the broken surface previously in contact with the bedrock. Scale in centimeters.

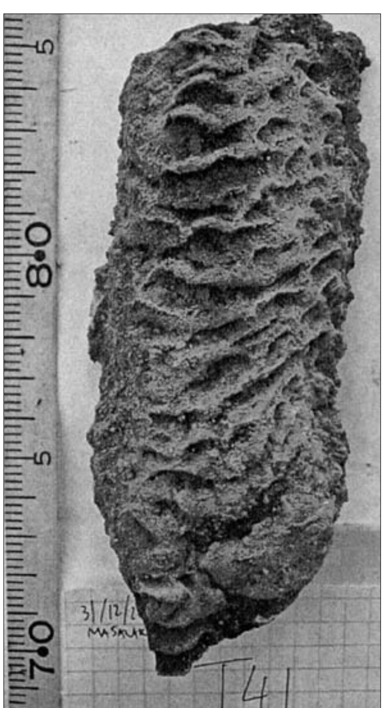

Fig. 17. A piece of marine notch wall deposit from Unai Masalok. Note the rippled texture reminiscent of speleothems. Scale in centimeters.

Both active (dripping) and apparently inactive formations have been documented on Tinian. While many of the active deposits are evidently fed by epikarstic water, this is not obvious in places where the formations are exposed to vigorous wave action and near continuous dripping of splashed-up seawater.

Internal structure of the deposits

Littoral dripstone and flowstone deposits are variable in both internal structure and density. The latter is particularly inconsistent, as became evident during the sample collection process, when some formations could easily be broken off by a single nudge of a hammer, while the removal of others required laborious cutting by a chisel.

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The deposits generally consist of layered microcrystalline aragonite and calcite, and almost invariably lack sparry calcite of true speleothems. They range in composition from pure calcite to almost pure aragonite, with most samples containing both phases in various proportions (Fig. 18). The banding is typically not concentric and tight as in speleothems, but rather sinuous and irregular, sometimes surrounding patches of non-layered micrite (Fig. 19). Cracks and open spaces between the layers

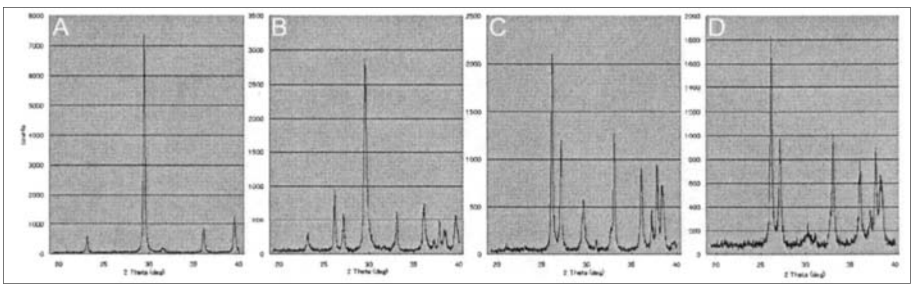

Fig. 18. Series of X-Ray diffractograms of powdered littoral dripstone and flowstone samples (only angles around the main peak of calcite are shown): a) "drapery" composed of pure calcite (same specimen as in Fig. 19); "stalactite" composed of mostly calcite with some aragonite (same specimen as in Figs. 11 and 20); a patch of littoral dripstone composed of mostly aragonite with some calcite (same specimen as in Figs. 16 and 22); a coralliform patch deposit composed of almost pure aragonite (same specimen as in Fig. 14).

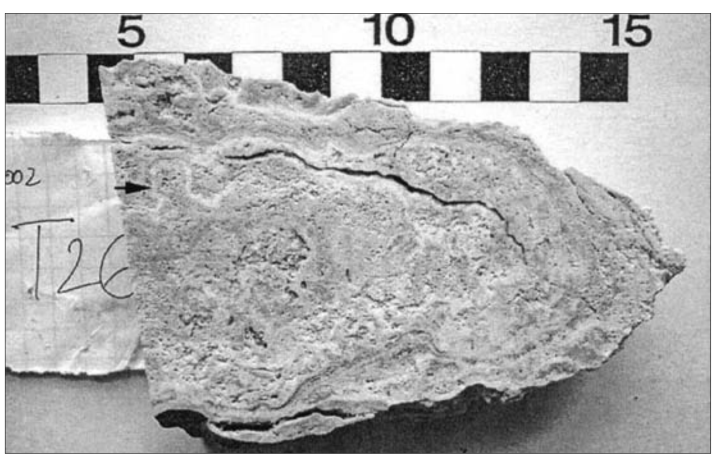

Fig. 19. Cross-section of a "drapery" from marine notch at Unai Chiget. Note the irregular banding, convolutions (one marked by arrow), and the non-layered micrite. Scale in centimeters.

