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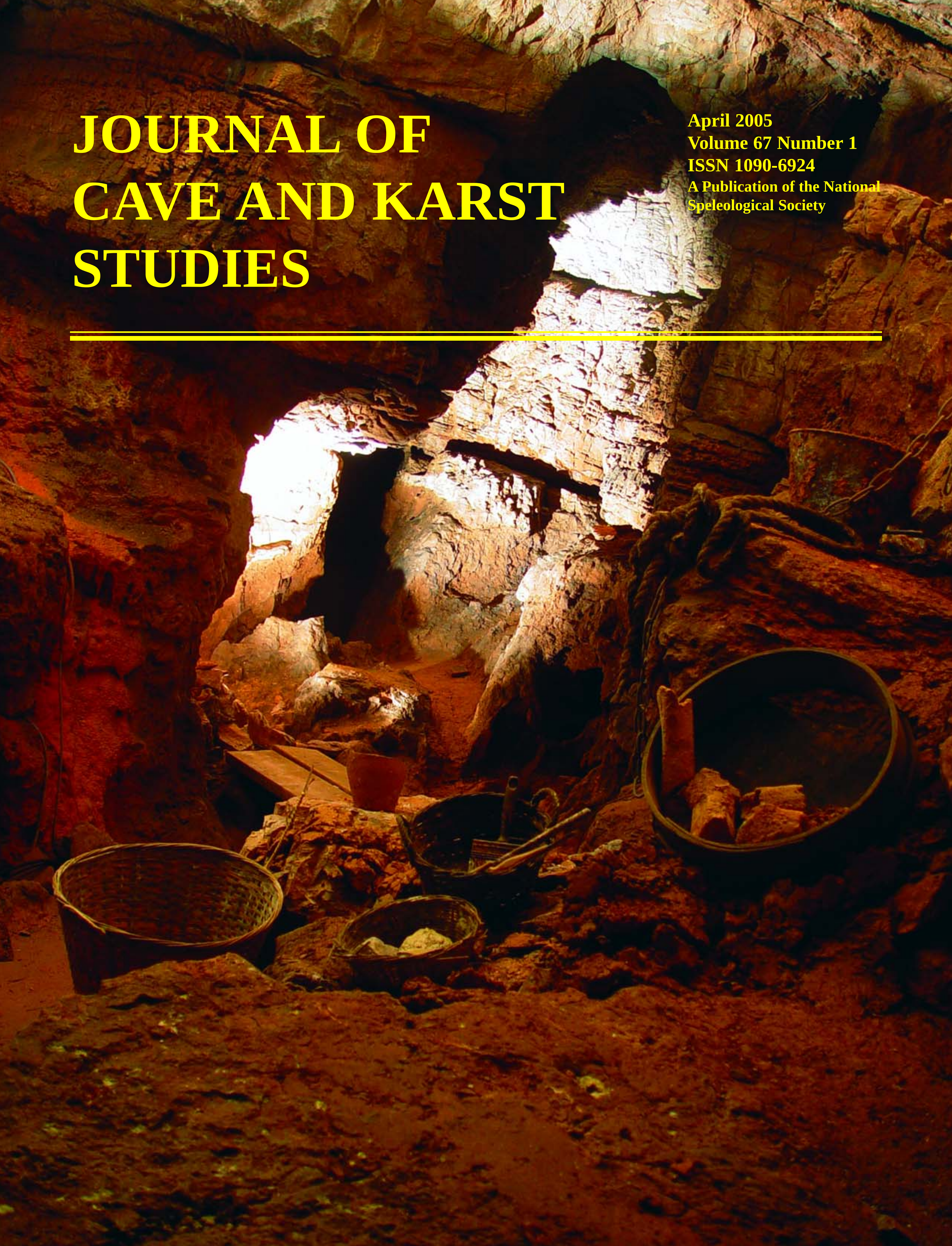

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Front cover: Reconstruction of Pengelly's excavations, the Charcoal Cave, Kent's Cavern. See Donald A. McFarlane and Joyce Lundberg, p. 39.

Editor
Malcolm S. Field
National Center of Environmental Assessment (8623D)
Office of Research and Development
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue NW
Washington, DC 20460-0001
202-564-3279 Voice 202-565-0079 FAX
field.malcolm@epa.gov

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pisarowicz@alumni.hamline.edu

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330-972-5389
ids@uakron.edu

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Cave Resources Office
3225 National Parks Highway
Carlsbad, NM 88220
(505)785-3106
paul_burger@nps.gov

Paleontology
Greg McDonald
Geologic Resource Divison
National Park Service
P.O. Box 25287
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303-969-2821
Greg_McDonald@nps.gov

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GENETIC PROCESSES OF CAVE MINERALS IN VOLCANIC ENVIRONMENTS: AN OVERVIEW

PAOLO FORTI
Italian Institute of Speleology, University of Bologna, via Zamboni 67, 40126 Bologna, ITALY forti@geomin.unibo.it

Volcanic caves have been considered of little mineralogic interest until recent years. As a consequence, very few papers have been printed on this topic in the past. In reality volcanic cavities are a very favorable environment for the development of different minerogenetic processes. Cave minerals actually present in volcanic environments constitute up to 40% of secondary chemical deposits found in all the caves of the world, and 35 of them (corresponding to ~10% of the actually known cave minerals) are restricted to such a environment. In the present paper, the six minerogenetic mechanisms active in the volcanic caves (degassing, solubilization, alteration, karst process, biogenic activity, phase change) are described following the decrease of cave temperature. The genesis of some of the most important secondary chemical deposits is discussed and a tentative list of the most interesting volcanic caves for hosted speleothems is given.

Volcanic caves are widespread in the world and are actively explored by cavers so it is common to find descriptions of the exploration, speleogenesis and morphology of these caves in the literature. However, the accurate study of the speleothems hosted by these caves is rather new because, until recently, lava tubes and other volcanic cavities have been considered of little interest from the point of view of secondary minerals (Forti 1994). Most volcanic caves allow for the development of only a few small speleothems apart from lava stalactites and stalagmites, which normally cannot be considered as true cave formations (Hill & Forti 1997).

The first written report of minerals found in a volcanic cave appeared only at the end of the 18th century, some one hundred years later than the first descriptions of speleothems in limestone caves (Shaw 1997). Lazzaro Spallanzani in his renowned "*Viaggio alle Due Sicilie*" (1792-97) first wrote of minerals he found in Alum Cave in the Vulcano Island:

> *"…but the most interesting object is a natural cave…from which a column of smoke continuously exits…Sublimated sulphur gives rise to conical yellow to pink stalactites up to 3 feet long and two inch thick. …Some water springs out from the cave wall giving rise to some deposits over the lava beds…consisting of stalactitic alum…sometimes with ammonium chloride…Deposits of iron sulphate are fairly common…"*

After this first paper only a few others were printed up to the middle of the 20th century (Recupero 1815; Sava 1842; Scacchi 1850; Ulrich 1870; Mac Ivor 1887; Bellini 1901; Zambonini 1907).

However, within the last 10 years it has become increasingly clear that volcanic cavities are one of the most important cave environments in which minerogenetic reactions can take place (Forti 1994). The peculiar physicochemical conditions, which dramatically change from the early stages of lava tube formation to the maturity of the cavity, together with the high number of different elements present inside the lava itself, allow for the development of a great variety of cave minerals (some tens of which are restricted to a volcanic environment). Even if only a few volcanic caves have been specifically studied from the mineralogical point of view, some of them are among the most interesting caves of the world for their hosted speleothems.

The present paper presents an update on the minerogenetic mechanisms active in a volcanic environment (Forti 2000) and it an overview of those minerals which are presently restricted to such an environment. Lastly, the most important volcanic caves in the world for the hosted speleothems are discussed.

MINEROGENETIC MECHANISMS IN THE VOLCANIC ENVIRONMENT

Despite the general scarcity of secondary chemical deposits, volcanic caves host up to six active minerogenetic mechanisms (Table 1; Fig. 1). The first two are absolutely peculiar to this environment; in fact, in the early stages of their development the extremely different environmental conditions that exist inside them allow for the activation of different processes which are practically controlled by the temperature of the cave atmosphere. In the time that passes as the lava walls cool, the active process changes, and therefore the chemical composition as well as the morphology of the resulting speleothems are quite different. The first place where such an evolution was experimentally demonstrated was the Cutrona lava tube on Mt. Etna (Forti *et al.* 1994). Here, the cave climate and the evolution of speleothems were monitored since the cave's discovery (some 8–10 months after the end of the eruption which generated the cave) until its internal temperature was no longer in equilibrium with the external environment. This study demonstrated that the evolution of secondary chemical deposits may start as soon as the lava stops flowing, and maybe even earlier, when the temperature inside the cave is still extremely high.

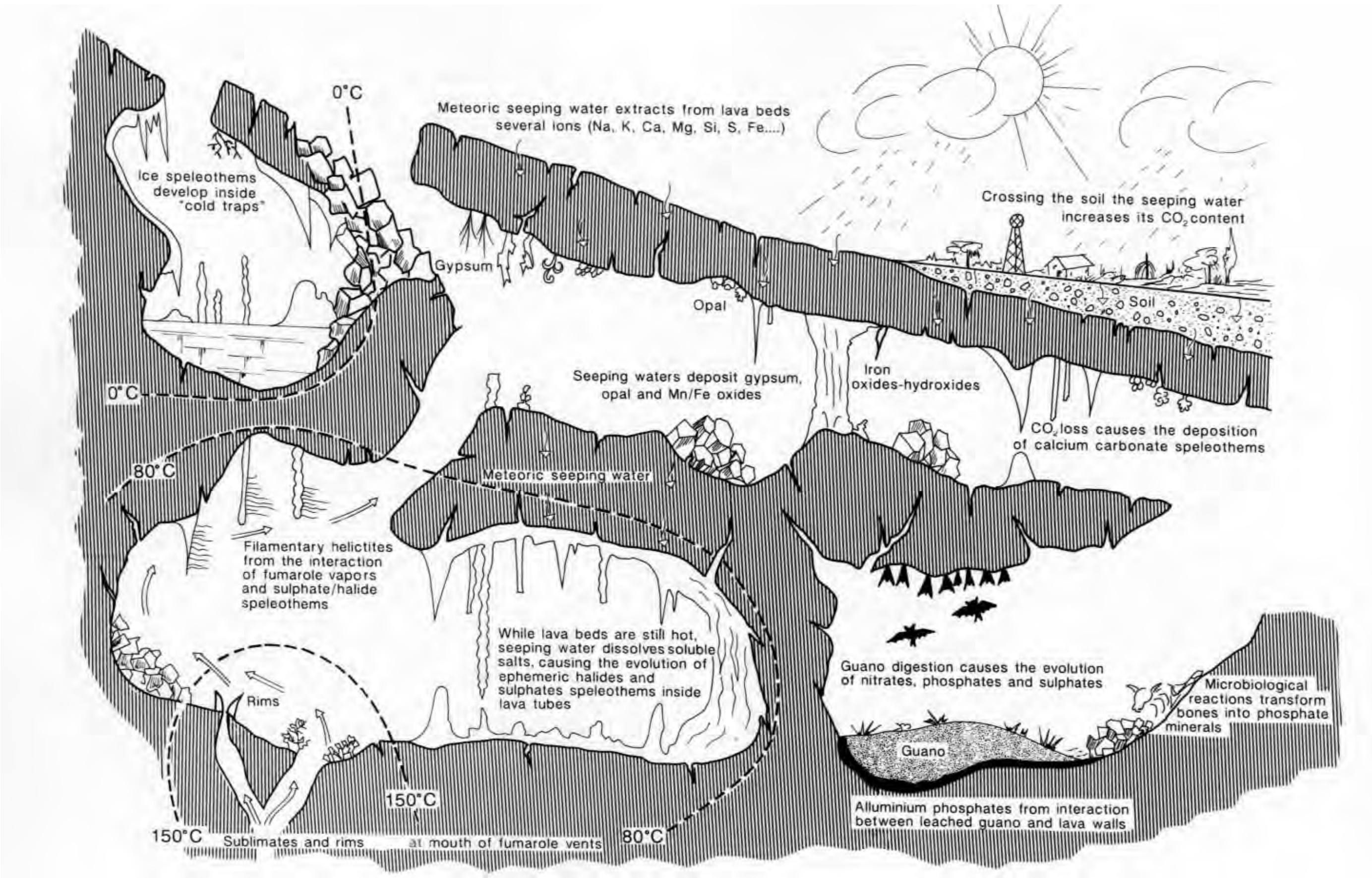

Figure 1. Minerogenetic sketch for cave minerals forming inside volcanic caves (after Forti, 2000).

Table 1. Temperature range, process, minerogenetic mechanisms and related chemical deposits in volcanic caves (after Forti, 2000, modied).

Process	Mechanism	T (°C)	Products
1 A- High temperature degassing	Sublimation	> 100	Elementary sulfur, oxides, hydroxides
B- Low temperature degassing	Deposition from aerosols and vapors	50–100	Sulfates, halides
2 Solubilization	Evaporation	10–100	Sulfates, halides
3 Alteration	Oxidation, hydration-dehydration, ionic exchange	0–100	Si-, Al-, Fe oxides-hydroxides, sulfates
4 Karst process	Diffusion	0–40	Carbonate
5 Biogenic activity	A- Digestion, dissolution-precipitation, double exchange	0–40	Phosphates, nitrates, sulfates, halides
	B- Guano combustion	200–400	Burned guano minerals
6 Phase change	Freezing	< 0	Ice

DEGASSING

When the lava walls solidify but the temperature is still very high the first minerogenetic mechanisms (1A of Table 1) become active, being related to the fluids seeping out from wall and/or floor fractures. The cooling down of fumarole gases, which is enhanced by their expansion in the cave atmosphere, allows for the deposition of sublimates of several different minerals, the most common being sulfur, but also some oxides, hydroxides and even sulfates (Figs. 2,3,4).

The fumarole activity, and therefore the process of sublimation, may last several months, but unavoidably when it does stop, the larger part if not all of the generated speleothems are demolished in a very short span of time. This is partly due to their intrinsic metastability and partly to delicate structures formed through the sublimation processes. For this reason, such deposits in volcanic caves are rarely observed long after the end of fumarole exhalation.

SOLUBILIZATION

When the temperature of the volcanic rock goes below 100°C, the second mechanism (mechanism 2 of Table 1) is activated by rainfall. From this moment on, at least some of the meteoric water starts seeping into the cracks and along the porosity of the volcanic rock thus dissolving the soluble sub-

Figure 2. Cutrona lava tube, Mt. Etna, Italy: sublimates of polyhalite and tenorite at the mouth of a fumarole vent: the photo was taken when the temperature within the cave was still over 40°C (photo by Paolo Forti).

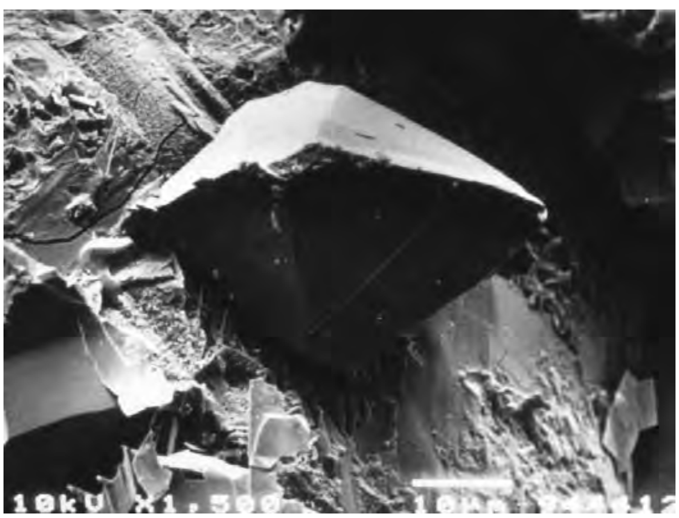

Figure 3. Cutrona lava tube: SEM image of pseudo–octahedral crystals of polyhalite in the sublimate of Fig. 2.

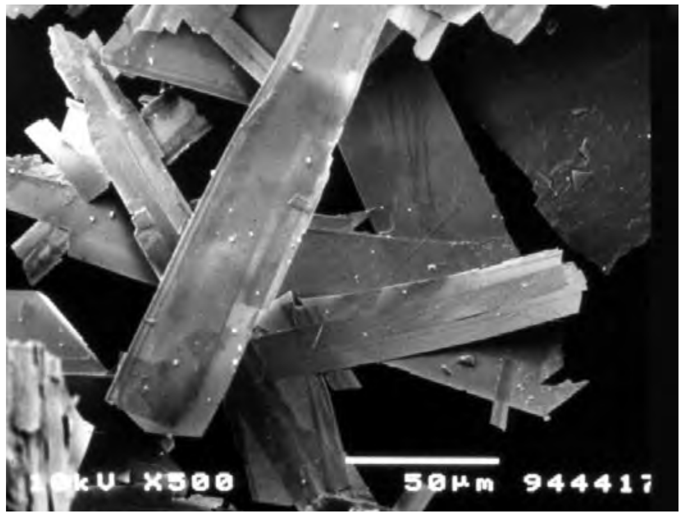

Figure 4. Cutrona lava tube: SEM image of thin blades of tenorite in the sublimate of Fig. 2.

Figure 5. General view of the huge speleothems deposited in the Cutrona lava tube by a dissolution evaporation mechanism: presently all these speleothems are completely washed away (photo by Paolo Forti).

stances existing therein. Once this water comes in contact with the still-hot cave atmosphere, it rapidly evaporates, causing the deposition of even larger amounts of speleothems consisting of a series of sulfates and chlorides.

It is most certainly a "golden moment" for the decoration of volcanic caves, because not only the ceiling, but also the walls and the floor may become completely covered by an incredible variety of polychrome speleothems (stalactites, soda straws, stalagmites, flowstones, popcorn, coralloids, etc.). An

Figure 6. Cutrona lava tube: oriented anemolite helictites of thenardite developed over a stalactite of the same material. The anemolites develop along the interference between the fumarole "wind" and the speleothem forming by evaporation (photo by Paolo Forti).

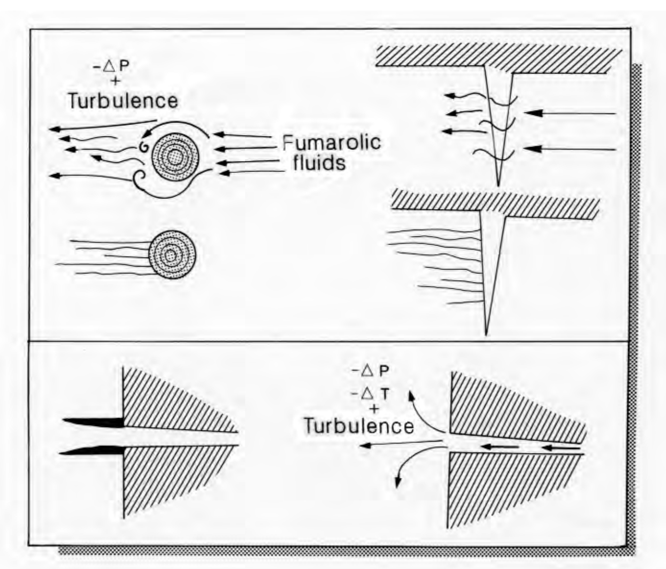

Figure 7. Genetic sketch for anemolite helictites and rims generated by fumarole vents (after Forti *et al.* 1994).

Figure 8. Cutrona lava tube: thenardite rims at the mouth of a fumarole vent (photo by Paolo Forti).

exceptional example of this kind of decoration was found in the Cutrona lava tube on Mt. Etna (Fig.5), but other caves are known in the world with similar formations (Jakobsson *et al.* 1992, Jónsson 1994, Davies 1998).

During this period, if the fumarole exhalations are still active, the interactions between these exhalations and the previous mineral deposits developing due to the evaporation can favour the evolution of peculiar speleothems which are deposited via aerosol and/or vapor condensation (mechanism 1B of Table 1). The most common deposits of this kind are extremely thin anemolite needles (hair-like with a diameter of 0.1–0.5 mm and over 10–15 cm long) which grow over the stalactite sides opposite to the fumarole exhalation, developing directly along the fumarole flow (Fig. 6). The anemolite genesis (Fig. 7) is related to the peculiar microclimatic conditions which develop immediately adjacent to the stalactites exposed to fumarole vapors. The enhanced gas turbulence in traversing the speleothem, and the lowered temperature due to the expansion of the vapors just after it, are responsible for the enhanced deposition of particles carried by the fluid itself. Other not-so-common speleothems originating by the same process are rims and bubbles, which develop along the border of the fractures from which the fumarole vapors escape (Fig. 8).

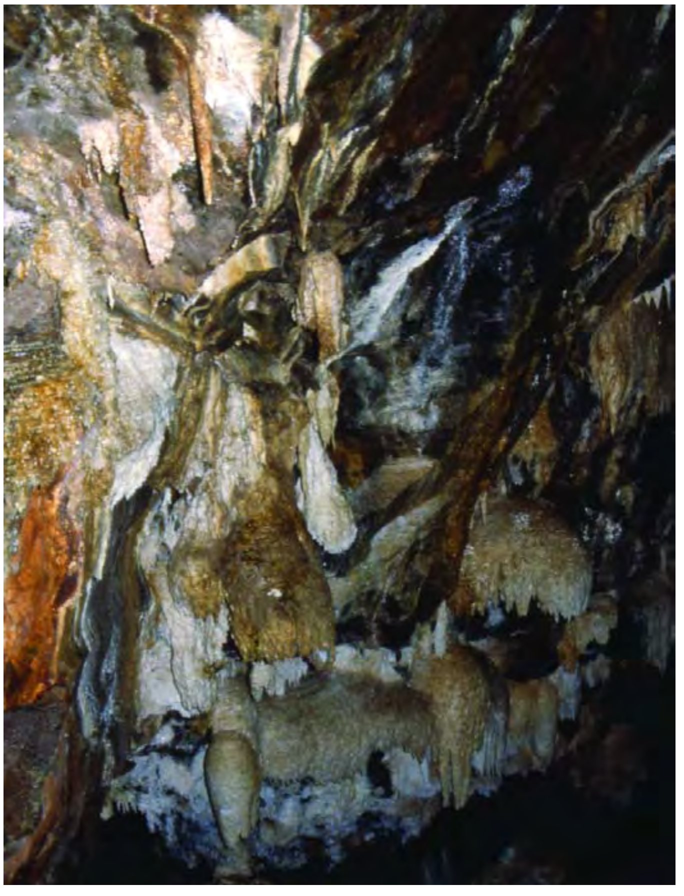

Figure 9. Gigantic opal flowstones in Algar do Carbalo magmatic chamber, Azores, Portugal (photo by Paolo Forti).

Figure 10. The wall of a lava tube in the Pico island (Azores, Portugal) covered by silica vermiculations (photo by Paolo Forti).

Unfortunately most, if not all, of the speleothems and cave minerals deposited by the second mechanism, similar to the first mechanism, are short-lived and are destined to disappear as soon as the cave temperature decreases. Basically, these deposits consist of highly soluble sodium, potassium and mag-

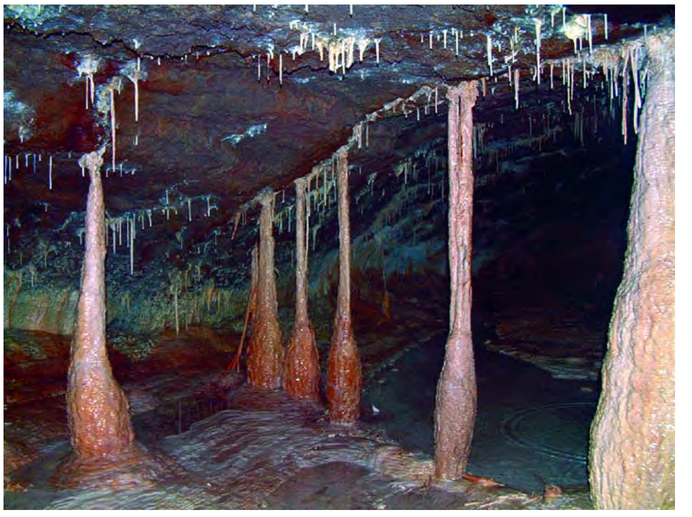

Figure 11. Calcite speleothems covering the ceiling and the wall of Dangcheomul lava tube, Jeju island (Korea) (photo by Kim Woo).

nesium sulfates and/or halides. Therefore, when the cave temperature becomes low enough to restore the normal hydrogeologic regimen, the mineral deposits are rapidly dissolved, leaving the walls and cavities completely bare. Of course, a higher degree of rainfall corresponds to a higher infiltration and therefore a faster redissolution. In the Cutrona lava tube on Mt. Etna, huge speleothems develop in a few months due to the second minerogenetic mechanism, but last for only a little more than one year even when snowfalls are normal during winter (Forti, 1994). Probably in drier areas, such as desert environments, the mineral deposits could develop over several decades and survive for hundreds of years.

ALTERATION

The removal of all the cave deposits formed during the second period does not signify that volcanic caves will no longer contain speleothems and cave minerals, however. In reality, quite the opposite occurs. In realtiy during the second period the third mechanism becomes activated consisting of an alteration of the minerals that make up the volcanic rock by seeping meteoric water. This alteration may result in the oxidation of sulfide minerals, the weathering of silicate minerals, or the simple dissolution of silica glass dispersed within the lava. In any case, these processes bring different ions and/or substances like silica, iron, aluminium, calcium, magnesium etc., into solution, which are deposited on the cave wall as opal, iron hydrated oxide-hydroxides, aluminium hydrated oxides and or silicates, gypsum and other sulfates (Marino, 1994).

At the beginning, the growth of such speleothems is very rapid as demonstrated by the evolution of a 3-cm-long opal soda straw in the Serracozzo lava tube (Mt. Etna) in less than four years (Del Monte *et al.* 1987), but this process normally slows down in a short span of time so it is very rare to see large cave deposits produced by this minerogenetic mechanism. Usually, they are only small earthy crusts (iron and aluminium

Figure 14. Kitum, erosional cave in volcanic ash, Kenya: a large void covered by tufts of natrolite, tetranatrolite and large crystals of apophyllite (photo by Paolo Forti).

Figure 15. Hibashi lava tube, Saudi Arabia: stalactites consisting of seven different cave minerals (archanite, biphosphammite, chlorapatite, niter, opal-C, quartz, whitlockite) (photo by John Pint).

oxides) or coralloids (opal). An exception, at times represented by gypsum for example, may also develop quite large crust and flowers. An absolutely unique display of gigantic opal speleothems (flowstones, stalactites, canopy bells, etc.) exists inside the Algar do Carbalo (Azores, Portugal) (Fig. 9), a very old magmatic chamber (Borges *et al.* 1991) where the mechanism of silica dissolution-redeposition is still active. This occurs not only because of the thickness of the lava field over the cavity, but also because some biogenic mechanisms have allowed for a rapid weathering of the volcanic rock to form highly soluble silica (Fig. 10) (Forti, 2001).

However, in general, only a few decades after the formation of the volcanic cave, even the third minerogenetic mechanism is practically extinguished, but with a signicant difference from the first two mechanisms. The formations developed in this period will not be re-dissolved, allowing them to become permanent decorations in the caves.

The last three mechanisms begin to evolve when the cave temperature has been stabilized and suitable environmental conditions exist for their development. The karst process and the biogenic digestion need particular conditions to start and therefore these processes may become efficient only after a long period of time. Consequently their effect can only be observed in very old volcanic caves, which are in reality not so common because their degradation is much faster than that of karst cavities.

KARST PROCESSES

This mechanism responsible for the decoration of normal limestone caves (diffusion of the CO_2 into the cave atmosphere causing supersaturation with respect to calcium carbonate and deposition of normal speleothems) is exactly the same in volcanic caves which leads to calcite-aragonite speleothems within the volcanic environment. However, the amount of carbonate deposits inside volcanic caves is normally extremely sparse for two different reasons. First, in order to have a high concentration of carbon dioxide in seeping meteoric water, the volcanic rock must be covered by a relatively thick soil layer where the microbiological reactions can develop in order to raise the partial pressure of this gas significantly (Fig. 1). A great length of time must pass (several thousand years) before a layer of earth can evolve over a lava field, and therefore the karst process must wait this amount of time before it becomes active, but this is not enough. There must be a second condition; in order to produce carbonate speleothems it is also necessary to bring in relatively high amounts of calcium and/or magnesium into solution, but normally the concentration of such ions in seeping water is sparse even if calcium and magnesium are present in common basaltic minerals like olivine and plagioclase. This is because, as previously stated when describing alteration mechanisms, the weathering process slows down rapidly so that after hundreds of years it does not allow release of enough Ca^{++} and Mg^{++} to achieve supersaturation with respect to calcite and/or dolomite. Therefore, even if the seeping water contains high amounts of CO_2, few if any carbonate speleothems develop in volcanic caves.

The best display in the world of calcite speleothems in volcanic caves is in the Hyeobjae lava tube in Cheju island (Korea), where flowstones, stalactites, stalagmites, helictites, conulites, gours and even cave pearls cover almost all of the cave walls and floor (Kashima & Suh 1984; Kashima *et al.* 1989). It is the peculiar environment of this lava tube that has allowed this exceptional development of calcite speleothems. The lava is covered by a rather thick layer of microcoquina (a clastic limestone composed by cemented sand-sized grain particles of shell detritus) deposited by the surrounding sea. Therefore, the meteoric water, enriched with CO_2 from the soil humus before reaching the lava tube, slowly crosses the microcoquina via its porosity and thus becomes saturated with respect to $CaCO_3$ which is immediately deposited as soon as the excess carbon dioxide is released into the lava tube atmosphere (Fig. 11).

BIOGENIC ACTIVITY

The fifth minerogenetic mechanism is often very active within volcanic caves, with processes that sometimes are absolutely restricted to this environment and being related to the silicate composition of the cave walls. The presence of high silica content in the walls and/or sediments of volcanic caves may allow development of peculiar organisms which may in turn give rise to biogenic mineralizations. In some volcanic caves of Japan and Korea (Kashima *et al.* 1987, 1989) the development of several silica coralloids and helictites has been found to be strictly related to the presence of colonies of diatoms (genus *Melosira*) and these speleothems consist mainly of skeletons of such organisms that alternate with layers of clay and detrital material cemented by silica. The presence of diatom skeletons is strictly confined to those parts of the cave where some external light can reach the diatom colonies because the diatom colonies need light energy to survive. The light control is evident not only by the fact that these speleothems develop only in the threshold light zone, but also by their shape, which always point towards the cave entrance.

But microorganisms may also induce the evolution of silica-rich speleothems in areas with a total absence of light. For example, in many of the lava tubes of Pico Island (Azores), the weathering of the basalt leads to the evolution of a widespread amorphous silica moonmilk which often gives rise to vermiculations over the cave walls (Forti 2001). These speleothems are extremely rich in organic matter (over 20%, unpublished data by the author) suggesting that the unusually high weathering of the basaltic rock could be driven by microorganisms.

Apart from these biogenic processes, which are restricted to their environment, volcanic caves may host other minerogenetic processes driven by microorganisms active in the same manner as in all other types of natural cavities. In general, these reactions are a “digestion process,” corresponding to all the different biochemical processes leading to the mineralization of organic matter. The digestion process needs the presence of rather large organic deposits inside the cave and requires substantial time to become activated.

The most common organic deposit in all types of caves is, by far, bat guano and rarely excrements from other animals. Mineralization of guano, like that of any other organic matter, is a complex mix of different reactions most of which are almost certainly biologically driven. The main reactions involved lead to the production of phosphoric, sulfuric and nitric acid (Forti 2001) which immediately react with different ions within the guano, allowing for the deposition of some secondary minerals (e.g., gypsum). Most of the guano-derived minerals (primarily phosphates and sulfates but also nitrates, halides, oxides, hydroxides) come from double exchange reactions between these strong acids and the different compounds present in the walls or on the floor of the volcanic cave. Generally speaking, even if the guano mineralization processes are identical in volcanic caves and other types of caves, the amount of resultant cave minerals is normally higher within the volcanic environment because the amount of different available ions is far higher than in limestone caves.

A peculiar minerogenetic mechanism strictly related to guano is the naturally induced combustion of guano deposits. The first, and up to now single, reference to such phenomena in a volcanic environment is that of Hibashi Lava Tube in Saudi Arabia (Forti *et al.* 2004). Guano fires may induce very high temperatures (up to several hundred °C) (Martini 1994a,b) and may cause the transformation of organic materials into extremely rare minerals (like arnhemite, pyrocoproite and pyrophospite).

PHASE CHANGE

The sixth and last minerogenetic mechanism consists simply of the solidification of seeping water, and obviously this process needs nothing other than a sufficiently low temperature for its activation. Ice speleothems inside most volcanic caves are only seasonal, but sometimes they may last perennially in areas where the annual average temperature is higher than 0°C. The lava, behaving as a very efficient thermal insulator, easily transforms caves with a single entrance and a general descending slope into “cold traps” where ice may accumulate in the wintertime without melting during the hot season. One very famous example of this is the Grotta del Gelo (Ice Cave) on Mt. Etna which has been renowned since antiquity because its ice deposits were exploited to supply Catania with ice cream even during summer months (Recupero 1815). Ironically, the Grotta del Gelo has become such a popular tourist attraction that the excessive amount of visitors, with consequent sharp alteration of the cave microclimate, may lead to the complete melting of its permanent ice formations in a few years (Centro Speleologico Etneo 1999).

It must be stressed that some of the just-outlined six minerogenetic processes may be active simultaneously. Moreover, if the environmental conditions change (for instance if a new eruption supplies new lava) all of them may be reactivated.

CAVE MINERALS IN THE VOLCANIC ENVIRONMENT

Even though thousands of volcanic caves have already been explored, cave minerals have only been reported from a few tens of them. Presently, less than 20 cavities have been fully investigated from the mineralogical point of view and most of them just in the last few years. Specific studies on volcanic cave minerals have been performed on all five continents.

Despite the small number of studied caves, the observed minerals within the volcanic caves presently correspond to about 35–40% of the whole known secondary chemical deposits in the cavern environment (Hill & Forti 1997). Even if the great majority of these minerals consist of sulfates, most of the chemical classes are represented as a consequence of the great number of different elements normally present within the lava. Only sulfides, arsenates, borates, and vanadates are still missing, but the absence of minerals from the last three classes is not surprising because they are scarcely represented in the

Table 2. List of the cave minerals restricted to volcanic environment.

Mineral	Cave	Characteristics	Process	References
Aluminiocopiapite	Alum (Italy)	Tuffs of small translucent to transparent crystals	1B-2	Forti *et al.* 1996
Alumogen	Zolfo (Italy)	Small white to transparent crystals	1B	Bellini 1901
Apophyllite	Kitum (Kenya)	Prismatic white to transparent crystals	3-4	Udluft 1928
Aubertite	Alum (Italy)	Pale green to transparent small masses	1B-2	Forti *et al.* 1996
Epidote (Pistacite)	Santo (Italy)	Small yellow elongated crystals	3	Del Monte *et al.* 1987
Galeite	Grillid (Iceland)	Thin pale-yellow to transparent crusts	1B	Jakobsson *et al.* 1992
Glauberite	Grillid (Iceland)	White to transparent hard microcrystalline crusts	1B	Jakobsson *et al.* 1992
Hydrobasaluminite	Alum (Italy)	Small plastic clayey masses	1B-2	Forti *et al.* 1996
Hydroglauberite	Grillid (Iceland)	Minor component of the glauberite crusts	1B	Jakobsson *et al.* 1992
Hydroxilapophillite	Kitum (Kenya)	Tetragonal prismatic crystals	3	Forti *et al.*, 2003
Kainite	Grillid (Iceland)	Colorless stalactites	1B	Jakobsson *et al.* 1992
Kalinite	Alum (Italy)	Small octahedral crystals	1B-2	Jervis 1881
Keramohalite	Alum (Italy)	Shining silver fibrous stalactites	1B-2	Panichi 1914
Kogarkoite	Suswa 13 (Kenya)	Aggregate of small bladed crystals	3-5	Forti *et al.*, 2003
Löweite	Grillid (Iceland)	Colorless stalactites with halite	1B	Jakobsson *et al.* 1992
Mendozite	(Kenya)	Blisters	3-5	Sutcliffe 1973
Metavoltine	Sulfur (Italy)	Thin yellow hexagonal blades	1B	Bellini 1901
Millosevichite	Alum (Italy)	Violet to green hygroscopic crusts	1B-2	Panichi 1913
Misenite	Sulfur (Italy)	Soft pale grey fibres	1B	Bellini 1901
Phillipsite	Kitum (Kenya)	Saccharoidal masses of twinned crystals	3-4	Forti *et al.*, 2003
Picromerite	Cutrona (Italy)	Sugar-like aggregates of pale-blue crystals	2	Forti *et al.* 1996
Polyhalite	Cutrona (Italy)	Minor component of shining yellow blades	1A	Forti *et al.* 1996
Portlandite	Eruption 1923 (Italy)	Spheroids of small crystals inside a calcite speleothem	1A	Forti & Marino 1995
Ralstonite	Surtsey 4 (Iceland)	Yellow brown crusts with opal and fluorite	1B	Jakobsson *et al.* 1992
Sal Ammoniac	Alum (Italy)	Minor component of alum stalactites	1B	Spallanzani 1792-7
Silhydrite	Post office (USA)	Small stalactites	2-3	Rogers & Rice 1992
Soda Alum	Alum (Italy)	Octahedral and cubic small transparent crystals	1B	Cossa 1878
Struvite	Skipton (Australia)	Present in the moist depth of guano	5	Ulrich 1870
Tamarugite	Sulfur (Italy)	Snow-white masses of elongated crystals	1B	Zambonini 1907
Tetranatrolite	Makingen (Kenya)	White acicular frostwork	3-5	Kashima & Ogawa 1998
Trona	Pisgah (USA)	Small white crystalline masses	3	Harter 1973
Voltaite	Sulfur (Italy)	Pale green crusts	1B	Bellini 1901
Zaherite	Alum (Italy)	Translucent to vitreous elongated crystals	1B-2	Forti *et al.* 1996

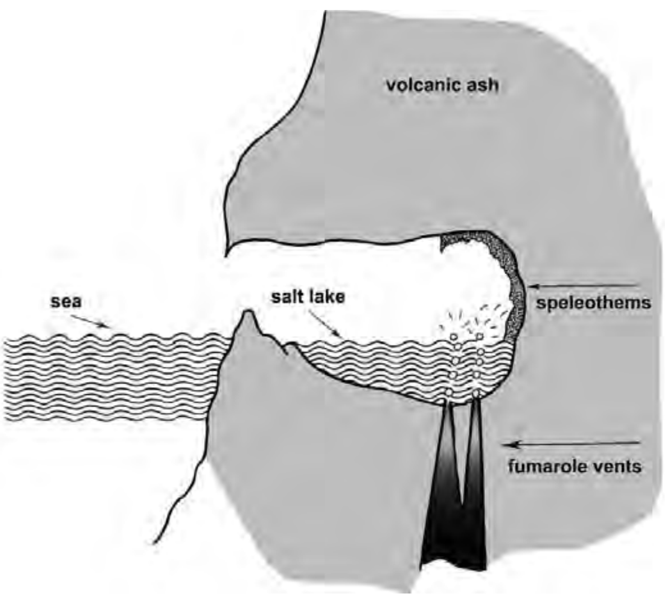

Figure 12. Minerogenetic mechanisms active in Sulfur Cave (sea cave in volcanic ash, Miseno Cap, Neaples, Italy) (after Forti 2003).

whole cave environment, whereas the lack of sulfides is explained by the peculiar conditions in which all the chemical deposits form within volcanic caves. Deposition may begin only when the melted lava does not fill up the entire cave thus allowing for the presence of a gas phase. The gas inlet provides oxidizing conditions which are incompatible with the development of any sulfides, but are extremely favorable for the deposition of sulfate minerals which in are relatively abundant in the volcanic caves. The mineralogical richness of the volcanic environment is also established by the very high number of cave minerals (33) which have been observed only inside volcanic caves (Table 2). These 33 minerals represent some 10% of the whole secondary chemical deposits known in the cavern environment, 18 of which have been discovered in the last 12 years.

In volcanic caves, the low-temperature degassing process (1B of Table 1), which has given rise to 20 new compounds, is by far the more important minerogenetic mechanism for new cave minerals followed by solubilization and alteration. Solubilization and alteration both give rise to nine new minerals, while biogenic activity produced just four new minerals and high temperature degassing and karst processes produced just two minerals each. If new minerals and the entire suite of

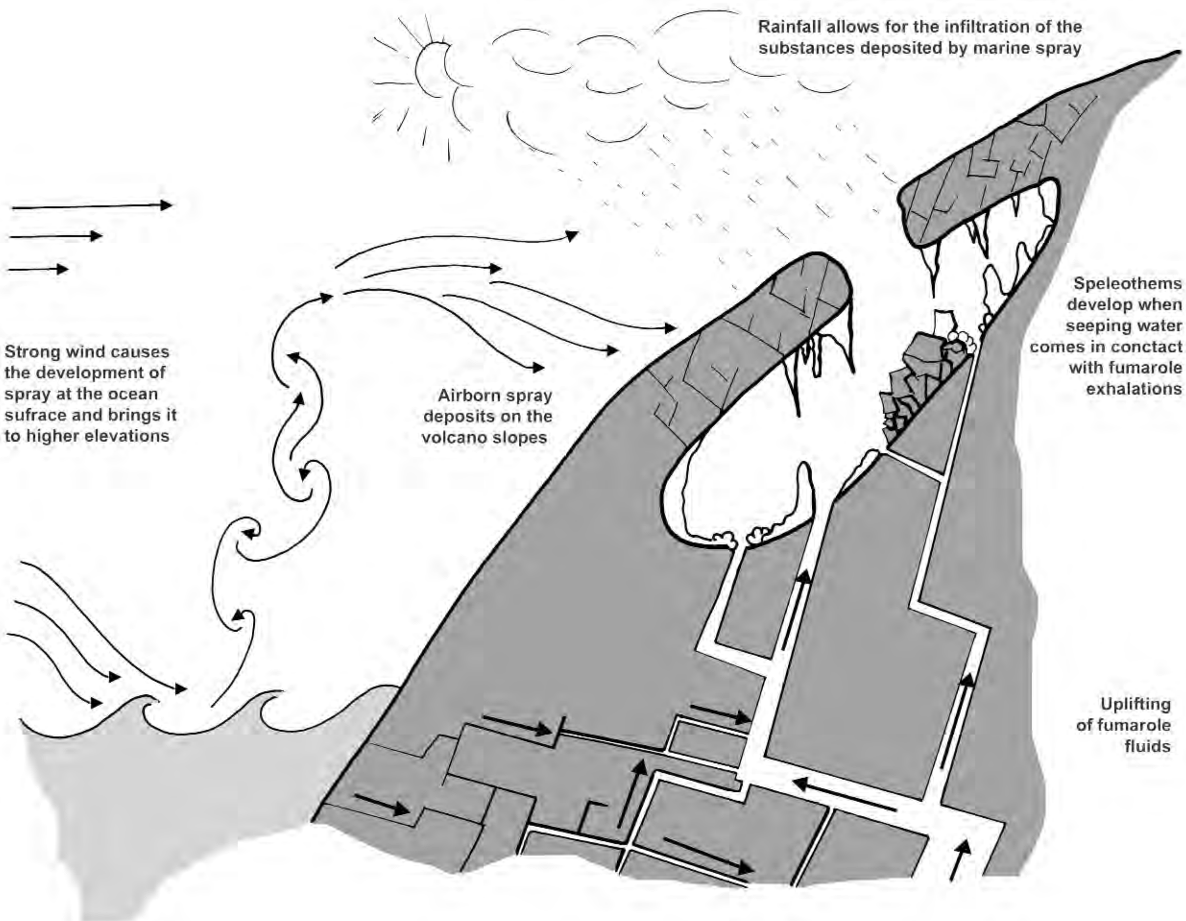

Figure 13. Minerogenetic mechanisms active in the Grillid Lava Tube, Surtsey Island, Iceland.

secondary chemical deposits developed within volcanic caves are considered collectively, the role of biogenic activity increases noticeably in importance similar to that of low-temperature degassing (fumarole activity) while that of the other processes remain relatively unchanged. This occurs because most of the reactions involving organic substances occur within the guano itself without contact with the host rock and therefore most of the products are the same in solutional and/or in volcanic environments. Except for some of the early research, the study of the guano deposits in volcanic environments has become reestablished only in the last decade and the actual knowledge of the related minerals is far from exhaustive. Therefore, it is reasonable to suppose that in the near future the importance of the biogenic digestion in the minerogenesis of volcanic minerals will become better recognized.

Finally, it is interesting to note that the three volcanic caves which actually host most of new cave minerals (Alum, nine new cave minerals; Grillid, five; and Sulfur, five) have the same environmental characteristics though not the same genesis. Alum and Sulfur are very small caves in volcanic ash while Grillid is a normal-size lava tube, yet all three host fumarole exhalations in direct contact with seawater which provides a large amount of different dissolved ions necessary for the development of the observed minerals. In Sulfur Cave the fumarole activity directly bubbles up into a small lake filled by seawater (Fig.12). In Alum Cave the contact between the hot vapors and seawater occurs just a few meters below the cave floor, while in the Grillid lava tube the contact between seawater and hot fluids occur deeper (Fig. 13). These three caves are also exposed to marine spray, which has a different minerogenetic importance in the three caves. Minerogenetic importance is limited in Sulfur Cave, a bit more significant, but still of second order, in Alum Cave and very important in the Grillid lava tube, where the spray may be the prevailing agent. The importance of sea spray in the Grillid lava tube depends upon two factors; the elevation of the cave entrance with respect to the sea and the climate.

