PROCEEDINGS OF THE X, XI, AND XII INTERNATIONAL SYMPOSIA ON VULCANOSPELEOLOGY

Edited by
Ramón Espinasa-Pereña and John Pint

ISV X, AZORES - 2004

AMCS Bulletin 19

SMES Boletín 7

PROCEEDINGS OF THE X, XI, AND XII INTERNATIONAL SYMPOSIA ON VULCANOSPELEOLOGY

Edited by
Ramón Espinasa-Pereña and John Pint

X Symposium
September 9–15, 2002
Reykjavik, Iceland

XI Symposium
May 12–18, 2004
Pico Island, Azores

XII Symposium
July 2–7, 2006
Tepoztlán, Morelos, Mexico

ASSOCIATION FOR MEXICAN CAVE STUDIES
BULLETIN 19

SOCIEDED MEXICANA DE EXPLORACIONES SUBTERRÁNEAS
BOLETÍN 7

2008

XI International Symposium on Vulcanospeleology

PICO ISLAND

Azores – 2004

ORGANIZING COMMITTEE:

Eduardo Carqueijeiro (President)
Emanuel Veríssimo
Paulino Costa
João Paulo Constância
Paulo Barcelos
Fernando Pereira

SPONSORS:

Assembleia Legislativa Regional
Presidência do Governo Regional
Direcção Regional da Cultura
Direcção Regional do Turismo
Câmara Municipal das Lajes do Pico
Câmara Municipal da Madalena
Câmara Municipal de São Roque do Pico
Câmara Municipal de Velas
Câmara Municipal da Horta
Câmara Municipal de Ponta Delgada
Câmara Municipal de Angra do Heroísmo
Câmara Municipal de Santa Cruz da Graciosa
Junta de Freguesia do Capelo
Casa de Povo do Capelo
Museu do Pico
Museu da Horta
Amigos do Açores, Associação Ecológica
S.E.E. "Os Montanheiros"
Escola Básica e Integrada/S da Madalena
Escola Básica e Integrada/S de São Roque do Pico
Bombeiros Voluntários de Velas
Cooperativa Vitivinícola do Pico
SIRAM-Açores

HOSTED BY

secretaria regional | direcção regional AMBIENTE

gespea

PREFACE

We are honored to welcome everyone to the XIth International Symposium on Vulcanospeleology, held at "Escola Cardeal Costa Nunes", in the town of Madalena (Pico Island). The meeting is hosted by the "Secretaria Regional do Ambiente" (Environmental Department of the Regional Government of the Azores). This is the first time that this international meeting is being held in Azores Archipelago, where volcanoes and volcanic caves are very important features of the natural landscape.

Pico is the second largest island in the Azores. It is about 1000 miles (1600 km) from the Portuguese mainland. Its area is 447 km^2 and the population is 14,804. Its inhabitants are grouped in three municipalities (Lajes, Madalena and São Roque do Pico). The island presents a wide range of volcanic landforms, including approximately 90 known volcanic caves and pits. Most of its lava tube caves are located on the flanks of the impressive Pico Mountain stratovolcano (2,351 m a.s.l.), in the western part of the island, which is the 3rd highest active volcano in the Atlantic Ocean. Among these caves is "Gruta das Torres", the longest in the Azores with about 5,150 m of passages.

This Abstracts Book includes all presentations at the XIth International Symposium on Vulcanospeleology, Azores – 2004, including invited lectures and oral and poster presentations. All underwent advance review by the scientific committee of the symposium.

Pico, May 2004

SCIENTIFIC COMMITTEE

João Carlos Nunes (President)
Paulo Alexandre Borges
Victor Hugo Forjaz
António Galopim de Carvalho
William Halliday (USA)
Pedro Oromi (Canary)
Paolo Forti (Italy)

XI

2004 SYMPOSIUM ABSTRACTS

Edited by João Carlos Nunes and William Halliday

Invited Lectures

Em Defesa do Património Geológico

António M. Galopim de Carvalho
Museu Nacional de História Natural, Universidade de Lisboa,
Rua da Escola Politécnica, 58, 1250 Lisboa.
galopim@netcabo.pt

À semelhança de qualquer património construído que, por características de significado, grandiosidade ou outros, é considerado monumento e, portanto, um recurso cultural a preservar, também algumas ocorrências naturais e, em particular, as geológicas têm características que nos levam a classificá-las como **geomonumentos**, entendidos como valores a incluir numa concepção de cultura alargada ao saber científico tradicionalmente subvalorizado na nossa sociedade.