are common and can be prominent. Many of them are apparently caused by desiccation; but some, particularly in the large, bulbous "stalactites", are primary, due to the deposition of outer layers in the form of a bumpy crust (Fig. 20). Although exceedingly common, such prominent open spaces should not be taken as a diagnostic feature of littoral dripstone and flowstone as they have also been observed in

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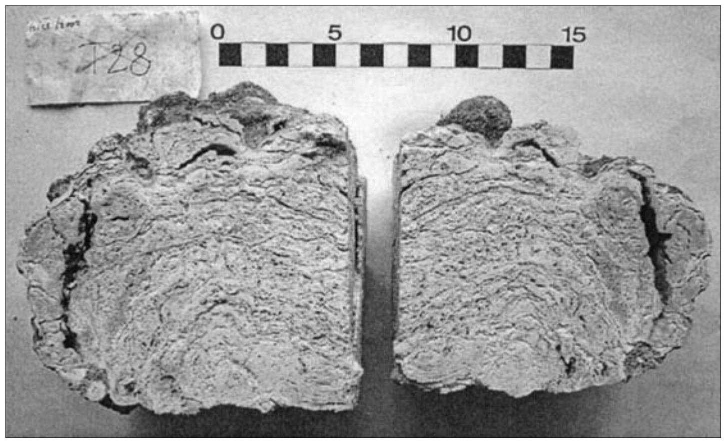

Fig. 20. Cross-section of a bulbous "stalactite" from marine notch at Unai Chiget (same specimen as in Fig. 11). Note the irregular banding and prominent open spaces between the layers. Scale in centimeters.

speleothems from deep inside karst caves on islands like the Bahamas (J.E. Mylroie, pers. comm.). The high porosity of littoral dripstone and flowstone is not always macroscopically apparent, and very finely laminated deposits are also found (Fig. 21). The layering and laminations can be extremely convoluted, and even polycentric. Many deposits, particularly the coralliform patches and "draperies", are composed of numerous pisolith-like bodies, seen on cross-sections as clusters of concentric circles up to 15 mm across (Fig. 22). Deposits commonly contain carbonate sand grains embedded within the calcite layers (Fig. 23).

The sampled specimens are characterized by a variety of densities, ranging from porous and crumbly tufas, to deposits so hard and finely laminated as to be hardly distinguishable from true cave speleothems (Fig. 23). The latter are of particular concern, because they apparently violate the premise that dense, layered calcite formations do not form outside of caves. As was already noted, it is quite common for true

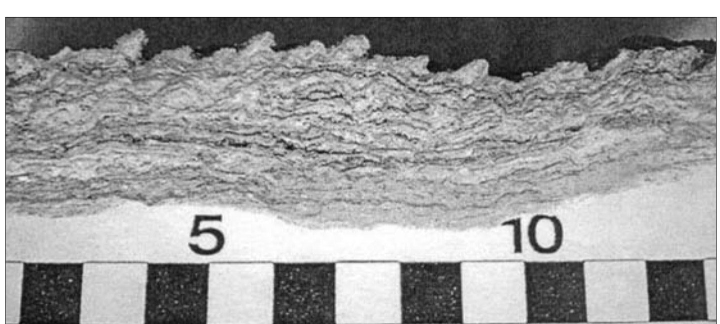

Fig. 21. Cross-section of a "drapery" from marine notch at Unai Masalok (same specimen as in Fig. 17). Scale in centimeters.