Sulfur and Alum caves are, respectively, at the sea level and only a few meters above it, their climate being Mediterranean dry with scarce rainfall and few storms. Therefore, marine spray is scarce and it percolates within the cave only rarely. The Grillid Lava Tube has an elevation of about 90–100 m above sea level and therefore the direct contribution of the seawater to the fumarole vapors is less than that for the other two caves, but the hard climate characterizing the northern Atlantic ocean (strong winds, frequent storms and rain) allows for the presence of a large quantity of sea spray even at its relatively high elevation. The abundant rain induces a constant infiltration of marine salts in the lava tube where the reaction between the cold and salt dripping with the hot fumarole exhalations is the most important process for the evolution of the observed speleothems.

Table 3. Volcanic caves noteworthy for their mineralogical development.

Cave	Location	Noteworthy features	Reference
Algar do Carbalo	Terceira Island (Portugal)	Best and largest display of opal speleothems	Hill & Forti 1997
Alum	Vulcano Island (Italy)	Largest number of secondary cave minerals in a volcanic cave	Forti *et al.* 1996
Cutrona	Mt.Etna (Italy)	Best display of anemolites, rims, and balloons related to low temperature degassing	Forti *et al.* 1994
Dangcheomul	Jeju island (Korea)	Best display of different calcite speleothems within a volcanic cave	Woo *et al.* 2000
Grillid	Surtsey (Iceland)	Single cave reference for five different new cave minerals	Jakobsson *et al.* 1992
Hibashi	(Saudi Arabia)	Noticeable variety of organic compounds, burned guano minerals	Forti *et al.* 2004
Kitum	Mt. Elgon (Kenya)	Silicate minerals related to meteoric water leaching	Forti *et al.* 2003
Skipton	Mt.Widderin (Australia)	Site for some new cave phosphates	Webb 1997
Togawa-Sakaidani-do	Kyushu (Japan)	Best display of coralloids made by diatoms	Kashima *et al.* 1987

THE MOST IMPORTANT VOLCANIC CAVES OF THE WORLD FOR HOSTED SPELEOTHEMS

Among the top ten caves of the world for hosted speleothems (Hill & Forti 1997), two were volcanic in origin; Alum Cave (Vulcano Island, Italy) and Skipton Cave (Australia), but other volcanic caves should be considered when the environment of interest is limited to a volcanic setting. Even though volcanic cavities in which a detailed mineralogical study has been made, it is not easy to choose those that might be considered the most valuable volcanic caves for hosted speleothems. The importance of a cave cannot be limited to the number of the minerals developed inside it. Many other factors should be considered such as the dimension and the beauty of these speleothems, the peculiarity of the minerogenetic mechanisms, and the different origin of the hosting caves.

On the basis of the outlined parameters Table 3 was constructed. The majority of these (six) are obviously lava tubes (Cutrona, Grillid, Skipton, Hibashi, Togawa-Sakaidani-do, Dangcheomul caves), but also a magmatic chamber (Algar do Carbalo), a sea cave in volcanic ash (Alum Cave), and a meteoric cave in volcanic ash (Kitum Cave) are represented. Four of these have been selected for the high number of hosted minerals, many of which are new to the cavern environment (Alum, Cutrona, Grillid and Skipton Caves) (Table 2). Three other cavities have been selected because of their speleothems. These are Algar do Carbalo for its gigantic opal speleothems (Fig. 9), Dangcheomul Cave for its calcite decorations which mask this lava tube as being a “normal” karst cave (Fig. 11), and Togawa-Sakaidani-do for being the first cave in which very small but completely new opal coralloids made by diatoms have been observed. Kitum Cave was chosen because of its peculiar genesis resulting from meteoric water seepage within thick ash deposits since their initial deposition, thus allowing for the evolution of peculiar silicates (Fig. 14, see page 8). Finally, Hibashi Cave (Fig.15, see page 8) has been inserted because the still ongoing studies of its chemical deposits evidenced the presence of different guano-related minerals, some of which are still unknown. In particular, Hibashi Cave is extremely important because it hosts some of the best occurrences of burned guano minerals of the world.

It must be stressed that the criteria utilized to select the caves are subjective and therefore this list must be regarded as a first attempt to define the most important volcanic cavities for hosted speleothems. Moreover, in the near future it is reasonably sure that new studies will discover plenty of other volcanic caves extremely important from a minerogenetical point of view.

CONCLUSIONS

Although this overview on the actual knowledge on cave minerals in volcanic caves may be regarded as short and far from exhaustive, it is sufficient to point out the importance of this environment for the development of cave minerals. In the last ten years more specific mineralogical studies have been performed in different volcanic caves around the world than ever before, and it is now clear that the volcanic environment often results in ever more interesting mineralizations than all other types of natural cavities.

Although it must be admitted that only a part of the mineral deposits developing inside volcanic caves are actually known, it is enough to consider that the cavities which have been the object of mineralogical observations, though not systematic, are far less than 5% of those presently known in the world. Furthermore, some minerogenetic mechanisms, like those connected with guano digestion, are still scarcely understood, and some mineral classes, like that of oxides-hydroxides (mainly of iron and manganese), have been only slightly investigated.

In conclusion it can be affirmed that in the near future the systematic study of the secondary chemical deposits in volcanic caves will provide great satisfaction to investigators. The number of secondary cave minerals will be much increased and some new mineral(s) for the cave environment will be discovered.

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KARST DEVELOPMENT ON TINIAN, COMMONWEALTH OF THE NORTHERN MARIANA ISLANDS: CONTROLS ON DISSOLUTION IN RELATION TO THE CARBONATE ISLAND KARST MODEL

Kevin Stafford[1]
Department of Geosciences, Mississippi State University, Mississippi State, Mississippi, USA kwstafford@juno.com
John Mylroie
Department of Geosciences, Mississippi State University, Mississippi State, Mississippi, USA
Danko Taboroši
Laboratory of Geoecology, School of Environmental Earth Science, Hokkaido University, Sapporo, Japan
John Jenson
Water and Environmental Research Institute of the Western Pacific, University of Guam, Mangilao, Guam
Joan Mylroie
Department of Geosciences, Mississippi State University, Mississippi State, Mississippi, USA

Tinian, located in the western Pacific Ocean, is an Eocene volcanic edifice mantled by younger algal and coralline limestones. Carbonate rocks are eogenetic, producing an island karst terrane as predicted by the Carbonate Island Karst Model. Surface karst features include epikarst, closed depressions, and freshwater discharge sites. Subsurface karst features include three morphologically distinct cave types: mixing zone, fissure, and contact. Controls on cave development inferred from morphology are supported by non-parametric statistical analyses. Mixing zone cave development is controlled by freshwater lens position, fissure cave development is controlled by structural deformation, and contact cave development is controlled by lithologic boundaries. Horizons of mixing zone caves preserve at least three previous sea level positions, but differential rates of uplift between fault blocks prevent correlation of horizons across the entire island. Tinian karst development demonstrates the functionality of the Carbonate Island Karst Model and illustrates how portions of individual islands may exhibit each of the ideal island categories to some extent.

Tinian lies across a six-km channel at the southwest end of Saipan in the Mariana Archipelago in the western Pacific Ocean, approximately 3000 km east of the Asian landmass (Fig. 1). The islands are formed along the Mariana Arc, 160 km west of the Mariana Trench, created by subduction of the Pacific Plate to the east under the Philippine Plate to the west. Of the 17 Mariana Islands, only the southern six islands (Guam, Rota, Aguijan, Tinian, Saipan, and Farallon de Medinilla) are overlain by carbonate rocks, while the northern 11 are exclusively volcanic (Cloud *et al*. 1956).

Most freshwater consumed on Tinian is extracted from shallow skimming wells in the karst aquifer. The unpublished Military Geology of Tinian (Doan *et al*. 1960) remains the most detailed geologic survey of the island and includes a 1:25,000 scale geologic map with cross-sections showing island lithology and structure. Gingerich and Yeatts (2000) investigated the freshwater lens and found that the top of the lens is generally less than 0.6 m above sea level and thins to less than 12 m total thickness in the vicinity of the island's municipal wells. Karst studies on the island have begun only recently (Stafford *et al*. 2002, 2003a,b; Stafford 2003). This paper is the first formal report on karst development on Tinian, with description and analyses based on the Carbonate Island Karst Model (Mylroie & Jenson 2001, 2002; Jenson *et al*. 2002).

Field setting

Tinian is the third largest island in the Marianas with a surface area of 102 km², 51.2 km of coastline, and a maximum elevation of 187 m. It is composed of Eocene volcanic rocks mantled by Miocene and Plio-Pleistocene coralline and algal limestone and Holocene raised beach and reef deposits. Located at 15.01° N latitude (Fig. 1), it has a wet-dry tropical climate with a distinct rainy season (July-September) and dry season (February-March). Annual precipitation averages 200 cm, and temperature ranges from 20° C to 32° C. Dense woody vegetation occupies carbonate regions, while grass dominates non-carbonate regions (Doan *et al*. 1960; Tracey *et al*. 1964; Gingerich & Yeatts 2000).

The Eocene volcanic tuffs and breccias that comprise the basement are exposed on less than 3 km² of the island surface. Volcanics have been extensively weathered, with only relict structures and textures remaining. Foraminifera observed in weathered tuffs indicate that pyroclastic deposits were probably ejected from a submarine vent. The carbonate rocks that

[1]Please send correspondence to Kevin W. Stafford, Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, New Mexico 87801, USA: kwstafford@juno.com

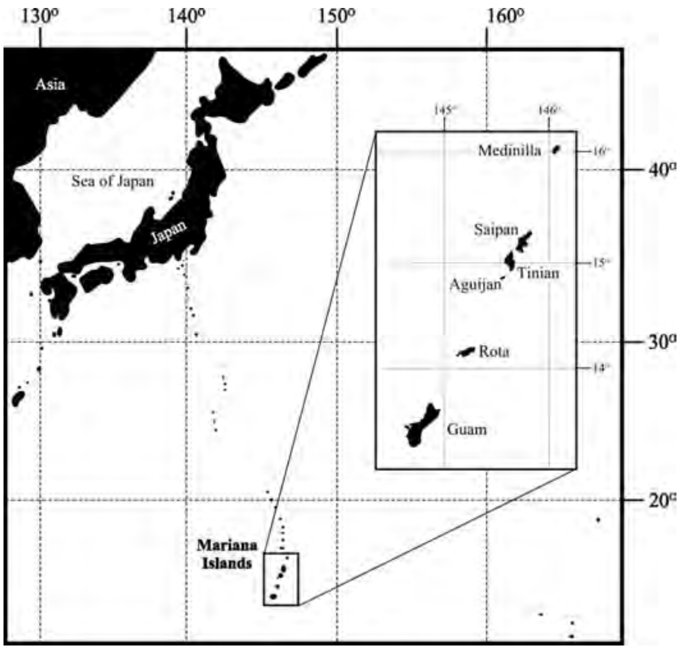


Figure 1. Location of study area, with carbonate islands of the Marianas expanded.

Cenezoic	Quaternary	Holocene	Recent sands, reefs, alluvium and colluvium
		Pleistocene	Mariana Limestone
	Tertiary	Pliocene	
		Miocene	Tagpochau Limestone
		Oligocene	No Recognized Units
		Eocene	Tinian Pyroclastic

Figure 2. Tinian geologic column (adapted from Doan *et al*. 1960).

mantle the volcanics are subdivided into three units (Fig. 2): Miocene Tagpochau Limestone, Plio-Pleistocene Mariana Limestone, and Holocene raised beach and reef deposits (Doan *et al*. 1960). The Tagpochau Limestone covers approximately 16% of the land surface and is composed of three contemporaneously deposited facies: detrital, argillaceous, and sandy. The Mariana Limestone covers approximately 82% of the island surface and is composed of seven facies based primarily on constructional and detrital compositions: constructional coralline, constructional algal, detrital coralline, detrital shelly, detrital Halimeda, detrital argillaceous, and detrital undifferentiated. Holocene raised beach and reef deposits overlie the Mariana Limestone in coastal regions, where developing sands, gravels, and reefs cover less than 1% of the island surface (Burke 1953; Doan *et al*. 1960; Siegrest 1988). Primary porosities remain high in limestone units because they have not undergone extensive burial and diagenesis that would increase cementation and compaction.

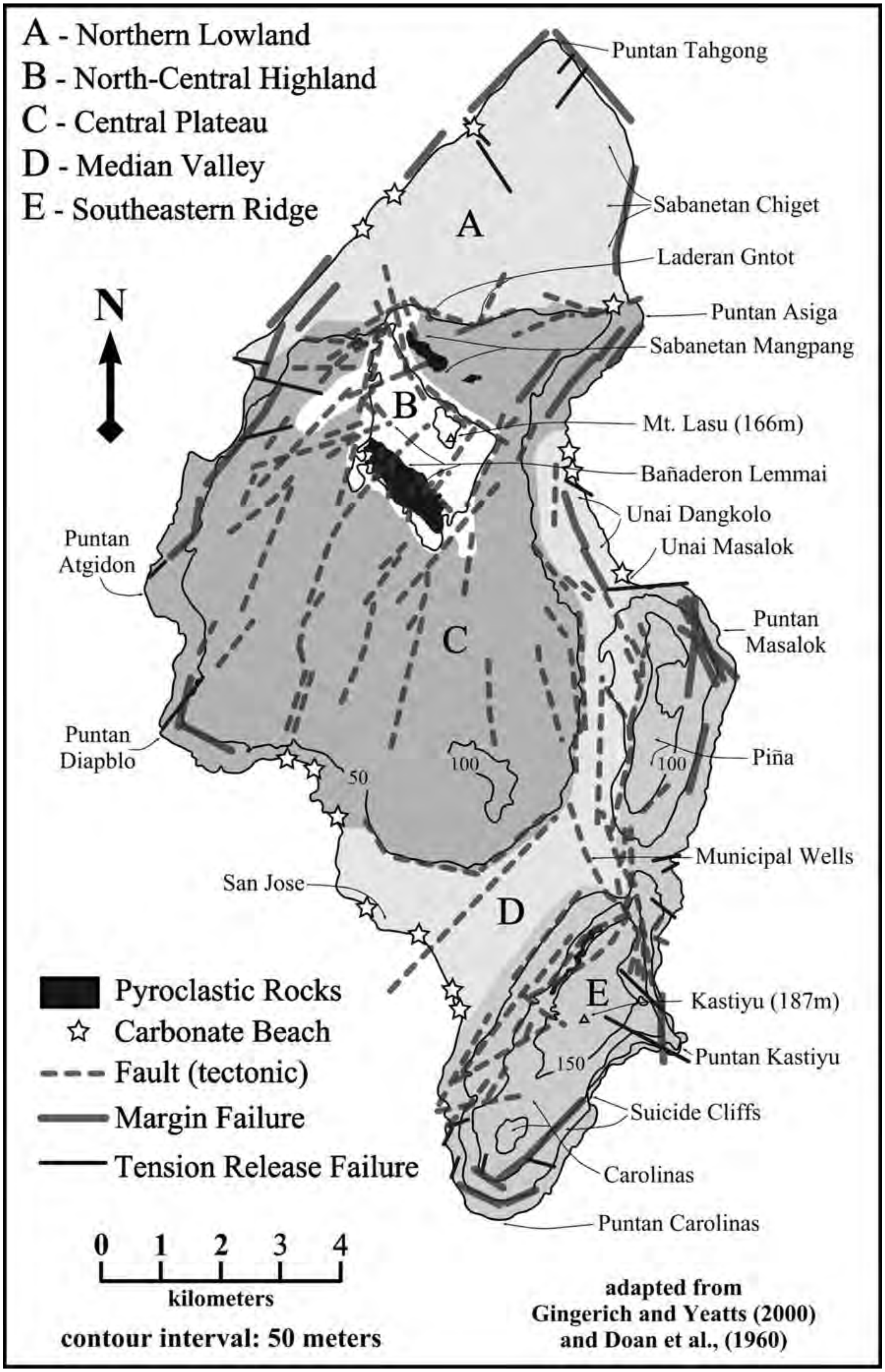
Tinian's geomorphology is primarily controlled by three factors: 1) original volcanic deposition, 2) original carbonate deposition, and 3) structural deformation, primarily brittle failure. Although obvious karst landforms such as sinking streams and large dissolutional closed depressions are rare, the overall effect of karst can be seen in the lack of surface streams, the many open cave entrances, and numerous small sinks and epikarst morphology not evident at topographic scale. Tinian's current coastline is mostly erosional with scarps and cliffs strongly controlled by structure (Fig. 3). Structural modification is seen in three contexts (Doan *et al*. 1960): 1) regional faulting associated with island arc tectonism, 2) brittle failure parallel to scarps and cliffs associated with margin failures, and 3) brittle failure near-perpendicular to scarps and cliffs associated with tension-release structures that form at right angles to margin failures. Although minor in the Marianas, passive isostatic subsidence may also induce additional brittle failures (Dickinson 2000).

High-angle faults have separated Tinian into five distinct physiographic provinces (Fig. 3): Northern Lowland, North-Central Highland, Central Plateau, Median Valley and Southeastern Ridge (Doan *et al*. 1960). The Northern Lowland forms a broad region covering the northern third of the island. The North-Central Highland contains most of the non-carbonate outcrops and forms the second highest plateau with a maximum elevation of 166 m. The Central Plateau, isolated by scarps, is located directly south of the Northern Lowland and extends from the east to west coast of Tinian around the North-Central Highland. The Median Valley is a fault-bounded, broad depression that separates the Central Plateau from the Southeastern Ridge. The Southeastern Ridge is developed on two large fault blocks forming the Piña and Carolinas ridges, and includes the highest peak on the island, Kastiyu, at 187 m.

CARBONATE ISLAND KARST

The Carbonate Island Karst Model is the current model for hydrologic development in island and coastal settings where eogenetic carbonate rocks (i.e., young rocks that have not been buried beyond the range of meteoric diagenesis) are present (Mylroie & Vacher 1999; Vacher & Mylroie 2002; Mylroie & Jenson 2002). It was originally designed to explain karst devel-

Figure 3. Map of Tinian showing important locations, physiographic provinces, igneous outcrops, brittle failure features, and beaches (constructional coastlines) (adapted from Doan *et al*. 1960).



opment in the Bahamas and Bermuda, and later expanded based on observations in the Pacific. Karst on small carbonate islands and coasts composed of young limestones is unique from karst in continental settings because of the extensive interaction between fresh and saline groundwater in young, highly porous carbonate rocks. On carbonate islands, a freshwater lens develops as a result of the density difference between fresh and saline waters, as defined by the Ghyben-Herzberg-Dupuit Principle (Raeisi & Mylroie 1995; Mink & Vacher 1997).

The Carbonate Island Karst Model was created to define the unique interaction of fresh and saline groundwater in diagenetically immature rocks (Mylroie & Jenson 2001, 2002; Jenson *et al*. 2002; Stafford *et al*. 2003a). The main elements of the model are (Fig. 4):

1. The freshwater/saltwater boundary creates mixing dissolution and organic trapping horizons.
2. Quaternary glacio-eustacy has moved the freshwater lens vertically.
3. Local tectonics and glacio-eustatic sea-level events may overprint one another.
4. Carbonate islands can be divided into four categories based on basement/sea-level relationships:
    a. Simple Carbonate Islands,
    b. Carbonate Cover Islands,
    c. Composite Islands,
    d. Complex Islands.
5. The karst is eogenetic.

Eogenetic karst of the Carbonate Island Karst Model was defined by Vacher and Mylroie (2002, p. 183) as "the land surface evolving on, and the pore system developing in, rocks undergoing eogenetic, meteoric diagenesis." Eogenetic carbonate rocks have not been extensively compacted or cemented and retain much of their primary depositional porosity. True island karst only develops in young carbonate rocks on coasts and small islands where the rocks are affected by sea-level variations, but have not been deeply buried. Island karst defined by the Carbonate Island Karst Model is distinctly different from karst development found on continents and the interior of larger islands, such as Puerto Rico, where karst development mimics continental settings and has been called "karst on islands" as opposed to "island karst" (Vacher & Mylroie 2002, p. 183–184).

Glacio-eustacy, tectonic uplift and subsidence cause the freshwater lens to migrate vertically within eogenetic rocks as sea-level changes, with important implications on the distribution of porosity and hydraulic conductivity in the aquifer. The four island types reflect the fundamentally different environments for the evolution of karst created by the structural and stratigraphic characteristics of the island, including the relationship between the rock units and sea-level (Fig. 4) (Jenson *et al*. 2002; Mylroie & Jenson 2002). Simple Carbonate Islands (Fig. 4a) are end members defined by observations in the Bahamas, where no non-carbonate rocks interfere with the freshwater lens and groundwater recharge is completely autogenic. Carbonate Cover Islands (Fig. 4b) introduce impermeable, non-carbonate rocks below the land surface that deflect the freshwater lens as observed in Bermuda during glacioeustatic sea-level lowstands. Composite Islands (Fig. 4c) place non-carbonate rocks at the land surface, which introduces allogenic waters into the system, while the freshwater lens is partitioned by impermeable rocks, a common occurrence in the Mariana Islands. Complex Islands (Fig. 4d) introduce the interfingering of carbonate/non-carbonate facies and faulting, which brings rocks of differing lithology into contact when they were not before, partitioning the freshwater lens as seen on Saipan (Mylroie *et al*. 2001; Jenson *et al*. 2002).

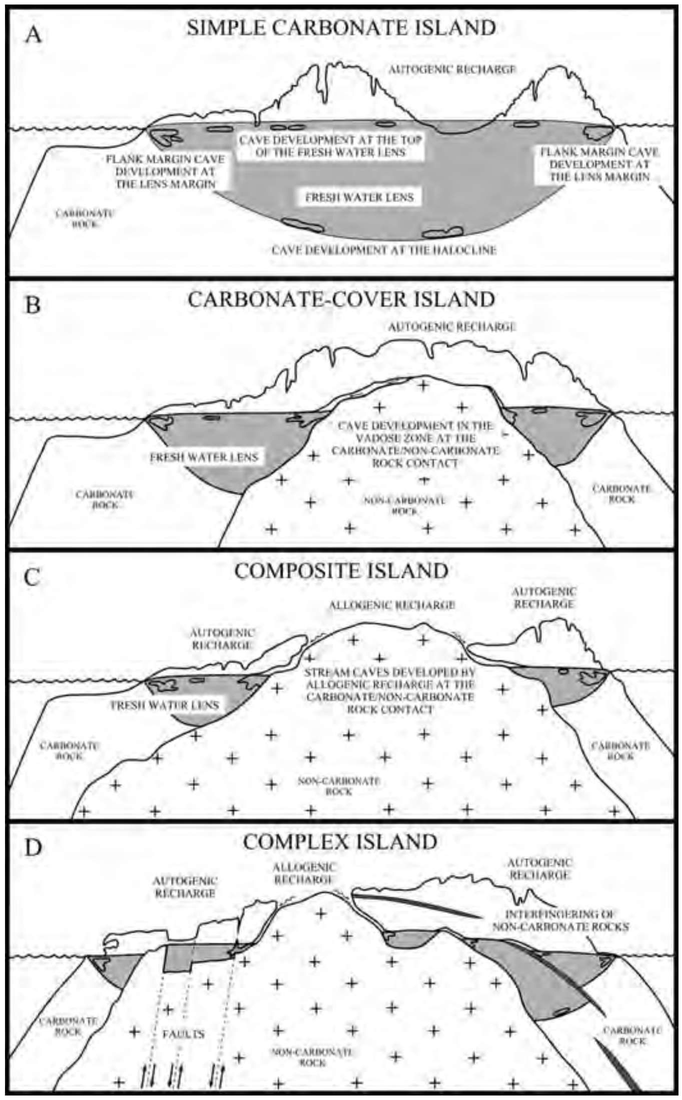


Figure 4. Carbonate Island Karst Model illustrating the 4 categories of carbonate islands that exist, based on variations in basement/sea-level relationships (adapted from Mylroie *et al*. 2001).

KARST DEVELOPMENT ON TINIAN

Karst development on Tinian is reported here in terms of surface and subsurface features. Surface features include epikarst, closed depressions, and freshwater discharge features. Subsurface features include three general cave types: mixing zone, fissure and contact. For a thorough description of Tinian karst development, including statistical analyses and detailed maps, the reader is directed to Stafford (2003).

SURFACE KARST FEATURES

Epikarst occurs in all carbonate rocks on Tinian and can be observed at all elevations with morphological variations associated with coastal proximity. In areas proximal to coasts, where limestone is constantly wetted by sea-spray, karren forms extremely jagged, centimeter to meter-scale pinnacles, variously defined as phytokarst (Folk *et al*. 1973), biokarst (Viles 1988), and littoral eogenetic karren (Taboroši *et al*. 2004). The rugged coastal karren on Tinian is attributed to a polygenetic origin that includes the interaction of meteoric water with salt spray, salt weathering, dissolution by meteoric waters, and biological weathering. When joints and fractures are present, coastal epikarst develops into enlarged planar features and shallow solution pans (kamenitzas). In more inland regions, where soil is present, surface karren features become more subdued, suggesting that salt weathering and the interaction of salt spray and meteoric water is largely responsible for the unique karren forms in coastal settings, although some of the variation likely results from soil processes. Inland karren generally expresses little relief but in highly fractured regions, closely-spaced, meter-scale canyons produce a highly irregular surface (Taboroši *et al*. 2004).

Closed depressions on Tinian are localized and represent three genetic types: dissolutional, constructional, and human made and modified (Mylroie *et al*. 2001). Interpretation of closed depressions can be problematic, because specific features may be polygenetic, having been one type of depression that was subsequently modified by dissolution, tectonics, or human activity (Mylroie *et al*. 1999). Twenty closed depressions greater than ten meters in diameter were identified on Tinian: seven dissolutional, eight constructional, and five anthropogenic.

Dissolutional depressions are associated with carbonate/non-carbonate contacts where allogenic waters from ephemeral streams in small valleys have increased dissolution along the contact between carbonate bedrock and non-carbonate basement. Two such depressions exhibited small caves at the recharge sites, while another two contained ponded water. Constructional depressions were present in regions more distal to volcanic terranes and showed no evidence of associated allogenic recharge. They appear to be either primary depressions formed during original carbonate deposition, or secondary structural basins from faulting. In the Northern Lowland, a large closed depression that contains a freshwater pond approximately two meters above sea-level appears to be a primary depositional feature. On the other hand, a large closed depression in the Median Valley, where the Tinian Municipal Well is located, is bounded by faults, which suggests a tectonic origin. Anthropogenic depressions are the result of the excavation of quarries, borrow pits and landfills. Only one active quarry remains on Tinian, while several abandoned quarries may be relicts from construction projects associated with World War II.

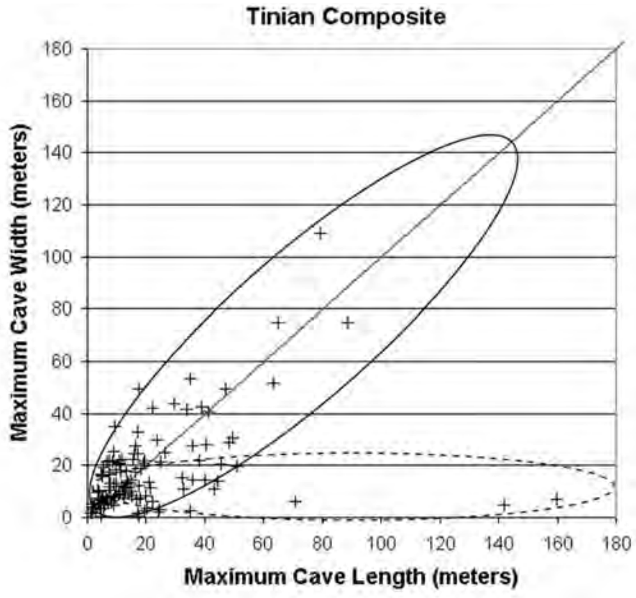


Figure 5. Plot of maximum width to length ratios for caves on Tinian. Note that that two distinct populations of caves exist. One population is approximately elliptical (circled with solid line) and one population is linear (circled with dashed line). This indicates that two distinctively different populations of cave development exist on Tinian.

Coastal discharge features identified on Tinian at low tide include seeps and springs. Seeps are diffuse discharge features that emerge through carbonate sands along beaches, whereas springs are focused discharge features that occur along bedding planes and fractures on scarped coastlines (Jenson *et al*. 1997; Mylroie *et al*. 1999, 2001). Although coastal conditions prevented a complete examination of the entire coastline, seeps were observed at three beaches on Tinian, and fourteen springs, commonly associated with fissure caves, were located along coastal scarps. Additional springs and seeps are expected to exist in coastal regions that were not accessible because of high wave energies.

SUBSURFACE KARST FEATURES

The central objective of the field study was to evaluate the occurrence, morphology, and field relationships of the island's caves with respect to structural features and other elements that control cave development. Simple analyses of length to width ratios of surveyed caves indicates that at least two dis-

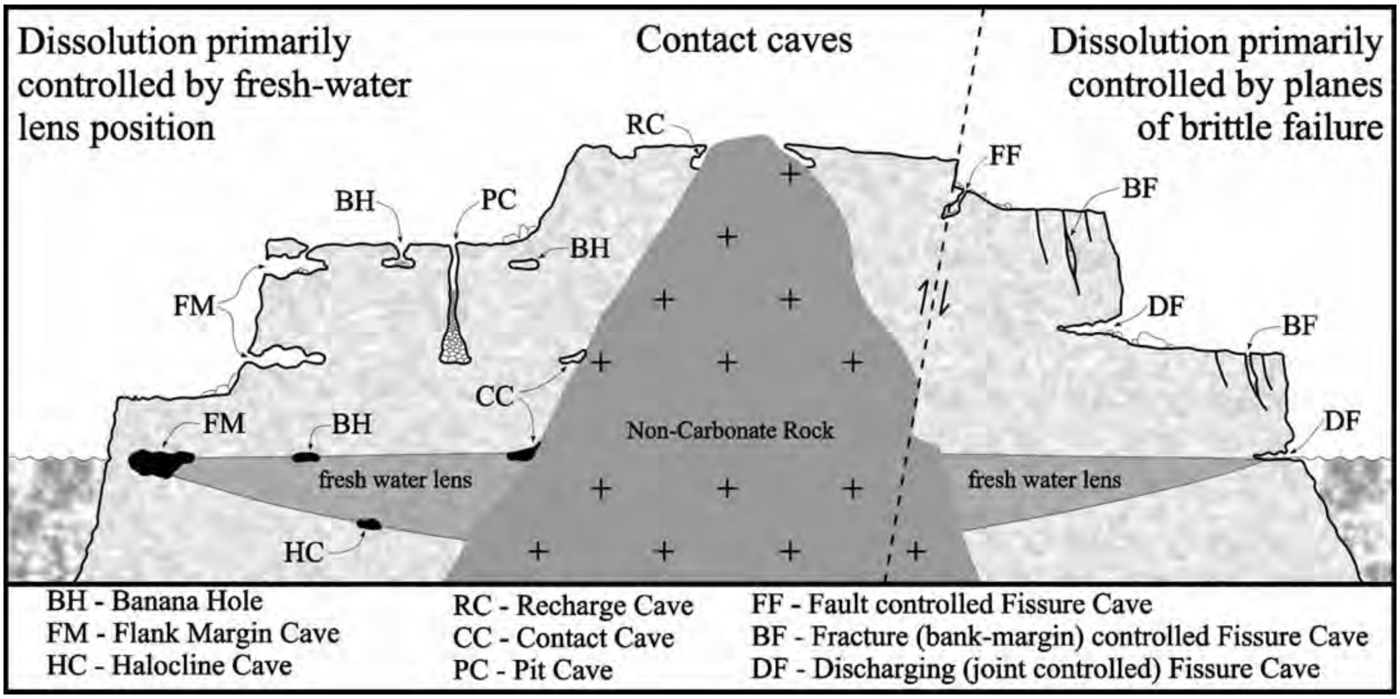


Figure 6. Schematic diagram illustrating the types of subsurface karst development on carbonate islands. Note that not all cave types occur on all carbonate islands.

Table 1. Caves surveyed on Tinian, including surveyed lengths and examples.

Cave Type	# of Caves Surveyed	Total Surveyed Length (m)	Example
Mixing Zone Caves	67	6132	
Water Table Caves	2	90	CUC Cave (Fig. 8a)
Flank Margin Caves	65	6042	Liyang Dangkolo (Fig. 8b)
Fissure Caves	13	1943	
Fault Caves	2	213	Plunder Cave (Fig. 8c)
Margin Failure Caves	6	1194	Danko's Misery (Fig. 8d)
Tension-release Caves	5	536	Cetacean Cave (Fig. 8e)
Contact Caves	2	34	
Stream Caves	2	34	Lasu Recharge Cave (Fig. 8f)

tinct populations of caves exist on Tinian of differing genetic origin (Fig. 5). Subsurface karst development on Tinian occurs as three morphologically distinct cave types (Stafford *et al.* 2002): mixing zone caves, fissure caves and contact caves (Fig. 6). Our fieldwork on Tinian resulted in an inventory of 86 caves or cave complexes (Table 1): 68 mixing zone caves, 16 fissure caves, and 2 contact caves. Based on reports from island residents, this is believed to include most of the accessible caves and adequately represents subsurface karst development on Tinian. No doubt there remain many unbreached caves and caves whose entrances are obscured by dense vegetation. It is reported that some caves were sealed with explosives or bulldozers during and after the battle to secure the island in 1944. Cave morphologies suggest that development of each cave type is controlled by variations in water chemistry, geologic structure, and lithology.

Mixing zone caves are the most common cave type on Tinian (Table 1), as on other carbonate islands of the Marianas. They are a type of hypogenic cave (Palmer 1991) that forms where waters of different original chemistry mix at the vadose/phreatic contact, freshwater/saltwater contact, or the margin of the freshwater lens, giving rise to three respective

Figure 7. Liyang Dangkolo is an archetypical flank margin cave in the Marianas. Note the larger chamber in the foreground that divides into smaller passages in the background, which is typical of mixing zone dissolution on carbonate islands.

subcategories: water table caves, halocline caves, and flank margin caves (Mylroie & Carew 1988; Mylroie *et al*. 1995a,b). Mixing zone caves form interconnected, globular chambers (Fig. 7). They are hydrologically interconnected and provide reliable indicators of former relative sea level because of their association with the freshwater lens position (Carew & Mylroie 1995; Mylroie *et al*. 1995a,b).

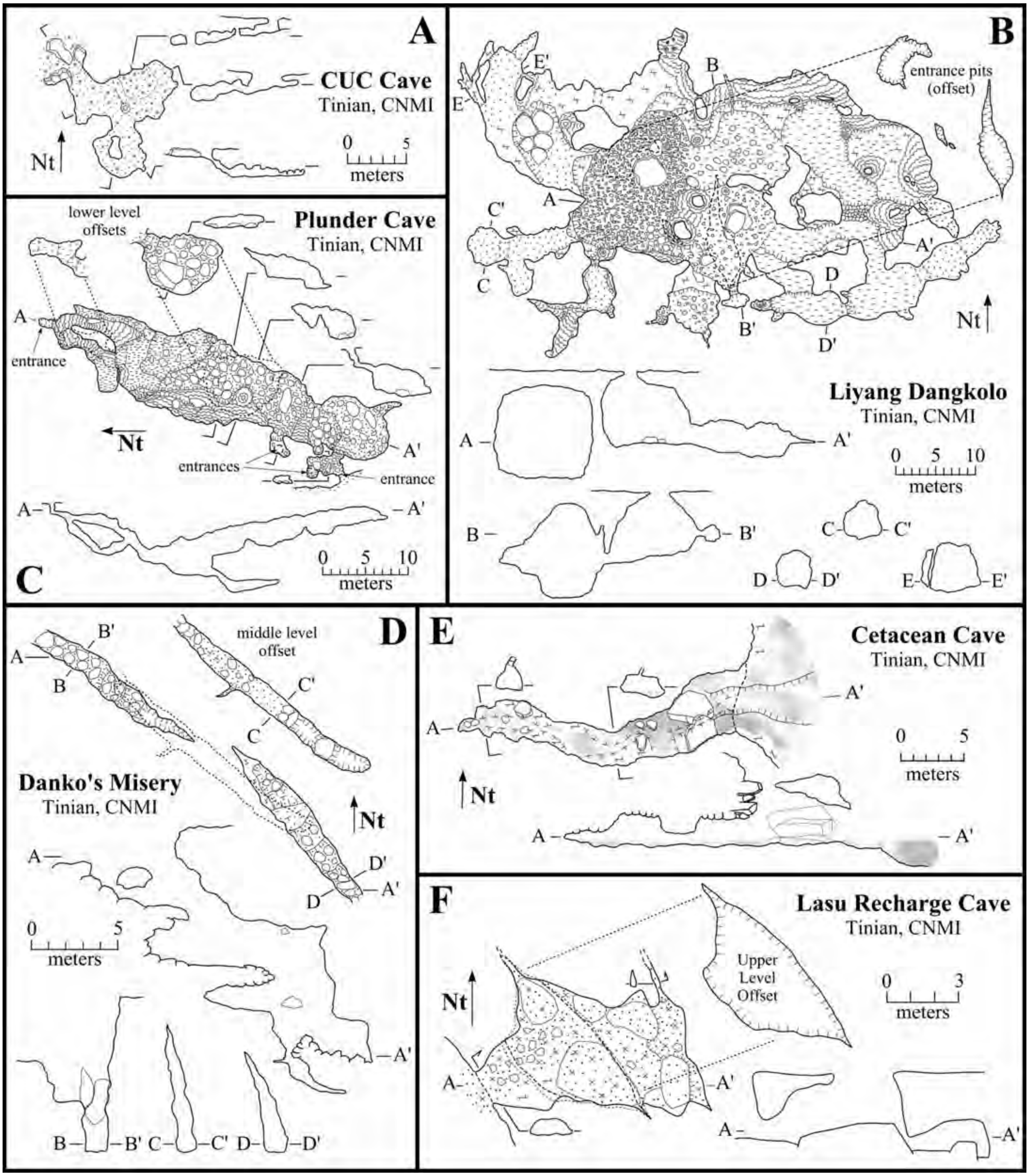
Small lenticular to oblate chambers, termed water table and halocline caves, have been reported to develop at the top and bottom of the lens (Mylroie & Carew 1995). Halocline caves form at the bottom of the lens where speleogenesis is enhanced by the decay of organics trapped at the water-density boundary and by the mixing of fresh and saline groundwater. Water table caves, commonly referred to as banana holes when breached at the land surface (Harris *et al*. 1995), are the result of increased dissolution induced by the mixing of vadose and phreatic waters, and the decay of organics trapped at the surface of the freshwater lens (Mylroie & Carew 1988). Small, lenticular features on Tinian (Fig. 8a) are interpreted as water table caves, because caves formed at the top of the modern or paleo-freshwater lens are more likely to be expressed by collapse at the land surface. However, if surface denudation completely removes the shallowest water table caves, then it is difficult to determine whether the caves formed at the top or bottom of the lens because multiple horizons of halocline and water table caves result from sea level change. Water table caves are rare on Tinian, but common on some carbonate islands. In the Bahamas, where the majority of the land surface is less than 10 m above sea level, only minor surface denudation is required to breach a water table cave (Harris *et al*. 1995); however, carbonate rocks crop out at 187 m on the Southeastern Ridge of Tinian, which could require significant denudation to breach caves formed at the top of the modern and other paleo-freshwater lens positions.

Figure. 8 (next page). Examples of the six morphological cave types observed on Tinian A) CUC Cave is a small banana hole feature on Tinian. Note that the cave map shows a globular central chamber that is generally less than 1 m tall. B) Liyang Dangkolo is a large flank margin cave. Note the large central chamber with smaller, interconnected passages extending from it. C) Plunder Cave is a fissure cave developed along a fault. Note the linear nature of the cave, which has been horizontally widened from mixing dissolution from intercepting the freshwater lens. D) Danko's Misery is a fissure cave developed parallel to a scarp apparently along a margin failure. Note that the cave is extremely linear and descends near vertically with several levels separated by breakdown floors. Larger features associated with scarp and margin failures have similar morphologies but reach greater depths and extend over larger distances. E) Cetacean Cave is a fissure cave developed perpendicular to the coastline at sea level apparently along a tension-release structure. Note the linear nature of the cave and horizontal widening from the mixing of fresh and saltwater as a result of freshwater discharge from the inland portion of the cave. F) Lasu Recharge Cave is a contact cave located in a large, dissolutional, closed depression at a non-carbonate/carbonate contact. Allogenic water enters the cave from the west, traverses a short distance through the cave and descends through a small fracture to the north on the eastern edge of the cave. Note that the majority of the cave has no ceiling due to collapse.

Flank margin caves are the most common and largest caves on Tinian (Table 1). They are reported to form at the distal margin of the freshwater lens where the mixing of fresh and saline waters and organic trapping horizons are in close proximity as the freshwater lens thins (Mylroie & Carew 1995). Flank margin caves tend to be globular with large, interconnected chambers. Small flank margin caves on Tinian consist of a single main chamber with several small alcoves radiating outward. Larger caves have more complicated morphologies and more extensive interconnected passages (Fig. 8b). These caves are commonly found along cliffs and scarps at consistent horizons (Fig. 9), because their position at the margin of the freshwater lens makes them highly susceptible to breaching from cliff retreat and erosion (Mylroie *et al*. 1999).

Fissure caves are the second most common cave type on Tinian (Table 1). They are linear features that appear to develop along faults, fractures, and joints (Stafford *et al*. 2003b). The planar surfaces created by brittle deformation provide paths for increased flow of groundwater, which results in preferential dissolution of vadose fast-flow routes that can locally distort the freshwater lens morphology (Aby 1994; Mylroie *et al*. 1995c). On Tinian, we have identified three distinctly different fissure caves, each associated with a different type of brittle deformation: faults, margin failures, and tension-release fractures.

Fissure caves associated with faults form linear features that descend at moderate slopes and show horizontal widening,



most likely from collapse of the hanging wall (Fig. 8c). Although no direct evidence of offsetting is visible in these caves, possibly because of extensive breakdown and calcite deposits covering the walls and ceilings, they do align closely with regional fault orientations reported by Doan and co-workers (1960).

Fissure caves that develop parallel to scarps and coastlines form laterally extensive features that descend near-vertically with relatively narrow widths (Fig. 10). We interpret these as associated with margin failures. They form the deepest caves on Tinian, can intersect the fresh-water lens, and contain

Figure 9. Suicide Cliffs on Tinian is an excellent example of mixing zone cave development along consistent horizons defined by previous sea-level stillstands. Note that most entrances are approximately 2.5 m tall.

extensive breakdown, which forms the majority of the floor and ceiling when present (Fig. 8d). Large portions of the caves are often unroofed but show evidence of being closed for significant periods in the past, based on the presence of calcite speleothem deposits on the walls.

Fissure caves oriented perpendicular and sub-perpendicular to scarps and coastlines (hence near-perpendicular to margin failures) are interpreted to be associated with tension-release structures. These features can extend inland for over 30 m with distinct joints or fractures located along the central axis of the ceilings and floors (Fig. 8e). When found at sea-level, they commonly discharge freshwater from their inland portions and show evidence of horizontal widening from the mixing of fresh and saline water. When found inland along scarps, they frequently show morphological evidence of past freshwater discharge and are interpreted as paleo-discharge features.

Contact caves, often referred to as stream caves, form at the carbonate/non-carbonate contact where allogenic water descending off surface igneous outcrops is funnelled into the subsurface. These features are generally associated with dissolutional closed depressions and are fed by perennial streams (Mylroie *et al*. 2001). Only two small contact caves were identified (Table 1). Mount Lasu Recharge Cave (Fig. 8f) shows evidence of rapid recharge with significant detritus accumulation in the vicinity of the cave, but little sediment coating the cave walls. Allogenic water enters the cave and after a short distance descends through a fracture less than ten centimeters wide. Although these features are rare on Tinian because of limited volcanic exposures, they have a significant role in subsurface recharge of allogenic waters.

STATISTICAL ANALYSES OF CAVE DEVELOPMENT

Previous studies of island karst suggest that mixing dissolution is the primary origin for cave development in eogenetic rocks on carbonate islands. In continental settings, variations in geologic structure and lithology provide primary controls for dissolution in diagenetically mature rocks (White 1988; Palmer 1991). Barlow and Ogden (1982) and Nelson (1988) showed that in continental settings cave development is significantly similar to regional brittle failure features when Kolmogorov-Smirnov statistical comparisons of cave passage orientations and regional geologic structure were evaluated. A similar study was conducted on Tinian (Stafford 2003) to investigate the possible relationships between cave development, geologic structure, and freshwater lens position.

Non-parametric, statistical comparisons for populations of orientation data from mixing zone caves and fissure caves were evaluated with respect to orientations for structural, coastline and scarp orientations (Stafford 2003). Populations of orientation data were evaluated using Kolmogorov-Smirnov statistical analyses because they are not normally distributed and because non-parametric analysis enable the comparison of two populations of data that contain large differences in the number of data samples within individual populations. Biases can be introduced into statistical comparisons based on the origin of data; therefore, orientation data was length-weighted into two length classes when available in order to reduce the amount of error introduced by using only one sample set for each population of data. Statistical comparisons were only considered to be similar if they showed a high degree of similarity amongst all length classes evaluated ($p < 0.01$) (i.e., 99% confidence). The use of non-parametric statistical analyses does not prove that the two populations of data are the same, but instead can only be used to show that they are not from dif-

Figure 10. Typical fissure cave passage associated with scarp and margin failures. Note that the cave descends near vertically and has a floor and ceiling composed primarily of breakdown.

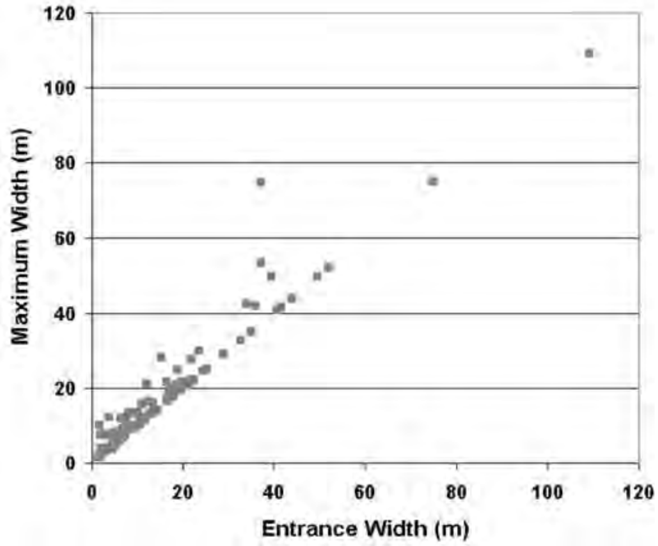


Figure 11. Diagram showing the relationship between mixing zone cave entrance width and maximum width. Note that a large portion of the caves plot with a ratio of one, indicating that the entrance width and the maximum width are the same because of significant scarp retreat.

ferent populations. If the two populations of data being tested show similarity and are not from different populations then it is inferred that they represent the same population.

Structural orientations for faults were measured from the unpublished geologic map of Tinian (Doan *et al*. 1960) and length-weighted into 50 and 100 m segments to apply greater significance to larger features, while joints (Doan *et al*. 1960) and smaller fractures of indeterminate length measured in the field were only measured for orientation (Table 2). Coastline and scarp orientations were measured from a digital elevation model of Tinian with a 10 m cell size (United States Department of the Interior Geological Survey 2001a,b,c,d,e) and length-weighted into 50 and 100 m segments (Table 2), similar to fault orientation measurements. In order to statistically evaluate cave development, individual cave passage orientations from the two primary cave types (Table 1), whose origin was inferred from morphology (mixing zone caves and fissure caves), were measured from surveyed features and length-weighted into 5 and 10 m segments to apply greater significance to larger passages (Table 3). Contact caves were not evaluated because only two features were identified in the survey area. Statistical evaluations were performed at the island scale, physiographic province scale and at small-scale sites (i.e., 1 km^2 sites) to determine if similarities existed between cave development and differing dissolutional controls at local or regional scales.

Statistical comparisons showed a high degree of similarity for orientations of cave development with structural (i.e., faults, fractures and joints) and geographic features (i.e., scarps and coastlines) at the island and physiographic province scales (Table 4). This high degree of similarity is likely a result of the complex depositional and tectonic regime of the Marianas, which complicates elimination of variables not significant in cave development. At the island and province scales, both coastline and scarp orientations as well as brittle failure features exhibited too large a range in orientations to accurately compare them with orientations of cave development. Distinct similarities were found between populations of orientations at the small-scale sites, however (Table 4). Within the small-scale sites, mixing zone cave orientations were found to be significantly similar to coastline and scarp orientations, consistent with control by freshwater lens position; however, brittle failure appears to significantly influence mixing zone cave development by intercepting diffuse lens flow. Fissure cave orientations showed significant similarity to brittle failure orientations including faults, margin failures and tension release structures at the small-scale sites, but did not show significant similarities with coastline and scarp orientations except where margin failures were parallel to scarps.

These results are consistent with the hypothesis that fissure cave development is controlled by brittle deformation, while mixing zone cave development is controlled by the position of the freshwater lens, but influenced by regional brittle deforma-

Table 2. Number of orientation measurements of geologic and geomorphic features used in statistical analyses. Fault, scarp and coastline orientations were subdivided into 50 m and 100 m segments, while fractures with limited vertical extent were not subdivided.

Region	faults[a] (50 m)	faults[a] (100 m)	fractures[a,b] …	scarps[c] (50 m)	scarps[c] (100 m)	coasts[c] (50 m)	coasts[c] (100 m)
Island							
Tinian	3322	1661	457	1264	645	939	501
Province							
Northern Lowland	324	162	104	0	0	206	113
Central Plateau	944	472	141	335	169	250	134
North-Central Highland	394	197	0	150	79	0	0
Median Valley	686	309	131	56	29	169	94
Southeastern Ridge	618	309	83	723	368	320	160
Small-Scale Sites							
Limestone Forest	53	29	40	32	20	24	12
Unai Dangkolo	26	11	44	0	0	22	9
Puntan Diablo	26	11	18	27	15	33	16

[a] Source: Doan *et al.* 1960
[b] Source: Stafford 2003
[c] Source: United States Department of the Interior Geological Survey 2001a,b,c,d,e

Table 3. Number of orientation measurements of cave passages (composite, fissure, and mixing zone), with orientations subdivided into 5 m and 10 m increments (Stafford 2003).

Region	composite (5 m)	composite (10 m)	fissure (5 m)	fissure (10 m)	mixing zone (5 m)	mixing zone (10 m)
Island						
Tinian	1277	614	297	135	980	480
Province						
Northern Lowland	13	11	2	2	11	9
Central Plateau	326	134	24	12	302	122
North-Central Highland	30	8	0	0	30	9
Median Valley	524	256	100	44	424	212
Southeastern Ridge	384	205	171	77	213	128
Small-Scale Sites						
Limestone Forest	91	34	68	24	23	10
Unai Dangkolo	263	134	46	23	217	111
Puntan Diablo	98	54	13	7	85	47

Note: Low sample populations (i.e., $n<6$) were not evaluated because the sample size was too small for Kolmogrov-Smirnov statistical analyses. For a complete list of all orientation measurements see Stafford 2003.

tion. Therefore, statistical analyses of cave orientations support genetic interpretations of cave morphology (Stafford 2003).

FRESH-WATER LENS MIGRATION

Distinct horizons of mixing zone caves throughout Tinian reflect previous freshwater lens positions related to relative sea-level positions (Fig. 9). Most mixing zone caves on Tinian are small compared to the large flank margin caves seen on other carbonate islands, such as Isla de Mona (Frank *et al*. 1998). The smaller caves reflect shorter periods of stable sea-level position, limiting the development of larger dissolutional voids. The short development time available for flank margin cave formation resulted in small, globular chambers that commonly did not grow large enough to intersect (Fig. 9) and form the type of complex flank margin caves found in other carbonate island settings.

Figure 11 shows that the vast majority of the breached

Table 4. Simplified non-parametric data matrix of statistical analyses.

Region	Fissure Caves	Mixing Zone Caves
Island-Scale		
Brittle Failure Orientations	similar	similar
Scarp and Cliff Orientations	similar	similar
Coastline Orientations	similar	similar
Province-Scale		
Brittle Failure Orientations	similar	dissimilar
Scarp and Cliff Orientations	dissimilar	similar
Coastline Orientations	similar	similar
Small-Scale Sites		
Brittle Failure Orientations	similar	dissimilar
Scarp and Cliff Orientations	dissimilar	similar
Coastline Orientations	dissimilar	similar

Note: Comparisons between cave orientations and brittle failure, scarp and coastline orientations were only considered similar if $p < 0.01$. For detailed results of statistical analyses, see Stafford 2003.

flank margin caves have entrance widths that are approximately equal to their maximum widths, indicating that the caves have been eroded at least halfway. Early erosion nicks into the globular cave chamber such that the entrance is much smaller than the maximum width of the cave. As erosion proceeds to the halfway point, and beyond, the entrance width will be the maximum width of the cave. If crystalline stalagmites were collected from these caves and U/Th dates could be obtained from them, it would be possible to establish boundary conditions for rates of cliff retreat and surface denudation. Because mixing zone caves form in the phreatic zone at sea level, they must be uplifted in order for speleothems to develop in them. Therefore, future research using speleothem dates from breached flank margin caves at differing terrace levels, which exhibit differing degrees of breaching, can be used to predict rates of cliff retreat because flank margin caves are generally ellipitical and any caves that exhibit an entrance width equal to the maximum width were originally at least 50% larger.

The effects of glacio-eustacy coupled with tectonic uplift of the Mariana Arc account for the absence of large mixing zone caves, where continual uplift has reduced the duration of sea-level stillstands. Although differential rates in uplift exist across Tinian and individual mixing caves are smaller than on some other carbonate islands, a North-Central Highland transect (Fig. 12) confirms the presence of at least four sea-level stillstands (three paleo horizons and the current horizon) that reflect freshwater lens migration.

Conclusions

Tinian displays well-developed island karst that reflects a polygenetic origin, both in surface and subsurface development, with multiple horizons of development associated with previous sea-level stillstands. Karst development is largely controlled by freshwater/saltwater interaction, but geologic structure and lithology greatly influence and often control the location and orientation of cave development. Genetic interpretations of morphology are supported by statistical analyses; however, at specific sites, mixing zone caves are influenced by brittle deformation and fissure caves show horizontal widening when intersecting the freshwater lens.

High-angle faults separate Tinian into distinct physiographic provinces, indicating that individual categories of islands in Carbonate Island Karst Model cannot be easily applied to the entire island. Significant fresh-water discharge along faults separating the Northern Lowland and Southeastern Ridge from the three central provinces (Central Plateau, North-Central Highland and Median Valley) suggest that three largely separate hydrologic regions exist on Tinian. Therefore, the three regions should be treated separately with respect to the model, as each region best fits a specific category: the Northern Lowland acts as a Simple Carbonate Island, the Southeastern Ridge acts as a Carbonate Cover Island, and the three central provinces act together as a Composite Island. Tinian provides an excellent example of the functionality of the Carbonate Island Karst Model but it demonstrates that the model often must be applied to island regions and not to the entire island.

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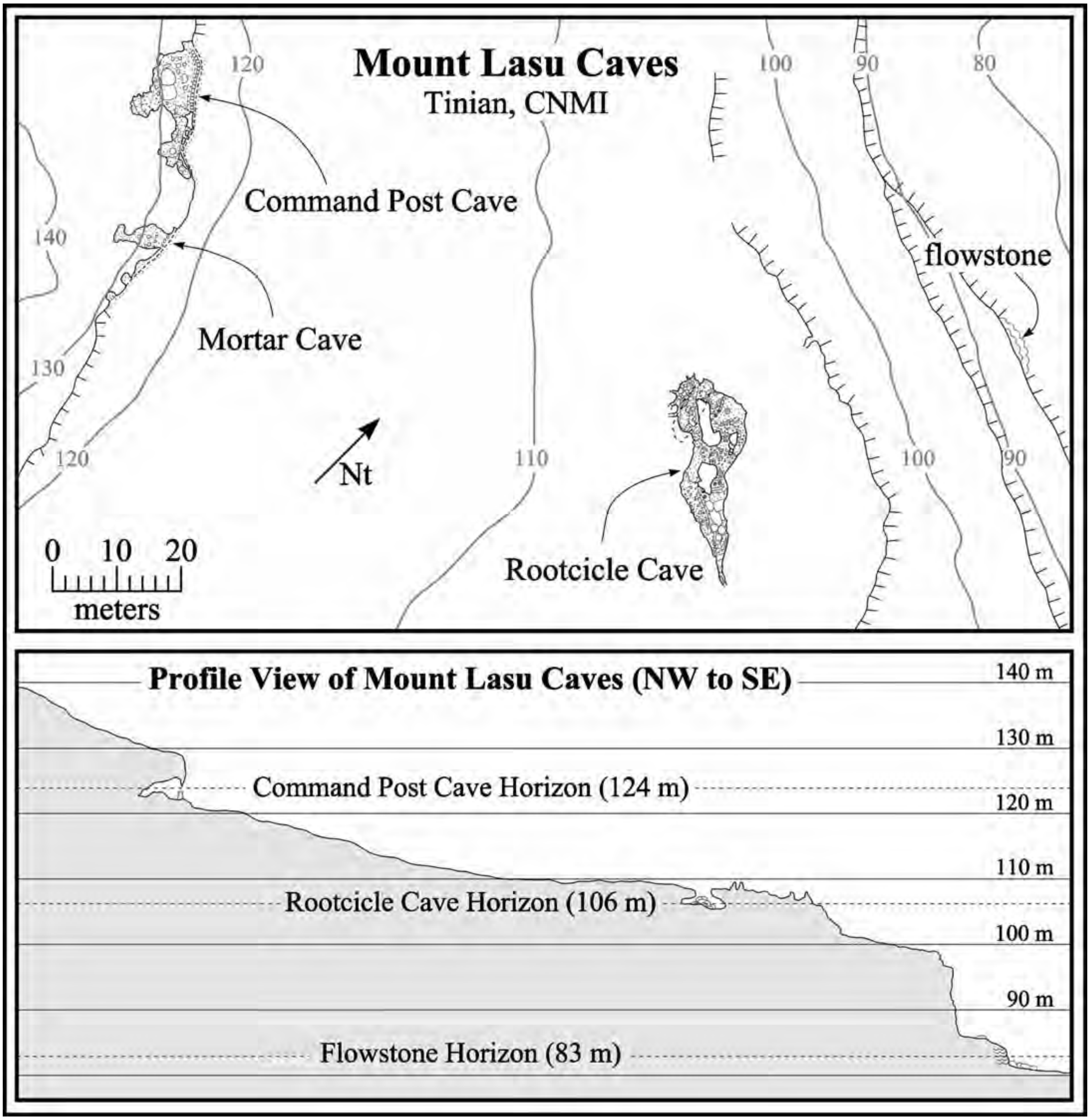

Figure 12. Overland transect of the Mount Lasu Caves provides evidence of three paleo freshwater lens positions, as indicated by two horizons of cave development and a third horizon indicated by speleothems present on a lower scarp.

ducting fieldwork. Joey Charfarous, of the Tinian Mayor's Office, provided significant logistical assistance, while the authors greatly appreciate the assistance and hospitality of Edwin Cabrera and his family, who helped with daily fieldwork. The authors are indebted to Andrew Grubbs and Charley Savvas of Texas for their involvement in fieldwork.

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MICROBIAL METABOLIC STRUCTURE IN A SULFIDIC CAVE HOT SPRING: POTENTIAL MECHANISMS OF BIOSPELEOGENESIS

HAZEL A. BARTON[1]
Department of Biological Science, Northern Kentucky University, Highland Heights, KY 41099, USA
FREDERICK LUISZER
Department of Geological Sciences, University of Colorado, Boulder, Colorado 80309, USA

Glenwood Hot Springs, Colorado, is a sulfidic hot-spring that issues from numerous sites. These waters are partially responsible for speleogenesis of the nearby Fairy Cave system, through hypogenic sulfuric-acid dissolution. To examine whether there may have been microbial involvement in the dissolution of this cave system we examined the present-day microbial flora of a cave created by the hot spring. Using molecular phylogenetic analysis of the 16S small subunit ribosomal RNA gene and scanning electron microscopy, we examined the microbial community structure within the spring. The microbial community displayed a high level of microbial diversity, with 25 unique phylotypes representing nine divisions of the Bacteria and a division of the Archaea previously not identified under the conditions of temperature and pH *found in the spring. By determining a putative metabolic network for the microbial species found in the spring, it appears that the community is carrying out both sulfate reduction and sulfide oxidation. Significantly, the sulfate reduction in the spring appears to be generating numerous organic acids as well as reactive sulfur species, such as sulfite. Even in the absence of oxygen, this sulfite can interact with water directly to produce sulfuric acid. Consequently, such metabolic activity may represent a mechanism by which biospeleogenesis can lead to passage enlargement through sulfuric acid production without the influx of oxygen or oxygen-rich waters. Such activity may lead to higher levels of sulfuric acid production than could be accounted for by inorganic hydrogen sulfide oxidation. Therefore, rather than generating localized pockets of speleogenesis within cave systems, such biogenic sulfuric acid production may have a regional impact on water chemistry and subsequent speleogenesis of large cave systems.*

The theory of hypogenic cave formation through hydrogen sulfide-rich groundwater and subsequent sulfuric acid dissolution was first proposed by Egemeier (1981, 1987) in the early 1970s, with further refinement by Jagnow (1978), Davis (1980), Palmer (1991) and Queen *et al.* (1977). This theory proposes that, given an appropriate geological setting, caves can form through the dissolution activity of ascending hydrogen sulfide (H_2S)-rich ground water (Palmer 1991; Palmer & Palmer 2000). As the dissolved H_2S approaches the oxic zone at the water table, the gas reacts with oxygen to form sulfuric acid (H_2SO_4) which subsequently dissolves the carbonate rocks, producing carbon dioxide and gypsum ($CaSO_4{\bullet}2H_2O$) (Hill 1987; Palmer & Palmer 2000). This hypothesis is supported in caves, such as Carlsbad Cavern, New Mexico, by the presence of numerous minerals known to be formed through sulfuric acid dissolution, including endellite and gypsum (Hill 1990). The fact that gypsum in these caves is also isotopically light suggests a biogenic component to the sulfuric acid speleogenesis theory (Canfield 2001; Canfield *et al*. 1998; Hill 1990; Klimchouk *et al*. 2000).

As the theory of sulfuric acid dissolution for caves in the Guadalupe Mountains of New Mexico became accepted as a valid process of speleogenesis, the number of such cave systems being similarly described around the world began to rise. Caves formed through sulfuric acid dissolution have now been described in countries as geographically diverse as Italy, Mexico, Romania and Turkmenistan (Hose & Pisarowicz 1999; Klimchouk *et al*. 2000; Klimchouk *et al*. 1995; Maltsev & Malishevsky 1990; Sarbu *et al*. 1996). Included within this group are caves such as Movile Cave, Romania, and Cueva de Villa Luz, Mexico, that are still undergoing active sulfuric acid speleogenesis. Of note is that both these caves demonstrate active microbial activity, with chemolithotrophic microbial communities growing within the cave systems (Hose *et al*. 2000; Sarbu *et al*. 1996; Sarbu *et al*. 1994). In these systems, acid production by the microbial communities may have a significant impact on the cave environment, leading to localized dissolution of the carbonate bedrock (Hose *et al*. 2000). Interestingly, within Movile Cave, such activity is occurring within a geologically confined area without a conduit to allow for the exchange of oxygen with the surface atmosphere. However, the inorganic interaction of oxygen with hydrogen sulfide is widely thought to be an important factor for cavern enlargement in sulfuric acid speleogenesis (Egemeier 1981, 1987; Hill 1987; Palmer & Palmer 2000; Sarbu *et al*. 1996). This would therefore suggest that microbial dissolution in these systems results in a localized secondary speleogenesis

[1]Hazel A. Barton, Department of Biological Science, Northern Kentucky University, SC 344, Nunn Drive, Highland Heights, KY 41099, Ph: 859-572-5303, Fax: 859-572-5639, Email: bartonh@nku.edu, www.cavescience.com

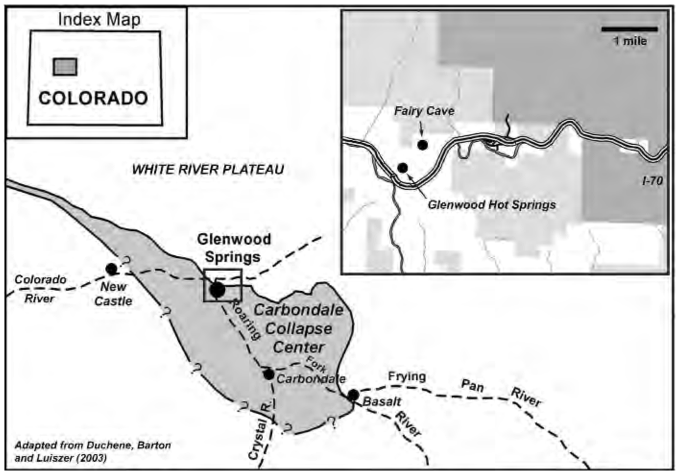


Figure 1. Location map of Fairy Cave and Glenwood Hot Springs with respect to the Carbondale Collapse Center, Colorado. Modified from Duchene, Barton and Luiszer (2003).

and may be an important factor in primary cave formation and enlargement.

In this study we examined the microbial community found in a sulfidic hot spring thought to be associated with active cave formation at Glenwood Springs, Colorado. The spring in question may be the hydrological conduit for the H_2S-rich ground water that formed the nearby Fairy Cave (commercially known as Glenwood Cavern and Fairy Caves). Morphologically, Fairy Cave appears to have been formed through a combination of carbonic acid and sulfuric acid speleogenesis; the sulfuric acid component is supported by the presence of gypsum deposits within the cave (Hill 1987). These deposits are isotopically light, also suggesting a biogenic component to speleogenesis within this system (H.R. DuChene, personal communication 2002). The aim of this study is to determine the metabolic activity of microorganisms found within this cave hot spring, and whether this activity plays any role in large-scale (regional) carbonate dissolution, or whether it is purely a localized phenomenon. Our results suggest that the primary component of cavern enlargement in sulfuric acid caves may be accounted for by microbial activity that results in increased sulfuric acid production and a greater role for biogenic speleogenesis of such cave systems.

Methods

Site description and sample collection

The water at Glenwood Springs comes primarily from snowmelt, which percolates through the Pennsylvanian Eagle Valley Evaporites and is heated as it descends down-dip. Some of the thermal waters percolate through the Belden Formation of the Carbondale Collapse Center to the Leadville Aquifer, whereupon a complex set of faults allows upward flow along the dip of the south flank of the White River Uplift (Figure 1). The sulfidic water then reaches the surface through artesian flow, generating Glenwood Hot Springs (Geldon 1989).

Microbial filament samples were taken using aseptic techniques from the cave spring on May 16, 2000, followed by preservation in either 70% ethanol for phylogenetic analysis, or 4% paraformaldehyde in phosphate-buffered saline for microscopy. All samples were stored on ice for transport. DNA samples were processed within 24 hours and the microscopy samples were stored at 4°C.

Water chemistry at the spring was carried out on November 10, 2000. *p*H and conductivity were measured by an Orion 290A *p*H meter and a Hach conductivity/TDS meter. Bicarbonate was measured by titration with sulfuric acid and bromcresol green-methyl red indicator. Hach AccuVac Ampuls and a Hach DR/2000 portable spectrophotometer were used to measure nitrite, nitrate and phosphate; nitrate was measured using the cadmium reduction method; nitrite was measured using the diazotization method; phosphate (orthophosphate) was measured using the ascorbic acid method; and total iron was measured using the FerroVer method. In the laboratory, major cations were measured with an ARL-3410+ inductively coupled plasma optical emission spectrometer and trace metals were measured with an a Varian UltraMass-700 inductively coupled plasma mass spectrometer.

DNA extraction

All DNA protocols were carried out in a laminar-flow hood (Nuaire, Inc.), using aerosol resistant pipette tips (Molecular Bio-Products, Inc.) to reduce the likelihood of contamination. Negative control isolations were carried out in parallel to measure any contamination of the final samples. DNA was extracted from the samples using the standard bead beating protocol (Kuske *et al*. 1997). Briefly, 0.5 g of microbial filament was resuspended in 500 µL 2x buffer A (200 mM Tris [*p*H 8.0], 50 mM EDTA, 200 mM NaCl, 3 mg/mL lysozyme) in a 2 mL screw-cap Eppendorf tube and incubated at 37°C for 30 min. Proteinase K (to 1.2 mg/mL) and sodium dodecyl sulfate (SDS to 0.3% wt/vol) were added and the mixture was further incubated at 50°C for 30 min. SDS was then increased to 5% and the samples were disrupted on a Mini-bead beater (Biospec) at low speed for 2 min and high speed for 30 s in the presence of 50% (vol/vol) phenol-chloroform-isoamyl alcohol (24:24:1) and approximately 0.1 g of zirconium-silica beads (0.1 mm diameter). Lysates were extracted with phenol-chloroform. Nucleic acids were precipitated with 0.3M sodium acetate and 2 volumes of ethanol. The nucleic acids were spun down at 13,000 x *g*, dried and resuspended in 20 µL dH_2O.

Polymerase chain reaction (PCR) and cloning

Community rDNAs were PCR amplified from approximately 50 ng of template (bulk) DNA in reaction mixtures containing (final concentrations) 1 x PCR buffer (Perkin Elmer), 2.5 mM $MgCl_2$, 200 µM of each deoxynucleoside triphosphate, 300 nM of each forward and reverse primer, and 0.025 U of AmpliTaq Gold (Perkin Elmer) per µL. Reaction mixtures were incubated on a Mastercycle Gradient thermal cycler (Eppendorf Scientific) at 94°C for 12 min for initial denaturation and activation of the AmpliTaq Gold. PCR was then carried out for 30 cycles at 94°C for 1 min, 53°C for 45 s, and 72°C for 1 min 30 s, and then a final extension period of 8 min at 72°C. Community rDNA was amplified with the Bacterial specific forward primer 8F (5' – AGA GTT TGA TCC TGG CTC AG – 3') and the universal reverse primer 805R (5' – GAC TAC CAG GGT ATC TAA T – 3'). For amplification of Archaeal rDNAs, the same PCR amplification conditions were used, along with the Archaeal specific forward primer 333Fa (5' – TCC AGG CCC TAC GGG – 3') and universal reverse primer 1391R (5'- GAC GGG CGG TGW GTR CA – 3'). The PCR products were separated on a 1% agarose gel, excised and purified on a Quiaquick gel purification column (Quiagen), and eluted in 30 µL dH_2O. The purified PCR products were cloned into a TOPO TA Cloning Kit according to the manufacturer's recommendations (Invitrogen Corp.).

SCREENING OF rDNA CLONES BY RESTRICTION FRAGMENT LENGTH POLYMORPHISM (RFLP)

rDNA inserts from recombinant clones were reamplified by PCR with reaction mixtures containing (as final concentrations) 1x PCR reaction buffer (50 mM KCl, 100mM Tris, *p*H 8.3), 2.5 mM $MgCl_2$, 100 µM of each deoxynucleoside triphosphate, 150 nM of each vector specific forward and reverse primer (T3 and T7 respectively) and 0.01 U of Pfu DNA polymerase per µL. 100 ng of purified plasmid vector was used as the template. PCR was then carried out for 30 cycles at 94°C for 1 min, 52°C for 45 s, and 72°C for 1 min 30 s, with a final extension period of 8 min at 72°C. 20 µL of crude rDNA product was then digested with 1.5 U of the 4-base-specific restriction endonucleases *HindPI*1 and *Msp*I in 1x NEB buffer 2 (New England Biolabs), in a final volume of 25 µL, for 2 hours at 37°C. Digested fragments were separated by electrophoresis on a 2% SeaKem LE agarose gel (FMC BioProducts) and visualized by ethidium bromide staining and UV illumination. RFLP patterns were grouped visually and representatives were selected for sequencing.

SEQUENCING OF rDNA CLONES

Plasmid templates from representative clones were sequenced on a Long ReadIR 4200 DNA sequencer (Li-Cor, Inc.), using the Thermo Sequenase Cycle Sequencing Kit (USB Corp.) in accordance with the manufacturer's instructions. Primers for sequencing were the vector primers T3 and T7, with sufficient coverage to sequence the 800 base insert of the bacterial and 1,000 base inserts of the archaeal rDNAs in both directions.

PHYLOGENETIC ANALYSES

Sequences were compared to available databases by use of the BLAST (Basic Local Alignment Search Tool) network service (http://www.ncbi.nlm.nih.gov/BLAST; (Altschul *et al*. 1997)). Partial sequences of the 16S rRNA gene were compiled using the AlignIR 2.0 Fragment Assembly and Contig Editor software (Li-Cor, Inc). Compiled sequences were aligned using the ARB Software Package (http://mpi-bremen.de/molecol/arb), with additional sequences from the Ribosomal Database Project (Cole *et al.* 2003). Before further phylogenetic analysis, those sequences displaying similar BLAST hits were directly compared using the pairwise BLAST alignment tool [http://www.ncbi.nlm.nih.gov/blast/bl2seq/bl2.html]. Any sequences that demonstrated ≥98% identity toward each other were considered representatives of the same phylotype and grouped accordingly. All presented dendrograms were constructed by use of ARB with evolutionary distance (neighbor-joining) algorithms. The robustness of inferred topologies was tested by bootstrap resampling of phylogenetic-trees, calculated with evolutionary distance using PAUP* software (Sinauer Associates Inc., Sunderland, MA). The sequences obtained from the rDNA clones in this study were deposited in the Genbank database, accession numbers AY702823-AY702856.

STATISTICAL APPROACHES

The statistical analyses were performed using EstimateS version 6.01b (http://viceroy.eeb.uconn.edu/estimates; Colwell 1997). Each clone represented a separate sample without replacement, and 100 randomizations were performed to obtain the Chao1 estimator for each sample size. Using the singletons and doubletons calculated for each sample collection by EstimateS, we used the log transformation of Chao to calculate the 95% confidence intervals (Chao 1987).

MICROSCOPY

Approximately 0.1 g of microbial filament material was critically-point dried prior to gold-sputtering and imaging on an ISI-30 scanning electron microscope at a magnification of 3000x.

RESULTS

DESCRIPTION OF SAMPLING SITES

The springs at Glenwood are produced from snowmelt water percolating through the Carbondale collapse center, containing the Pennsylvanian Eagle Valley Evaporites, several miles to the south (Figure 1). This water is heated as it descends, dissolving halite (NaCl) and gypsum ($CaSO_4 \cdot 2H_2O$), whereupon faults in the limestone bedrock allow the water to ascend as artesian springs (H. DuChene 2002, personal communication; Geldon 1989). These springs have been commercialized as Glenwood Hot Springs, leading to the containment of the main spring and its diversion into a bathing pool. The cave spring emerges near the main spring in an underground conduit and continues to flow through a cave. The waters of this spring have undermined the soil in one spot, producing an entrance collapse that allows access to the cave. We measured the volume of water issuing from the cave spring as approximately 25–30 L/s.

Table 1. Physical and chemical parameters of the water measured at the cave spring.

Parameter	Spring Water (SD)
PHYSICAL	
Temperature	49.6°C
*p*H	6.39
CHEMICAL (mg/L)	
Dissolved oxygen	0.048
Total dissolved solids	18755 (±144)
Total alkali	544
HCO_3	664
NO_3	0.166 (±0.018)
SO_4	1102 (±2.83)
NO_2	0.0100 (±0.000)
PO_4	0.238 (±0.167)
Fe (total)	0.093 (±0.007)
Na	6574 (±125)
Cl	9706 (±19.8)
K	125.0 (±6.5)
Mg	84.60 (±3.05)
Ca	490.4 (±0.22)
SiO_4	30.23 (±0.11)
H_2S*	1.65 (±0.63)

* Average readings of the waters at Glenwood Springs according to Geldon (1989).

The water flowing through the cave was tested using several chemical and physical parameters (Table 1). The concentrations of dissolved solutes (Na^+, Cl^-, Ca^{2+}, and SO_4^{2-}) are comparable to the chemical characteristics of waters that pass through evaporative sedimentary rocks in a karstic setting (Hose *et al*. 2000). The spring water is essentially anoxic, with the sampling site being close to the spring source and giving the water insufficient time to become oxygenated. Isotopic fractionation analysis indicates that the sulfates present in the water do not have a biogenic origin, with a $\delta^{34}S$ of 15.7‰ (C. Bern 2002, personal communication), which agrees with the postulated source of the SO_4^{2-} being the Pennsylvanian Eagle Valley Evaporites (Geldon 1989). Hydrogen sulfide (H_2S) has previously been measured in the spring at 1.2–2.1 mg/L, and is probably a by-product of microbial activity in the anaerobic, sulfate-rich subterranean water (Geldon 1989).

MOLECULAR PHYLOGENETIC ANALYSIS OF SAMPLES

To determine the community composition of the cave spring microbial filaments we carried out comparative phylogenetic analysis of the the small subunit ribosomal RNA (16S rDNA) gene. Community DNA was isolated from approximately 0.5 g of microbial filament material, and 16S rDNA gene fragments for both bacterial and archaeal species were amplified using the polymerase chain reaction (PCR). Amplification of gene products for both archaeal and bacterial sequences was successful (data not shown). The PCR products were cloned and 96 representative clones each from the Archaea and Bacteria were isolated, generating two clone libraries: the DZ, dark zone bacterial library and the DZ_Ar, dark zone archaeal library.

The RFLPs in each clone library were grouped according to similarity, and one or more representatives from each group were sequenced. Within the bacterial clone library, six sequences were identified as chimeras using the CHIMERA_CHECK program (http://rdp.cme.msu.edu/html/) and unstable phylogenetic placement. These sequences were removed from further analysis. The remaining 90 representative bacterial clones from the cave spring were compared by pairwise BLAST, allowing us to identify 25 unique phylotypes within the community that were widely distributed through nine divisions of the bacteria, including the *Nitrospira*, *Cytophagales/Flavobacteria/Bacteroides* (CFB), Green non-sulfur relatedness-group, and the OP11 division (Table 2). Of the 96 archaeal clones isolated from the cave, sequencing revealed that 75 contained ambiguous sequences. These were removed from consideration, resulting in 21 representative 16S archaeal rDNA phylotypes. Once again, direct sequence comparisons were made, resulting in the grouping of the archaeal clones into five unique phylotypes (Table 2).

PHYLOGENETIC DISTRIBUTION

Phylogenetic analyses not only allow us to determine the distribution of phylotypes identified within an environment, but by phylogenetically aligning a phylotype with its nearest cultivated relative we may make some assumptions as to the role of this organism in the environment (Pace 1997). Therefore, dendograms were created for the phylotypes identified in this study (Figs. 3 & 4). The resultant dendograms indicate that the phylotypes generally group with the divisions identified via the BLAST search (Table 2), the exception being DZ_C11 and DZ_B10, which were identified as members of the Green Non-Sulfur group via BLAST, but belong to the OP11 division by sequence alignment.

Several of the phylotypes identified within the cave had low sequence identity to previously cultivated organisms, allowing us to make only general assumptions about their metabolic activity based on the genera to which these phylotypes belong. However, all the phylotypes demonstrated identity to organisms from environments characteristically devoid of light: benthic and lacustrine sediments, caves, hydrothermal vents and activated sludges, many of which rely on sulfidic compounds for energy conservation (Angert *et al*. 1998; Bond *et al*. 1995; Donachie *et al*. 2002; Lopez-Garcia *et al*. 2002; Teske *et al*. 2002).

Among the *Gammaproteobacteria* phylotypes isolated, DZ_A2 shows identity with the *Thiothrix* spp. Members of this group are usually found living at the boundary of oxidation/reduction gradients, such as where oxygen-rich waters run over H_2S-sediments. These bacteria oxidize

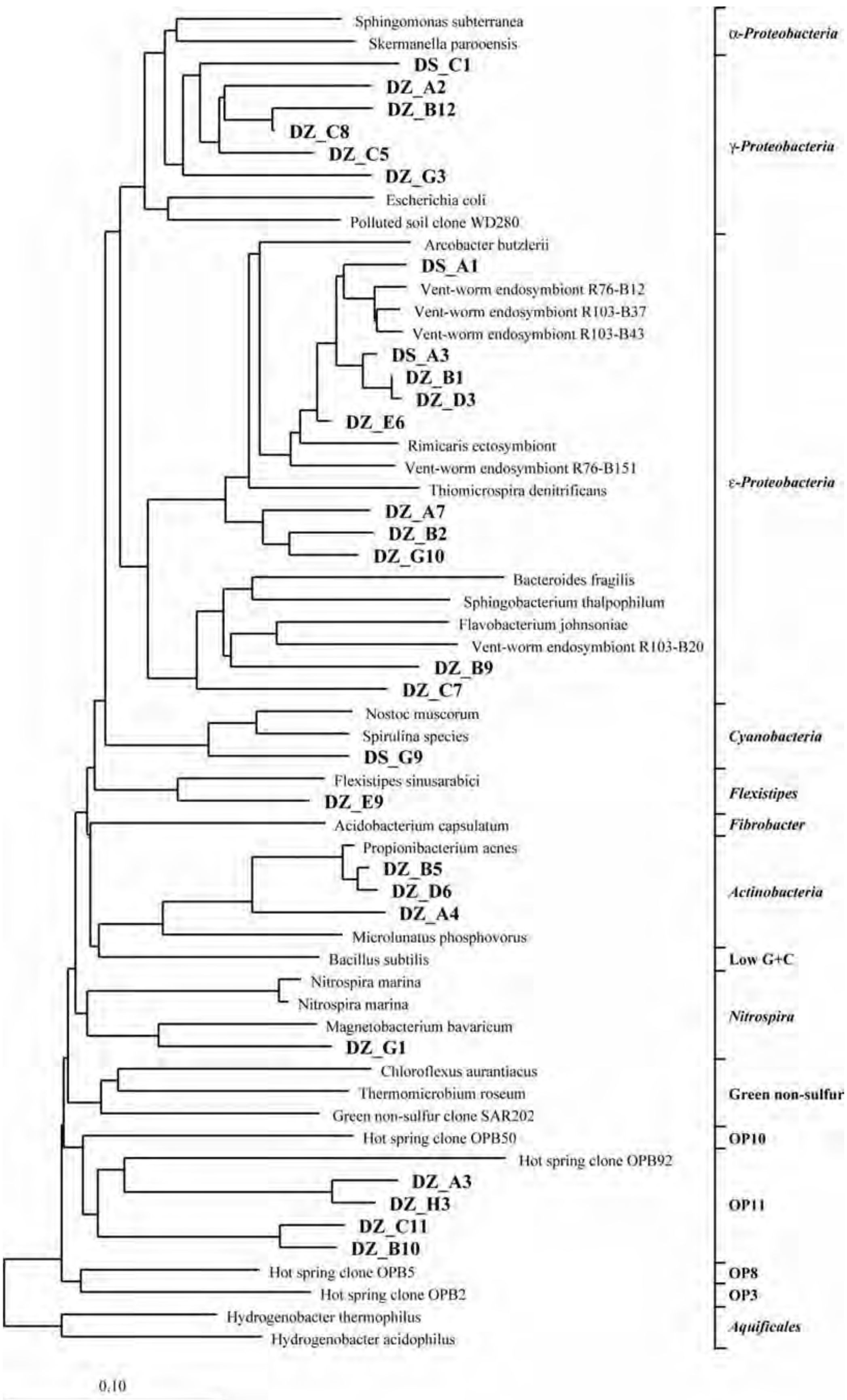
Table 2. Phylogenetic affinities of rDNA sequences identified from Glenwood cave hot spring.

Division (% representation)	Clone	# clones/ group	Closest identified relative	% Sequence identity[a]	NCBI Accession #
BACTERIA					
Gammaproteobacteria (9.4%)	DZ_A2	1/8	*Thiothrix fructosivorans*	92%	AY702830
	DZ_B12	1/8	*Methylobacter whittenburyi*	88%	AY702833
	DZ_C5	2/8	Unidentified sediment bacterium	92%	AY702855
	DZ_C8	3/8	*Alkalispirillium mobile*	94%	AY702842
	DZ_G3	1/8	*Achromatium sp.* HK6	93%	AY702849
Deltaproteobacteria (1.2%)	DZ_H2	1/1	Uncultured sludge bacterium A11b	92%	AY702850
Epsiloproteobacteria (60.0%)	DZ_A5	6/51	Uncultured hydrocarbon seep bacterium	87%	AY702853
	DZ_A7	2/51	Uncultivated bacterium VC2.1	95%	AY702832
	DZ_B1	27/51	Uncultured *Proteobacterium* a1b030	94%	AY702834
	DZ_B2	12/51	*Wolinella succinogenes*	90%	AY702835
	DZ_C10	1/51	Uncultivated sediment Proteobacterium	92%	AY702838
	DZ_D3	1/51	Uncultured *Proteobacterium* a1b030	94%	AY702843
	DZ_E6	1/51	Uncultured *Proteobacterium* R103-B43	97%	AY702845
	DZ_G10	1/51	*Wolinella succinogenes*	90%	AY702847
OP11 (2.3%)	DZ_A3	1/2	Uncultivated candidate OP11	87%	AY702831
	DZ_H3	1/2	Uncultured lake bacterium	86%	AY702851
Actinobacteria (14.1%)	DZ_A1	10/12	*Propionibacterium acnes*	98%	AY702829
	DZ_A4	1/12	Uncultured *Propionibacterium* PH-B24N	98%	AY702852
	DZ_D6	1/12	Uncultured *Propionibacterium* PH-B24N	98%	AY702844
Low G+C Group (4.7%)	DZ_B9	1/4	Uncultured travertine eubacterium	97%	AY702837
	DZ_C7	3/4	Uncultured sediment bacterium	99%	AY702841
Green Non-Sulfur (5.9%)	DZ_C11	1/5	Uncultured sludge bacterium SRB109	96%	AY702839
	DZ_B10	4/5	Uncultured sludge bacterium SRB109	93%	AY702854
Flexistipes (1.2%)	DZ_E9	1/1	*Flexistipes sp.* Vp180	91%	AY702846
Nitrospira (1.2%)	DZ_G1	1/1	*Saltmarsh clone* LCP-6	89%	AY702848
ARCHAEA					
Euryarchaeota					
Thermoplasmata	DZ_ArA2	11/21	*Picrophilus oshimae*	91%	AY702826
	DZ_ArB2	1/21	*Thermoplasma acidophilium*	92%	AY702827
	DZ_ArA3	7/21	*Ferroplasma acidarmanus*	96%	AY702823
	DZ_ArE3	1/21	*Thermoplasma acidophilium*	91%	AY702824
	DZ_ArF4	1/21	*Thermoplasma acidophilium*	90%	AY702828

[a]Data obtained via an on-line BLAST search (Altschul *et al.* 1997).

reduced forms of sulfur and directly fix CO_2 for biosynthesis via a circumvented Calvin cycle (Dworkin 2002). DZ_B12 is related to members of the *Methylobacter,* which oxidize biogenic methane to formate and CO_2. These organisms are a natural component of most microbial ecosystems, but optimally grow below 40°C and are generally not found in hot spring environments. DZ_C8 is related to *Alkalispirillium mobile*, a moderately halophilic, obligate anaerobe that uses organic anions such as acetate and succinate as carbon sources. *A. mobile* is also unable to grow at the temperatures or pH encountered in the cave spring, preferring *p*H values > 9.0 and temperatures in the 35–38°C range. The final *Gammaproteobacteria* identified, DZ_G3, is related to *Achromatium* sp. These organisms are characterized by large $CaCO_3$ inclusions and are generally found in areas where calcium is plentiful, so their presence in this karstic spring is not

Figure 2. Evolutionary distance consensus dendogram of the Bacterial domain and the bacterial DZ 16S SSU rDNA phylotypes identified within the Glenwood Hot Spring microbial community. Reference sequences were chosen to represent a broad diversity within the Bacterial domain, with members of the *Acquificales,* as the most deeply divergent members of the domain, as the outgroup for analysis. Branch points were supported by consensus agreement of phylogenetic analysis using neighbour-joining, parsimonious and maximum-likelihood algorithms. The bar indicates 10% sequence divergence.



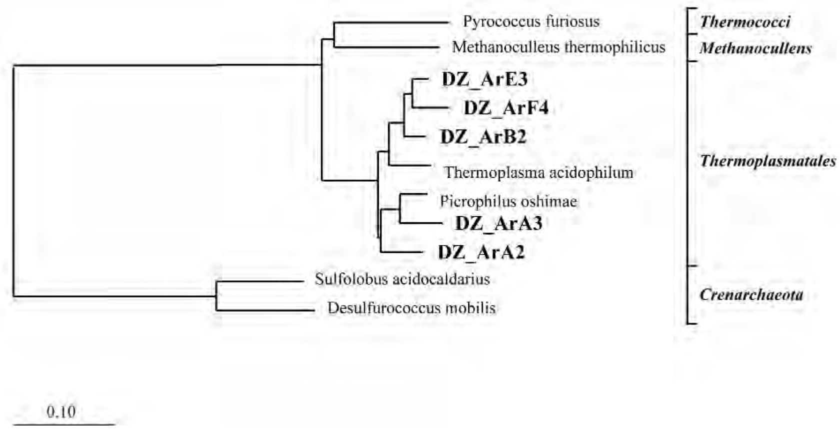


Figure 3.
Evolutionary distance consensus dendogram of the Archaeal domain and the DZ_Ar 16S SSU rDNA phylotypes identified within the Glenwood Hot Spring microbial community. Reference sequences were chosen to demonstrate the lineage of the identified phylotypes. *Sulfolobus acidocaldarius* and *Desulfurococcus mobilis,* as members of the *Crenarchaeota,* were used as the outgroup for analysis. Branch points were supported by consensus agreement of phylogenetic analysis using neighbour-joining, parsimonious and maximum-likelihood algorithums. The bar indicates 10% sequence divergence.

surprising (Dworkin 2002). Further, while the other identified *Gammaproteobacteria* in the cave spring carry out oxygenic respiration, *Achromatium* sp. are strict sulfate-reducing anaerobes. It is thought that the cellular $CaCO_3$ inclusions in this species are required to buffer the H_2SO_4 produced by the organism through incomplete sulfate reduction to sulfite (Dworkin 2002).