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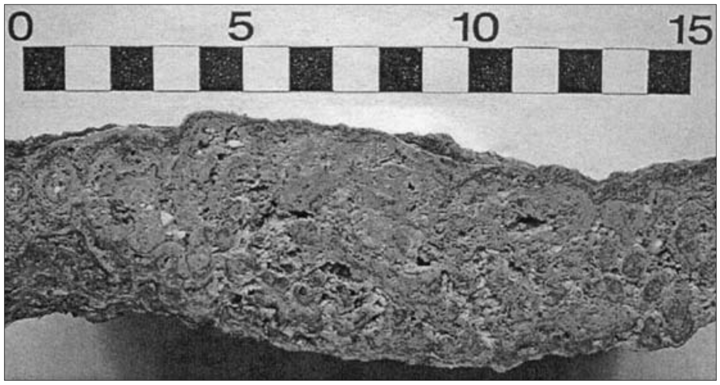

Fig. 22. Cross-section of an elongate patchy deposit from the roof of marine notch at Unai Chiget (same specimen as in Fig. 16). Note the convoluted layers and pisolith-like concentric circles. Scale in centimeters.

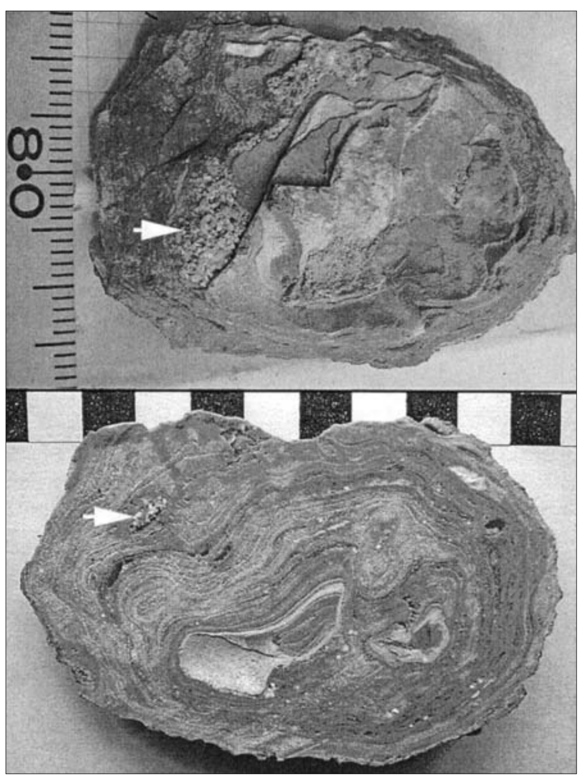

Fig. 23. Broken (top) and cut (bottom) surface of a piece of flowstone from the walls of a shelter cave in Unai Masalok (shown in Fig. 7). Note the carbonate sand inclusions (marked by arrows) and very dense calcite layering, atypical of littoral dripstone and flowstone. Scales in centimeters.

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speleothems to become exposed in modern coastal settings by breaching of solution cavities by coastal erosion, so careful examination of the contact with the bedrock might be necessary to avoid mistaking them for littoral dripstone and flowstone. In the rare cases, where such exceptionally dense deposits occur superimposed on bioerosional scars, it is most likely that they have formed in relatively enclosed settings, such as might develop by obstruction of littoral caves or marine notches by collapse or beach deposits.

Discussion

Deposition of $CaCO_3$ in caves is usually governed by the outgassing of CO_2 from vadose water, which typically carries a high load of dissolved Ca^{2+} and HCO_3^- as it enters a cave. This increases the local pH, causes the removal of carbonate ion species from solution, and precipitates solids that form speleothems. Correspondingly, epikarstic water, dripping from the roofs of relatively open, non-spelean, but overhung environments, is in equilibrium with the high partial pressure of CO_2 in the soils above. As it drips, it is not surprising that some degassing of CO_2 and precipitation of $CaCO_3$ should occur. However, while the enclosed atmosphere of caves exhibits minimal evaporation due to high humidity, the evaporation effects in the more open settings are much greater. This induces rapid deposition of calcite, causing a more random orientation and smaller size of crystals than those precipitated inside caves. This phenomenon is commonly observed in cave entrances, where the characteristic speleothem is often moonmilk, a soft, powdery and pasty microcrystalline aggregate (Borsato *et al.*, 2000). However, in tropical areas and especially on tropical coasts, a number of additional climatic and biologic factors facilitate the precipitation of aragonite and calcite and can result in the deposition of formations much more convincingly speleothem-like than the amorphous moonmilk.