The predominant phylotype identified in the *Epsiloproteobacteria* is DZ_B1. This organism belongs to an uncultivated pyhlogenetic group previously seen in sulfidic, anoxic aquatic environments, including Parker's Cave, Kentucky, the Cariaco Basin of Venezuela and deep sea sediments, which suggests that these organisms are also involved in sulfate reduction (Angert *et al*. 1998; Madrid *et al*. 2001; Orphan *et al*. 2001; Teske *et al*. 2002). All of these environments are also aphotic. A large number of the identified *Epsiloproteobacteria* phylotypes (DZ_A7 and DZ_G10), share similarity to *Wolinella succinogenes*, a sulfate-reducing bacterium. *W. succinogenes* is commonly found in anaerobic muds where it ferments complex organic compounds, such as cellulose, with sulfate as an electron acceptor. When organic carbon sources are not readily available, this organism is capable of fixing CO_2 and surviving chemolithotrophically. Notably, *W. succinogenes* does not always fully reduce SO_4^{2-} to H_2S, and produces thiosulfate and elemental sulfur that can be used by numerous other sulfate-reducing species (Dworkin 2002).

Beyond members of the *Proteobacteria*, another predominant group within the cave spring are the *Actinobacteria* (Fig. 2). The isolated phylotypes share identity with members of the *Propionibacteria,* from which the skin commensal *P. acnes* has been found as a PCR contaminant (Tanner *et al*. 1998). However, identification of *Propionibacteria* contamination in our laboratory is rare (<1% per clone library), and identified phylotypes share 100% identity with *P. acnes* via BLAST search. In this study, the *Propionibacteria* accounted for a much greater percentage of the clone library (14%) and displayed 98% identity with previously cultivated *Propionibacter* species, suggesting these clones did not represent contamination. Members of this group have also been previously identified in environmental samples (Donachie *et al*. 2002). The *Propionibacteria* are generally halotolerant anaerobes, although no growth has previously been observed at the temperatures of the cave spring. They also ferment lactate, carbohydrates and polyhydroxy-alcohols, to acetate, CO_2 and propionate (Dworkin 2002).

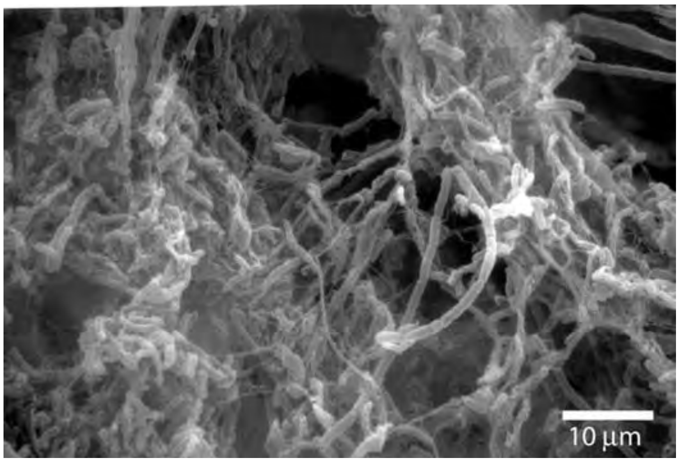


Figure 4. Scanning electron micrograph of the filament community structural morphology. Numerous microbial cell structures can be observed, including coccoid, septate and filamentous morphotypes. A glutnous matrix appears to be holding the community together, which is likely responsible for the gross structural morphology of the microbial filaments. (Magnification 3000x).

Other organisms identified in the cave spring include members of the anaerobic CFB group, which specialize in degrading complex biomolecules to organic acids, such as lactate. The *Nitrospira* oxidize nitrite to nitrate, and are capable of sulfate-reducing, chemolithotrophic and chemoorganotrophic growth. The *Flexistipes* are obligate anaerobes and are very adept at using a variety of electron acceptors for growth, which is unique given their anaerobic fermentation (Dworkin 2002; Madigan *et al*. 2000). Finally, DZ_C11 and DZ_B10 are mem-

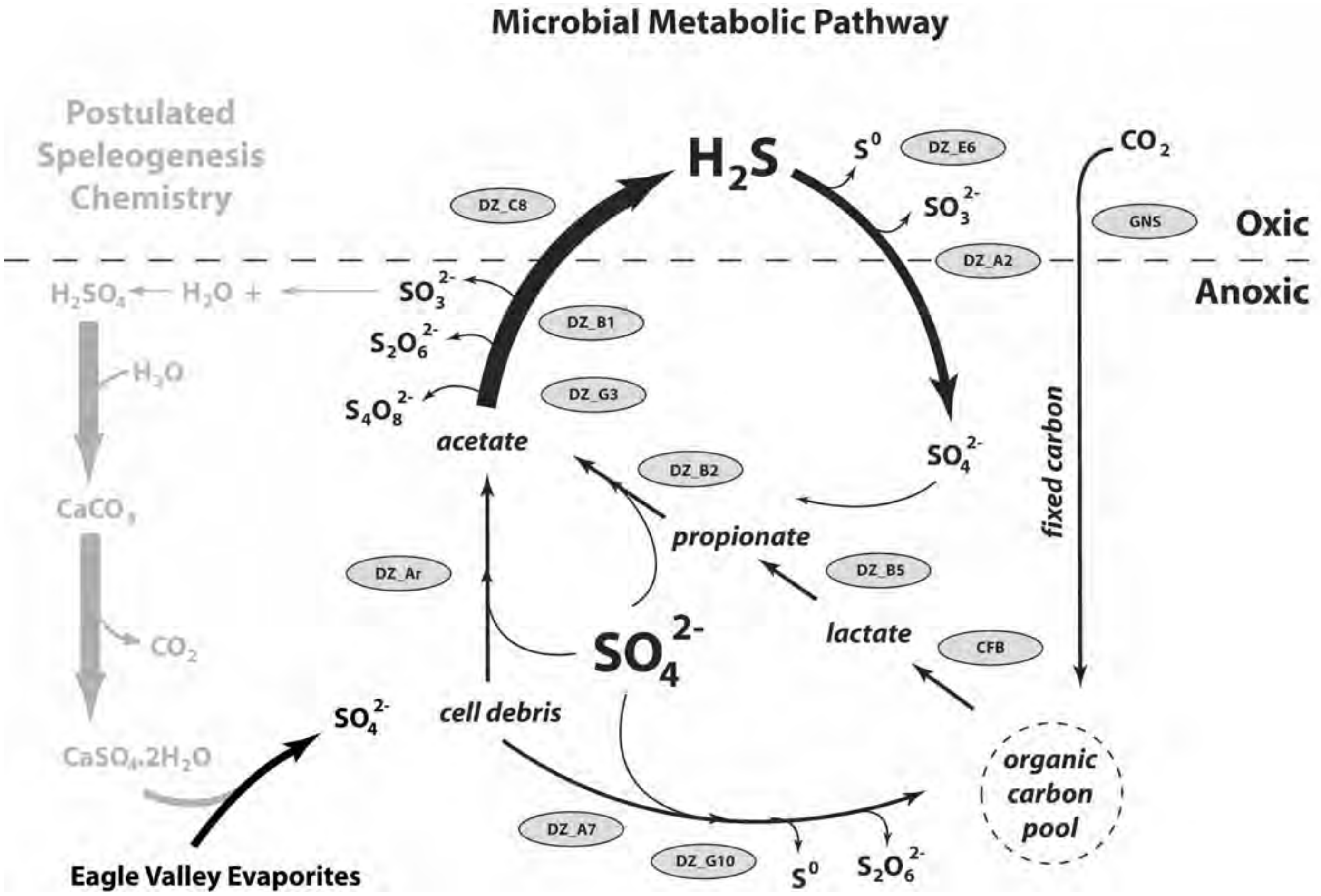


Figure 5. Proposed metabolic network that sustains the microbial filament population identified in the Glenwood Hot Spring cave (only the major community phylotypes are shown). Each phylotype is shown with a shaded oval. The putative metabolic activity for each phylotype is indicated with an arrow, with thicker arrows indicating reactions that appear to drive the metabolic network. The source of sulfate into the system is dissolved gypsum from the Eagle Valley Evaporites. Metabolic by-products, such as acetate and propionate, and the major sulfur species present, are indicated. A presumed oxic/anoxic boundary that allows sulfur-cycling in this system is shown as a dotted line.

bers of the green non-sulfur group, normally associated with anoxygenic photosynthetic growth in neutral to alkali hot springs (Ward *et al*. 1998). Members of this group can grow equally well autotrophically in the dark, using an aerobic lifestyle and have previously been identified in aphotic environments (Schabereiter-Gurtner *et al*. 2002; Teske *et al*. 2002). Members of the green non-sulfur group can oxidize H_2S and reduce CO_2 to glyoxylate through the 3-hydroxypropionate pathway.

Finally, several representatives of the *Thermoplasmata* division within the Archaea were identified in the cave spring (Figure 3). Members of this group have previously been identified only in aphotic environments such as coal refuse piles and hot-spring sediments (Dworkin 2002; Madigan *et al*. 2000). The *Thermoplasmata* are obligate heterotrophs, generally fermenting the breakdown products of cellular decomposition with SO_4^{2-} as an electron acceptor. While the temperature of the cave spring is favorable to growth of the *Thermoplasmata* (35–67 °C), members of this genus are not known to survive above pH values of 4.0 due to the loss of protons that maintain cellular integrity (Dworkin 2002). While the *p*H of the cave spring was 6.39, it is possible that extremely acidic microhabitats exist within the microbial filaments to allow survival of these organisms. Such microhabitats appear to be common within microbial consortia (Boetius *et al.* 2000; Pallud *et al.* 2004).

Community diversity

With the advent of molecular phylogenetic techniques, it is becoming possible to use the tools employed by traditional ecologists to measure microbial community diversity (Begon *et al*. 1998). Recently, Hughes *et al.* recommended the use of nonparametric estimators to reliably determine microbial diversity (Hughes *et al*. 2001). Using the assumption that each clone represented a sample, we used the species richness estimator Chao1 to estimate the true richness of the cave spring microbial community (Chao 1987). This estimator was used due to the small sample size and the likelihood of underestimation (versus overestimation) of the true richness of the community. After sampling 90 clones the Chao1 estimator curve did not level off, suggesting that this sample size is insufficient to measure diversity at this spring. Ninty-five % confidence intervals indicate that in order to sufficiently sample the cave spring bacterial community more than 500 clones would need to be isolated.

MORPHOLOGY OF CAVE SPRING MICROBIAL COMMUNITIES

The cave spring contained microbial communities in the form of filaments. On a gross morphological scale these filaments are approximately 2–5 mm in diameter and 35–50 mm in length. Electron microscopy was used to examine the morphological structure of the microbial filament communities. The results (Fig. 4) demonstrate a high morphological complexity in the cave spring community, which appears to be held together by a glutinous matrix, as seen in similar filamentous microbial communities (Angert *et al*. 1998; Hose *et al*. 2000). Numerous granules are interspersed between the cells, which presumably represent precipitated sulfur forms and agree with both the metabolic activity and community diversity postulated from this study (Angert *et al*. 1998; Hose *et al*. 2000; Knickerbocker *et al*. 2000). Several different cell morphologies were observed in the spring community, such as small individual rod and cocci forms, up to large cells forming long chains.

DISCUSSION

It was the aim of this study to determine whether the activity of the microorganisms found in the Glenwood Hot Spring cave suggests a more regional biogenic influence on water chemistry and subsequent sulfuric acid speleogenesis, or whether such activity is a localized, secondary function that causes microscale cavern enlargement. Our results suggest that the community structure of the microorganisms found in this cave environment is complex, with the metabolic activity of the community resulting in the production of a number of different reactive sulfur species. To simplify the structure of this community, the metabolic activities of the primary phylotypes are presented in Figure 5; the exception are members of the OP11 division for which no metabolic function is presently known. The microbial community contains both sulfate-reducing and sulfide-oxidizing species, even though the filaments do not form classic stratified microbial communities (Cohen & Rosenberg 1989). Therefore, in order for the described metabolic network to function, an oxic/anoxic boundary must occur within the filaments. Such ordered community structure in microbial consortia has previously been demonstrated to account for anaerobic oxidation of methane in anoxic sediments (Boetius *et al*. 2000). If such an ordered structure does exist in the filaments, the metabolic network described in Figure 5 accounts for the activity of all identified phylotypes.

An important observation of the putative metabolic network found within the cave spring is the potential to generate numerous sulfur species, including sulfide, sulfite, thiosulfate, tetrathionate, sulfate and even elemental sulfur (Barrett & Clark 1987; Le Faou *et al*. 1990). While Palmer's model of sulfuric acid speleogenesis suggests that sulfide gas must interact with oxygenated waters for acid production, it does not take into account the potential for the production of such acid by anoxic sulfate reduction (Egemeier 1981, 1987; Hill 1987, Palmer & Palmer 2000). For example, sulfite can react with water directly to produce sulfuric acid, thereby bypassing the requirement of oxygen for sulfuric acid production. Such activity could explain the high levels of speleogenesis in deep groundwater systems, such as Lechuguilla Cave, where the high levels of oxygen required for large scale carbonate dissolution cannot readily be accounted for. Thus microbial activity may provide an important component to sulfuric acid production and speleogenesis on a large scale (Palmer & Palmer 2000). Such activity could also explain some of the local conditions of rapid speleogenesis not easily accounted for by H_2S movement within groundwater. At localized zones where anoxic water may meet the surface or interact with oxygenated waters, there may be a very aggressive, localized speleogenesis. Microbial activity may be continually oxidizing and reducing sulfur species to increase the amount of acid produced in the system, and such activity is supported by the presence of the *p*H-sensitive *Thermoplasmata* (Palmer & Palmer 2000; Socki *et al*. 2001). Indeed, multiple rounds of microbial oxidation/reduction must be occurring within such systems to account for the level of isotopic fractionation seen in the gypsum deposits and therefore cannot reflect static inorganic processes (Canfield 2001; Canfield *et al*. 1998; Hill 1990; Hose *et al*. 2000). Localized increases in microbial activity through interactions with organic-rich surface water or an oxygenic atmosphere may explain the localized pockets of aggressive sulfuric acid dissolution seen in sulfidic-cave systems, including the presence of features such as rillenkarren and dissolution notches (Hose *et al*. 2000; Palmer & Palmer 2000). Such microbial metabolism, with the production of several different ionic forms of sulfur, can also help account for the numerous sulfur minerals found in Lechuguilla Cave. This includes elemental sulfur, which is produced as an energy storage molecule by many sulfate-reducing and sulfide-oxidizing species (Dworkin 2002).

Despite the metabolic activity within the cave spring appearing to suggest a biogenic component to sulfuric acid speleogenesis, there is sometimes a disparity between identification of species based on phylogenetic analysis and the metabolic function of that species in an ecosystem (Achenbach & Coates 2000). Therefore, further geomicrobial studies are needed to confirm our findings that there may be a broader biogenic component in the speleogenesis of sulfuric acid caves. Recently Engel *et al.* (2004) demonstrated localized dissolution of carbonates by *Epsiloproteobacteria* in Kane Cave, Wyoming. The bacteria locally produced sulfuric acid that dissolved the host rock, leaving behind obvious solution pockets from the microbial metabolic activity. Further, these investigators demonstrated that dissolved H_2S in the cave spring water entering the cave was quickly consumed by sulfide-oxidizing bacteria before it could generate inorganic sulfuric acid. However, our results are based on a free-floating microbial community that does not interact with the host rock, suggesting that reactive sulfur species produced by these organisms must enter the water directly. It should be noted that in caves such as Cueva de Villa Luz, Mexico, the anoxic water entering the cave system, where the dissolved H_2S has not yet had the opportunity to interact with O_2, is slightly acidic, while oxygenated inlets into the system have a pH above 7. As the most oxygenated waters entering this system have the highest pH, this suggests that the oxygen does not sufficiently interact with the hydrogen sulfide to acidify the water in these inlets (A. Palmer, personal communication 2004). Further, the large number of microbial filaments found within the Cueva de Villa Luz inlets indicates an active subsurface microbial community below the cave, with the anoxic nature of the water reflecting the microbial consumption of available oxygen (Lavoie, personal communication 2004). Such observations are in agreement with our hypothesis as, after the oxygen has been consumed within this system, sulfate will continue to be reduced to sulfite with the associated production of sulfuric acid.

Our results remain a preliminary, descriptive investigation of the metabolic activity of a microbial cave community that may be involved in biospeleogenesis. While comparisons are made with other sulfuric-acid cave systems, all these systems were formed through the activity of sulfidic waters well below the conditions of temperature found in Glenwood Hot Springs. While there may be significant differences in community structure between these systems, many of the identified phylotypes in our study are also capable of growth in more temperate conditions. Therefore, additional investigations are needed to confirm our hypothesis, including comparative studies with other springs, the distinct observation of reactive sulfur species production by such communities, and the direct observation of calcium carbonate dissolution by metabolic by-products of community growth.

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Donald A. McFarlane and Joyce Lundberg - The 19th century excavation of Kent's Cavern, England. *Journal of Cave and Karst Studies,* v. 67, no. 1, p. 39-47.

THE 19TH CENTURY EXCAVATION OF KENT'S CAVERN, ENGLAND

DONALD A. MCFARLANE
W. M. Keck Science Center, The Claremont Colleges, Claremont CA 91711, USA. dmcfarlane@jsd.claremont.edu
JOYCE LUNDBERG
Department of Geography and Environmental Studies, Carleton University, Ottawa, ON K1S 5B6, CANADA

Between 1858 and 1880, William Pengelly developed revolutionary new techniques for the archeological and paleontological excavation of cave deposits. His work at Brixham Cave and Kent's Cavern, England, yielded tens of thousands of specimens from the mid-Pleistocene to the Holocene, settled the intellectual debate over the co-existence of humans and extinct mammals, and accumulated an unparalleled resource for continued study. Although the Brixham Cave work was thoroughly summarized in print, Pengelly never published the plans of his much more thorough and extensive excavations at Kent's Cavern. Here we present a reconstructed plan of the Pengelly excavations that we hope will be a valuable resource for future analyses of the archaeological and paleontological collections.

In the mid-19th century, the preeminent philosophical question facing the emergent archaeological and paleontological community was the contentious issue of the "Antiquity of Man", and the controversial but apparent co-occurrence of anthropogenic artifacts with the remains of extinct mega-faunal mammals. As early as 1771 Johann Esper had found human bones intermingled with those of cave bear (*Ursus spelaeus*) in the excavations at Zoolithenhöhle, Burggaillenreuth, Germany (Esper 1774). In 1792, John Frere reported stone hand-axes deeply buried in gravels at Hoxne, England, commenting that [these axes] *may tempt us to refer them to a very remote period indeed; even beyond that of the present world* (letter to the Society of Antiquities, London, quoted in Daniel 1959).

Since the publication of James Hutton's *Theory of the Earth* (1785), informed scientific opinion had consistently pushed the presumed age of the Earth back in time, whereas the tenure of *Homo sapiens* was still widely considered to be constrained by the Ussherian timescale of ~6000 years which had been the foundation of Thomas Burnet's influential *Sacred Theory of the Earth* (1681).

When William Buckland published *Reliquiae Diluvianae* (Buckland 1823), he advanced an influential case for the traditional Catastrophist view, interpreting cave deposits as direct evidence of the Noachian Flood that had incorporated the bones of those doomed "antediluvian" species swept away in the great Catastrophe. Buckland's own excavations had uncovered human remains; most famously the "Red Lady" of Paviland Cave, but Buckland argued that "she" (now known to be "he"; North 1942) was…*clearly not coeval with the antediluvian extinct species…* (Buckland 1823, p. 89). Similarly, Buckland interpreted human remains from a cave at Burrington, England, as the remains of …*wretches that perished in it, when the country was suffering under one of our numerous military operations.* (Buckland 1823, p. 164). Nevertheless, by 1838 Boucher de Perthes had reported "antediluvian" artifacts from gravels in the Somme Valley of northern France (de Perthes 1838).

Between 1825 and 1829, Father John MacEnery of Torre Abbey conducted a series of excavations in Kent's Cavern, a well known site in Wellswood (now a suburb of Torquay), England. MacEnery broke through a laterally extensive flowstone floor and recovered bones of extinct mammals and flint artifacts from the "cave earth" beneath. Because the flowstone floor sealed the bones from modern intrusions, MacEnery recognized that their co-occurrence with flint tools was significant. Buckland, however, disagreed, considering the tools to have entered the cave earth in post-Diluvian times through "oven pits" dug through the flowstone by Celtic inhabitants (Kennard 1945). In light of MacEnery's lack of experience in geology and cave excavation, and the fact that the Great (entrance) Chamber of Kent's Cavern had been extensively modified by centuries of use and souvenir hunting, MacEnery's views carried little weight and did not appear until 1859 (MacEnery 1859), 18 years after his death and by then superseded by work at Brixham Cave.

William Pengelly became intrigued with the problem of the "antiquity of Man" in the mid-1800s, and conducted some additional excavations at Kent's Cavern under the auspices of the Torquay Natural History Society in 1846. However, in 1858 the discovery of Brixham Cave provided him–and the British geological community–with a unique opportunity. The cave, which had no open entrance, was discovered during quarrying operations on January 15, 1858. The owner, John Philp, enlarged a small hole through which a quarryman's "jumper" (crow-bar) had been lost and entered a cave with a pristine flowstone floor which was embedded with a reindeer (*Rangifer tarandus*) antler. Breaking the floor, Philp discovered more fossil bones and within days had secured the site with a locked gate and opened it as a tourist attraction. When Pengelly visited the site shortly afterwards he recognized the potential for an excavation through a largely undisturbed flowstone floor in a previously sealed cave: any artifacts that might be recovered from the bone stratum would be undeniably coeval with the extinct fauna already known to be present. Finding Mr. Philp*…not disinclined to dispose of his Cavern, or rather the right of working it, to any person prepared to pay him well for it* (Pengelly 1858), Pengelly sought to lease the site for excavation. In due course, the Geological Society of London established a Cave Committee and obtained Philp's lease fee of 100 £ from the Royal Society.

THE EXCAVATIONS

Pengelly assumed local oversight of the excavation, and employed Henry Keeping, a professional fossil collector, and local laborers to conduct the actual digging. Excavation began on July 15, 1858. Of great importance, Pengelly devised and introduced a fundamentally new approach to cave (and archaeological) excavation. The standard method of excavation in the mid-1800s was to sink multiple vertical shafts through the deposits, to locate the richest accumulations of bones or artifacts. Little attention was paid to stratigraphy, so that the specimens from different levels were intermingled by the time they reached the museums. Pengelly began with a survey of the cave. Next,

It was decided to remove the stalagmitic floor, then the entire bed immediately below (if not of inconvenient depth) horizontally throughout the length of the cavern, or so far as practicable; this accomplished, to proceed similarly with the next lower bed, and so on until all the deposits had been removed.

The more effectually to guard against the chance of error, the materials were first carefully examined in situ, after which they were taken at once outside the cavern, where they underwent a further inspection. In no instance were they removed, for even temporary convenience, from one part of the cavern to another.

Whenever a bone or other article worthy of preservation was found, its situation (that is to say, its distance from the mouth or entrance of the gallery in which it occurred, as well as its depth below the surface of the bed in which it lay) was carefully determined by actual measurement. In order to [facilitate] *their identification, the specimens were all numbered; those that were found in the same place received the same numeral, and were packed in one and the same box, so that at the close of exploration the number of boxes indicated the number of localities in which fossils had been found; the boxes were distinguished by numbers, each bearing that which each specimen within it bore. Finally an entry of each box was made in a journal, in which were registered the number and situation of the specimens it contained, with the date on which they were found, and occasionally a few remarks respecting them*. (Pengelly *et al*. 1873, p. 482).

Pengelly's survey of the cave, which appears in detail in the Royal Society report of 1873 (Pengelly *et al*. 1873), divides the cave into 8 galleries and 2 chambers. His notation system was based on horizontal distance from the entrance of each gallery or chamber; although only in the case of the first (the Reindeer Gallery) can this point of origin be fixed with reasonable confidence.

Following completion of the Brixham cave project, Pengelly focused his attention on the much larger Kent's Cavern in nearby Wellsworth, Torquay. Kent's Cavern was well known locally and much visited: inscriptions carved into flowstone bosses in the cave date from as early as 1571. Moreover, MacEnery had proven the site to be productive of extinct fauna and human artifacts. Pengelly appreciated that any lingering doubt as to the co-occurrence of humans and extinct species could be dispelled only with a major and very tightly controlled excavation. There must be no doubt as to the exact provenance of each excavated specimen.

Having obtained the provisional consent of the landowner, Sir Lawrence Palk, Pengelly was able to enlist the financial support of the British Association for the Advancement of Science for a sustained campaign. On the September 20, 1864, the British Association passed a resolution establishing the Kent's Cavern Committee, consisting of Sir Charles Lyell, Professor Phillips, Mr. John Lubbock, Mr. John Evans, Mr. E. Vivian, and Mr. William Pengelly, *…for the purpose of promoting researches on special points not yet sufficiently explored in the Kent's Hole, Torquay, provided satisfactory arrangements can be made for the final disposition of specimens; that Mr. William Pengelly be the Secretary; and that the sum of £100 be placed at their disposal for this purpose* (Pengelly1858). The project would eventually occupy Pengelly and his excavators six days a week for 16 years.

The Cavern Committee held its first meeting on November 23, 1864, in the rooms of the Geological Society, London, and Pengelly went to work making the necessary formal arrangements with the landowner and hiring labourers. On March, 19, 1865, Pengelly hired Charles Keeping (brother of Henry Keeping, the Chief Workman at the Brixham Cave excavation), and on March 27, 1865 he engaged George Smerdon. Smerdon was to remain in the employ of the Cavern Committee for its duration, eventually receiving a small pension and assuming the custodianship of the cave, which had become popular with adventurous visitors. Smerdon's son-in-law, Francis Powe, took over the custodianship of the cave from Smerdon and purchased the property in 1903; it has remained in the Powe family to the present day.

Pengelly's excavation system was to become one of the foundations of the modern scientific archaeological method. At Brixham Cave, Pengelly had developed a system to relate the origin of each fossil or artifact to its horizontal position along the length of the relevant gallery, and to its vertical level. In the Brixham cave context, where the passages are rectilinear and quite narrow, this was adequate for Pengelly's purposes. At Kent's Cavern, however, Pengelly faced a much more complex situation. Kent's Cavern is more than 900 m long (although much of that was unknown when Pengelly started work), and several chambers were wide enough that a truly three-dimensional system of documentation was needed.

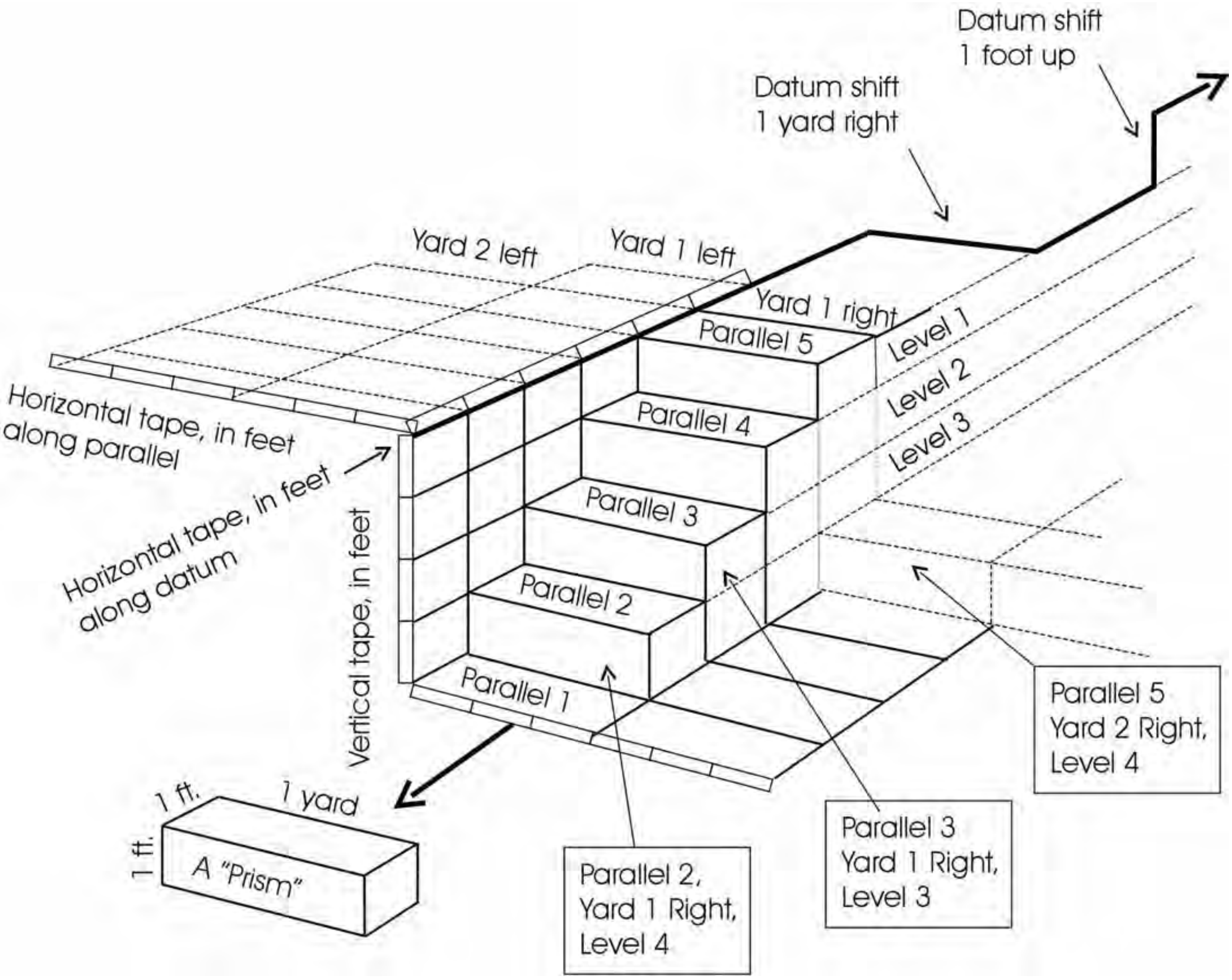


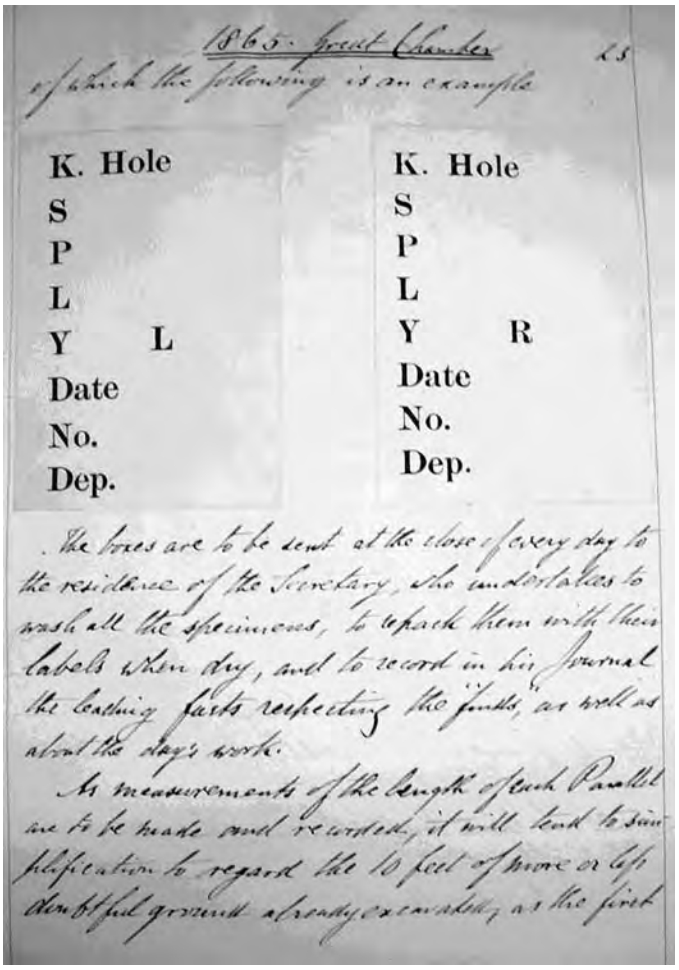
Figure 1. The Pengelly excavation system.

Pengelly's solution was to create a system (Fig. 1) of *Series*, each consisting of a leveled *Datum* line suspended over the cave floor. *Series 1* was tied to the masonry at the South Entrance, and extended 62 ft (19 m)[1] across the Great Chamber to the far wall on a bearing of 275° magnetic (Appendix 1). Each *Series* was intersected by lateral *Parallels* at 90° to the *Datum*, and set 1 ft (0.3 m) apart. Each *Parallel* extended in successive 1 yard (0.9 m) segments perpendicular to the left and right of the *Datum*. Finally, Pengelly added vertical control; he removed surficial deposits and any flowstone capping and then excavated in 4 one-foot (0.3 m) *Levels* (extending this to 9 *Levels* in the Long Arcade). Thus, material was removed in units measuring 1 ft x 3 ft x 1 ft deep (0.3 m x 0.9 m x 0.3 m deep), which Pengelly called *Prisms*. In order to follow the meanderings of the cave passages, Pengelly periodically shifted his Datum line, always at 90° left or right (and/or up and down), by the appropriate number of feet or inches. In Pengelly's own words:

We make a vertical section down through the deposits, say at ten feet from the entrance, at right angles to a datum line drawn horizontally from a point at the entrance to another at the back of the first chamber, in the direction as it happens, of W.5° N. We draw a line at right angles to the datum at eleven feet from the entrance, so as to define or mark off a new "parallel" a foot wide. Along this entire belt or parallel we take off the Black Mould from side to side of the chamber and examine it carefully by candlelight in situ. (Pengelly 1875, p. 16).

The finds from each *Prism* were placed together in their own box, and given a single identifying number. By the time excavations in the cave ended on June 19, 1880, 7340 boxes

[1]Editor's note: English units followed by metric were allowed in this article for historic reasons.


1865. Great Chamber 25
of which the following is an example

K. Hole
S
P
L
Y L
Date
No.
Dep.

K. Hole
S
P
L
Y R
Date
No.
Dep.

The boxes are to be sent at the close of every day to the residence of the Secretary, who undertakes to wash all the specimens, to repack them with their labels when dry, and to record in his Journal the leading facts respecting the "finds", as well as about the day's work.

As measurements of the length of each Parallel are to be made and recorded, it will tend to simplification to regard the 10 feet of more or less doubtful ground already excavated, as the first

Figure 2. An original Pengelly specimen label (Torquay Museum).

had been accessioned, many containing dozens of individual bones, bone fragments, teeth, and artifacts. Each numbered box contained a standardized label (Fig. 2) locating the origin of its contents in three-dimensional cave-space (*Series, Parallel, Yard, and Level*). Pengelly produced monthly progress reports to the Cavern Committee, an annual report to the British Association, the latter being published (Pengelly 1868, 1869, 1871, 1878, 1884), and copious diary notes.

The Pengelly excavation was pioneering in its exactitude, which was not replicated in subsequent cave excavations in Kent's Cavern or anywhere else for decades thereafter; for example, the Torquay Natural History Society excavations in Kent's Cavern, 1926–1940 (Dowie 1928; Benyon *et al*. 1929; Smith 1940). The value of Pengelly's meticulous work in a modern context is enhanced by the fact that Pengelly's diary, more than 900 pages of hand-written notes, survives in the Torquay Museum archives, together with the majority of the specimens. Most of the remaining important specimens (particularly anthropogenic artifacts) went to the British Museum, and the remainder were disbursed in small lots to 15 other museums in Britain, to the Jardin des Plantes in Paris, and to the Smithsonian Institution in Washington D.C. Only Pengelly's charts and maps of the excavation are missing.

Kent's Cavern is now recognized as one of Britain's oldest archaeological sites, having yielded artifacts from all the recognized stages of the Paleolithic. Paleontologically, Kent's Cavern is no less important, having preserved a rich fauna spanning multiple full glacial-interglacial cycles. Remarkably, there has been only a single attempt to utilize the full potential of the archived spatial data. Campbell, in an exercise preparatory to the publication of his *Upper Paleolithic of Britain* (Campbell 1977), attempted to plot the origin of critical specimens excavated from the Great Chamber–South West Gallery area of the cave on a portion of Lake's survey (Lake 1934) of the cave (Campbell and Sampson 1971). Although Campbell's conclusions, based on the vertical distribution of specimens, remain valid, he apparently made some errors of transcription. Since Pengelly's system is always referenced back to the origin of Series 1, any error is propagated through all subsequent Series.

Pengelly's notes and published accounts do not contain any diagrams, maps or stratigraphic sketches. We do know that at least one survey was made, because the costs appear in the financial accountings, but this and other graphical materials have not survived in any known collection. Therefore, we have transcribed the entire sequence of Pengelly's grid system records (78 Series), and plotted them in their entirety for the first time. These records are preserved in multiple manuscript volumes in the collections of the Torquay Natural History Society, usually as daily entries. We have also overlain the resulting "Pengelly grid" on the 1989 survey of the cave (Proctor & Smart 1989) to identify both errors of transcription in Pengelly's records, and the cumulative error implicit in Pengelly's survey technique—undertaken by candle light, in constricted or choked passages not yet cleared of sediment.

METHODOLOGY AND RESULTS

Pengelly's system is referenced to his 1st Series, which began as follows;

A line, termed the "Datum line" was stretched horizontally from a fixed point on the external face of the masonry at the Entrance to another point at the back of the Great Chamber…The direction of this line, carefully ascertained by compass was W.5°N magnetic." (Pengelly diary entry, April 11, 1865).

Because the exact position of the starting point is slightly ambiguous, we used the stated length of the first datum line, "62 feet" (19 m), in conjunction with a laser rangefinder and an obvious projection on the west wall of the Great Chamber to reconstruct the first datum ("Series 1"). Pengelly's compass bearing of "W.5°N magnetic", equivalent to 275° $N_{mag1865}$ in modern terminology, is indistinguishable from our reconstruct-

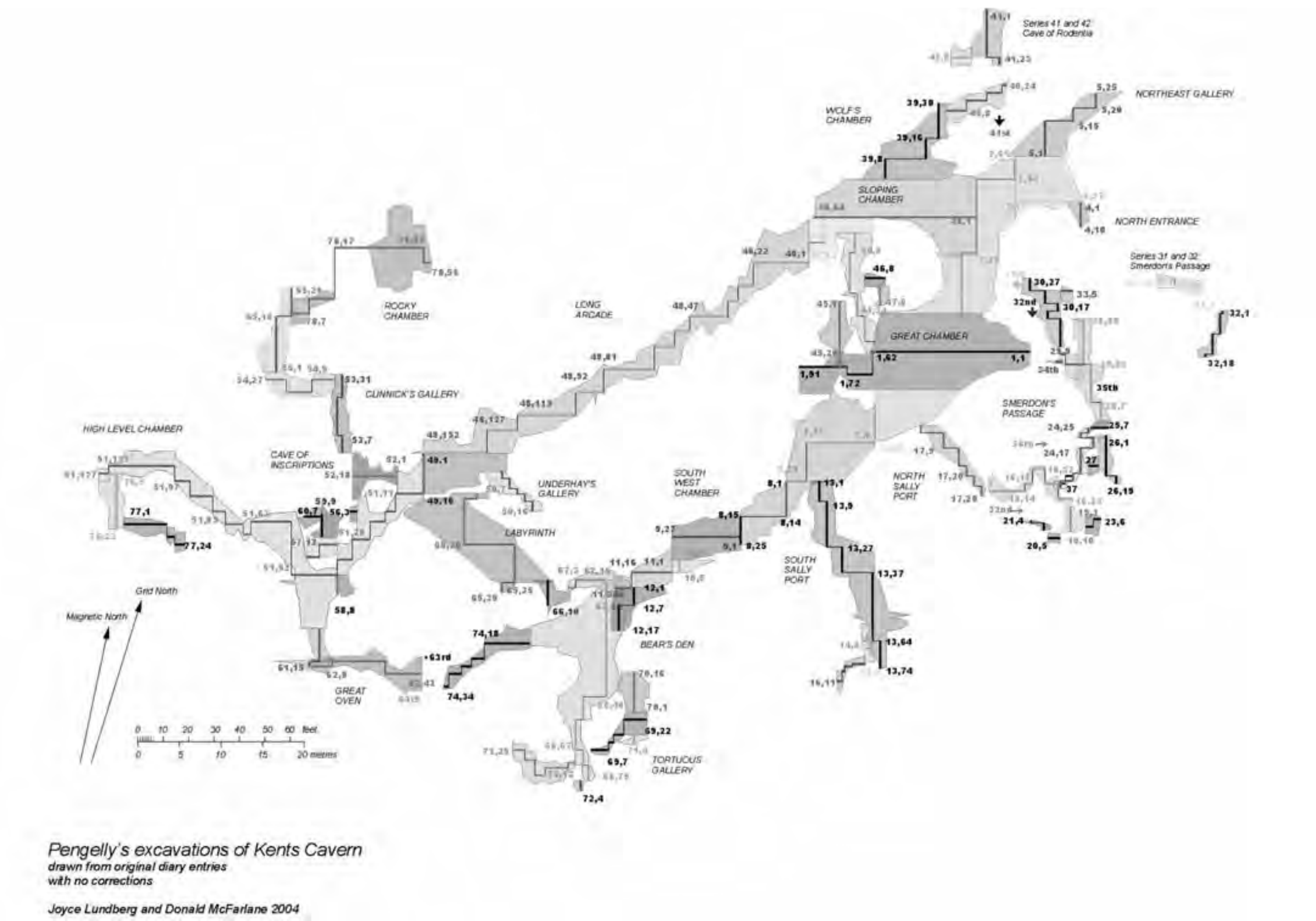


Figure 3. The Pengelly excavations, as recorded without corrections.

ed Series 1 bearing of 252° $N_{mag1989}$ (see Appendix 1). From Series 1, all subsequent series and their parallels were plotted using the datum origins and shifts recorded in Pengelly's diaries. A plot of these data, as transcribed, appears in Figure 3.

We used a modified version of the Proctor and Smart survey of Kent's Cavern, completed in 1989 with a traverse closure error of ~0.5% (Proctor & Smart 1989), and overlaid the Pengelly excavation plot, identifying a number of significant errors. We carefully examined the locations of these errors in the cave, and then made conservative corrections to the Pengelly plot to achieve the best fit with the Proctor and Smart survey (Fig. 4[1]). The apparent errors resulted from (a) occasional misplacement of the origin ("Parallel") of a datum shift, (b) occasional omission of a datum shift from the manuscript record, and (c) most commonly, a cumulative error in establishing offset datums at 90° to their origin. Apparently, after Series 1, datum offsets were set by eye or set-square rather than by compass bearing. A listing of our corrections appears in Appendices 2 and 3.

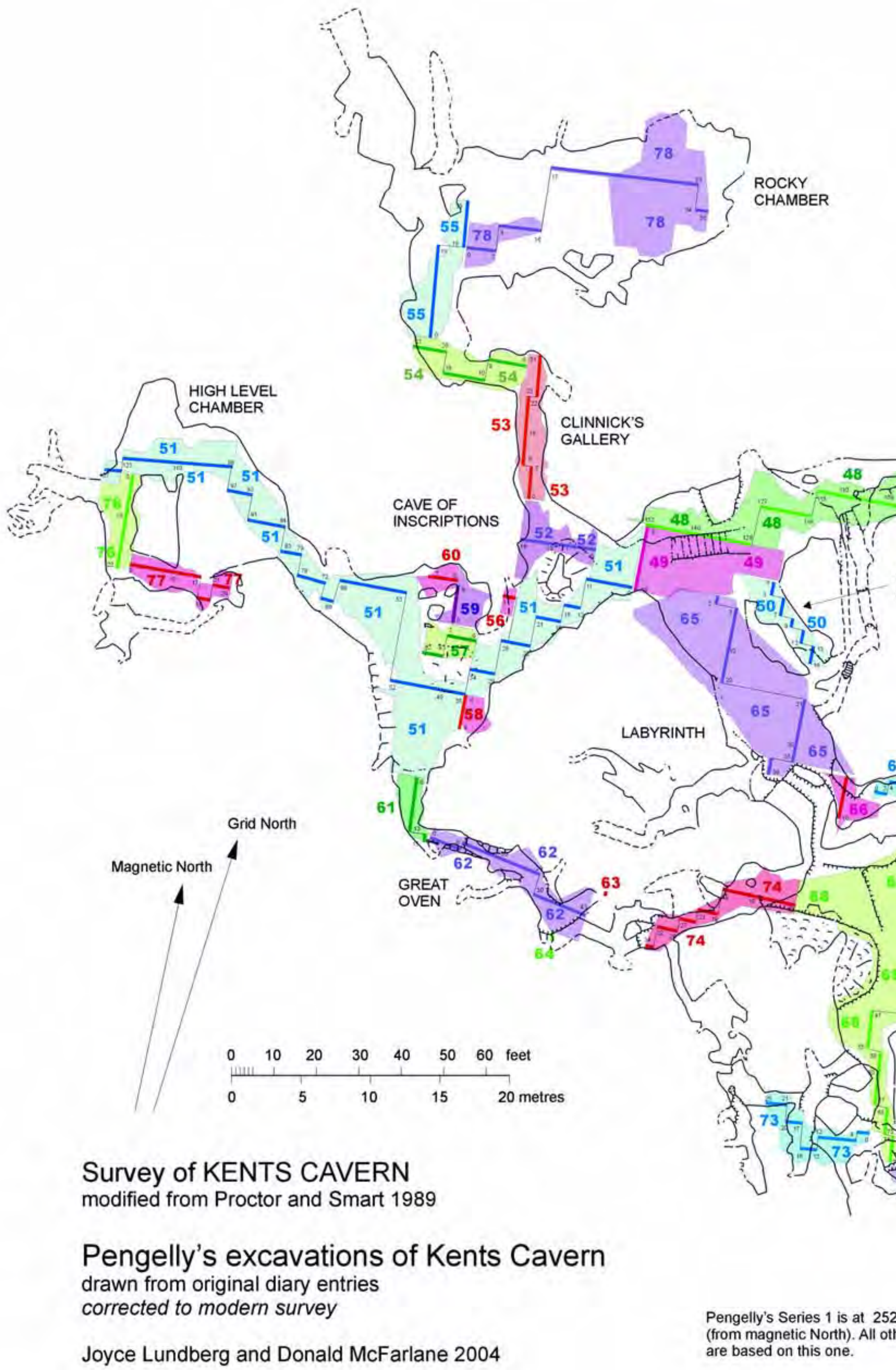
Discussion

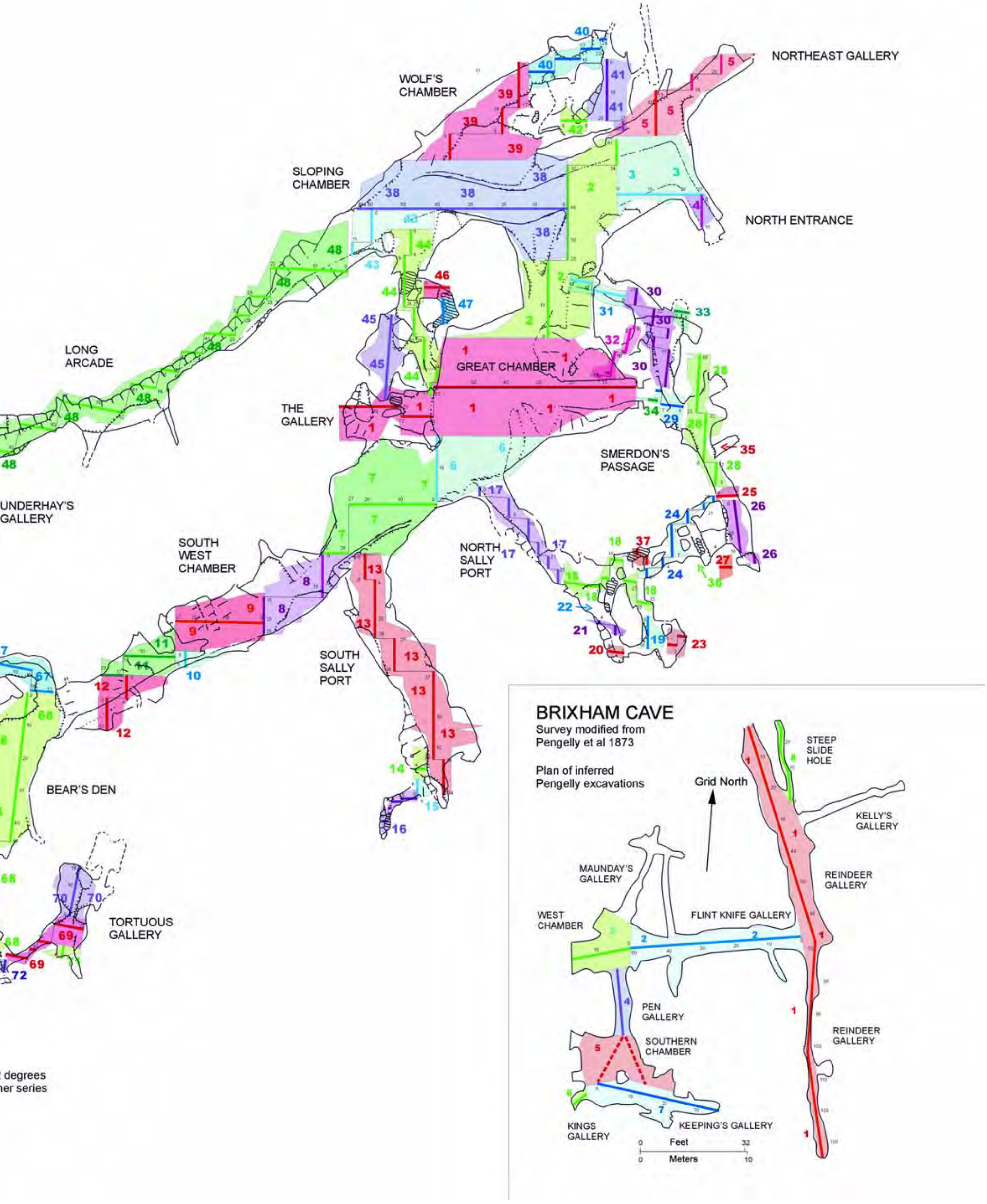
In recent syntheses of archaeological methodology, the origin of modern archaeological excavation techniques in Britain has sometimes been credited to Lieutenant General A. Pitt-Rivers, whose *Excavations at Cranborne Chase* (1887, 1888, 1892, 1898) introduced three-dimensional grids and levels to the excavation of surface barrows (Renfrew & Bahn 2004). However, as Warren and Rose (1994) have pointed out, credit for these innovations is more properly due to William Pengelly, who developed them two decades before Pitt-Rivers began work at Cranborne Chase, and with whose work Pitt-Rivers was demonstrably familiar. Curiously, Pengelly has been more directly credited with the development of these methods in French and American archaeology (Browman 2003).

The very large collections of paleontological and archaeological material from Kent's Cavern have, for the most part, survived and remain an irreplaceable resource for the study of the British Pleistocene; indeed, research continues as new technologies become available (e.g., Bocherens & Fogel 1995). Nevertheless, application of the wealth of information

[1] Available in digital form from the authors, or from the NSS archives.

Figure 4.
The Pengelly excavations, with corrections.




NORTHEAST GALLERY
WOLF'S CHAMBER
SLOPING CHAMBER
NORTH ENTRANCE
LONG ARCADE
GREAT CHAMBER
THE GALLERY
SMERDON'S PASSAGE
UNDERHAY'S GALLERY
SOUTH WEST CHAMBER
NORTH SALLY PORT
SOUTH SALLY PORT
BEAR'S DEN
TORTUOUS GALLERY
degrees
her series
BRIXHAM CAVE
Survey modified from Pengelly et al 1873
Plan of inferred Pengelly excavations
Grid North
STEEP SLIDE HOLE
KELLY'S GALLERY
REINDEER GALLERY
MAUNDAY'S GALLERY
WEST CHAMBER
FLINT KNIFE GALLERY
PEN GALLERY
SOUTHERN CHAMBER
REINDEER GALLERY
KINGS GALLERY
KEEPING'S GALLERY
Feet
Meters

preserved in Pengelly's records has been hindered by the difficulty of extracting this information in the absence of a summary report and plan of the excavations. The presentation of such a plan in this study opens up new possibilities for the analysis of the spatial information in the Kent's Cavern collections.

ACKOWLEDGEMENTS

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Appendix 1. Series 1 Bearings

Pengelly 1865 "W. 5°N magnetic."

Magnetic declination at Kent's Cavern in 1865 was -22.333° (pers. comm. Susan MacMillan, British Geological Survey), making Pengelly's bearing equivalent to 252.67° NGrid. Our plot of Series 1 from Pengelly's notes and in-cave ground truthing is 252° Ngrid

Magnetic north on our survey is plotted for 1989, as per the Proctor and Smart (1989) survey. Nmag1989 was -5.816°, or 354.18° Ngrid (NOAA 2004).

Appendix 2.

Corrections to the Pengelly Plot.

Series 1 drawn at 252 N° magnetic.

At 12th Series there is a cumulative offset of ~2 ft (0.6 m); Series 8 through 12 corrected +1.2°.

Series 11and 12 shifted North 3 ft (0.9 m).

Series 14-15 overlap Series 13; Series 14-16 corrected with a shift 3.6 ft (1.1 m) southwest.

North Sally Port.
Origin of the 17th Series in the 6th Series is too far east. Corrected with a shift of Series 17 through 35 of 5 ft (1.5 m) West (changes 6S/14P from an offset of 18 ft (5.5 m) to offset of 13 ft (4.0 m))

Parallelogram shift of 17th Series by 6° S. (no change in E/W). This ends 17th Series at the correct known landmark.

18th Series moved 3 ft (0.9 m) South.

Smerdon's Passage–each series individually tied to passage.

24th Series; penultimate datum shifts recorded as Left (west) but MUST be Right (east).

Exact position of 37th Series relative to its origin in the 24th Series is very ambiguous in Pengelly's notes; we have fitted it to available unexcavated passage on left of 24th Series.

No obvious modification possible to 28th Series to make it fit. UNRESOLVED.

38th Series (and subsequent connected series) shifted 1.5 ft (0.5 m) North to eliminate overlap of excavations with 2nd Series.

Origin of 48th Series is ambiguous, leading to an error (impossible zig-zag in excavation) at 48th Series. Possible unrecorded datum shift at 48th Series, 47th Parallel. We have inserted a datum shift of 3ft (0.9 m) South.

Rocky Chamber offset, listed as 20 feet left, is too wide for passage (25 ft (8 m) max) – reset to 15ft (5 m).

77th Series, final datum shift switched from Right to Left.

65th Series 1st datum shift moved 5 ft (1.5 m) left instead of right.

68th Series, 2nd datum shift switched from left to Right to bring end into passage and connect line with 69th Series.

48th Series (Long Arcade) progressively deviates from the curvature of the passage; we have corrected for this mis-alignment which therefore affects all subsequent series.

29th Series has to start in the 23rd Parallel instead of 22nd Parallel.

37th Series; origin and directions ambiguous; fitted to passage.

41st series moved to 24th Parallel, 7 ft (2.1 m) right (from 22nd Parallel, 9 ft (3 m) right)

46th direction not indicated in Pengelly notes- must be East

Appendix 3.

Since the position of each Series is dependent on the position of each preceding Series in the sequence, we list these sequences here. {Example; an error or correction in the 9th Series would affect the 10th, 11th and 12th Series but not the 13th Series whose origin is in Sequence 3.} Series underlined and boldfaced are points of origin for subsequent Series.

Pengelly's Series sequences:

1-2-3-4-5

1-**6**-**7**-8-9-10-11-12

7-13-14-15-16

6-17-**18**-19-20-21-22-23

18-24-**25**-26-27

25-28-29-30-31-32-33-34

2-**38**-39-40-41-42

38-**43**-44-45-46-47

43-48-**49**-50-**51**-76-77

51-52-53-54-55-78

51-56

51-57-59-60

51-58

51-76

51-58

51-61-62-63-64

49-65-66-67-**68**-69-70-71-72

68-73

68-74

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KARST DISTRIBUTION AND CONTROLS ON YORON-JIMA, AN EMERGED REEF ISLAND IN SUB-TROPICAL JAPAN

JAMES P. TERRY
Head of Geography Department, The University of the South Pacific, Private Mail Bag, Suva, FIJI ISLANDS

Yoron-jima is a small carbonate island located in the central Ryukyu Island Arc of southern Japan. The island was raised above sea level in the Quaternary period, and most of the 21 km² land area is underlain by carbonate rock types associated with the regional Ryukyu Limestone Group. The island's landscape is characterized by many surface depressions. This paper describes Yoron's closed depressions and interprets their uneven spatial distribution. Some areas covered by unconsolidated Holocene deposits are almost free of closed depressions. Elsewhere, depression clusters are observed on a variety of carbonate rocks. Small depressions (average long axis 76 m, area 2320 m²) tend to be shallow with regular elliptical morphologies, and are densely clustered. These have developed on a low elevation, emerged marine platform on the island's western peninsula, where there has been minimal structural deformation of the coral limestone bedrock. In contrast, larger (average long axis 103 m, area 4060 m²) and deeper closed depressions (5–10 m), more often with irregular or star-shaped plans, have developed across the north and east-central region of Yoron, in association with 1.) outcrops of rhodolith limestone geology, 2.) major fault escarpments, and 3.) carbonate/non-carbonate geological boundaries. Aggressive dissolution has also produced large elongated closed depressions trending along the northeast coast of Yoron close to sea level, where tidal fluctuations control the salinity and surface height of the water table. Correlation with depressions elsewhere in the Ryukyu Islands on similar geology suggests that limestone surface denudation rates on Yoron may be 5–10 mm/1000 yrs.

Although there are a large number of both wholly carbonate and composite carbonate/volcanic islands in the humid tropical Pacific, there has been less attention given to Oceania in the karst literature than elsewhere. This is, in part, a function of the remoteness for research purposes of most of the small "outer" islands of the Pacific. The work by Ollier (1975) on the Trobriand Islands of Papua New Guinea, Montaggioni *et al.* (1985) on Makatea in French Polynesia, Strecker *et al.* (1986) on Santo island in Vanuatu, Mylroie *et al.* (2001) on Guam and Terry & Nunn (2003) on Niue are some exceptions. This paper describes Yoron Island of southwest Japan, a small raised limestone island in the center of the Ryukyu Island Arc chain (Fig. 1). Yoron's geology mainly comprises Miocene to Holocene age carbonate rocks and deposits, uplifted to different elevations above sea level. The island is partially karstified, although the distribution of karst features across the island is uneven. Yoron therefore presents an interesting opportunity for the study of karst geomorphology on a small emerged carbonate island. The aim here is to examine the form and distribution of closed depressions on Yoron Island and to interpret their occurrence in terms of geological influences.

PHYSICAL SETTING

Yoron's location is 27°01'N, 128°24'E, near the large volcanic island of Okinawa to the southwest. The circumference measures approximately 23 km and the land area covers just 21 km². The resident population numbers around 6000. Most of the native sub-tropical forest cover has been cleared. Sugar cane farming and beef cattle grazing are now the two predominant agricultural land uses. Yoron's climate is subtropical, with a mean annual temperature of 23°C and an annual precipitation of approximately 2200 mm. Typhoons often bring torrential rains during the summer and early autumn seasons from July to September.

Yoron Island was slowly raised above sea level during the Pleistocene (Omura 1972). Inland Yoron can be divided into several main geomorphic zones, reflecting the influences of uplift and structural geology. The western peninsula is a flat limestone lowland between 5 m and 20 m above sea level. Traversing the island from NNW to SSE is an escarpment occurring along a pair of parallel faults. The scarp slope rises to 50–90 m elevation. The highest point of the island at 97 m elevation lies along the top of the escarpment near its southern end. The north and eastern topography of Yoron, east of the top of the escarpment, is a series of low undulating hills, which gradually lose altitude towards the east coast. These may represent a series of denuded marine terraces indicating intermittent uplift processes or still-stands of paleo-sea level. Inland from the eastern coast is an area of Holocene coralline deposits forming low relief dunes. The subdued relief in the eastern segment is broken by an unusual narrow arcuate ridge of outcropping reef limestone called Uro Yama. The ridge is 20–100 m wide, rising 10–20 m above the surrounding terrain.

Since Yoron's bedrock geology mostly comprises permeable carbonates, there are no permanent surface watercourses. Ephemeral streams drain the area below and to the west of the fault escarpment into Haki Bay and Chahana Bay. Within the limestone bedrock beneath the surface, there exists a large freshwater aquifer. In the eastern segment of the island, Momii *et al.* (2001) calculated that this aquifer is 30–40 m thick, using a numerical approach based upon measurements of the fresh-

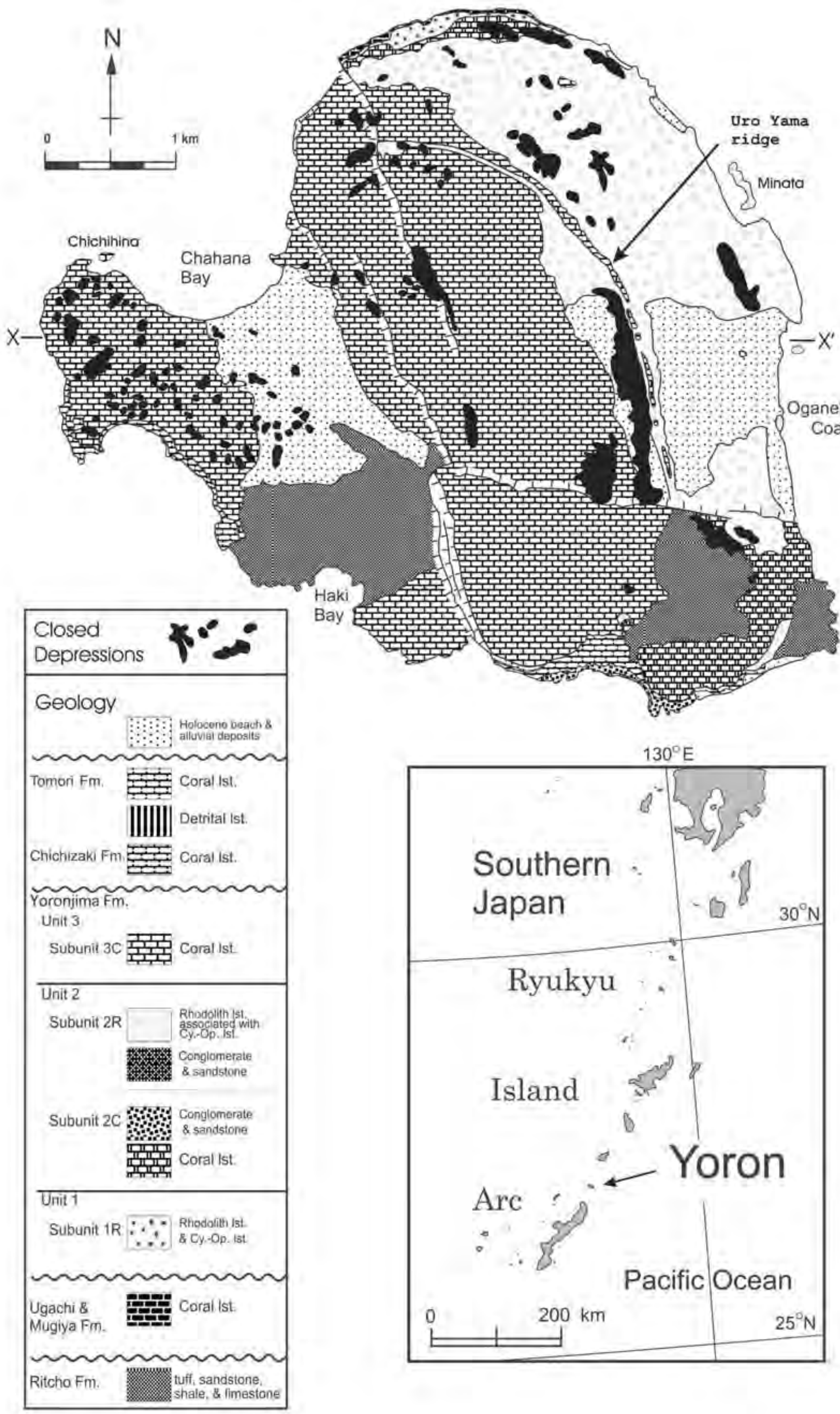

Figure 1. Location of Yoron Island in the Ryukyu Island Arc chain, simplified geology of Yoron (by Odawara and Iryu 1999), and map of enclosed depressions. X–X' shows the line of cross section in Figure 2.

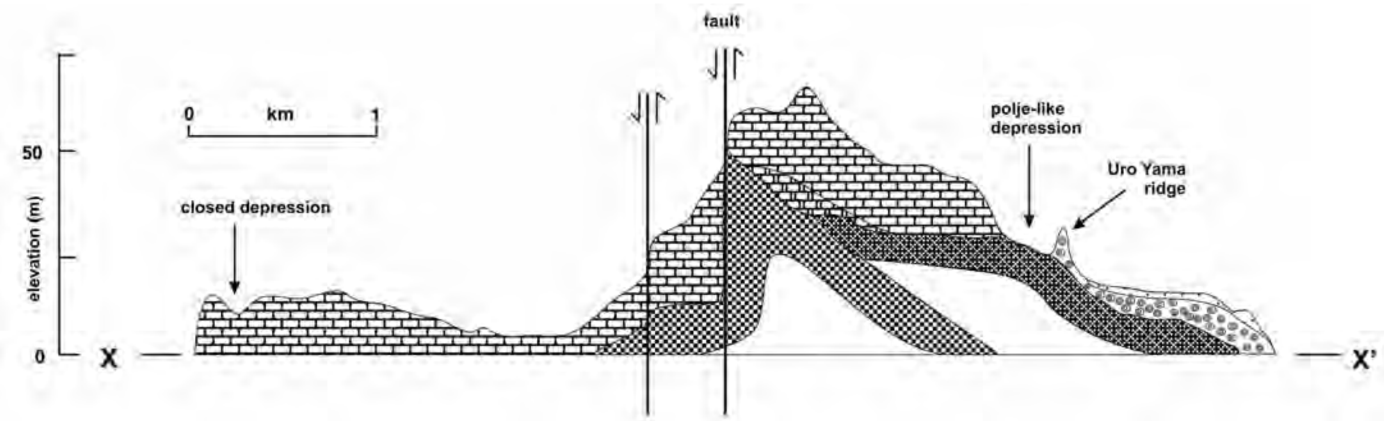

Figure 2. A geologic cross section of Yoron island by Odawara and Iryu (1999).

water lens surface in 10 groundwater wells. The lens may be thicker still towards the center of the island where there is a greater depth of limestone bedrock. Momii *et al.* (2001) also estimated the hydrological balance of the aquifer (evapotranspiration 45%, runoff 15%, groundwater recharge 40%) and hydraulic conductivity of the freshwater zone and effective porosity of 0.28 cm s^{-1} and 0.08, respectively due to the presence of unconsolidated clays contained in pores influencing the limestone permeability.

GEOLOGY

The Ryukyu Island Arc is produced as the result of the northwest movement of the Philippine Sea Plate and its subduction under the Eurasian continental plate at the Ryukyu Trench. Yoron exists as a series of raised Pleistocene limestone terraces, overlying folded and faulted Mesozoic basement rocks of various lithologies associated with volcanism. Odawara and Iryu (1999) have constructed the latest geologic map of the island (Fig. 1). Their work supersedes previous geologic maps and makes major revisions to earlier limestone stratigraphy.

Yoron is a composite island according to the Carbonate Island Karst Model (CIKM) of Mylroie & Jenson (2000). The oldest surface rocks on Yoron are of Mesozoic age, known as the Ritcho Formation. These are strongly altered slates, volcanic greenstone (diabase), tuffs, sandstones and detrital limestones, which crop out in two separate areas in the south and southeast of Yoron. Lying unconformably above are Pleistocene-age limestones of the Yoronjima Formation, equivalent to the Gusuku and Nama Formations described in earlier work by Omura (1972). The Yoronjima Formation is the predominant carbonate sequence on Yoron and occurs over approximately 70% of the island, with a maximum thickness of 55 m. From the evidence of stratrigraphic position and age-diagnostic fossils, Odawara and Iryu (1999) suggest that the Yoronjima Formation may be correlated with the main Ryukyu Group limestones, which are widely distributed throughout the Ryukyu Islands (Nakamori *et al.* 1995). On the nearby islands of Okinoerabu and Tokunoshima, the Ryukyu Group limestones range in age from 390 to 890 ka.

The Yoronjima Formation is extensively exposed on Yoron and has a basal unit of conglomerate of angular pebbles, cobbles and boulders (Omura 1972). The clasts are derived from the underlying Mesozoic age Ritcho Formation. The upper unit of the Yoronjima Formation can be broadly differentiated into two types of carbonate rocks, proximal coral limestone and distal rhodolith limestone (algal ball limestone). The latter has more than 20% concentration by volume of rhodoliths (algal balls), deposited in an insular shelf environment at 50–100 m depth. Distal rhodolith limestone is a hard, massive limestone, and is the bedrock in the northeast segment of the island. The proximal coral limestone is a massive indurated limestone, showing framework structures of hermatypic corals and other fossils of coralline algae, foraminiferans, molluscs, bryozoans and echinoids (Omura 1972). The coral limestone formed as a reef flat and forereef slope 0–50 m deep. It occurs on the western peninsula and as a broad band 1–1.5 km wide traversing NNW–SSE across the center of the island.

Several normal faults run NNW–SSE and W–E across the latter area, and are expressed as escarpments in the island's topography as described earlier. The eastern side of the main NNW–SSE fault is the upthrown block, and has therefore been raised to a higher elevation above sea level. Faulting is probably still active (Odawara & Iryu 1999), and is probably associated with expansion of the nearby back-arc basin called the Okinawa Trough during the Holocene (Kawana 2001). A geologic and topographic cross section from west to east across Yoron, from Odawara & Iryu (1999), is shown in Figure 2.

Holocene beach and alluvial deposits are found covering low-lying areas behind Chahana Bay and Oganeku Beach. Limited exposures of cemented beachrock also occur in several coastal locations. Throughout the Ryukyu Islands, Holocene reefs began forming on older carbonate foundations around 8,500 years to 8,000 years BP. Yoron's Holocene reefs appear to have grown at 1–3 mm a year, and reached modern sea level about 5,000 years ago (Kan *et al.* 1995). The thickness of Holocene reef deposits ranges from 3 to 15 m. Today, Yoron is fringed by coral reefs around almost the entire coastline.

CHARACTERISTICS AND DISTRIBUTION OF SURFACE DEPRESSIONS

The Geographical Survey Institute of Japan (1976) has produced a detailed topographic map of Yoron at 1:25,000 scale. This map was used here to examine the distribution and size of depression features across Yoron. In addition, fieldwork on Yoron was carried out in December 2003 to examine the characteristics of various individual depressions.

The map in Figure 1 shows that Yoron has many closed depressions, but that their spatial distribution over the island is very uneven. Concentrated depression swarms occur in some areas whereas elsewhere closed depressions are absent. The southern and eastern segments of the island, as well as the center of the island, are virtually depression-free. In the east, the lack of closed depressions may be explained by bedrock porosity and hydraulic conductivity. Here, Momii *et al.* (2001) monitored groundwater fluctuations in several boreholes as part of their study on tidal influences on the freshwater aquifer. They noted that the relatively low permeability of the bedrock is influenced by the presence of unconsolidated clay contained in pores. Another factor for the lack of closed depressions in the two areas of Holocene beach and alluvial deposits (inland of the east coast and west of the escarpment) is that these unconsolidated coralline materials are less suitable for retaining depression structure, compared to hard and jointed bedrock in adjacent areas. Closed depressions are also absent on the two outcrops of Mesozoic basement rocks (Ritcho Formation slates, volcanic greenstone and sandstone) in the southeast and southwest sectors of the island.

In the central east of Yoron is the island's largest surface depression, oriented in a N–S direction. This 2-km-long linear depression is a low-lying trough, partly infilled with Holocene deposits, and gives the initial impression of a polje-type feature. However, closer inspection of the local geology shows that the trough is bounded by gently dipping rocks on the western side and on the east by the 10–20 m high Uro Yama arc-shaped ridge of reef limestone described earlier. Although the origin of Uro Yama remains unclear, the origin of the adjacent large depression is probably neither a true karst feature, because there is no source for allogenic water to account for increased dissolution rates, nor a graben-like feature formed by structural deformation because there are no faults associated with the Uro Yama ridge. The depression is probably a constructional feature inherited from an original topographic low formed between different carbonate facies during deposition.

Elsewhere on Yoron, there are two notable areas where depression swarms are observed, although these areas differ in terms of depression sizes and clustering. The smaller cluster, but the one with the highest concentration of closed depres-

Table 1. Size characteristics of all closed depressions on Yoron Island.

Ranked maximum length across enclosing contour (m)							Ranked area (m^2 x 1000)						
Western Peninsula				**Northern and Eastern Area**			**Western Peninsula**				**Northern and Eastern Area**		
44	63	76	101	52	89	163	1.16	1.74	2.32	4.06	1.16	2.32	8.13
45	63	77	107	58	91	169	1.16	1.74	2.90	4.06	1.16	2.32	9.29
48	64	78	110	60	91	185	1.16	1.74	2.90	4.06	1.16	2.90	9.29
49	64	78	111	62	95	190	1.16	1.74	2.90	4.65	1.16	2.90	13.35
50	65	79	113	62	99	268	1.16	2.32	2.90	4.65	1.16	3.48	19.74
50	67	82	116	64	101	330	1.16	2.32	2.90	4.65	1.16	3.48	19.74
57	67	82	126	64	103	348	1.16	2.32	2.90	5.23	1.74	3.48	21.48
62	68	82	132	66	103	350	1.16	2.32	2.90	5.81	1.74	4.06	22.06
62	68	84	132	66	103	369	1.16	2.32	2.90	6.39	1.74	4.06	23.23
62	73	86	140	66	105	381	1.16	2.32	2.90	6.39	1.74	4.06	24.97
63	73	86	140	68	113	439	1.74	2.32	2.90	6.97	2.32	4.65	31.93
63	76	88	149	72	124	470	1.74	2.32	3.48	7.55	2.32	5.81	39.48
63	76	89	150	78	128	470	1.74	2.32	3.48	8.13	2.32	5.81	44.13
63	76	89	151	80	130	546	1.74	2.32	3.48	8.71	2.32	5.81	59.81
63	76	91	160	82	140	591	1.74	2.32	3.48	9.87	2.32	6.39	96.39
63	76	94	252	87	161	1690	1.74	2.32	3.48	20.32	2.32	6.97	232.83
63	76	94	285				1.74	2.32	3.48	29.03			
63	76	98					1.74	2.32	3.48				
Number of depressions			71			48				71			48
Mean			89			205				3.68			16.09
Median			76			103				2.32			4.06
Standard Deviation			42			262				4.13			36.57
Total			–			–				261.29			772.25

Note: The contour interval is 5 m on the 1:25,000 scale 1976 topographic map of Yoron.

sions, occurs on Yoron's western peninsula. This is a low-lying platform of Yoronjima coral limestone, 5–20 m above sea level. The northern and southern bays of the western peninsula are cusp-shaped. From the work of Back *et al.* (1979) along the Yucatan coast of Mexico, a cusp morphology suggests coastal limestone dissolution by freshwater/seawater mixing. Yoron's western peninsula has 71 individual closed depressions with a total area of 21.6 hectares in an area of approximately 3 km². The relative area of the peninsula covered by depressions is therefore approximately 7.2%. During fieldwork, it proved impossible to measure depression depths or side wall angles because they tend to contain good accumulations of soil and are therefore farmed with sugar cane. Others have been mechanically excavated and lined, to be used as water reservoirs for sugar cane irrigation (Fig. 3). However, most of the closed depressions on the western peninsula were observed to be simple elliptical, shallow, saucer-shaped features, less than 4 m in depth. The median measurement of depression long axes is 76 m, generally without a large range in size of individuals from this average (Table 1). Median depression area is 2320 m² (medians are given because the population means may be skewed by a few large individuals).

According to the karst research of several workers, (e.g., Mylroie & Carew (1995) and Wilson *et al.* (1995)), the closed depressions produced by dissolution on young carbonate islands are of small to modest size, (i.e., meters to tens of meters). This is because "areas with autogenic recharge are unlikely to develop deep depressions because dissolution tends to be dispersed rather than focused" (Mylroie *et al.* 2001, p. 13). Most of the small depressions on Yoron's western peninsula seem to fit this general model.

The other important area of depressions is in the northern and east-central segment of Yoron. The bedrock here comprises both coral and rhodolith limestones. The landscape is an area of low hills with gentle topography, 10–50 m above sea level. Figure 1 shows that there are fewer closed depressions here, more widely dispersed and exhibiting less clustering compared to Yoron's western peninsula. However, the north and east-central area has generally large closed depressions. This area also has the deepest depressions on Yoron—those formed along the base of the fault escarpments reach 5–10 m in depth. Measurement of 48 closed depressions in the northern and east-central area gives median values for depression long axes and area of 103 m and 4060 m², respectively. The total area of all depressions is 77.2 hectares, within a region of 13.67 km² (i.e., 5.6 % coverage).

The average depression size in the northern and east-central region is skewed by three sub-sets of large closed depressions within the population. Several large depressions are those with star-shape or irregular plans, rather than the more usual elliptical morphology. Star-shaped depressions are produced where dissolution has caused several smaller depression perimeters to coalesce into a single feature. These occur most often in the northeast of Yoron on the rhodolith limestone, suggesting that this rock type may be more soluble than the adjacent coralline rock. An alternative origin for star-shaped and irregular depressions is increased dissolution along the intersection of several bedrock fractures. This would suggest that the rhodolith limestone is more fractured than the coral limestone, but this idea cannot be independently substantiated by evidence from existing geologic maps, which only indicate the occurrence of major faults and not the extent of bedrock fracturing.

Figure 3. Top: Typical small shallow depression on Yoron; most closed depressions are used for agriculture. Bottom: Excavated and lined depression to be used as a water reservoir for irrigation.

A second sub-set of large depressions are those lying along the base of fault escarpments, and at the northern edge of the exposure of Ritcho Formation geology in the southeast of Yoron. The depressions in escarpment-foot locations are subject to more aggressive dissolution than elsewhere. Evidence for this idea is that the small ephemeral streams on Yoron also have their source areas at the base of these escarpments, and must therefore be receiving fault-guided resurgence of groundwater from the higher land to the east. In the case of the large depressions along the edge of Ritcho Formation rocks, aggressive dissolution is likely to be associated with allogenic water originating on these non-carbonate rocks and funnelled to the contact with the adjacent Yoronjima Formation carbonates.

The third sub-set of large closed depressions is a chain of four elongated features formed along the north and east coasts. The orientation of their long axes trends very closely to the shoreline. This trend is explained as follows. Weathering at the base of elongated coastal depressions which mostly lie at or close to sea level is enhanced by the rapid dissolution typical at the brackish mixing zone between the fresh groundwater lens and seawater, because the coastline marks the groundwater aquifer transition zone between freshwater and saltwater (see Gillieson 1996). This is supported by the work of Momii *et al.* (2001), who observed that the coastal zone of Yoron's aquifer is strongly affected by tidal fluctuations. Thus bedrock dissolution and depression formation is encouraged by the vertical movement of the aquifer surface with every tidal phase. Any large coastal depressions which are more than 1 m above sea level, and therefore not affected by present tidally-induced fluctuations of the freshwater lens, probably represent paleo-features nonetheless developed in a similar way during a previous sea-level stillstand, when they were at sea level. Nunn (1994, p. 199) points out that on small limestone islands, dolines occurring along the coast and being breached by the sea commonly give rise to a coastline where an erosional outlier is found at the entrance to a bay. This idea may present a reasonable origin for the small islets called *Minata* and *Chichihina* lying short distances off Yoron's northeast and northwest coasts.

The closed depressions on Yoron are comparable with those on nearby Okinoerabu Island, which lies 27 km to the northeast of Yoron and has similar uplifted Pleistocene geology of the Ryukyu Group limestones. On Okinoerabu, Maekado (1984) examined the shape of 10 closed depressions at 30–40 m above sea level. The plan view of Okinoerabu closed depressions was found to be circular or elliptical, with cross-sections generally bowl-shape. The average measured long diameters of depression mouths was 57 m and depression bottoms was 43 m (Ryukyu University 1976). Depression side-wall angles range 10°–26° and depths 1.6–5.1 m. Using the 313–625 ka age range for the limestone determined by electron spin resonance (reported by other workers), Maekado (1984) estimated the rate of surface lowering by solution to be 5.0–9.9 mm per 1000 years.

CONCLUSIONS

Yoron is a small carbonate island in the central Ryukyu Island Arc of southern Japan, formed by the Quaternary uplift and emergence of coral reefs and associated carbonate rocks. The sub-aerial geology therefore comprises an interesting range of lithologies, including Pleistocene fossil reefs, rhodolith (algal ball) limestone and partly-cemented Holocene coralline sands and gravels. The most abundant karst features in the landscape developed on these carbonate sequences are a variety of closed depressions. These have formed as a result of the interaction of uplift, faulting and dissolution processes, and are influenced by changes in carbonate geology across the island. According to location, Yoron's closed depressions display differences in maximum long axes (medians 76 m and 103 m), shape (elliptical, elongated, irregular or star-shape), depth (< 5 m or 5–10 m), size (0.23–0.41 Ha) and relative density (5.6–7.2% cover).

Factors controlling these depression characteristics, and their uneven spatial distribution, include bedrock type and permeability, juxtaposition along the base of fault escarpments or carbonate/non-carbonate geologic boundaries, and the effects of tides on coastal water table fluctuations and consequent freshwater/saltwater mixing. The primary origin of the largest polje-like feature in the center of the island is not dissolution, but probably inheritance from the morphology of original reef-and-shelf construction. Correlations with other Ryukyu Islands nearby suggest that limestone surface lowering rates may be 5–10 mm per 1000 years. The karst geomorphology is an important economic asset for Yoron, as many closed depressions are now excavated for water storage reservoirs in the absence of rivers on the island.[1]

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[1] Most of the depressions now exhibiting anthropogenic modification were excavated after the surveying for the 1976 topographic map used in this study, so the reliability of depression measurements is not affected.

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DISCUSSION: PERSISTENT COLIFORM CONTAMINATION IN LECHUGUILLA CAVE POOLS

Hazel A. Barton
Department of Biological Sciences, Northern Kentucky University, Highland Heights, KY USA
Norman R. Pace
Department of Molecular, Cellular and Developmental Biology, University of Colorado, Boulder, CO USA

Hunter *et al.* (2005) recently reported, based on crude presumptive tests, that *Escherichia coli* is present within many of the drinking pools of Lechuguilla Cave, indicating fecal contamination of these pools by explorers. We believe that these results are misrepresented and do not accurately reflect the presence of fecal contamination within these pools.

The bacterium *E. coli* is a common resident of the intestinal system of most mammals, but is generally not known to persist for more than about 2–3 weeks in the environment (Neidhardt *et al*. 1996). *E. coli* is also easily identified by its ability to grow in the absence of oxygen (referred to as fermentation) on lactose with the production of acid and gas. The source of *E. coli* in the mammalian intestinal tract, its easy identification and rapid loss from the environment allows this bacterium to be used in the rapid identification of fecal contamination incidents *(*Edberg *et al*. 2000). Although the concept of using *E. coli* as an indirect indicator of water quality and health risk is sound, it is complicated in practice. This is due to the presence of other enteric bacteria such as *Citrobacter*, *Klebsiella* and *Enterobacter* that can also ferment lactose and are similar to *E. coli* in phenotypic characteristics (Holt *et al.* 2000). As a result, the term "coliform" was coined to describe this group of enteric bacteria. Coliform is therefore not a taxonomic classication, but rather a working definition to describe a group of Gram-negative, facultative anaerobic rod-shaped bacteria that ferment lactose to produce acid and gas. Consequently, while the presence of coliforms in the environment may be indicative of fecal contamination, it is by no means a confirmation of the presence of *E. coli* or direct evidence of fecal contamination itself. Rather, these tests are considered presumptive and must be followed by additional experiments to either conclusively confirm or rule out the presence of fecal *E. coli* strains (USEPA, 2001).

In their study, Hunter *et al.* used a number of presumptive tests to determine whether the lakes in Lechuguilla Cave were contaminated with fecal coliforms. These tests included the LaMotte [sic] Company TC-5 coliform indicator test, the most probable number (MPN) test and the use of mENDO indicator plates. The TC-5 coliform test is used to identify lactose fermentor species with the production of acid and gas (LaMotte Company, personal communication, 2005). The most probable number (MPN) test contains the detergent lauryl sulfate, which excludes the growth of gram-positive bacteria and false positives by members of the *Lactobacilli, Propionibacteria, Serratia and Streptococci*. Finally, the mENDO agar test is slightly more selective for coliforms, with the addition of deoxycholate to limit the growth of *Proteus* species. Nonetheless, members of the genus *Aeromonas*, which are routinely identified in karstic waters, display an identical growth pattern to *E. coli* on mENDO plates (D. Lye, EPA, personal communication, 2005; Legnani *et al*., 1998). Each of these tests is presumptive: in order to conclusively identify fecal contamination within this water, the presence of thermotolerant *E. coli* must be identified by growth at 44.5°C (Edberg *et al*. 2000; Neidhardt *et al*. 1996). Indeed, standard regulations by the Environmental Protection Agency (EPA) and the American Public Health Association require presumptive tests to be confirmed by the mTEC test for thermotolerant *E. coli* before any statement regarding fecal contamination can be made (USEPA, 2001).

We therefore believe that the results presented by Hunter *et al.* (1995), while indicative of lactose-fermenting bacterial species within the pools of Lechuguilla Cave, do not represent conclusive evidence of fecal contamination; for example, in a recent study on bacterial species isolated from Carlsbad Cavern, Barton and collaborators were able to demonstrate that 23% of isolated species demonstrated sufficient lactose fermentation to produce a false positive coliform test (Barton, unpublished results, 2005). It is interesting to note that the MPN tests carried out by Boston failed to identify coliforms within many of these pools during 1999 (Hunter *et al.* Table 1, we assume 'ND' corresponds to microbiological convention of 'none-detected', although this is not claried in the paper), which may reflect the more selective nature of this test (Hunter *et al.*, 2004).

Following the identification of lactose-fermenting species within the cave pools, Hunter *et al.* proposed that microbial biofilms forming on tubing support the growth and persistence of *E. coli* species. Such a hypothesis, and the data presented in Figure 6, would imply that *E. coli* was selectively enriched by the presence of this biofilm. Given the nature of biofilm structure and formation, this enrichment would suggest that *E. coli* demonstrated either a grazing or predatory nature (Hall-Stoodley *et al*. 2004). This behavior would be the first description of any such activity by this highly characterized organism (Neidhardt *et al.* 1996).

To support their biofilm hypothesis, Hunter *et al.* presented a bacterial growth curve that they propose demonstrates an enrichment of *E. coli* growth in the presence of biofilm material (Hunter *et al.* Figure 6). The investigators clearly state that these tubes were set up with a "loop-full" of *E. coli* starter culture, rather than a defined number of bacterial colony forming units. While the investigators control against the numbers of organisms at Day 0, there is no accounting for how the variability in the total number of cells added may affect the growth rate. It is known that cell density, access to nutrients and quorum sensing have significant effects on the growth rate of *E. coli*, but the investigators did not control against this variability (Neidhardt *et al.* 1996; Sperandio *et al*. 2001). There is also no indication that the experiment was performed in triplicate (with no error or standard deviation bars on Figure 6) to control against the inherent variability in growth assays. Finally, the experiment was only carried out for six days in a medium that was shown to support the growth of *E. coli*, preventing any conclusions from being drawn regarding persistence. This makes it impossible to conclude from the data presented in Figure 6 whether the biofilm material is directly responsible for *E. coli* growth and long-term persistence.

It is the transient nature of *E. coli* in the environment that makes it such an ideal indicator organism of fecal contamination (Edberg *et al*. 2000; Neidhardt *et al.* 1996; Sperandio *et al*. 2001). The only exception to this rule is in highly organic-rich tropical soils and effluent pools associated with animal farming *(Carrillo et al. 1985; Rahn et al*. 1997). Numerous research groups have attempted to identify conditions that would promote *E. coli* long-term survival in low-nutrient conditions without success, while other investigators have suggested that *E. coli* may survive extended starvation by entering the viable but non-culturable state (Bogosian *et al*. 1996; Carrillo *et al.* 1985). However, to date it has not been possible to demonstrate the persistence of this organism within the environment or entry into the VBNC state (Bogosian *et al*. 1998; Bogosian *et al*. 1996). In conclusion, we believe that the work presented by Hunter *et al.* does not provide sufficient evidence to conclude that there is fecal contamination within the pools of Lechuguilla Cave, or that this paper demonstrates a dramatic shift in our understanding of the natural history and ecology of *E. coli*.

The work carried out by Hunter *et al.* should be commended for its goal toward understanding the impact that human activity has on pristine cave environments. Their demonstration that certain tubing is inappropriate for long-term storage within the cave and should be replaced by non-biogenic formulations is an important step toward minimizing impact during exploration. Nonetheless, with new microbial species and phylotypes being identified on a regular basis in cave environments, we should be careful when using tests that have been developed for chemically defined surface environments to analyze microbial communities within caves (Barns & Nierzwicki-Bauer 1997; Barton *et al*. 2004; Chelius & Moore 2004; Kuznetsov *et al*. 1979; Northup *et al*. 2003; Pedersen 2000; Sarbu *et al*. 1994).

Finally, while it is important to monitor and limit human impact in cave environments, our understanding of the structure and potentially unique microbial habitats that these caves represent is still solely dependent on the initial exploration and description by speleologists; there remains a delicate balance between the appropriate techniques to safely map and explore cave environments and the needs of minimal impact to conserve them. As microbiologists, with a much deeper understanding of the intricacies of microbial growth and metabolic activity, it is essential that we take a great deal of care when providing material to cavers and land managers who may not be able to objectively critique microbiological data. Such care is especially important, given that resultant management decisions could have profound impacts on our abilities as microbiologists to identify and understand microbially-important cave environments in the future.

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FORUM: PERSISTENT COLIFORM CONTAMINATION IN LECHUGUILLA CAVE POOLS

DONALD G. DAVIS
441 S. Kearney St., Denver, CO 80224-1237 USA dgdavos@nyx.net

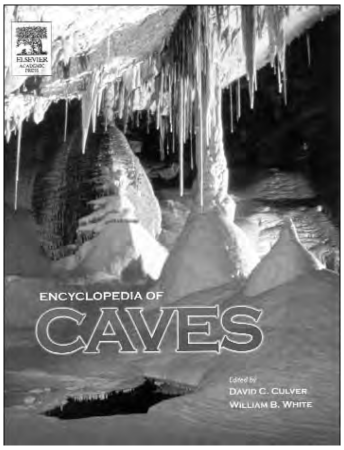
As an active explorer, surveyor and student of Lechuguilla Cave from 1986 to 1999, I am concerned about some of the recommendations in Hunter *et al*. (2000) (*JCKS* 66(3), 102-110). The paper states that "...Red Lake...has been closed for several years due to coliform contamination...Lechuguilla's drinking pools are few and far between and should be regarded as both valuable drinking water resources and research study sites. If coliform contamination in these environments persists, then the resources may have to be put off limits to avoid negative human health and safety issues. Alternative methods for controlling coliform introduction and amelioration of the techniques employed to obtain drinking-water from cave pools may make such draconian measures unnecessary. However, such management decisions are complex."