Because the source of soil CO_2 is microbial activity, which correlates with the temperature (Andersson & Nilsson, 2001), the tropical soil atmosphere can reach CO_2 partial pressures much higher than in other climates. The amount of dissolved organic carbon in the soil is also positively correlated with the soil moisture content (Christ & David, 1996), which is high in the humid tropical areas. As a result, tropical soil atmospheres exhibit CO_2 partial pressures of several percent, compared to the few tenths of a percent characteristic of temperate regions (Dreybrodt, 1988). The dissolution potential of epikarstic water in the tropics is thus increased, and so is the amount of dissolved $CaCO_3$ that can be carried as well as precipitated. Furthermore, evaporation, which limits the deposition of speleothems, can be minimized in the humid tropics. Evaporation is likely impeded in the microclimates of marine notches and littoral caves, through a combination of overall relative humidity values close to saturation point, ubiquitous sea spray and mist, and shading effects by overhanging rock.

Somewhat surprisingly, wave action appears to have an important role in the precipitation of littoral dripstone and flowstone. This is apparent in the distribution pattern of secondary deposits in both Unai Chiget and Unai Masalok. They are abundant

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in locations that are regularly, but indirectly splashed by waves; but are absent in places exposed to more direct surf, as well as areas completely protected from the surf. Positive effects of sea spray and freshwater interaction on aragonite and calcite precipitation on tropical coasts are not improbable and are well documented in beachrock literature (see Gischler, 2003 for review). Although, in the case of beachrock, the precipitated components are only the cements binding together pre-existing carbonate particles, some of the mechanisms hypothesized likely contribute to the deposition of littoral dripstone and flowstone as well. Those include a number of physiochemical processes, including the mixing of freshwater and seawater (e.g., Moore, 1973), CO_2 degassing due to groundwater discharge (e.g., Hanor, 1978), wave agitation, and/or increasing temperature (Gischler & Lomando, 1997), and the evaporation of seawater (e.g., Taylor & Illing, 1969). The high aragonite content of littoral dripstone and flowstone indicates that the role of seawater, high in magnesium, is significant. A likely situation involves sea spray entering the fractures in rock, flowing through it, and re-emerging to precipitate aragonite in littoral dripstone and flowstone, while the calcite portion is precipitated from vadose freshwater, which also flows through the same pathways following the rain events. Seawater precipitated secondary deposits of aragonite have been reported from the Bahamas, but are limited to several mm thin coatings on coastal rocks (J. Wilber, pers. comm.).

Biologic processes, including the uptake of photosynthetic CO_2 by microflora (Merz, 1992) and/or increased pH levels by heterotrophic microbes (Webb *et al.*, 1999), are also considered instrumental in the formation of beachrock, and their influence on the deposition of littoral dripstone and flowstone should not be discounted. The profound influences of biota on calcite precipitation are well documented in literature, and affect a wide range of depositional karst features including speleothems (e.g., Barton *et al.*, 2001), travertine (e.g., Bayari *et al.*, 1994), tufa (e.g., Pentecost, 1985), calcrete (e.g., Khadkikar *et al.*, 2000), moonmilk (e.g., Gradzinski *et al.*, 1997), etc. The effects of biota on karst features can be especially prevalent in tropical and littoral environments (Viles, 1988; Spencer, 1988; Taboro?i, 2002). The strikingly dark coloration exhibited by littoral dripstone and flowstone deposits certainly invokes some biological influence, as such aspect of tropical coastal limestones has been linked to colonization by microorganisms (e.g., Jones, 1989).

Conclusion

Speleothem-like secondary deposits occur in the non-spelean environments of marine notches on tropical carbonate coastlines. Although shaped as stalactites, stalagmites, draperies, etc., they are not nearly as well developed, dense, crystalline, and massive as the analogous cave formations. Termed "littoral dripstone" and "littoral flowstone", they are composed of microcrystalline aragonite and calcite, and their depositional mechanisms are presently unknown but are under active study. Future work will focus on petrographic and geochemical studies, aimed at understanding the microstructure and dripwater chemistry of littoral dripstone and flowstone deposits and comparisons to those of genuine speleothems.

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Because true speleothems, remnants of solution voids breached by coastal erosion, are also commonly present in the modern littoral environments on tropical carbonate islands, care must be taken not to confuse them with the littoral dripstone and flowstone deposits. The distinction between the two is crucial, because true speleothems are indicators of karst cave paleoenvironments, while littoral dripstone and flowstone are contemporary parts of the modern coastal landscape.

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