I do not understand why any water sources should be put off limits on the grounds of microbial risk to cavers' health and safety. Should not simple iodine disinfection or other water purification systems (recommended later in the paper in any case) be sufficient to render any Lechuguilla Cave water safe for drinking? The continued, and in my opinion unnecessary, closure of the campsite using Red Lake water has had significant negative effects. It has made survey trips to the west end of the cave two hours longer from camp, thus reducing surveyor productivity, increasing physical impact on the travel route, and increasing caver fatigue, which makes accidents more likely.

Some of the amelioration methods suggested by Hunter *et al*.'s study (notably changing water collection tubing to silicone or Teflon) are valuable and can be implemented without undesirable effects. Others are problematic—particularly "packing out all fecal and urine waste in properly sealed containers would also help reduce new sources of contamination." Fecal waste is already routinely packed out, and has been since early in the exploration. Packing out urine, however, has not been required because it would place an excessive burden on explorers. Individuals' urine-production rates vary widely, but range up to more than a gallon per 24 hours, so on a typical six-day camp trip, a caver could need to store and haul out up to 50+ pounds of urine, which is more weight than the entire load that most cavers carry *into* the cave. Such a requirement would overburden or exclude those who couldn't handle this, and/or encourage minimal fluid consumption, again with undesirable productivity, health and safety implications.

Other recommendations, such as wearing clean boot covers and Tyvek suits when approaching pools, are less blatantly troublesome, but nevertheless add incrementally to the already complex protocols required by the Park for work in the cave. Proposed new requirements should be critically considered, because each new one makes it more complicated and difficult to do everything properly, takes more time and effort away from primary goals, and makes trips less enjoyable. I believe that this has already gone past a reasonable balance between protecting the cave and expediting exploration, resulting in fewer experienced personnel who remain interested in working in Lechuguilla.

I encourage microbiologists working in the cave to focus on ways to facilitate renewed exploration. Several of the best remaining unexplored leads would involve traversing water and have been kept off limits for several years, on grounds that they must be kept microbially pristine. I propose that if no researchers have committed to study these locations within a reasonable time, they should be released to exploration. Microbiologists could assist by devising practical techniques for crossing water with minimal contamination.



ENCYCLOPEDIA OF CAVES

Culver, David C., and White, William B. (eds.), 2005, Burlington, MA, Elsevier, Academic Press, 654 p. Hardbound (8.5 x 11 inches). ISBN 0-12-406061-7. $99.95. Order on-line at http://www.books.elsevier.com/ default.asp?.

Encyclopedia of Caves is one of two such books devoted to caves, both published less than a year apart. The other, *Encyclopedia of Caves and Karst Science*, edited by John Gunn, was reviewed in the August 2004 issue of this journal. The idea for each encyclopedia was suggested by the publishers, while the editors chose the topics and authors.

The Culver and White volume contains 107 individual articles, which cover geology, biology, physics, chemistry, anthropology, geomorphology, hydrology, speleology, exploration, and several well-known cave systems. The editors intended the articles to be useful not only to scientists but to a diverse readership. Most of the scientific articles are clearly technical, but there are also sections on subjects such as cave rescue, equipment, underground camping, and cave stewardship, which will appeal to non-scientific readers. There are hundreds of photos and figures, both in color and in black and white. Photo reproduction is very good but not exceptional. The use of color has greatly enhanced the clarity of some of the maps and diagrams. Altogether it is a very attractive volume, which invites the reader to browse.

This encyclopedia covers the most up-to-date topics about caves, such as cave-related geomicrobiology and dating caves with cosmogenic radionuclides. Special emphasis is given to biology, to which at least a third of the book is devoted. This depth of coverage is shown by a perusal of the section titles (e.g., "Worms"). However, there is no specific entry on paleoclimatology as recorded in speleothems, which is a topic of great interest today.

The alphabetical listing in an encyclopedia is not ideal for a specialized subject like caves, in which the topics cannot be identified neatly by single-word headings. For example, in the Culver and White volume, the topic "Speleothems" is divided into two essays: "Speleothem Deposition" and "Speleothems: Helictites and Related Forms," while other speleothem topics are covered elsewhere under different titles. Cave dating is covered under two topics, cosmogenic isotopes and the paleomagnetic record in cave sediments, with no overall synthesis. It would appear to be easy to find a subject because of the two tables of contents (one alphabetical and the other by subject) and a subject index at the end. However, if we look up "dating" in the subject index, we are led to two entries that mention dating, but we are not led to either of the two main articles representing dating (cosmogenic isotopes and the paleomagnetic record in cave sediments). This arrangement thwarts the purpose of the alphabetical listing. But within the formidable constraints of the encyclopedia format, the editors and authors have done a fine job of presenting the excitement and diversity of caves.

Some topics proposed by the editors did not materialize. For example, the original list included alpine karst, which was intended to complement "Solution caves in regions of moderate relief." Alone, the latter seems an odd topic. Even with alpine karst as a separate heading, the two would have been at opposite ends of the book, with no clear link. Links between sections are given, but these are tucked away at the ends of each entry and do not yield to quick perusal.

The Gunn encyclopedia provides more numerous but shorter entries. The Culver and White encyclopedia covers fewer topics, but each is allotted a lengthy essay. The science is intermixed with topics related to exploration. Descriptions of major caves in the US are given mainly by explorers rather than scientists. This is a valid approach, because the scientific aspect of these caves has been covered amply in other books, including the Gunn encyclopedia and the NSS volume "Speleogenesis" (Klimchouk *et. al* 2000). There is some unavoidable overlap between the two encyclopedias, even to the extent that some topics are covered in both volumes by the same authors. The Gunn volume describes a much wider range of karst areas from all over the world and has a more internationally diverse group of authors. As a result the two encyclopedias are unique and complementary.

For those who wonder which encyclopedia to buy, both are appropriate as reference books for scientists with an interest in caves. There is also some appeal to cavers and the general public. The Culver and White volume will probably be preferred by those interested in cave biology, a US orientation, or exploration. The Gunn volume has greater international appeal and a more geological slant. The Gunn volume costs about twice as much but is about 30% longer. Both are great achievements, especially given the fact that each was carried through from inception to publication in only a few years.

Reviewed by Victor J. Polyak, Research Scientist, Dept. of Earth and Planetary Sciences, University of New Mexico, 200 Yale Blvd., Albuquerque, NM 87131 (polyak@unm.edu), and Margaret V. Palmer, 619 Winney Hill Rd., Oneonta, NY 13820 (palmeran@oneonta.edu).

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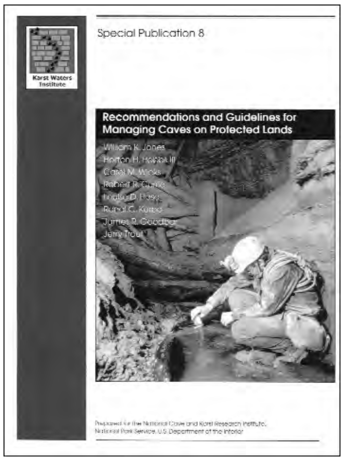


RECOMMENDATIONS AND GUIDELINES FOR MANAGING CAVES ON PROTECTED LANDS

Jones, W.K., Hobbs, H.H., Wicks, C.M., Currie, R.R., Hose, L.D., Kerbo, R.C., Goodbar, J.R. and Trout, J., eds., 2003, Karst Waters Institute, Special Publication 8, 95 p. Softbound, 8.5 x 11 inches. ISBN 0-9640258-7-6. $16.00 plus shipping. Order on-line at http://www.karstwaters.org or from Publication Sales, c/o E.L. White, 4538 Miller Rd., Petersburg, PA 16669-9211 (publications@karst-waters.org).

The stated intent of this publication is to provide federal land managers with guidelines for the development of cave-management plans and policies based upon the Federal Cave Resources Protection Act (FCRPA). It is a useful introduction to cave management (more appropriately, cave stewardship) in the United States but is far from the definitive text on the subject. While the intent is excellent, the execution has some weaknesses.

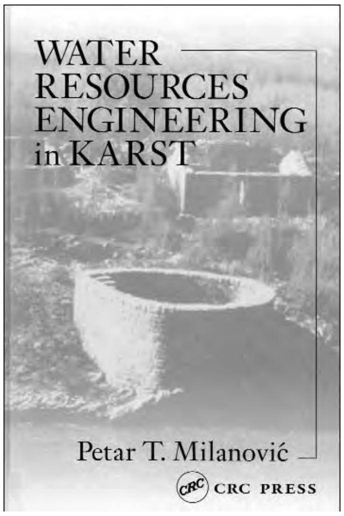
The manual is divided into three parts: Part one describes the features to be protected and gives an overview of the science behind management guidelines. Part two describes typical problems in protecting karst. Part three, which is relatively short, outlines management and investigative methods. In all, these three sections comprise a total of 52 pages, of which 32 are devoted to the first section, which gives the impression that the science is more important than the recommendations and guidelines. The manual concludes with a two-page summary, references, a glossary of terms, and six appendices totaling 18 pages. The appendices outline the Federal Cave Resources Protection Act of 1988 (FCRPA), cave management resources, the National Park Service's criteria for significant cave designation, NPS management policies, regulations and legislation related to NPS cave resources management, and the Bureau of Land Management Cave and Karst circular.

Perhaps because of multiple authors, Part 1 contains some lapses and contradictions. It gives the impression that cave management (more appropriately cave stewardship) deals only with physical cave resources, as it does not discuss the human dimension. After a statement that the goal of the FCRPA is to protect caves and their resources, there is a comment that the FCRPA should not only be applied to "proper caves," but also to other natural geologic features including natural bridges and arches, which is not in the scope of the legislation. A separate section on limitations of the Act and how to address them would have been useful. Citations are lacking for much of the information presented, a curious fact considering the emphasis on scientific backing for management plans. Part 1 includes many black-and-white photos, which are clear and well printed. Some show karst features in countries other than America, which may not be appropriate for a book whose focus is on federal land stewardship.

Parts 2 and 3 could have used more attention and space. For example, the book would have benefited from examples of cave management plans. The preface indicates that such plans are included in an appendix, but none are given. Although citations are given for what I consider some of the best texts on cave stewardship, they do not do justice to the full value they offer to cave stewards. It would have been useful to summarize guiding principles and concepts, and to provide an annotated list of recommended readings for each subject category. The book does not mention the National Cave and Karst Management Symposia, a valuable resource in the constantly evolving field of cave and karst stewardship. It would also have been nice to see something from the US Fish and Wildlife Service regarding their cave management plans and policies.

With such a large number of authors, more careful editing would have been helpful in avoiding overlaps and contradictions. However, this is still a valuable reference for those federal land managers who know little about the stewardship of caves and karst. I certainly recommend it as a useful introduction to the subject and hope that an expanded and more detailed volume will be forthcoming.

Reviewed by Patricia E. Seiser, Cave Stewardship Specialist, National Cave and Karst Research Institute, 1400 University Drive, Carlsbad, NM 88220 (pseiser@cemrc.org).



WATER RESOURCES ENGINEERING IN KARST

Milanovic, Petar T., 2004, Boca Raton, Florida, CRC Press, 312 p. Hardbound, 6.4 x 9.5 inches. ISBN 1-56670-671-8. $129.95. Order on-line at http://www.crcpress.com.

This book is third in a series by one of the world's authorities on engineering in karst. Its stated goal is to guide engineers in the "geotechnical improvement of karstfied rock masses at dam sites, around tunnels, and along river banks." His previous books, *Karst Hydrogeology* (1981) and *Geological Engineering in Karst* (2000), cover similar ground but with different emphasis.

His third, the subject of this review, concerns water supply, dams, reservoirs, and tunneling in karst. A lengthy first chapter sets the stage with a broad introduction to karst geomorphology and hydrology. The main chapters are aimed at practical applications, with case studies that draw heavily on the author's field experience in the Balkan karst as a consultant and university professor. Many other examples are drawn from around the world. More than 70 pages are devoted to field examples of dams and reservoirs alone. The last few chapters are short reviews of groundwater protection zoning, water tracing, and geophysical field methods.

Detailed instructions are given for such topics as grouting, construction of cutoff walls, determining local hydraulic conductivity with packer tests, and detecting the presence of conduits. Among the most unusual and interesting techniques are the use of PVC foil liners on reservoir bottoms, which rise and burst where underwater springs are present, and the "geo-bomb," which is set to explode during its travel through a water-filled cave so that its whereabouts can be detected seismically. Only brief descriptions of tracing and geophysics are given, and many of the techniques are out of date. For example, there is no discussion of quantititative dye tracing. The book is well illustrated with diagrams and maps, most of them to support the case studies. Some diagrams could have used more labeling. Grayscale photographs show specialized techniques and some impressive effects of land and structural failures in karst.

To the engineer, caves are mainly threats to structural integrity, and this book provides an important background that is often lacking. Those who view karst aesthetically may be taken aback by the many descriptions of how caves can be filled with rubble, cement, or asphalt. This is not a book for the cave enthusiast, although it describes examples where "speleologists" are called in–rather like ghost-busters–to help with projects.

The presentation stays at a general and somewhat non-quantitative level. This largely descriptive approach is appropriate because it avoids the impression that karst problems can be solved from behind a desk. There is no mention of numerical analysis or computer applications, and there are few of the equations, graphs, and tables that pepper the typical engineering book. One exception, carried over from previous volumes, is a curious equation for "karstification vs. depth" based on permeability tests (p. 10). The karstification factor has no units and yet includes a coefficient with six significant figures.

Some case studies are included mainly for the sake of completeness, as they provide sketchy details and little new insight. A few references are so incomplete that their sources are difficult to track down. Outside the engineering realm a few facts have gone astray. The "deepest known shaft" is identified as Gouffre Mirolda (France) at "-1773 m," a statement that is wrong on all counts.

There are also some idiosyncrasies in wording, as is understandable when an author writes in a language not his own. Some are distracting but not difficult to decipher, such as "overabstraction of aquifer," "momentarily actual base of erosion" (i.e., present base level), "molted asphalt," and use of the word "dip" for water-table gradient. Some are puzzling, such as the statement that "caves are less frequent than shafts." But we are fortunate that the author has overcome the language barrier to share his insight. Still, more careful editing at the American end would have been appropriate.

This book is best suited for the engineer who knows little about karst but is forced to deal with it at the professional level. The main overlap is with the several books emanating from the Multidisciplinary Conferences on Sinkholes and the Engineering and Environmental Impacts of Karst, which are offered biennially in the US. These volumes include more detail on a broader range of subjects, but they do not focus so exclusively on hydrologic problems, as the Milanovic book does.

General readers may find this book expensive for its size, but the cost is typical for a technical book written for specialists. Those who own one or both of the earlier Milanovic books will find the new one to have considerable overlap but different emphasis. The first (1981) deals mainly with water supply and the hydrologic function of karst and is a good complement to the third volume. The second (2000) covers many of the same topics as the third, and they do not make as versatile a pairing.

Reviewed by Arthur N. Palmer, Dept. of Earth Sciences, State University of New York, Oneonta, NY 13820 (palmeran@oneonta.edu).

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PRESERVATION OF PREHISTORIC FOOTPRINTS IN JAGUAR CAVE, TENNESSEE

P. Willey[1]
Anthropology Department, Chico State, Chico, CA 95929-0400 USA
Judy Stolen
892 Vallombrosa Avenue, Chico, CA 95926 USA
George Crothers
Anthropology Department, University of Kentucky, Lexington, KY 40560 USA
Patty Jo Watson
2870 Solterra Lane, Missoula, MT 59803 USA

More than 4500 years ago, a group of prehistoric cavers negotiated complicated cave passages and discovered a side passage approximately two hours' journey from the cave's entrance. They explored the passage toward its end, came to the termination of the easily traveled portion, turned around and exited the same way they entered, leaving footprints and torch material in the cave mud. Their remarkable journey is the earliest evidence of human cave use in the eastern United States.

A total of 274 relatively complete footprints remained in the passage's moist substrate when the passage was re-discovered approximately 30 years ago. The malleable deposits were pliable then, and remain so today. This pliability made the prints' preservation vulnerable to subsequent events, agents and processes. The purposes of this paper are to describe the prehistoric cavers' accomplishments, document the alteration of the prints, and describe efforts to study and preserve them.

Jaguar Cave (Fig. 1) is a complex cave system in north-central Tennessee. There are approximately 13 km of mapped passages. Prehistoric Native Americans probed deep into the cave interior using cane torches for light.

Ancient cavers would have entered through the large, easily accessible cave mouth, wading into the small stream that emerges in times of normal water flow. Before exiting the cave, this stream courses through large trunk passages, which the prehistoric cavers probably followed into the interior. About 600 m from the entrance, they climbed a steep breakdown pile (now known as the Towering Inferno; (Fig. 1)) beyond the wet trunk passages. Direct evidence for the prehistoric cavers' route through these wet areas is lacking because flooding and other hydrological processes have destroyed cane charcoal, torch smudges, and any other remains.

From the top of the breakdown pile they entered more passages, including the Only Crawl, where the first evidence of their presence is observable: charcoal and smudges or stoke marks. These marks are locations where the hot ends of the torches were brushed or knocked against walls and ceiling. Exiting from the crawl, they continued through more walking passages. Along the course of this route they passed, but left unmodified, calcium carbonate and calcium sulfate deposits, materials that were of considerable interest to later prehistoric cavers in other caves. From there they entered Tremendous Trunk, a large, mostly dry passage. From Tremendous Trunk the ancient cavers located and explored the easily traversed portions of a 500-m-long dead-end side passage, now called Aborigine Avenue. Near the end of Aborigine Avenue, they turned around and exited, presumably retracing their route to the cave entrance.

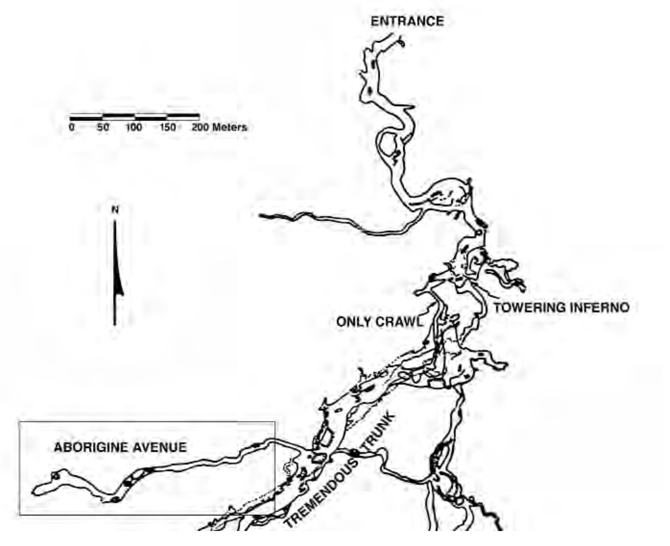

Figure 1. Jaguar Cave map showing Aborigine Avenue (rectangle); location of the prehistoric footprints. Modified from cave map produced by Lou Simpson with the aid of 39 other NSS cavers.

[1]Contact P. Willey at pwilley@csuchico.edu, 530 898-4793, or the address above.

ARCHAEOLOGICAL REMAINS

Evidence of their journey comes in two forms: charcoal remains and footprints[1]. The charcoal derives mostly, if not exclusively, from cane (presumably *Arundinaria*), which aboriginal people of the Midsouth often used as torch materials (e.g., Watson 1969, pp. 33-36). In addition to the charcoal fragments, features involving charcoal include smudges and stoke marks. Charcoal and a few marks are found in the Only Crawl as well as the dry passages beyond it, and are scattered here and there in Tremendous Trunk and in Aborigine Avenue.

The association of charcoal with the exploration is fortunate. Not only does the charcoal indicate the route followed by the prehistoric cavers, but also charcoal is amenable to radiocarbon dating, providing chronometric dates of the event. Charcoal collected (Robbins *et al*. 1981) from a dry passage between the Only Crawl and Tremendous Trunk yielded calibrated dates of 5465–4870 years B.P. (SI 3005) and 5600–5090 years B.P. (SI 3006). A third charcoal sample was collected from Aborigine Avenue and dated 5575-4990 B.P. (SI 3003). These dates demonstrate dark-zone cave exploration more than 5,000 years ago during the Late Archaic period.

These dates are the earliest from deep cave interiors of the eastern and southeastern United States. The only earlier dates for deep cave use in the United States come from a Colorado cave where a 45-year-old male died nearly 8,000 years ago (Mosch & Watson 1996, 1997) and from Idaho ice caves that were apparently used for meat preservation 8,000 years ago (Henrikson 2003).

The other source of evidence regarding prehistoric cave exploration, other than charcoal, is footprints (Fig. 2). Left in the soft substrate of Aborigine Avenue's floor, 274 relatively complete prints have been identified. Most of the prints appear to have been made by bare, unshod feet (Fig. 2A), but one of the prehistoric cavers may have been wearing some sort of footgear (Robbins *et al*. 1981; (Fig. 2B)), called "moccasins" in the preliminary publication. It is likely that these moccasins were not made of hide, but rather were woven of tough vegetable fibers like the footgear found in dry portions of other caves (see Watson 1969, p. 36-41, and King 1974 for examples).

The footprints are not continuous in Aborigine Avenue from the entrance to the rear of the passage. There are interruptions in the trail (Fig. 3). These discontinuities in the footprint trail were caused by the prehistoric cavers walking on harder portions of the cave floor, where their feet left no impressions.

The trails generally follow the most easily traveled route through Aborigine Avenue. Footprints indicate that the cavers simply walked through the passage, occasionally deviating from the easiest route to inspect cave passage features. Some of these detours, such as the examination of pits in the floor of the passage, may indicate attempts to find alternate routes through the cave as well as additional passages. For example, at least one prehistoric caver walked to the edge of a pit, apparently examined the drop-off, and, finding no alternative passage, continued along Aborigine Avenue (Fig. 4).

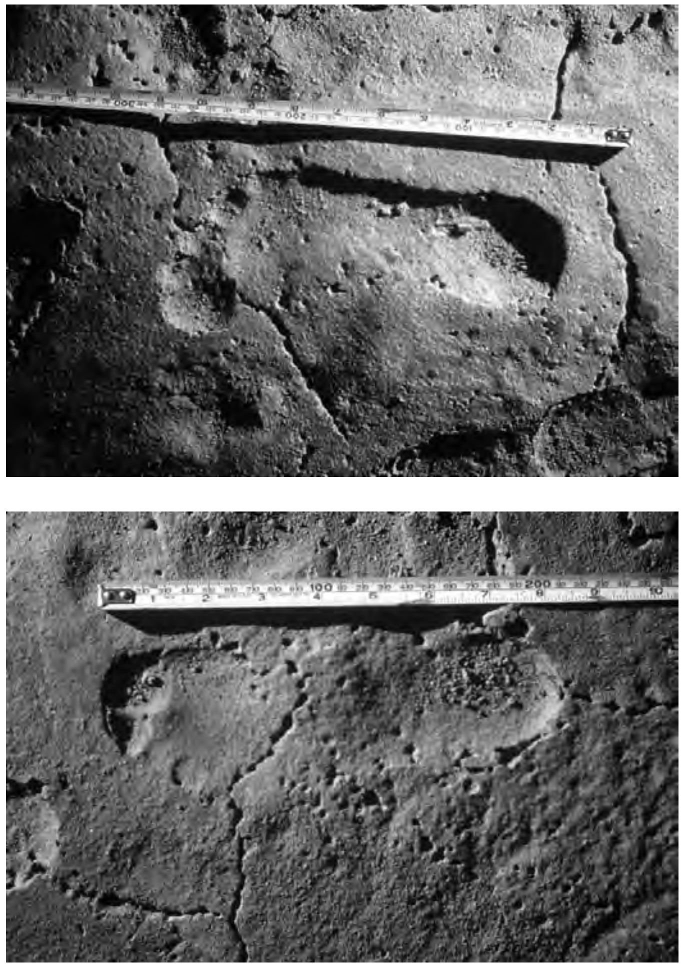

Figure 2. Prehistoric footprints in Aborigine Avenue. A (top) unshod footprint; B (bottom) shod footprint. CRF photos, November 1976.

In addition to such exploratory searches, one person deviated from the main route to inspect a fallen flowstone column (Fig. 5). Following the inspection, the prehistoric caver returned to the trail that the others were making to the end of the easily traveled portion of Aborigine Avenue. There is another 130 m of passage, requiring belly crawling, beyond the last prehistoric footprints, but the ancient cavers apparently did not explore this crawlway. Instead, they milled about on the muddy portion of the walking passage, then turned around and headed back to Tremendous Trunk.

Detailed analysis of the footprints identified microerosional differences among some of them, suggesting that there were at least two trips into Aborigine Avenue (Robbins *et al*. 1981).

[1] The "footprints" in Jaguar Cave are not footprints in the strict sense of the term. Technically they are foot impressions. Foot impressions indicate the three-dimensional imprints left by feet in plastic materials, such as those in wet sand or in the mud of Aborigine Avenue. Footprints, on the other hand, refer to the two-dimensional oils, blood, inks or other liquids left by the soles of feet on hard, unyielding surfaces. The tracks in Jaguar Cave are technically foot impressions, but we call them footprints here based on established precedent, and continued in adherence to convention.

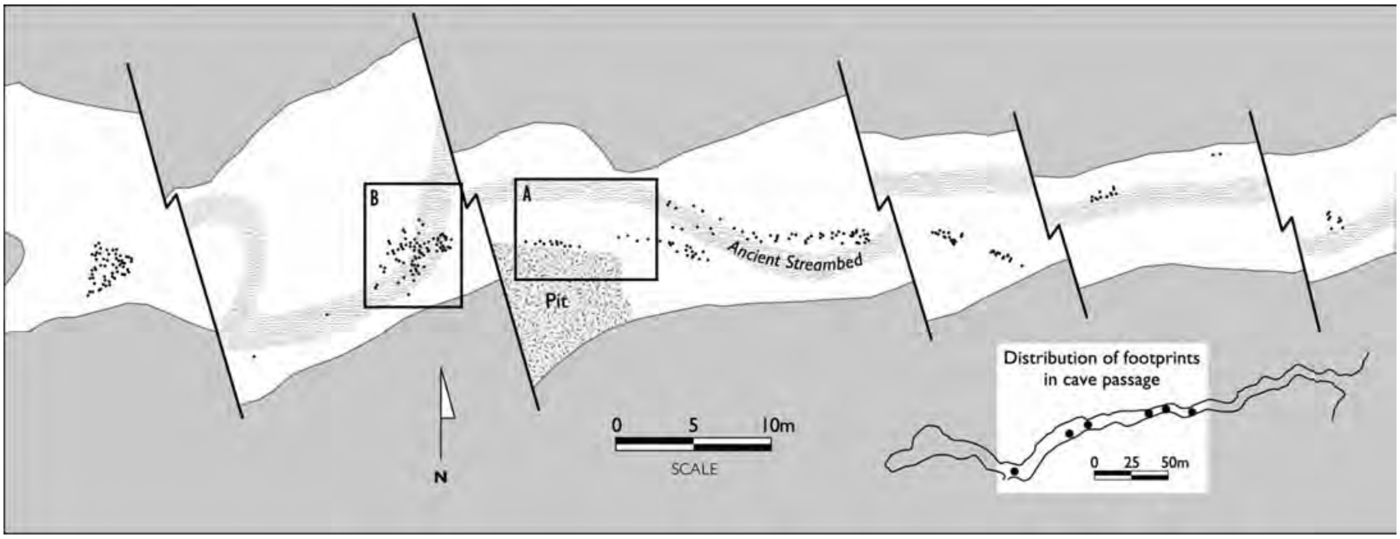

Figure 3. Map of Aborigine Avenue, showing prehistoric footprint distribution (small dots). The segments of the passage shown are indicated by locations of the large dots on the insert. A is enlarged in Fig. 4; B is enlarged in Fig. 5. Based on the original detailed map by Michael Voligny.

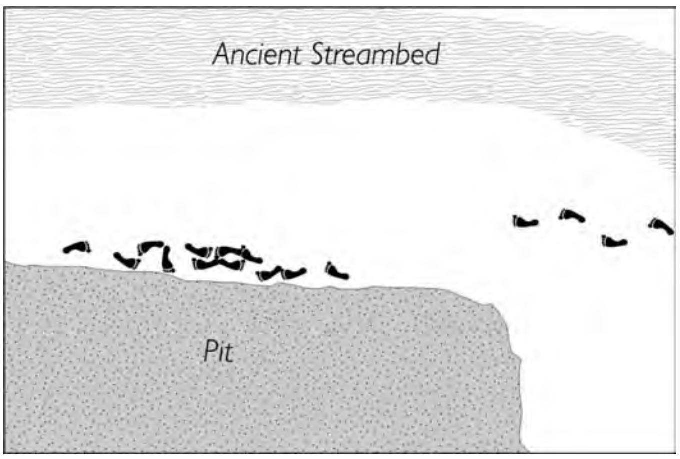

Figure 4. Detail of prehistoric footprints near pit edge suggesting reconnaissance. This location is indicated by A in Fig. 3; details from master footprint map by Michael Voligny.

These combined trips involved nine individuals, including members of both sexes, and adults as well as a possible adolescent (Robbins *et al*. 1981). Recent research (Watson *et al*. in press) established that there were more prints directed out of the passage than into the passage. This fact indicated an emphasis on exploration, ambling and searching while going into the passage, and a more direct journey while exiting.

PREHISTORIC ALTERATION OF THE PRINTS

The prints discernible today are the "survivors" of the total number left more than 5,000 years ago, a subset of the actual number made. The processes affecting that survival occurred in two periods: an early period when the prehistoric cavers

Figure 5. Detail of prehistoric footprint trail going to fallen column (upper center) suggesting examination of cave features. This location is indicated by B in Fig. 3; details from master footprint map by Michael Voligny.

themselves and natural processes dominated, and a recent period when modern cavers and researchers have had marked effects.

The modifications of the prints started when the prints were being made. Prehistoric cavers who were following the leaders walked in their predecessors' tracks, altering and obscuring some of the prints. In addition, if there were at least two separate prehistoric parties that went into Aborigine Avenue, then the second party, and any subsequent parties, would have walked over and destroyed the preceding parties' footprints. We suspect that a substantial number of the total set of prints made was obscured in this manner.

Following the last prehistoric caver's departure from Aborigine Avenue, the prints were left untouched by humans for thousands of years. During those millennia, the prints continued to be altered by natural processes. As an example previously mentioned, one researcher observed greater micro-erosion on some of the prints than others suggesting, to her thinking, that at least two different visits to Aborigine Avenue were made prehistorically (Robbins *et al*. 1981). Water dripping from the ceiling has also pocked a few of the prints.

On the other hand, the prints were little affected by other processes. There was no checking or cracking of the substrate after the prints were made; moisture and relative humidity apparently remained consistently high during those thousands of years. No major erosional changes took place. Other than occasional dripping from the passage ceiling, no moving water significantly altered the prints.

RECENT ALTERATION OF THE PRINTS

The cave entrance and wet portions of the cave near the entrance were well-known to Euroamericans since the early 19th century (Hogue 1933). The convoluted route to the rear portions of the cave, however, eluded modern cavers until three decades ago. Once the route up the breakdown slope and through the Only Crawl was rediscovered in the mid-1970s, the rear portions of the cave were found and extensive modern exploration took place. Aborigine Avenue was re-discovered by modern cavers as a part of their exploration in 1976.

Since the prints' discovery, their destruction accelerated beyond the relatively slow rate resulting from natural alteration. Even on the discovery trip, for instance, modern cavers walked over some of the prehistoric prints before recognizing them. Because modern explorers were alert for indications of previous cavers, however, relatively few of the prehistoric footprints were destroyed before they were noticed, thus limiting this destruction to the front part of the passage. The care used once the discovery was made ensured protection of prehistoric footprints toward the rear of the passage.

The footprint discovery was reported to Watson. She agreed to undertake the daunting task of documenting the prints, supported by Cave Research Foundation (CRF) and National Speleological Society (NSS) members as well as Washington University (St. Louis) anthropology and archaeology students. Watson's initial efforts to preserve the footprints included posting a sign and placing surveyors' flagging. A conspicuous sign was posted at the entrance to Aborigine Avenue describing the importance of the prints and contact information for those who wished to know more. In addition to the sign, areas in the passage with prints were marked with survey tape, indicating sensitive areas to be avoided.

Figure 6. Mapping footprints near fallen column in Aborigine Avenue (see Fig. 5 for map of this area). Left to right: George Crothers, Kathleen Dickerson, Michael Fuller, Sue Schofield (back), Patty Jo Watson (front). CRF photograph by James Goodbar and Kenneth Russell, November 1979.

Watson's archaeological research in Aborigine Avenue included collecting charcoal samples and dating them. She also oversaw photographing, measuring, mapping, and, in some cases, casting selected prints (Fig. 6). This work indicated that at least 274 footprints were complete enough to enable at least some observations. Data collection for each footprint included three measurements (foot length, heel width, and ball width), and orientation into or out of the passage. The prints were also mapped in relation to one another. Some of the conclusions resulting from that mapping and other observations have already been presented above. They have been reported in a preliminary fashion (Robbins *et al*. 1981) and are the subject of another, more lengthy paper (Watson *et al*. in press).

Archaeologists and volunteers altered some of the prints during their fieldwork. As an example of an accidental modification, there is a modern handprint made during the archaeological work when a student researcher lost her balance and fell toward one of the footprint areas.

In addition to this accidental modification, there were purposeful alterations made by the researchers. "Type" footprints were selected representing the nine individuals identified during the archaeological fieldwork. Those nine footprints were cast to preserve permanent models of them. The casting process, by its nature, destroyed or severely damaged those prints (3.3% of the total 274 mapped prints; Robbins *et al*. 1981, p. 377).

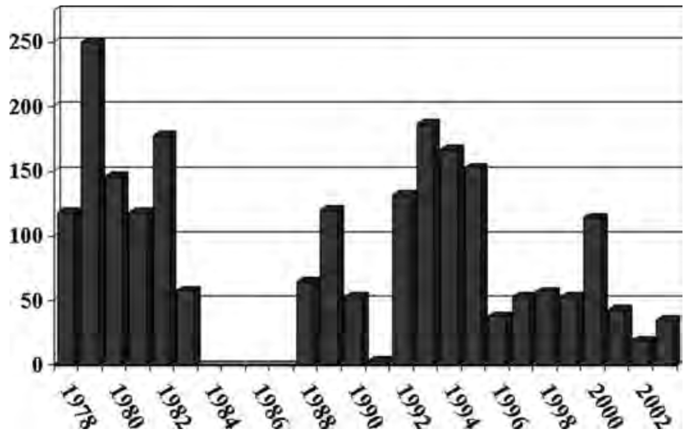

Figure 7. Number of Jaguar Cave visitors registering by year. Note large numbers of visitors in the late 1970s and the early 1990s.

While the archaeological documentation was going on (1976 through 1986) and after it was completed, modern cavers have walked over some of the prints, altering and modifying them. As an example, sometime between 1996 and 2002, a modern caver ignored the sign at the entrance of Aborigine Avenue and the surveying tape circling the prehistoric footprints and walked across them, altering at least five of eleven prints near a pit edge. Today nearly all of the areas with prehistoric footprints display at least some modern damage.

In addition to the human visitors, a dog, apparently accompanying a late 1970s caving party, entered Aborigine Avenue and its pawprints are now present among some of the prehistoric human footprints near the passage entrance.

RECENT VISITATION TO JAGUAR CAVE

We suspect that the amount and rate of the destruction of the prints by modern cavers is correlated to the number of modern cave visitors. Although the number of people visiting Aborigine Avenue has not been systematically documented except in various trip reports, there is another means of appraising overall visitation to the cave interior. A register was established in a prominent location a short distance from the end of the Only Crawl, a location that must be passed by all those heading toward the deeper portions of the cave.

There are, of course, limitations to using the number of registrants as an indication of visitation to Aborigine Avenue. It is obvious that not all people entering the deep portions of the cave signed the register, that not all people registering necessarily visited Aborigine Avenue, and that not all registers have been saved, curated, or are available for examination. Nonetheless, the numbers of people registering is an indication of the minimum number of people visiting the deep portion of the cave, and a general indication of the relative number of cavers visiting Aborigine Avenue.

The number of modern cavers registering is summarized and presented in Figure 7. It appears that the number of visitors was greatest in the late 1970s and early 1980s, soon after the deep portions of the cave were discovered. During the year with the greatest number of visitors (1979), 250 people registered. That is an enormous number, which consists of several large parties, and reflects a period of active cave exploration, mapping, and research.

The chart (Fig. 7) also indicates a relative absence of visitors in the mid-1980s and a complete absence for some years (1984-1987). Rather than a decline in the number of cavers visiting deep portions of the cave, this absence probably reflects a period when the register was being poorly maintained, was not curated, or at least was unavailable for this tabulation. The same may be true for 1991.

The number of visitors in the 1990s is probably more representative of the use of the deep sections of the cave in that decade as well as the preceding one. From 1990 through 1999, an average of nearly 90 people per year registered. The trend through the 1990s may be more telling about cave visitation than the average for that decade, however. There seems to be a general decrease in deep cave visits from the first half of the 1990s (mean = 108.4 persons per year even including the spuriously low 1991 figure) to the second half (mean = 70.8 persons per year). Perhaps this decrease in registrations indicates a lessening of interest in exploring the cave, as well as the end of research and mapping projects.

There was a spike in cavers registering during the year 2000 (number = 114), the year when the cave was gated. That was not only the beginning of a new millennium, but also the beginning of a new period for protection of the footprints.

The gating of the cave several years ago and creation of a preservation plan provides protection for the prints. During the two years after the cave was gated, the average number of cavers registering fell to 32 visitors per year. If the number of visitors is related to the probability of footprint destruction, then there is hope for preservation of the remaining prints. Potential for destruction of the remaining intact prints persists, however. Understanding the modifications documented in this paper aids protection of these rare and fragile remains. Policies must be established to conserve the traces left by intrepid prehistoric explorers.

ADDITIONAL TECHNIQUES

The archaeological fieldwork during the 1970s and 1980s, completed under difficult circumstances, was highly successful. Trips to the cave required long-distance travel, work in the cave was logistically difficult, and preservation of the footprints was uncertain. Whether the prints would survive from one trip until the next constantly weighed on the researchers' minds. Since the original fieldwork was completed two decades ago, new techniques and approaches have become available. These techniques provide the opportunity to document the prints more precisely and more permanently than previously possible. They could eliminate the major obstacles to further study: difficulty of access and the time required to reach the prints. Best of all, these techniques can be applied while causing minimal damage to the footprints.

Systematic photography offers a time-tested method for recording the footprints. Although selected prints and footprint areas were photographed during the original archaeological work, photographs of all prints in all areas are needed. This would provide a permanent record for each print, and of the prints' relations to each other and to cave features. For example, Charles Swedlund (1995, n.d.) used a photographic mosaic in Gothic Avenue, Mammoth Cave, Kentucky, to document 4300 historic names on a long expanse of the ceiling. Using a series of overlapping images made by a camera on a track system, he captured the entire ceiling on one photographic mosaic. A similar approach could be applied to ancient pathways on the floor of Jaguar Cave.

Stereographic photogrammetry is similar in many ways to conventional photography. In addition to the advantages of the latter, however, photogrammetry documents images in three dimensions, producing fine-grained topographic maps. Depths and other three-dimensional details can be observed and measured from the topographic images. Photogrammetry has been successfully applied to the 3.6 million-year-old hominid footprints at Laetoli, Tanzania (Agnew & Demas 1998), and offers opportunities for Aborigine Avenue in Jaguar Cave.

Automated laser scanning is an even more recently developed technique that also provides a permanent, high resolution, three-dimensional record. Once at the site, it is quick, relatively inexpensive, and avoids some of the problems associated with photography and photogrammetry. It is more precise than either and avoids problems with lighting and time-consuming setup required by the other techniques. Resulting data can be manipulated electronically to permit accurate measurements, to show spatial relationships, and to produce three-dimensional models. For example, an Upper Paleolithic carved horse on a rock shelter wall at Cap Blanc, France, was laser scanned to create a three-dimensional model (Brown *et al*. 2001).

Ideally speaking, photographic, stereographic photogrammetric, and laser scanning approaches could all be applied to the Jaguar Cave footprints to preserve the maximum amount of information.

OTHER CAVES WITH PREHISTORIC FOOTPRINTS

Prehistoric use of caves included a variety of activities: namely, mining and quarrying various minerals and chert, disposal of the dead, and ceremonial uses (Crothers *et al*. 2002, Watson 1986). In addition to these uses, some caves have been identified as "footprint caves," those that display no indications of use other than the footprints (Watson 1986). The Jaguar Cave prehistoric footprints, extraordinary as they are, are not unique.

Prehistoric footprints have been found in at least six other southeastern U.S. caves. These caves, together with relevant chronometric dates and published sources, are listed in Table 1.

Access to these prehistoric foot impressions, at least by modern cavers, requires crawling, climbing and walking various distances into the caves. Some of the preserved footprint sets are hours from the cave entrances. All the impressions are vulnerable to present-day destruction by natural processes, such as erosion, although the greatest threat to their preservation is from that un-natural source: the boot soles of thoughtless modern cavers.

In several ways, the footprints in the Unknown Cave portion of the Mammoth Cave System are most similar to those in Jaguar Cave. Although only two prehistoric cavers entered Unknown Cave, their exploration was well into the dark zone of a complex cave (more than five hours from the nearest modern, readily accessible natural entry), and among the earliest deep cave explorations (3670 $\pm$ 50 B.P.; Crothers *et al*. 2002: 509). These cavers were apparently not involved in mining, quarrying, disposing of the dead, or conducting ceremonies.

There are particulars that set Jaguar Cave apart from Unknown Cave and other footprint caves. Of all the foot impression sets in southeastern caves, those in Jaguar Cave are the greatest in number and the best documented (Robbins *et al*. 1981, Watson *et al*. in press). They have been systematically mapped, there are three radiocarbon dates associated with them, some of the impressions have been photographed, and all of the more complete prints have been measured. The Jaguar Cave footprints number more than those in all the other footprint caves in the southeastern U.S. combined. The prehistoric explorers of Jaguar Cave set a high standard by finding passages that were not rediscovered for thousands of years.

CONCLUSIONS

The Jaguar Cave footprints represent an early example of what seems to have been exploration for exploration's sake. There was no apparent effort to mine cave deposits that the prehistoric explorers passed during their journey, although speleothems and in at least one locale selenite crystals are visible and easily accessible. Later, Woodland period miners would surely have rejoiced on finding such deposits and readily exploited them.

There are no indications that the cave was used as a mortuary facility. Some later prehistoric Southeastern peoples (during the Woodland and Mississippian periods) did employ caves in this way. Within a few miles of Jaguar Cave, there are several caves that were used for burials, presumably by some of these later people. Two of those caves were burial pits, and the third contained human remains near the cave entrance.

There are no obvious indications of ceremonial use in Jaguar Cave. No mud glyphs, petroglyphs, or pictographs have been found so far.

Table 1. Southeastern U.S. caves with prehistoric footprints and associated radiocarbon determinations.

Location	Age		Number of Impressions	References
	Radiocarbon Years Before Present	Calendar Years Before Present[a]		
Aborigine Avenue, Jaguar Cave, TN	4695 ± 85	5600 – 5090	≥ 274	Robbins *et al*. 1981; Watson *et al*. in press; present study
	4590 ± 75	5575 – 4990		
	4530 ± 85	5465 – 4870		
3rd Unnamed Cave, TN	4350 ± 60	5210 – 4830	≥ 6	Crothers *et al*. 2002; Ferguson 1982, 1983; Franklin 1999; Simek *et al.* 1998
	3360 ± 60	3810 – 3465		
	3330 ± 70	3805 – 3390		
	3115 ± 65	3470 – 3085		
	3060 ± 50	3380 – 3080		
	3060 ± 70	3440 – 3075		
	3050 ± 70	3435 – 3005		
	2970 ± 40	3320 – 2995		
	2970 ± 40	3320 – 2995		
	2950 ± 65	3335 – 2890		
	2950 ± 110	3380 – 2785		
	2805 ± 75	3160 – 2755		
	2745 ± 75	3000 – 2745		
	2010 ± 60	2120 – 1825		
Upper Crouchway, Unknown Cave, KY	3670 ± 50	4150 – 3840	≥ 12	Watson 1969:62-64; Crothers *et al*. 2002
Fisher Ridge Cave, KY	3175 ± 80	3625 – 3210	≥ 18	Watson 1982, 1983; Kennedy *et al*. 1984
	2750 ± 85	3135 – 2745		
Sequoyah Caverns, AL	520 ± 50	640 – 500	7	Sneed 1984[b]
Footprint Cave, VA	430 ± 60	545 – 315	≥ 30	Crothers 1997
	410 ± 50	530 – 315		
Lon Odel Memorial Cave, MO	No radiocarbon dates		≥ 10	Beard 1997a, 1997b

[a]Maximum of calibrated ages ($\sigma = 2$) using CALIB program Version. 4.3, Method A (Stuiver and Reimer 1993). Ages rounded to the nearest five years.
[b]Sneed (1984) erroneously reports the Sequoyah Caverns date as A.D. 520, instead of 520 B.P. The determination (estimated by the Smithsonian Institution Laboratory: SI 5705) presented in this table is correct.

Based on the absence of evidence for these or other activities, we think that the prehistoric people who entered Jaguar Cave were exploring for its own sake. Although we may never know the motives and objectives of these ancient cavers, there is the additional possibility that they had some aesthetic interest in the cave and its formations, and that their exploration may have been a successful effort to examine a previously unknown part of their world. If these conjectures are somewhat accurate, then the motivations of the prehistoric Jaguar Cave cavers may have been much the same as those of many present-day cavers.

With the thrill of discovering prehistoric footprints, or any other fragile cultural remains, comes a grave obligation. We are responsible for preserving them for future cavers. They link the past to the present, and ultimately tie the present to the future.

ACKNOWLEDGEMENTS

Barb Shaeffer, Lou Simpson, Dave Socky, and 39 other members of the NSS mapped the cave. Lou Simpson drafted the map, a portion of which is published here, and M. Clark provided the ink reduction. The original, detailed footprint map of Aborigine Avenue showing all of the measured footprints was drafted by Michael Voligny, to whom we are deeply grateful. Louise Robbins contributed significantly to the design and execution of documentation procedures applied to the footprints during the 1970s and 1980s. She also made casts of nine footprint impressions, and began analyses of the combined data prior to her untimely death from cancer in 1987. We are thankful to local residents who owned land above the cave, and supported our trips into its remote interior: Mr. and Mrs.

Juan Copley, the Misses Lera and Loma Pile, and Mr. and Mrs. James Williams. Three people, who must remain anonymous for reasons of cave confidentiality, provided copies of the cave registers. CRF cavers Roger Brucker, Mark Elliott, James Goodbar, and Kenneth Russell provided photographs. Washington University students, CRF and NSS members, as well as other volunteers aided the archaeological investigations. Byron Wolfe, of Chico State's Communication Design Department, provided access to and instruction in scanning equipment and software. Joseph Douglas invited us to present a paper in his Cultural Resources in Caves Symposium at the 2003 NSS Convention, Porterville, CA, on which this article is based. We also owe him a debt of gratitude for reviewing the draft of this manuscript and generously sharing his knowledge of Tennessee caves.

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CARBONATE PRECIPITATION ALONG A MICROCLIMATIC GRADIENT IN A THAILAND CAVE – CONTINUUM OF CALCAREOUS TUFA AND SPELEOTHEMS

Danko Taboroši
Laboratory of Geoecology, Graduate School of Environmental Earth Science, Hokkaido University, N-10 W-5, Sapporo, Japan 060-0810
taborosi@gmail.com
Kazuomi Hirakawa
Laboratory of Geoecology, Graduate School of Environmental Earth Science, Hokkaido University, N-10 W-5, Sapporo, Japan 060-0810
hkazu@ees.hokudai.ac.jp
Takanobu Sawagaki
Laboratory of Geoecology, Graduate School of Environmental Earth Science, Hokkaido University, N-10 W-5, Sapporo, Japan 060-0810
sawagaki@ees.hokudai.ac.jp

Variations in the local microclimate can profoundly affect vadose carbonate precipitation. This may be negligible deep inside caves, but is intense in climatically less stable environments, such as cave entrances and twilight zones. In such settings, microclimate can exert primary control on the characteristics of actively forming stalactites, far outweighing the other factors, notably dripwater properties.

Based on temperature, humidity, and light intensity monitoring of a cave in southern Thailand and analyses of associated cave deposits, we have seen that microclimatic (and ensuing biologic) gradients that exist between the cave entrance and cave interior are closely reflected by the morphology and petrology of actively forming stalactites. Spanning the cave's microclimatically most variable and most stable parts, these stalactites comprise uninterrupted morphologic and petrologic series, ranging from extremely porous and largely biogenic stalactitic accretions of calcareous tufa growing around the dripline (and even outside the cave) to the dense coarsely crystalline stalactites (speleothems) in the cave interior. This rarely observed continuum between tufas and speleothems indicates that the boundary between the two is hardly distinct (or justified) and any observed differences can be simply a result of different microclimatic regimes of their depositional settings.

In this paper we will demonstrate that the local environment can exert primary control on the characteristics of actively forming stalactites, producing a far greater morphologic and petrologic range than other factors, specifically dripwater properties, are known to bring about. We will show that the end members of this range correspond to calcareous tufa and speleothem travertine, and that the two are not necessarily distinct types of sediments but parts of a continuum of genetically allied carbonate fabrics mediated by environmental factors.

There are two variables that control the abiotic precipitation of carbonate speleothems, as karst waters emerge from bedrock and enter karst cavities (Atkinson & Smith 1976, Dreybrodt 1988). These are the properties of 1) water dripping into a cave, and of 2) environment within a cave. Both directly influence carbonate precipitation and, combined, they account for most of the morphologic, mineralogic, and petrologic properties of speleothems. While the links between volumes, rates and geochemistry of water with the crystal habit and structure of speleothems (e.g., Given & Wilkinson 1985, Gonzales *et al*. 1992, Frisia *et al*. 2000, 2002) and other freshwater carbonates (e.g., Emeis *et al*. 1987, Chafetz *et al*. 1991) have been extensively studied, the influence of local environmental factors has remained largely unaddressed since early inquiries established that its importance is secondary to water properties (Gams 1968). Nonetheless, environmental factors, microclimate in particular, can have significant impact on the formation of speleothems. Microclimatic parameters, especially temperature and humidity, are known to affect the deposition of speleothems (e.g., Harmon *et al*. 1983, Railsback *et al*. 1994, Borsato *et al*. 2000) and genetically allied tufas (e.g., Pedley *et al*. 1996). This should be clear even intuitively, from the simple observation that stalactites regularly grow in the humid atmosphere of caves, but are normally not expected to form at the land surface where their growth is limited by evaporative effects (Hill & Forti 1997).

However, any study attempting to relate particular microclimatic conditions with stalactite properties faces unique design problems: research within a single cave is nearly impracticable because of minuscule spatial variability of microclimatic parameters (e.g., Buecher 1999), whereas comparative research on several caves is precluded by the existence of too many added variables, which make any impact of microclimate on carbonate fabrics difficult to isolate and assess. Opportunely, cave entrances can show significant spatial variability in the microclimate, while keeping the other numerous parameters essentially even. This is perhaps not so obvious in classical karst regions, where the small entrances and infinitesimal width-to-length ratios of fluviokarst caves

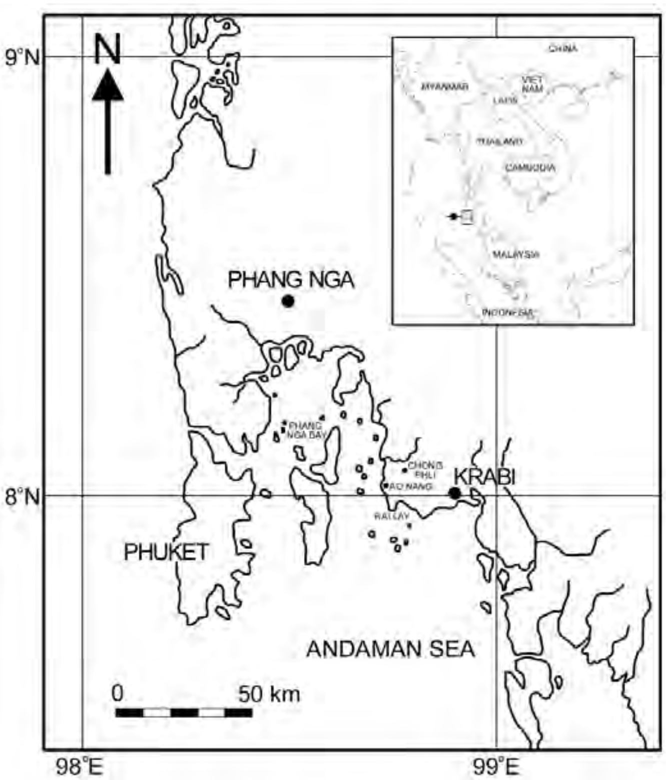


Figure 1. Location map of Krabi area in southern Thailand, with locales mentioned in text.

(Ford & Ewers 1978, Bögli 1980) combined with the stark climatic contrasts between the epigean and spelean realms (Cropley 1965) result in limited air circulation, sharp microclimatic clines at the entrances, and little variation elsewhere. In tropical areas, however, 1) cave entrances are often enormous, formed by collapse rather than speleogenesis per se; 2) certain cave types exhibit widths greater than their lengths (Mylroie & Carew 1995); and 3) generally high and stable outside humidity and temperature levels do not radically differ from cave interiors. Actually, in the humid tropics, stalactites can be prolific even outside of caves (Sweeting 1973, Longman & Brownlee 1980, Jennings 1985, Taboroši *et al*. 2003a, 2003b), indicating that microclimatic conditions necessary for their growth can be found in parts of the epigean environment, as well. All of these factors contribute to less "dramatic" transitions between the epigean and spelean environments in the tropics as opposed to temperate areas, thereby producing more gentle microclimatic gradients over greater distances in the tropical caves. Indeed, in some tropical caves with large entrances, the transitional ("twilight") zones between the land surface and cave interiors are so broad that they exhibit distinct microclimates of their own, ceasing to be mere interfaces between epigean and spelean realms. Enclosed enough to sustain abundant stalactite growth, yet open enough to exhibit considerable light penetration and marked diurnal fluctuations in temperature and humidity, these large entrances of tropical caves present nearly ideal natural laboratories for evaluating environmental impact on the morphology and fabrics of vadose carbonate precipitates.

In our initial assessment of links between microclimatic parameters and the properties of stalactites, based on observations from Guam, Mariana Islands, we have demonstrated that the two are indeed closely related (Taboroši & Hirakawa 2003). The present study, carried out in a single cave in Krabi Province, Thailand, builds on those foundations and refines the original work by applying improved methodology and demonstrating a wider geographic relevance. Following a thorough examination of spatial and temporal variations in temperature, humidity, evaporation rates, and light levels experienced by different parts of the cave, we related that environmental data to the petrologic properties of actively forming stalactitic deposits. We found that the deposits range from highly porous and largely biogenic accretions of calcareous tufa (shaped convincingly like stalactites) growing at the entrance to the dense coarsely crystalline stalactites in the cave's interior. These deposits display a wide range of distinct fabrics forming an uninterrupted morphologic and petrologic series, as they span the microclimatically most variable and most stable parts of the cave. Because certain stalactite morphologies and fabrics appear to form under highly specific environmental conditions, these observations promise to be a valuable tool in paleoenvironmental interpretation.

STUDY AREA

The study was carried out in Krabi Province, southern Thailand (Fig. 1). The area has been described as "some of the most geologically interesting and scenically stunning landscape" in the world (Wasseman 1984) and is characterized by steep cliffs and immense karst towers developed in massive Permian limestone (Waterhouse 1981). The limestone towers, belonging to the vertical-walled turmkarst and cone-shaped kegelkarst types, emerge from shallow waters of Phang Nga Bay or mangrove swamps along the coast, and from Quaternary alluvial plains in inland areas (Harper 1999). The local climate is tropical monsoonal, and most of the average annual rainfall of 2379 mm falls from May to October. The wettest month is usually September, and the driest is February, with 361 mm and 25 mm of rain respectively. The mean daily temperature is 28.1°C (min. 24.0°C; max. 31.3°C), while the average relative humidity ranges from 68% in February to 81% in October (Sarigabutr *et al*. 1982).

The studied cave (Fig. 2) is located at the base of an isolated 40-m-tall vertical-walled tower in the village of Chong Phli, 15 km from Krabi town and 5 km northeast of Ao Nang beach. The cave, named Pop Kan Mai, was discovered during an informal field survey of the area. Although it is well known to the local people of the village, it seems to be rarely visited and does not appear to be referenced in Thai cave compendia (e.g., Dunkley 1994, 1995). The cave's entrance area is defined by overhanging rock at the base of the tower, and is thoroughly

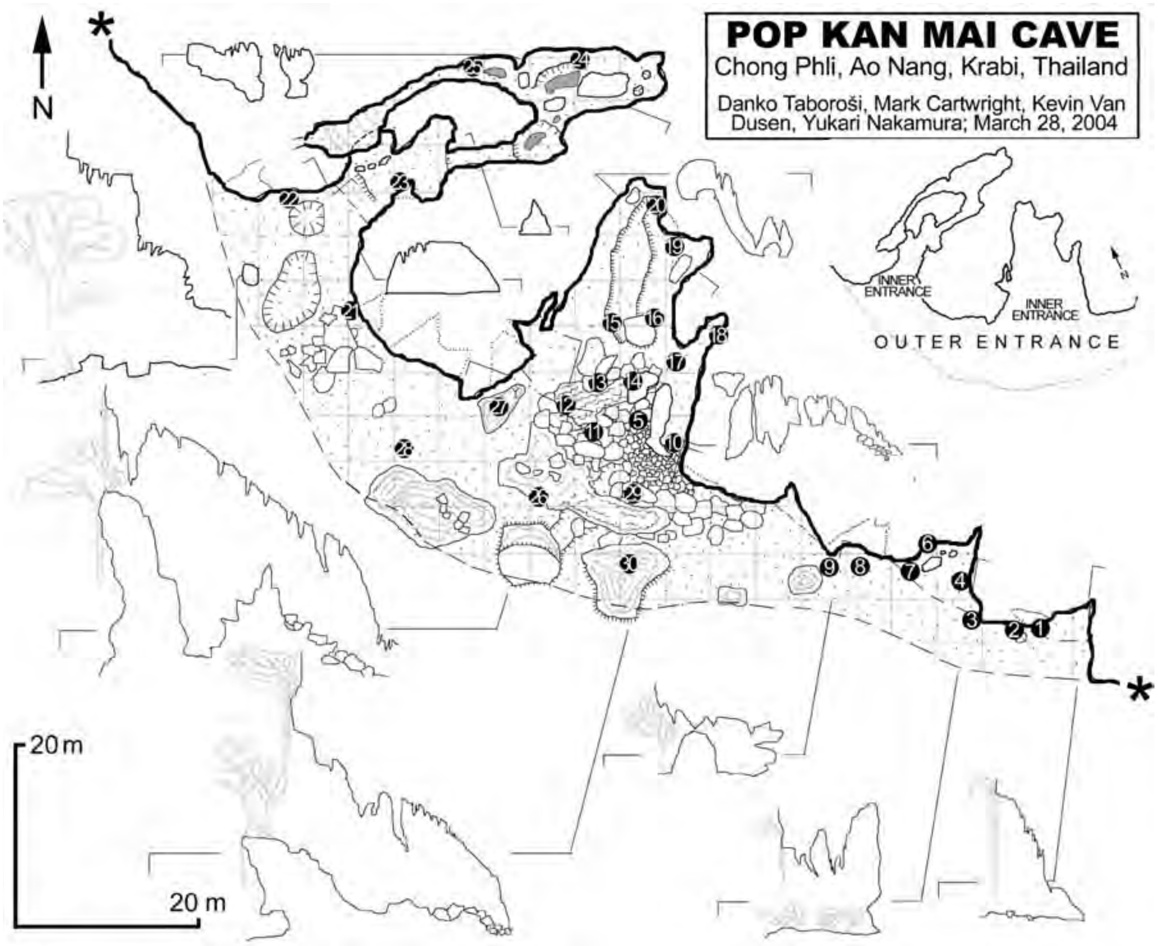


Figure 2. Plan and selected profiles of Pop Kan Mai Cave. Numbered black dots indicate stalactite sample locations and sample ID numbers. Grid cells are 5 m x 5 m. Dashed line represents the dripline and the two asterisks (*) indicate continuing karst tower cliff line. Inset shows the extent of what we termed "outer entrance" and "inner entrances."

concealed behind a thick, curtain-like canopy of vines and roots of trees growing at the top of the cliff. Following the perimeter of the tower, the undercut area is over 100 m wide and up to 20 m tall at the dripline. This spacious zone, designated as "outer entrance", accounts for more than half of the total area of the cave and is covered by colluvium and soil, piles of collapse blocks and large boulders, and inactive remnants of flowstone banks. Within 5–15 m inward from the dripline, the slanting roof meets the inner vertical wall of the undercut, forming a shelter cave along most of the width of the outer entrance, except in two places where inner entrances lead to separate cavities. The larger of the two inner entrances, 20 m wide and up to 3 m tall, is to the southeast and is partly blocked by collapse. It leads to a single down-sloping chamber, that branches off to several minor passages, which promptly pinch off, evoking the morphology of flank margin caves (Mylroie & Carew 1990). The other, smaller inner entrance is located some 20 m to the northwest, and is 8 m wide and 3.5 m tall. This cavity exhibits markedly different morphology from the previous, and consists of a narrow, mostly horizontal linear passage that extends 25 m northeast to a small chamber, from where it meanders and continues 25 m in the opposite direction, until it becomes to tight to follow. This passage is inhabited by a bat colony in excess of 100 individuals.

METHODOLOGY

The project was comprised of three components: 1) surveying of the cave and preparation for subsequent work; 2) monitoring and assessment of microclimate; and 3) sampling and analyses of local stalactites. Fieldwork was carried from March 12 until April 17, 2004.

The cave was surveyed applying standard National Speleological Society techniques (Dasher 1994), using a compass, clinometer, and metric tape. Following the drafting of the map, a 5-m grid was superimposed on it (Fig. 2), each grid square was numbered, and corresponding markers were placed in the field. This was done to improve the spatial accuracy of subsequent work in microclimate measurements and stalactite sampling.

Microclimate was evaluated by data loggers, evaporation pans, and periodic spot measurements. Data loggers were used to monitor temperature, humidity, and light intensity. The same

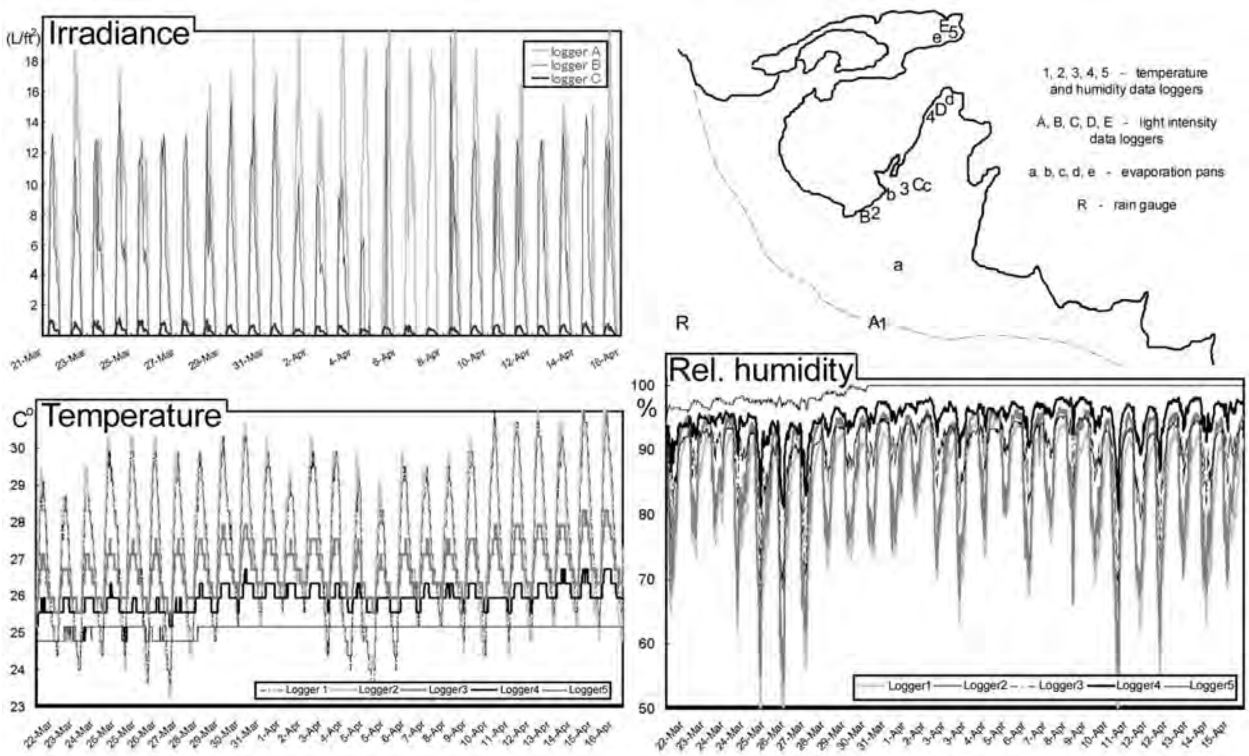


Figure 3. Data recorded by microclimate sensors in Pop Kan Mai Cave. The simplified plan shows positions of the data loggers. Temperature/ humidity sensors, light intensity sensors, and evaporation pans are denoted by numbers, capital letters, and lower-case letters, respectively. Note that mostly straight horizontal temperature and humidity lines correspond to conditions at the back of the cave (logger 5), and that the minor oscillations in humidity seemingly stabilize at 100%, as a consequence of the sensor's worsened performance in a high humidity environment. Light intensity values obtained by the innermost light intensity sensors (D and E) are constantly zero and are not shown in the graph.

parameters were checked by occasional spot readings, during which time photosynthetic photon flux and presence of air currents were also assessed. Temperature and humidity were monitored using Onset Hobo® H8 Pro data loggers, whose sensors record temperature between –30 and +50°C (with an accuracy of ±0.2°C and a resolution of 0.02°C) and humidity from 0% to 100% on a relative scale (with an accuracy of up to ±4% in condensing environments, such as cave interiors). The specified accuracy levels were deemed adequate for the purposes of our research, considering that the goal was a comparative assessment of microclimatic conditions rather than obtaining absolute values. Light intensity was measured by Hobo® LI data loggers, whose specifications indicate a wide spectral response and a range from less than 0.01 lm/ft² (0.11 lx) to over 10,000 lm/ft² (1.08 x 10^5 lx) or full sunlight. To avoid condensation damage to LI sensors, they were placed in clear quartz glass jars with silica desiccants. The data loggers were attached to cave ceilings or walls, roughly delineating a horizontal transect from the entrance to cave interior (Fig. 3). Loggers in the cave entrance were carefully placed in order to avoid exposure to direct sunlight, which would cause exaggerated readings. Loggers were set to collect temperature and relative humidity measurements every 15 minutes and light intensity readings every 60 minutes, during the period from March 21, 2004 until April 16, 2004. In addition, five plastic pans (surface area 104 cm²) with drip shields were filled with exactly 350 mL of water by using volumetric flasks and placed throughout the cave (Fig. 3). The volume of water necessary to restore the original volume was measured after 28 days, and evaporation rates were calculated in mL/m²/day. Securing the evaporation pans and data loggers was particularly challenging and we had to use strong wire and mesh casings to prevent macaque monkeys and tree shrews, which frequent the site, from tampering with them. Several days worth of data were lost from one of our LI loggers due to animal interference, and the plastic casing of one H8 Pro data logger had deep gnaw marks left by a tree shrew.

Besides long term monitoring, we took several series of spot measurements, each as contemporaneously as possible, at dozens of points throughout the cave, at all stalactite sample sites, and along a number of horizontal transects. These were used to validate data logged by sensors and obtain additional data for improved understanding and mapping of the cave's microclimate. Temperature and humidity were measured by a hand-held thermometer/psychrometer and irradiance levels were checked by a light meter. Airflow was gauged by a digital anemometer with a resolution of 0.2 m/s. In order to assess the light energy at wavelengths available to plant and microphyte growth, we have estimated photosynthetically active radiation (PAR) by a Spectrum Technologies quantum meter and obtained relative measurements by comparison with unobstructed sky. Finally, a tipping bucket rain gauge was installed near the cave, but the area experienced only a single day of significant rainfall during the fieldwork period.

Thirty stalactites to be sampled were chosen by randomly selecting thirty 5 x 5 m squares in the prepared grid and picking one actively dripping specimen growing within each square. Nine squares lacked stalactitic deposits, so samples were taken from other areas by judgment and convenience (all sample locations are indicated on Fig. 2). Actively dripping specimens were chosen in order to ensure that only contemporary, diagenetically-unaltered deposits growing in equilibrium with the present microclimate are considered. Drip rates were measured on several days and found to vary dramatically with time. Most of the specimens actually ceased to drip by the end of the fieldwork period, due to the lack of rainfall. Prior to the collection of stalactites, each specimen was photodocumented, measured and thoroughly examined in situ (Table 1). At the end of the fieldwork period, samples were removed by hammer and chisel and no preservation methods were used to treat them. They were allowed to dry at room temperature in the lab for several weeks prior to analyses. Following cutting, and macroscopic and binocular microscope examination, the samples were studied through conventional transmitted-light microscopy of resin-impregnated petrographic thin sections (one transverse and one longitudinal per specimen). Additionally, small fragments (two or three per specimen) were glued to aluminum stubs, sputter-coated with platinum and observed with a Hitachi S-3000H Scanning Electron Microscope (SEM), under operating conditions at 20 kV and 60 µA. Mineralogy was ascertained by X-ray diffraction (XRD) analyses on a Bruker AXS MX-Labo powder diffractometer.

RESULTS

CAVE MICROCLIMATE

We describe the microclimatic environment of the cave in terms of four factors: temperature, humidity, light availability, and airflow that can be expected to affect carbonate deposition. The first two are intrinsic parameters, which directly affect the chemistry of precipitation. Light levels have no immediate impact, but can indirectly affect the process by defining the local biologic environment. Airflow can physically influence stalactite formation.

TEMPERATURE, HUMIDITY AND EVAPORATION RATES

Microclimate of the studied cave is defined by cooler, more humid and stable conditions in the rear, and greater variability toward the entrance (Fig. 4). The temperature regime is characterized by 1) a distinct pattern of daily variations at the entrance; 2) a gradual buffering of daily temperature changes toward the interior of the cave, so that both minimum and maximum values experienced are progressively closer to the mean; and 3) a stable temperature in the farthest portions of the cave (Fig. 3). Therefore, although the temperatures throughout the cave are comparable in terms of mean values, with an average of 27.3° C in the outer entrance and 25.1° C in the cave's innermost part, they greatly differ over time. Maximum temperatures in outermost parts of the cave reached 31.5° C, while the temperature deeper inside the cave never exceeded 25.2° C. The daily temperature range is reduced by 8.3° C in the outer entrance and by 3.1° C in the inner entrance and dwindles to a virtually constant temperature further inside. Statistical analysis indicated that the variance in temperatures decreases from the entrance, with coefficients of variance ranging from 6.9° C in the outer entrance and approaching zero inside the cave (Table 2).

Relative humidity changes exhibit a similar pattern, except that there is a clear increase in mean values toward the cave's interior (Fig. 4). The overall situation is thus typified by 1) the greatest range and lowest relative humidity values at the entrance; 2) progressive increase of minimum and mean values toward the cave interior; and 3) nearly constant, ~100% levels deeper inside the cave (Fig. 3). In the outer entrance, the relative humidity shows an average of 83% and a coefficient of variance of 11, while in the inner entrance, the mean is 90% and a coefficient of variance is five (Table 2). The humidifying effect of the cave entrance is even more apparent from the minimum values, which were 19% apart. Finally, in the rear of the cave, the data indicate largely stable and highly humid conditions in excess of 95%. Accordingly, evaporation rates dramatically decrease toward the interior of the cave (Fig. 4). While the outermost evaporation pan indicated a daily loss of 714 mL/m², the one placed deepest inside the cave was evaporating 36 mL/m²/day. One significant observation is that maximum relative humidity values regularly reach levels above 95% even in the cave's outermost entrance area (Table 2), and indeed, outside the cave as well. This indicates that high humidity characteristic of caves temporarily occurs at the land surface, and is surely one of the factors enabling the prolific growth of stalactites in cave entrances and even on limestone scarps in the tropics.

LIGHT LEVELS AND AIRFLOW

Light intensity levels, obviously, diminish toward the cave interior. Daylight penetration into caves declines exponentially (Pentecost & Zhaohui 2001) or shows sudden drops caused by passage configuration. Accordingly, most of the study cave's larger chamber to the southeast is penetrated by at least some daylight, whereas much of the narrow and winding linear passage is in complete darkness. The outermost parts of the cave, at the dripline, are best illuminated but rarely experience levels greater than a quarter of full daylight (Fig. 4). This is due to effective shading by the vegetation growing on the cliff face. Uneven distribution of this canopy and geometry of the

Table 1. Physical description and other characteristics of sampled stalactites.

Physical description		Position		~Size		Deflection		Exterior surface		Drips[f]		
#	[all samples are stalactitic]	D[a] (m)	H[b] (m)	L[c] (cm)	C[d] (cm)	Angle (deg)	Direc. note[e]	Texture	Visible plants & animals	4/9/04 (mL/day)	Tem. (°C)	RH (%)
3	Crooked, partly attached to wall	3	2	90	42	<10°	W-NW	velvety organic coating	algae, fungus, spiderweb	<1	32	72
2	Massive, bumpy base with 3 stalactites	3	3	165	180	variable <30°	N	bumpy, rough	roots, algae, mud waspi	<1	32.2	74
30	Irregular, enlarged pendant-like tip	3	~15	20	20	variable<10°	S-SW	rough, earthy	algal coating	n/a	32.2	73
4	Slightly arched, bumpy, with 2 tips	3	2.5	90	45	<10°	N	bumpy, rough	algal coating at the tip	2	32.1	73
1	Step-like, projecting out of the wall	4	3	36	54	variable 45-75°	S	smooth, some corraloids	partial moss covering	4	32.1	73
28	Cylindrical, with a bulbous tip	5	~15	25	12	<2°	S-SE	reminiscent of sand-paper	algal coating	n/a	31.3	75
9	2 fused stal., hole between, arched	5	4.3	180	75	25°	N-NE	entirely moss covered	moss, large plant, insects	41	32	73
8	Massive, bumpy, thin 30cm-long tip	5	4.1	180	150	<5°	N-NE	extremely bumpy, rough	moss, small plant, insects	54	32	73
29	Highly irregular, prong-like, 3 tips	7	~10	30	25	variable<30°	S-SW	smooth	moss, algae	n/a	30.3	80
7	Irregular, stubby	7	2.3	17	20	15°	S-SE	shaded smooth, lit part rough	moss, lichen, insects	2	32	73
6	Irregular, elliptical in cross-section, 2 tips	8	2	90	84	variable5-10°	S	smooth, some coralloids	moss, lichen, mud wasp	7	32.1	73
22	Irregular, attached to wall, projects out	8	5	60	60	variable <60°	S-SW	botryoidal, few coralloids	2 large plnts. moss, insects	24	30.2	79
26	Irregular, deflected stalactite	10	~12	20	30	<10°	S-SW	earthy, crusty	algal coating	n/a	31.5	75
27	Irregular, somewhat flattened	12	~15	15	14	<5°	S-SW	wet, pasty	thick, pasty algal coating	n/a	30.9	79
21	Changing deflection, defl. stalagm. below	12	2.1	150	80	variable<30°	S-SW	bumpy, earthy	luxuriant moss, insects	144	30	80
23	Irregular, attached to wall, soda straw	*17*	1.1	60	40	follows wall, soda straw <2°		small coralloids	algal coating at the tip	39	30	81
10	Regular, conical	*17*	1.7	35	12	vertical		reminiscent of sand-paper	none	<1	27.5	95
11	Irregular, flattened, partly curtain	*18*	2.4	60	60	variable <10°	S-SW	bumpy, crusty	algal coating, white fungus	6	31.5	77
12	Irregular, step-like, 3 soda straws	*21*	2	40	55	variable <35°	SW	smooth, earthy	light algal coating	65	31.4	78
5	Conical, slightly-arched	*22*	0.25	30	15	<5°	E-SE	wet, pasty organic coating	thick moss, black fungus	30	29.2	83
13	Irregular, step-like, bulbous	*23*	1	50	50	variable <35°	SW	smooth, flaky	algae (light), mud wasp	13	31.2	79
14	Several stalactites joined laterally	*27*	0.5	45	45	<2°	SW	rough, sharp coralloids	none	2	30.5	81
15	Cylindrical, abruptly narrow tip	*31*	1.5	27	14	<3°	SW	crumbly, some coralloids	algal coating at the tip	2	28.9	88
16	Conical, lowermost part of a pendant	**32**	0.7	60	40	vertical		rough, many coralloids	light greenish hue	14	29.2	86
17	Largely regular with a bulbous base	**30**	2.2	33	36	vertical		rough, few small coralloids	none	<1	27.6	91
18	Regular, elliptical in cross-section	**35**	2.1	35	21	vertical		smooth	none	<1	27.7	96
19	Almost perfectly conical	**36**	2	70	19	vertical		rough, lots of coralloids	none	17	28.6	96
20	Bulbous base with a thin stalactite	**41**	0.9	40	30	vertical		very rough to smooth	none	2	27.5	97
24	Conical, tip broken, new soda straw	**>45**	0.9	30	10	vertical		smooth	none (bats roost near)	47	27.9	94
25	Cylindrical, with 5 soda straws	**>45**	1.8	16	20	vertical		rough, lots of coralloids	none (bats roost near)	2	27	98

Note: Samples are arranged in the order of increasing distance from the dripline toward to the cave's rear. Numbers in the first column (#) are sample ID numbers, corresponding to locations indicated deposits in the outer entrance, inner entrance to innermost twilight zone area, and cave beyond the twilight zone). [b]H= height above ground. [c]L= maximum length. [d]C= maximum circumference. [e]Defle nally selected, but many dried out due to virtually no rainfall following 03/20 rain event. Drip rate was not measured for the five stalactites located in very high ceilings. [g]Rock type qualification is highl ed tufa and laminated tufa deposits respectively) and more solid deposits speleothems (abbreviated as Sm and S for microcrystalline speleothems and "normal" macrocrystalline speleothems respectively - aragonite with lesser calcite, A=C - aragonite and calcite in roughly equal proportions, C>A - calcite with lesser aragonite, C - mostly calcite. [i]Mud wasps (Hymenoptera: Sphecidae) often plaster thei

Microclimatic data			Rock desc.	
	4/9/04 at 12:00 noon			
air flow (m/s)	PAR (mmol/m²/s)	LI (lx)	phys. type[g]	XRD min.[h]
0.4	167	1378	Te	A=C
0.2	173	54	Tl	A>C
0.4	22	926	Tl	A>C
0.4	144	1055	Tl	A<C
0.2	148	1055	Te	A<C
0.2	38	861	Te	A=C
0.4	88	603	Te	C>A
0.4	93	603	Tl	A>C
0.2	17	807	Tl	C>A
0	69	527	Te	C>A
0	59	527	Te	A>C
0	31	1378	Te	C>A
0.2	11	646	Tl	A=C
0	16	667	Te	C
0	15	850	Te	A=C
0	1	78	Tl	C>A
0	0	0	S	A>C
0	8	205	Tl	A=C
0	4	97	Tl	A>C
0	3	43	Sm	C>A
0	2	11	S	A=C
0	1	5.4	Sm	A>C
0	0	2.2	S	A=C
0	0	1.1	S	A
0	0	0	S	A>C
0	0	0	Tl	A>C
0	0	0	S	A>C
0	0	0	S	A
0	0	0	S	A>C
0	0	0	S	A=C

on Figure 2. [a]D= distance from the dripline (normal font, italic font, and bold font respectively indicate
ection direction is italicized if prominently away from the light. [f]All stalactites were dripping when origi-
y subjective. We chose to call friable microcrystalline deposits tufa (abbreviated as Te and Tl for encrust-
). [h]Mineralogy as determined by XRD analyses. Abbreviations are as follows: A - mostly aragonite, A>C
r mud-cell nests to stalactites.

cliff causes minor spatial discrepancies in light levels in the cave's outer entrance zone (Fig. 4, see transect), and also accounts for somewhat patchy distribution of vegetation in the area (Fig. 4, inset). At the cave's inner entrance, enough light penetrates to allow human eyes to see quite well, but the availability of wavelengths suitable for photosynthesis is attenuated to less than 2% of open sky levels. This roughly coincides with the extinction of autotrophic biofilms that coat the rock surfaces in the cave's outer entrance and progressively diminish inward. Photosynthetically active radiation extinguishes some meters sooner than all visible wavelengths. Nonetheless, we have seen that the measurements of irradiance by normal light meters well approximate PAR levels (Fig. 4, see transect).

Airflow in the cave was evaluated because it is known to have an effect on stalactite morphology (Hill & Forti 1997). In cave entrances, in particular, where the growth axis of stalactites is commonly not vertical, air currents are sometimes suggested as one reason for deflection (e.g., Sevenair 1985). At our study site, however, no airflow into and out of the cave was registered. Minor air movement was occasionally detected in the outer entrance area, but its direction was usually along the outside cliff face (Fig. 4).

Properties of stalactites

All specimens considered in this study are stalactitic in appearance and can clearly be referred to as stalactites. Nevertheless, they form a highly disparate set (Table 1), exhibiting divergent morphologies and a considerable number of distinct fabrics. They range from the highly irregular and crumbly stalactitic features in the most exposed locations to ordinary-looking speleothems found deeper inside the cave (see Table 1: Physical description). The greatest contrast exists between deposits in the outermost and innermost parts of the cave (see Table 1: Position), whose rock types correspond to calcareous tufa and normal speleothem travertines, respectively. The studied deposits are described here, in the "order of appearance" when entering the cave, in terms of external macromorphology, surface textures, internal macromorphology, and fabrics.

External macromorphology

In Krabi area and similarly humid tropical karsts elsewhere, "stalactites" can grow outside of caves, and are prolific on limestone towers and cliffs. Despite their convincingly stalactitic appearance, however, these deposits are distinct from and are not to be considered true speleothems. They form in essentially epigean settings (Taboroši *et al*. 2004a), including transitional environments (e.g., shelter caves, cave entrances) and are ubiquitous in the humid tropics (Lehmann 1954, Wilford & Wall 1964, Longman & Brownlee 1980, Crowther 1982, Taboroši 2002). In Pop Kan Mai Cave they dominate the outermost parts, and range in size from a centimeter to meter scale (see Table 1: Size; but comparable deposits reaching tens of meters occur elsewhere in the Krabi area, most notably Rai Lay peninsula cliffs). The overall mor-

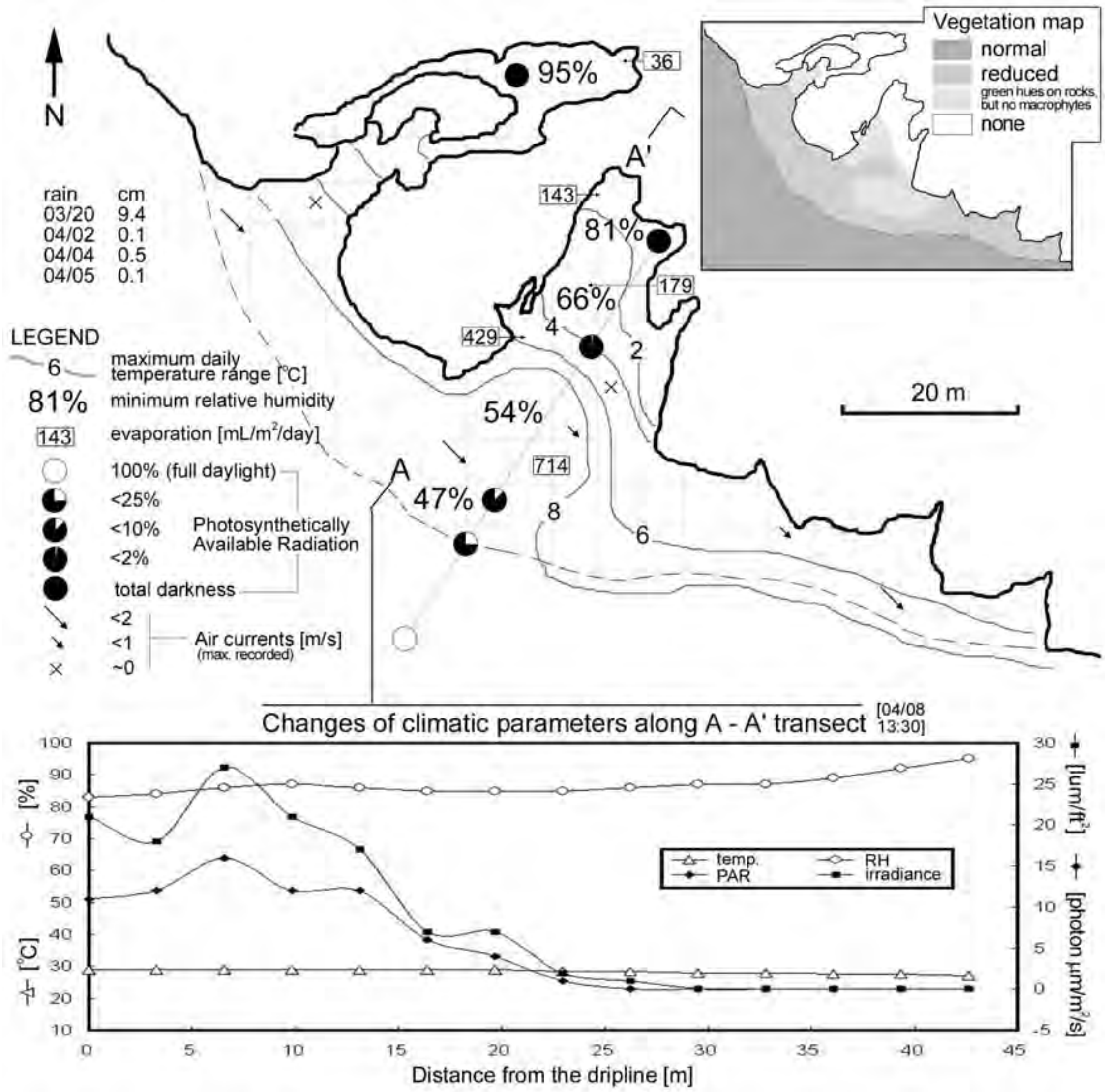


Figure 4. Microclimate map of Pop Kan Mai Cave, depicting approximate daily temperature ranges, minimum relative humidities, evaporation rates, PAR light levels, and predominant air currents. Inset map illustrates vegetation distribution, and the graph shows changes of climatic parameters along a transect from the entrance to cave interior.

phologic aspect of these “stalactites” is erratic, and shapes ranging from slightly asymmetrical (Fig. 5A) to highly irregular, such as bulbous, pendant-like, club-like, flattened, slanting, step-like, branching, and variously contorted forms are the norm. They can also be quite thin and elongated (Fig. 5B), but soda straws do not form. Growth is naturally guided by gravity, but is not entirely controlled by it, and deflections of growth axes are common (Fig. 5C). Tilting is often, but not necessarily, in the direction of light, and can be so pronounced as to approach horizontal growth in some locations. While most of the non-vertical growth is surely due to biologic processes, it cannot always be attributed simply to the preferential calcite deposition on light-facing sides by photosynthetic microorganisms, as generally suggested (e.g., Bull & Laverty 1982). Photo-orientation is, indeed, a common trait of epigean and cave entrance stalactitic deposits, and many of our samples clearly face the direction of sunlight. However, deflections are certainly caused by more complex imbalances in microbial biofilm dynamics, as suggested by the presence of deposits exhibiting inconsistent curvatures (Fig. 5C), specimens leaning away from the light, and adjacent stalactites slanting in conflicting directions (see Table 1: Deflection).

Further inward, in much of the twilight zone, stalactites are less lopsided than those in the more exposed areas. Many of them mimic the recognizable cylindrical and conical shapes of normal stalactites, but retain some irregularities. Generalizations are difficult due to the great variety of forms, but common shapes include somewhat globular, bent, and stunted (Fig. 5D) features, deflected deposits ranging from conspicuously step-like (Fig. 5E) to slightly bowed (Fig. 5F), and ordinary-looking stalactite bases with bulbous or disproportionably thin and elongate tips (Fig. 5G). When deflections are present, orientation towards the daylight source, as opposed to any direction, appears to be the rule and is most likely elicited by the dramatically reduced availability of PAR light. Another feature that contrasts these stalactites with their counterparts forming in more exposed parts of the cave is that they frequently have slight, often multiple, soda straws attached (often deep green or black due to microbial colonization).

Table 2. Descriptive statistics for the microclimate of Pop Kan Mai Cave. Note that maximum humidity levels experienced at the dripline (and probably outside the cave as well) are comparable to those deep inside the cave. This is certainly one of the factors allowing stalactite growth in epigean settings in the tropics. Also note that data logger 2 exhibits a greater temperature range and maximum value than logger 1, even though it was placed more inward from the dripline. This is probably due to uneven shading by the canopy.

Cave area	Outermost dripline	Outer entrance	Twilight zone front	Twilight zone rear	Cave interior
Data logger ID	1	2	3	4	5
Temperature (°C)					
Mean	27.3	27.3	26.7	25.9	25.1
Minimum	23.6	23.2	25.2	25.2	24.8
Maximum	31.1	31.5	28.3	26.7	25.2
Range	7.5	8.3	3.1	1.6	0.4
Standard deviation	1.8	1.9	0.6	0.3	0.1
Variance	3.1	3.6	0.4	0.1	0.0
Coeff. of variance	6.4	6.9	2.3	1.2	0.5
Relative humidity (%)					
Mean	83	87	90	95	99
Minimum	47	54	66	81	95
Maximum	96	97	96	98	100
Range	49	43	29	18	5
Standard deviation	9	9	4	3	1
Variance	79	74	19	7	2
Coeff. of variance	11	10	5	3	1
Data logger ID	A	B	C	D	E
Light intensity (lx)					
Maximum	275.5	212.1	12.9	0.0	0.0

Proceeding deeper into the cave, in the inner parts of the twilight zone and beyond, the morphology of stalactites gradually becomes no different from typical speleothems known from elsewhere. Reaching about 1.5 meters in length, they exhibit the familiar conical shapes (Fig. 5H), well developed soda straws, and strictly vertical growth axes (Fig. 5I).

SURFACE TEXTURES

The outer surfaces of stalactitic deposits in areas exposed to daylight exhibit a unique "organic" feel and distinctive pale to deep dark green, brownish, gray, and black coloration (Fig. 5A). Specimens found in the most exposed portions of the cave (as well as those outside it) are covered by moist and velvety coatings of algae, lichens, and especially mosses (Fig. 5B; 5C; also see Table 1: Exterior surface). In some cases, these outside layers can be dry and exhibit desiccation cracks, wrinkles, and flaking. Such dehydrated stages are probably a part of the annual cycle. Also evident can be roots of higher plants, which grow nearby or emerge from the stalactites themselves (Fig. 5B).

Further into the twilight zone, the obvious growths of bryophytes and higher plants are replaced by epilithic microbial biofilms, resulting in wet and pasty or powdery or earthy coatings (Fig. 5D; 5E; 5F). These organic layers can vary significantly in composition, causing sundry coloration: white, gray, yellowish, light to dark green and brown, purplish, and black. The biofilms are particularly pronounced on the sides facing the light (Fig. 5E), and support prolific colonies of prokaryotes and microphytes. The portions of the stalactites facing the darkness of the cave generally lack such biologic consistency and their surfaces are flat and smooth, rough or botryoidal, or exhibit jagged coralloid textures.

In the innermost twilight zone and deeper into the cave, significant biofilms gradually diminish, receding to the most damp areas near the stalactites' growing tips (Fig. 5G) and eventually dying out. As abiotic surfaces take over, stalactites gradually gain the crystalline luster of typical speleothems. They are colored white, yellowish, light gray, or brown, and their most common textures are coralloid, slightly rough (Fig. 5H), and smooth surfaces (Fig. 5I).

INTERNAL MACROMORPHOLOGY

Internal structure of stalactitic deposits found around the dripline is in stark contrast with usual cave speleothems. They are generally lightweight, porous, and friable, and many are weak enough to be plucked by hand. When broken, they reveal vuggy interiors, white to gray or brown, and composed of mouldy or layered calcareous tufa. They often contain soil and plant material (Fig. 6A), and almost invariably lack sparry crystals. Some of the most typical structures result from bryophyte encrustation and are composed of extremely porous spongy frameworks which may entirely lack (Fig. 6B) or display only rudimentary layering (Fig. 6C). Also common are laminated tufa deposits, which may be combined with encrusted fabrics (Fig. 6D) or concentrically layered and homogeneous, but nonetheless highly porous (Fig. 6E). Finally, in some cases, the laminae are surprisingly fine and ordered and convincingly resemble normal speleothems, but the deposits crumble easily and are fragile and powdery, reminiscent more of chalk than travertine (Fig. 6F).

Inside much of the cave's twilight zone, stalactites are denser and less porous than their analogues from the more exposed locations, but are still generally flimsy and can contain prominent voids (Fig. 6G). Classification is difficult due to the great diversity of morphologies and fabrics exhibited by individual specimens, but mostly microcrystalline makeup, with fairly irregular layering and some coarsely crystalline calcite, is the norm recognizable in most hand samples (Fig. 6H). Essentially, these deposits are transitional forms between the extremely irregular epigean tufa stalactites and normal cave speleothems. Some specimens can be heterogeneous, exhibiting discrepancies between light-facing sides (more tufa-like) and darkness-facing portions (more speleothem-like). In general, the former are vuggy and less organized, whereas the latter are denser and evenly laminated.

Further into the cave, stalactites are progressively dominated by solid, regular, concentrically layered coarsely crystalline structures (Fig. 6I). At the rear parts of the twilight zone, the familiar dense laminae and sparry crystals are the standard composition, although some micritic material remains locally enclosed. The latter gradually recedes in specimens beyond the twilight zone, as stalactites assume the macrocrystalline make-up and consistent structure of typical speleothems.

STALACTITE FABRICS

Petrology of the stalactites we investigated is extremely varied. Containing both calcite and aragonite, they exhibit a bewildering array of fabrics, which contrast considerably among, but also within, individual specimens. As a preliminary classification, they can be broadly grouped into predominantly microcrystalline and macrocrystalline fabrics, in the order of progression from the most exposed to best enclosed parts of the cave (Table 3).

In general, microcrystalline fabrics correspond to calcareous tufa (or rather, an unusual subaerial, stalactitic form of it) and many are comparable to those well known from aquatic, traditional tufa deposits. They characterize the relatively open and microclimatically variable parts of the cave, with encrusted macrophyte fabrics (Fig. 7A; 7B) dominating the most exposed areas, and encrusted microbial fabrics (Fig. 7C; 7D) and amorphous (Fig. 7D; 7E) and laminated microcrystalline fabrics (Fig. 7E; 7F) typifying the twilight zone. In the inner reaches of the twilight zone, the fabrics become progressively ordered, less porous, and gradually dominated by spar (Fig. 7G; 7H). Within the stable and humid conditions beyond the twilight zone, the fabrics come to reflect ordinary speleothems (Fig. 7I).

The end member found in the cave's outermost parts is encrusted fabrics almost entirely bioconstructed by calcite precipitation on plant structures. They develop by deposition of microcrystalline $CaCO_3$ on exposed plant surfaces, resulting in highly porous (exceeding 90% porosity) fragile structures. A representative example is extremely vuggy lace-like networks (Fig. 7A) that have evidently formed by encrustation of bryophytes, which colonize vadose water drip points and whose living shrubs continue to grow as older parts become incorporated into incipient stalactitic deposits. The characteristic morphologies display well-defined molds and remains of moss stems and protonema (which also occur within other fabrics; Fig. 7E - top right) and are quite comparable to biogenic fabrics observed in conventional tufa (e.g., Weijermars *et al.* 1986). Similarly irregular, porous and easily recognizable tufa fabrics (Fig. 7B) form when hanging plant roots influence and guide the deposition of calcite by providing support and nucleation sites (resulting in tufaceous equivalents of cave rootsicles; see Taboroši *et al*. 2004b).

Microbial structures can also become encrusted by calcite (Fig. 8A), resulting in yet another series of distinct fabrics. One of the most fascinating encrusted microbial morphologies develops by calcification of colonies of filamentous cyanobacteria (Fig. 7C), which grow on the surfaces of stalactites reached by sufficient light to enable photosynthesis. Calcite is precipitated on the surfaces of cyanobacterial filaments, creating hollow tubes surrounded by one to several layers of calcite. Groups of filaments may be oriented along consistent axes or be randomly tangled, and the pore space between them may be empty or infilled by secondary calcite. In addition to filamentous cyanobacteria, numerous other calcified and uncalcified microbes and microbial structures (Fig. 8B) are exceedingly common in the twilight zone.

Alongside encrusted morphologies, stalactitic deposits at the entrance and in the twilight zone comprise other microcrystalline fabrics, both amorphous and layered. Amorphous fabrics are characterized by microcrystalline groundmass (Fig. 7D; 7E), often with interspersed organic-rich material (Fig. 7D), microbial structures (Fig. 8C; 8D), detrital grains and interred invertebrate and plant fragments (Fig. 7E–top right). Pore spaces can be infilled partly or completely by secondary calcite and aragonite (Fig. 7E–bottom right). Layered fabrics are analogous to laminated tufas and appear as highly porous layers of optically unresolvable crystallites (Fig. 7F). In many specimens, the white or transparent microcrystalline laminae are intercalated with brown and opaque organic material (Fig. 7F; 7G). Equivalent structures recognized by Chafetz & Meredith (1983), Chafetz & Folk (1984) and Folk *et al*. (1985) in various travertine deposits are attributed to bacterial activity. The laminae are seldom regular as in normal stalactites, and are generally undulatory, convoluted, and even discontinuous. They can also include layers of microsparitic or sparry calcite flanked by microcrystalline laminae, producing polycyclic spar/micrite couplets (Fig. 7G). This arrangement, as well, has been previously reported from normal, aquatic tufas (e.g., Jannsen *et al*. 1999, Pavlovic *et al*. 2002).

As the distance from the entrance increases, biogenic and amorphous structures become rare, and most deposits are organized as concentrically layered microcrystalline aggregates (Fig. 8E). They are progressively less porous and more orderly, exhibiting greater proportions of macrocrystals while retaining some microcrystalline material (Fig. 7H; 8F; 8G). Beyond the twilight zone, most fabrics are composed of equant and columnar calcite and acicular aragonite, initially poorly arranged (Fig. 8H) but progressively better organized and densely layered. They come to contain no significant microcrystalline or organic material and reflect quintessential speleothems (Fig. 7I; 8I).

DISCUSSION

CAVE MICROCLIMATE

Climatic data from tropical caves are limited, as the majority of relevant research was carried out in temperate regions. In the most comprehensive bibliography of spelean microclimatology to date only a few references are related to tropical caves (see Wefer 1991 and references therein). The distinctiveness of tropical cave microclimates as opposed to those of temperate caves was examined by Gamble *et al*. (2000). By identifying a number of idiosyncrasies that may be unique to tropical caves, they showed that extant cave microclimate models may not be applicable in the tropics. The microclimatic observations reported in this paper and data from previous work (Taboroši & Hirakawa 2003) generally conform to the conclusions of Gamble *et al*. (2000). Specifically, we have also found that external atmospheric variations project into a cave and diminish toward the rear, and that the deep cave microclimatic zone (Cropley 1965) can be missing due to small size of caves relative to their entrances. A significant difference, however, is that while Gamble *et al*. (2000) found warmer conditions in the back portions of caves, we recorded consistently cooler temperatures at the rear, both in Thailand, as well as in the Mariana Islands (Taboroši & Hirakawa 2003). While this may be a consequence of different monitoring periods and seasonal variations, it is more likely due to the differences in the caves' physical configuration, such as passage geometry and size and number of entrances, which are known to largely determine microclimate regimes of individual caves (de Freitas *et al*. 1982).

MICROCLIMATIC CONTROLS ON FORMATION OF STALACTITES

Since all the specimens we collected are from a single cave located in an isolated karst tower, we deem that all are fed by the same groundwater body overlying the cave and expect no major geochemical variations in their respective dripwaters. Although we did go into the field prepared to check dripwater *p*H and conductivity, the dry weather and slight drip-rates prevented us from taking meaningful measurements (as degassing and evaporation modified water chemistry during the days-long periods it took to acquire volumes sufficient for testing by hand-held meters). While documenting dripwater geochemistry remains an objective for future related research, we believe that the small size of the studied cave and its location in a discrete limestone tower imply that dripwater feeding all stalactites comes from a single perched and clearly delimited groundwater body, isolated from local input of any other vadose water. Therefore, we view the profound morphologic and petrologic differences among the studied specimens predominantly as the function of each stalactite's own microclimatic and ensuing biologic environment, determined by its specific position in the cave.

The general trend is that as diurnal variations are alleviated and humidity increased and stabilized, the deposits show progressively lower porosity and heterogeneity and greater crystal size and level of organization (Fig. 9). At the land surface, the effects of increased evaporation cause rapid precipitation of calcite from karst water, resulting in poorly arranged and randomly oriented microcrystalline aggregates. This is a well-known phenomenon influencing the fabric of calcareous tufa deposits worldwide (Ford 1989, Viles & Goudie 1990, Ford & Pedley 1992, 1996), but is generally not considered in the case of cave stalactites. Nonetheless, the irregular crumbly stalactites we observed in the most exposed parts of the cave are produced partly by this process, and essentially comprise a unique, subaerial category of tufa. In addition to increased evaporation, the precipitation of these deposits is affected by the pronounced diurnal, seasonal, and annual variations in temperature and humidity levels (as well as other indirectly-linked parameters such as changes in canopy abundance and shading effects). Due to these oscillations, calcite deposition is inconsistent and results in the observed heterogeneities in macromorphology and fabrics.

In better-enclosed settings, the relative humidity is increased and the variations in temperature and humidity are reduced, allowing the precipitation of progressively larger and more regular crystals and more consistent fabrics. This is manifested in stalactites that form in the cave's twilight zone and contain both microcrystalline and sparry calcite and aragonite. As the humidity levels increase and stabilize with distance inward from the cave entrance, the proportion of macrocrystalline to microcrystalline $CaCO_3$ is amplified and heterogeneities in the fabrics are reduced. Finally, as consistently high humidity levels are reached deeper inside the cave, the effects of evaporation are nearly eliminated, and the resultant deposits are composed of orderly coarsely crystalline fabrics precipitated by CO_2 degassing. Within such a microclimatically stable environment, variations in water availability and geochemistry are expected to overcome microclimatic (and biologic) factors as the primary controls of precipitated carbonate morphology.

BIOLOGIC CONTROLS ON FORMATION OF STALACTITES

Concomitantly with the physico-chemical precipitation, living organisms exert their influence on carbonate deposits. The mechanisms by which biota interact with sediments are numerous and still insufficiently known, but it is now generally accepted that most carbonate precipitates are shaped by biologic activity in addition to the inorganic processes, and many are almost entirely biogenic (Viles 1988). Since the presence of living organisms on any given substrate is controlled by environmental conditions, the gradients in temperature, humidity, and illumination in spelean settings translate directly into gradients in abundance, diversity, and species composition of local biota. Numerous studies have demonstrated that biologic diversity declines as a response to reduced light levels in caves (Piearce 1975, Cubbon 1976, Pentecost & Zhaohui 2001), which entails a decrease in biologic involvement in carbonate precipitation. Consequently, many epigean carbonates are often biogenic (Viles 1988) whereas most cave carbonates are considered abiotic (Thraikill 1976). This relationship is clearly visible in the cave we studied, where the patterns of microclimatic change from the entrance to interior are closely reflected by biology.

In the outermost, best-illuminated part of the cave, many stalactitic deposits are colonized by bryophytes and higher plants, and are consequently dominated by encrusted macrophyte structures. This encrustation process, driven by the photosynthesis-respiration cycles of the substrate plants (Pentecost 1996), is a well-known phenomenon in cascade and other classic tufas (e.g., Pavlovic *et al*. 2002), but is rarely documented in connection with stalactites. Only a few moss-encrusted

Table 3. Stalactite fabrics broadly grouped in the order of progression from the cave's most exposed to best enclosed parts. (See Fig. 9 for a schematic diagram.)

Stalactite Fabrics	Type	Position	Climate	Illumination
Microcrystalline fabrics		entrance	variable	normal
a) Encrusted macrophytes	tufa			
b) Encrusted microorganisms		cave		reduced
c) Amorphous microcrystalline		twilight	buffered	
d) Laminated microcrystalline	transitional	zone		
Macrocrystalline fabrics				minimal
a) Poorly organized, some microcrystalline	(travertine)			
b) Classic carbonate speleothem microfabrics	speleothems	interior	stable	none

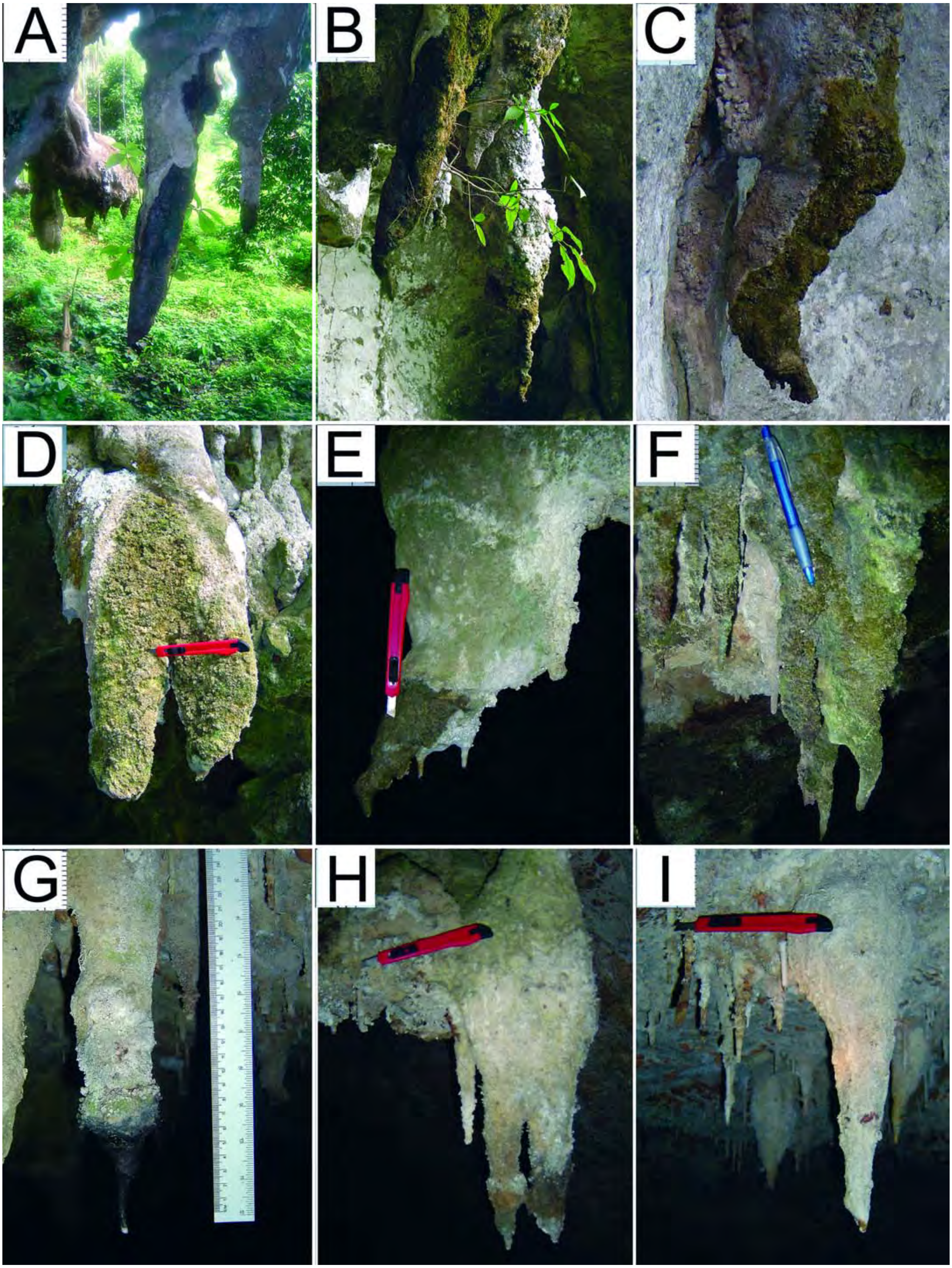
"speleothems" have been described before (e.g., Lichon 1992, Zhaohui & Pentecost 1999), but their occurrence in the tropics is much wider than the occasional reports seem to suggest.

As light is reduced further into the cave, macrophytes disappear but photosynthetic microbes continue to thrive in complex epilithic biofilms. This is macroscopically apparent from the greenish hues on cave walls and especially on stalactites (which, being endpoints of vadose flow paths, are wet and preferentially colonized by organisms) and is also evident in stalactite fabrics, which commonly contain calcified filaments and microorganisms. In some cases, microbial colonies, notably obligatory calcifying cyanobacteria, are sole builders of some stalactites, as they provide the frameworks subsequently strengthened by secondary calcite precipitation in pore spaces (Taboroši & Hirakawa 2004). Unlike passive calcification by macrophytes, which is generated by photosynthetic modification of the medium and leads to spontaneous precipitation (e.g., Weijermars *et al*. 1986), microbial calcification is thought to be a more active process, or rather, a suite of processes (e.g., Pedley 1994). Cyanobacteria, for example, are thought capable of initiating and controlling the precipitation (Pentecost & Riding 1986, Merz 1992, Schneider & Le Campion Alsumard 1999), and so are other microbes (e.g., Chafetz & Folk 1984).

Specialized autotrophic microorganisms are capable of photosynthesis even at extremely low light levels (Cox & Marchant 1977) and persist deep into the twilight zone. Nevertheless, overall photosynthesis is dramatically reduced with distance from the entrance, which leads to a loss of biodiversity and complexity of epilithic biofilms and their relative participation in the formation of secondary carbonate deposits. This is apparent from the fabrics of stalactites in the twilight zone: they retain some evidence of calcified microbes and biologically precipitated material, but steadily transition to more abiotic microcrystalline and macrocrystalline deposits. Although certain chemotrophic and heterotrophic microorganisms can impact the formation of speleothems deep within the spelean realm (Northup et al. 2000, Jones 2001), most carbonate precipitates in the complete darkness of caves are considered "absolutely inorganic" (Forti 2001) and we have seen no evidence of microbes in stalactites beyond the twilight zone.

The fact that living organisms can directly control the fabrics of stalactites we studied should not lead to underestimating the importance of the microclimate. In fact, the succession in biologic involvement in precipitation is a reflection of the microclimatic gradient (Fig. 9), with which it is intricately linked. Microclimatic variations, and especially different illumination levels, define the ability of specific microorganisms to colonize a particular substrate, and thus determine the nature of epilithic biofilm that develops on a given surface (Taboroši & Hirakawa 2004). This, in turn, impacts carbonate precipitation and influences the incipient deposits. In effect, the mor-

Figure 5 (next page). Stalactitic deposits *in situ*, including those in the outer entrance (A-D), twilight zone (E-G), and innermost twilight zone and beyond (H-I). Sample ID numbers of illustrated specimens are indicated in brackets. A) A slightly arched stalactite growing just a few meters from the dripline. Its monotonous gray color is due to a pervasive powdery biofilm [9]. B) Stalactites adjacent to the previous specimen. Note the irregularities such as non-vertical growth, inconsistent width, and an elongate tip. Stalactite in the foreground is dark due to a thorough moss cover. Note the large plant rooted in the stalactite itself [8]. C) A stalactite that starts as a drapery and grows on a cliff wall, in a very open location. Note its bent shape due to a changing growth direction, and a luxuriant moss cover (dark) on its light facing side [21]. D) A stunted stalactitic deposit, covered by thick, but largely dry and flaking, organic coating [6]. E) A stalactite inside the cave's twilight zone. Its step-like growth faces the entrance [12]. F) Twilight zone stalactites, with hooked shapes and covered by copious gooey organic material [5]. G) A cylindrical stalactite with a disproportionately narrow tip. Only the moist tip is colonized by a lush microbial biofilm (dark-colored and in stark contrast with the rest of the deposit) [15]. A rough-surfaced stalactite in the innermost reaches of the twilight zone [16]. I) Archetypal stalactites and soda-straws in the rear of the cave [17].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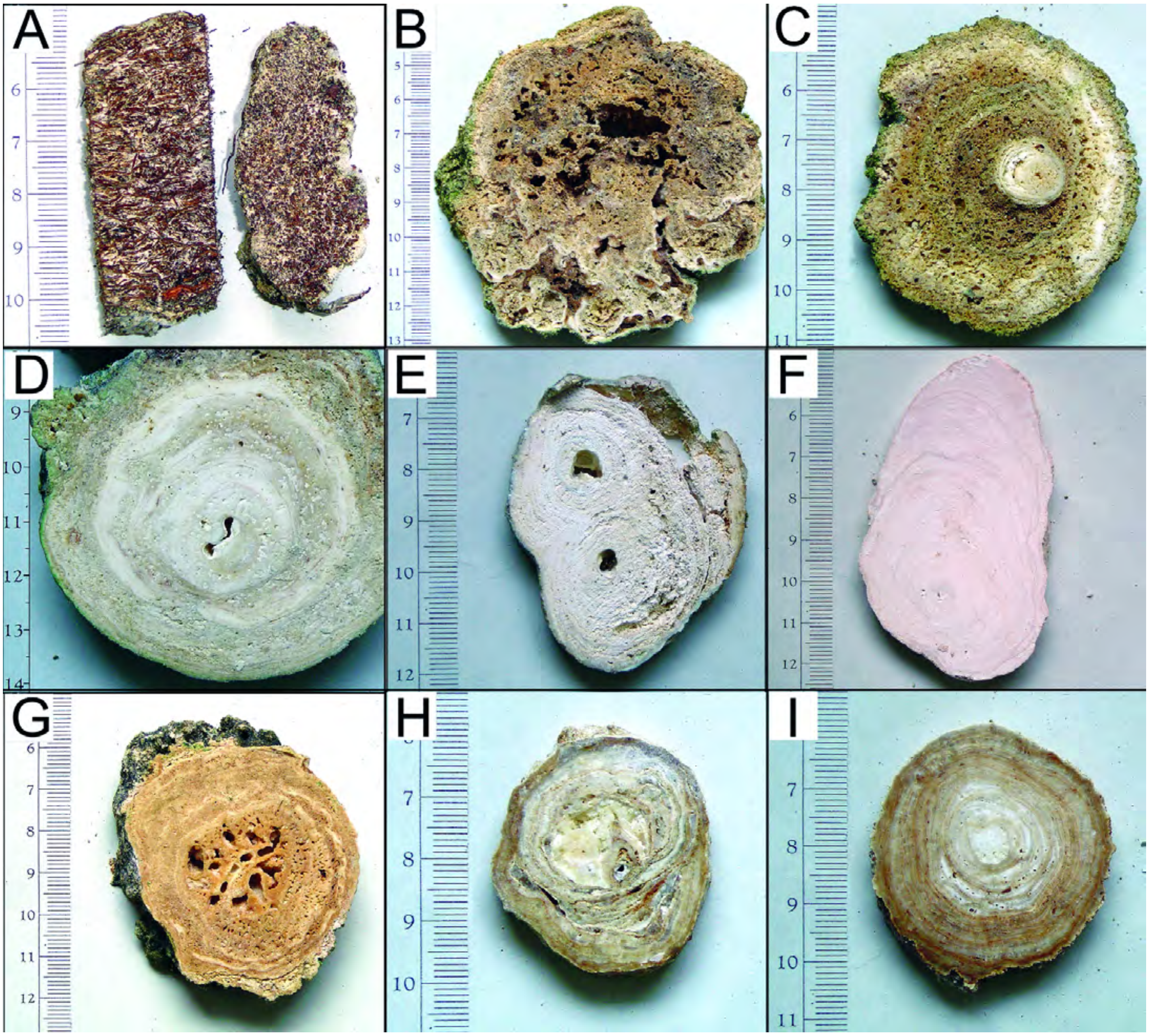

Figure 6. A series of cross-sections of stalactites approximating a transect from the entrance to the interior of the cave, consisting of encrusted (A-D) and layered microcrystalline (D-F) fabrics, transitional specimens (F-H) and a normal speleothem (I). Scales in centimeters. Sample ID numbers of illustrated specimens are indicated in brackets. A) An extremely fragile fragment formed by encrustation of hanging plant roots [9]. B) A highly porous, spongy stalactite formed by bryophyte encrustation [21]. C) A visibly layered bryophyte-encrusted feature, formed by moss colonization of an incipient microcrystalline stalactite (deposit core) [28]. D) A laminated tufa stalactite with outermost parts composed of encrusted material [8]. E) A regularly layered and homogeneous, but nonetheless highly porous, tufa stalactite exhibiting no macrophyte encrustation [4]. F) An extremely finely laminated, chalk-like microcrystalline stalactite resembling a normal speleothem but displaying no spar whatsoever [18]. G) A hard, concentrically layered microcrystalline deposit, exhibiting convoluted laminae and macroporosity [14]. H) A stalactite composed of microcrystalline material and spar crystals, arranged in somewhat irregular laminae [24]. I) A hard, dense macrocrystalline stalactite composed of regular, finely layered concentric laminae [19].

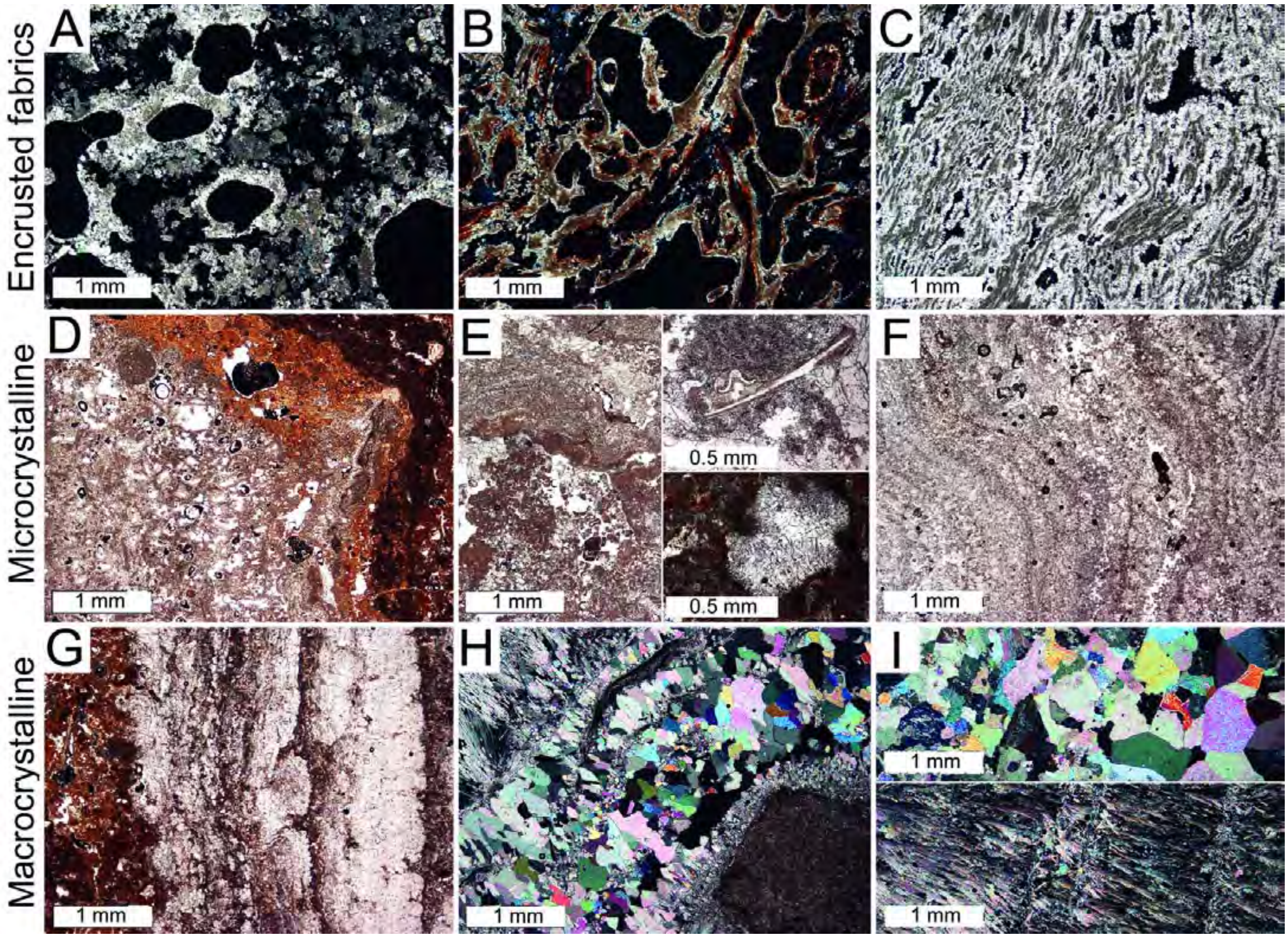

Figure 7. Thin-section micrographs of fabrics characterizing the range of stalactites from cave entrance to interior, including encrusted (A-C), amorphous (D-E) and laminated (F-G) microcrystalline, and partially (H-I) and completely (J) macrocrystalline fabrics. Note that all micrographs (except the two insets) were taken at the same magnification. Sample ID numbers of illustrated specimens are indicated in brackets. A) An extremely porous deposit formed by bryophyte encrustation [21]. B) An analogous feature formed by encrustation of hanging plant roots [9]. C) A fabric comprised of calcified cyanobacterial filaments [27]. D) A microcrystalline deposit comprised of calcified microbes (light material), amorphous organic-rich mass (dark), and numerous detrital grains [26]. E) Amorphous microcrystalline groundmass (left half) [22], moulds of moss stems and protonema (top right) [8], and pore spaces partially filled by secondary calcite and aragonite (bottom right) [28]. F) A porous, laminated deposit composed of microcrystalline material and some detrital grains (black) [11]. G) A laminated deposit composed of intercalated laminae of microcrystalline and organic-rich material (dark layers) and larger crystals (light layers) [10]. H) A complex deposit typical of the twilight zone, where microcrystalline material (lower right) is in close association with macrocrystalline calcite (middle) and aragonite (top left) [15]. I) Typical speleothem fabrics composed of homogeneous, well-organized equant calcite (top) [25] and acicular crystals of aragonite (bottom) [20].

phology and petrology of stalactites are a function of environmental factors by two parallel pathways: microclimatic variations directly influence carbonate precipitation; and also determine the composition and dynamics of biologic communities, which then influence carbonate precipitation in their own right.

DIAGENETIC CHANGES AND IMPLICATIONS TO PALEOENVIRONMENTAL INTERPRETATIONS

We have demonstrated that morphologic properties of stalactites are partly determined by the microclimate in which they are deposited, and that specific fabrics can be correlated to different temperature, humidity, and illumination regimes. This can be a useful tool in the interpretation of former environments and microclimates. For example, an excellent paper

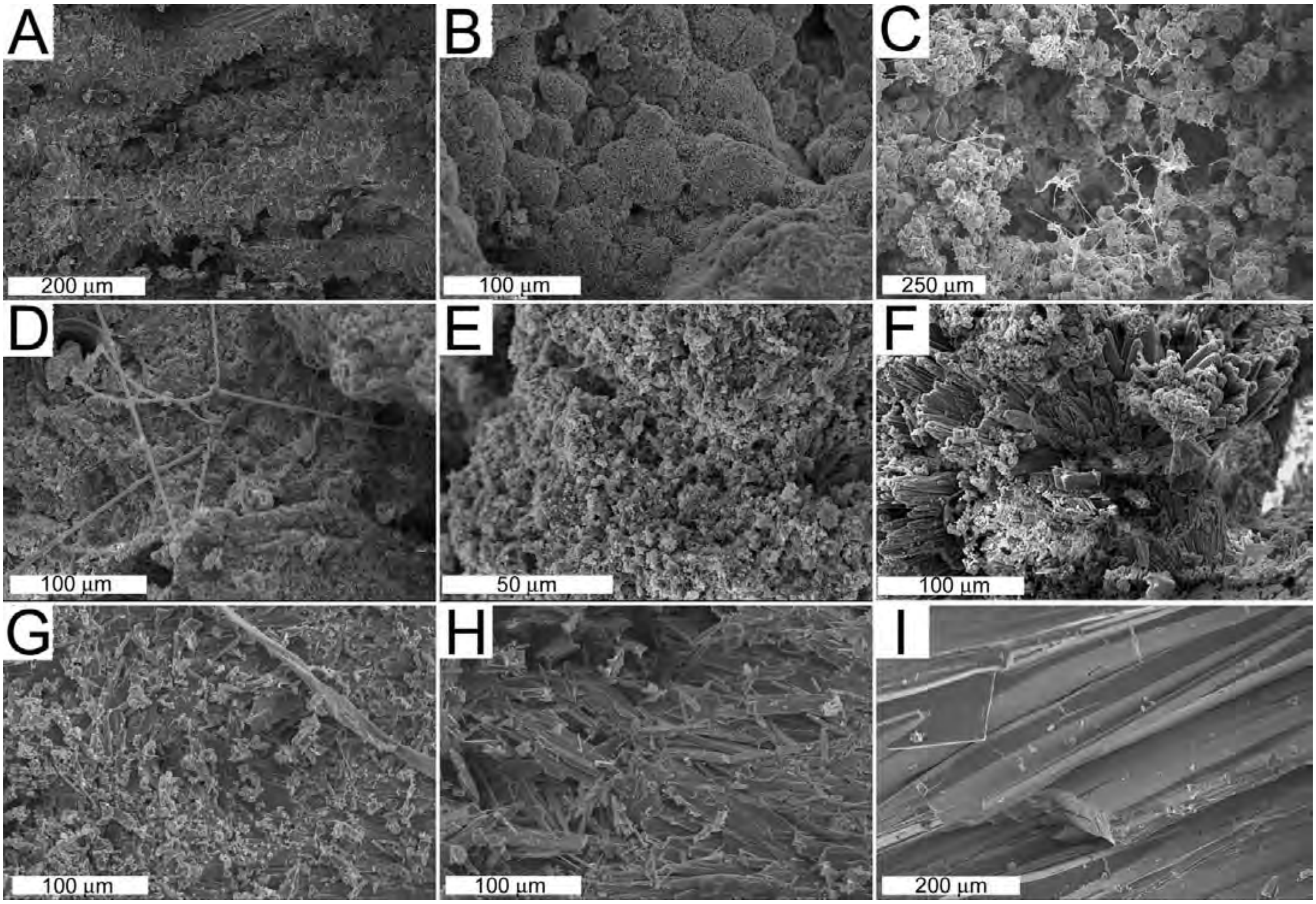

Figure 8. SEM micrographs of stalactites from cave entrance to interior. Sample ID numbers of illustrated specimens are indicated in brackets. A) Rod-like structures formed by encrustation of microbial filaments [4]. B) Shrub-like structures thought to be produced by microbial calcification [1]. C) Highly porous matrix of crystallites entangled in filamentous organic structures [30]. D) Microcrystalline substrate with copious microorganisms [9]. E) Microcrystalline aggregate lacking apparent microbial structures [22]. F) Small columnar crystals of calcite combined with much microcrystalline material [11]. G) Poorly organized macrocrystals interspersed with some crystallites and an organic filament [15]. H) A homogeneous deposit consisting solely of poorly arranged calcite crystals [18]. I) Solid columnar calcite structure of a typical speleothem [25].

by Jones & Motyka (1987) describes stalactites from the Cayman Islands, unusual in the fact that they are composed of biogenic structures and microcrystalline calcite. The stalactites are inactive, broken deposits from "ancient, filled caves," now embedded in calcarenite. Given descriptions by Jones & Motyka (1987), we believe the stalactites in question correspond to intermediary fabrics between subaerial tufa and normal speleothems and would have formed in a microclimatically transitional environment, rather than a well enclosed cave. The location where they were found, therefore, probably corresponds to cave entrance facies.

In addition to helping identify former microclimatic and geomorphic settings, petrologic idiosyncrasies of stalactites can indicate microclimate changing events, for instance breaching and collapse of caves. Such events cause shifts in local microclimatic gradients and force the actively forming speleothems to equilibrate with the new conditions. We have seen deposits that had started as normal stalactites but later abruptly assumed deflected growth and continued forming as tufa (most likely as a result of cave breaching), and suppose that opposite sequences could also be produced (e.g., by blocking of entrances by collapse). Dating of the different fabrics could pinpoint the timing of such events.

However, there are some important considerations regarding the use of stalactites in paleoenvironmental interpretation. As emphasized at the beginning of this paper, petrologic properties of stalactites are affected by both microclimatic conditions and the properties of the water from which they are precipitated. As a result, it is not unlikely that different mechanisms can, under specific conditions, produce comparable

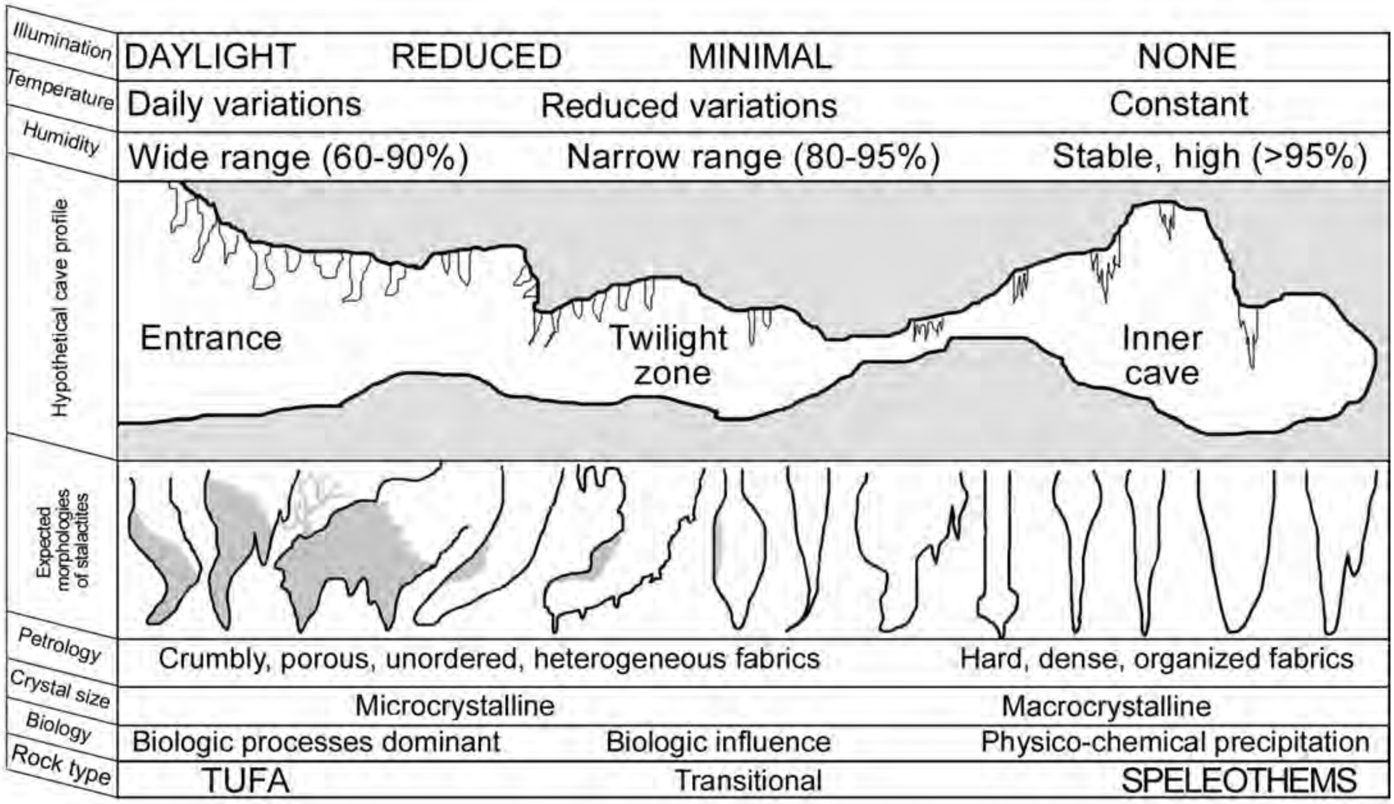

Figure 9. A schematic diagram of a hypothetical cave, showing expected microclimatic patterns and the likely characteristics of stalactites forming the range from irregular, microcrystalline tufa deposits at the cave entrance to normal speleothems at the back. The illustrations of expected stalactites illustrate diversity of morphologies, not progression. Predictable moss-covered surfaces are shown in dark gray. (Modified from Taboroši & Hirakawa 2003).

depositional fabrics. Microcrystalline stalactite fabrics are known to occur deep in some caves and even calcareous tufa—an intrinsically epigean deposit whose precipitation is controlled by environmental and biologic factors normally found at the land surface, can be, in rare instances, produced in spelean settings, from water under geochemical disequilibrium conditions (Frisia *et al*. 2000). Even more importantly, carbonate deposits can be profoundly altered by diagenesis, which sometimes obliterates original calcite fabrics. For instance, tufa is known to recrystallize into coarsely crystalline calcite, losing much of the biologic structure in the process (Love & Chafetz 1988, Pedley 1987). Conversely, tufa-like stalactites could conceivably form by decay and diagenesis of true cave speleothems, if the latter are exposed at the land surface conditions by cave collapse, as suggested by Bar-Matthews *et al*. (1991). Transformation of sparry calcite into micrite is known to occur (e.g., Jones & Pemberton 1987, Chafetz & Butler 1980, Chafetz *et al*. 1994), although there is no evidence that this is a wide-ranging process capable of transforming entire stalactites. Jones (1987), for example, observed spamicritization in just the top few microns from the rock surface in Oligocene-Miocene limestone in a humid tropical climate, while Hill and Forti (1997) mention chalkified layers up to 3 cm deep on the surfaces of old, inactive speleothems.

Therefore, reliable use of stalactite fabrics in paleoenvironmental interpretation requires an improved understanding of the extent to which diagenetic changes occur on stalactites, and ways to distinguish between diagenetically-altered fabrics and the primary depositional fabrics which they may mimic.

CONCLUSION

In their review of tufa and travertine deposits of the world, Ford & Pedley (1996) suggested that speleothems may be considered an "inorganic end-member of a continuum which, at the other extreme is represented by biomediated tufa." This continuum, however, has been largely theoretical, because typical tufas and speleothems develop in very different depositional environments that can hardly be spanned by actual intermediary forms. Because the overwhelming majority of tufa grows subaqueously in springs, rivers, lakes and swamps, whereas most speleothems form subaerially inside caves, the two are rarely exposed in the vicinity of each other and the continuum between them is based on an array of analogous fabrics, rather than any visible gradation of deposits in a given locale.

The most casual observations in tropical cave entrances reveal that stalactites are soft and fragile in the most exposed locations, and more dense and solid in better-enclosed areas. A detailed look at a single cave in Krabi Province, Thailand, clearly demonstrated the full range of progressively denser and more organized deposits, from calcareous tufa stalactites at the dripline to classic speleothems deeper inside caves, and the veritable sequence of fabrics, from biogenic microcrystalline forms to densely layered travertines. While the most porous and friable "stalactites" at the land surface and in cave entrances exhibit much more in common with typical (aquatic) calcareous tufas than with speleothems, they are genetically clear analogues of spelean dripstone: just like their equivalents deeper inside caves, these stalactites are precipitated from epikarstic water dripping from bedrock ceilings. The underlying physical and chemical mechanisms involved in their precipitation are, thus, no different from normal cave stalactites, and it is the microclimate of their depositional setting and superimposed biologic processes that are responsible for the observed morphologic and petrologic idiosyncrasies.

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