Como resposta ao chamado desenvolvimento e à imparável ocupação do espaço natural pelos múltiplos e variados equipamentos civilizacionais, importa divulgar e impor a ideia de **georrecurso cultural** aplicável a alguns exemplos do património geológico, por natureza não renovável.

A experiência de muitos anos de busca de soluções que salvaguardem e valorizem alguns dos nossos mais importantes geomonumentos tem sido, nas duas últimas décadas, uma tarefa árdua e uma preocupação do Museu Nacional de História Natural da Universidade de Lisboa. A grande resistência à sua classificação, no âmbito da legislação existente, decorre, sobretudo e em última análise, de uma generalizada falta de cultura geológica na sociedade portuguesa, a começar pelos responsáveis da administração.

Genetic Processes of Cave Minerals in Volcanic Environments: An Overview

Paolo Forti
Italian Institute of Speleology, University of Bologna, Italy.
forti@geomin.unibo.it

Volcanic caves are widespread in the world and are frequently visited by cavers. Therefore it is common to find published descriptions of their exploration, speleogenesis and morphology. But lava tube caves and other volcanic cavities traditionally have been considered of little interest from the standpoint of secondary minerals (Forti, 1994). Thus detailed studies of their speleothems are comparatively new.

Recently, it has become evident that volcanic cavities are very favourable environments for the actions of different processes of mineral development (see Tab. 1). Two of these (sublimation and deposition from aerosols) are largely restricted to volcanic caves. Most known volcanic caves have conditions favourable for development of at least a few small true speleothems (apart from lava stalactites and stalagmites), which normally do not meet the technical definition of the term "speleothem" (Hill and Forti, 1997).

Even from these recent studies of a small number of volcanic caves, 40% of the entire list of cave minerals of the world is known to occur in volcanic caves. Furthermore, 35 of them (about 10% of all known cave minerals) are found only in volcanic caves.

Among the published list of ten caves leading the world in terms of speleothems (Hill and Forti, 1997), two are volcanic: the Alum cave on Vulcano Island, Italy and Skipton Cave, Australia.

Even detailed mineralogical studies have been made just for a few volcanic cavities, the choice of selection criteria for such a list is far from simple. Clearly, the importance of a cave cannot be selected entirely by the number of different minerals which developed within it. Other factors to be considered include the size and beauty of their speleothems, peculiarity of genetic mechanisms, different types of speleogenesis, and the geographical location of the cave.

On the basis of these parameters, it was made a tentative list of the ten most important volcanic caves of the world from the standpoint of mineralogy (Tab. 2).

This overview on the present knowledge on cave minerals in volcanic caves is short and surely not exhaustive. However this presentation and discussion seems sufficient to point out the extreme importance of volcanic cave environments in the development of cave minerals.

Volcanic caves which have been the subject of mineralogical observation to date, are far less than 5% of those presently known around in the world. Thus, it is reasonable to expect that in the near future, broad systematic study of secondary chemical deposits in volcanic caves will significantly increase the number of known cave minerals.

Final remark: This research was performed within the MIUR 2002 Project "*Morphological and Mineralogical Study of Speleothems to Reconstruct Peculiar Karst Environments*", Resp. Prof. Paolo Forti.

References:

Forti P. 1994. *Cave minerals in volcanic caves*. Acta I° Encontro Internacional de Vulcanoespeleologia das Ilhas Atlanticas, Terceira, Açores, 1992: p. 1-98.

Forti P. 2000. *Minerogenetic mechanisms and cave minerals in the Volcanic caves of Mt. Etna (Sicily, Italy)*. Mitt. Verb.

Table 1 (Forti). Temperature range, process, genetic mechanisms, and related chemical deposits in volanic caves (modified after Forti, 1999).

Process			Mechanism	T (°C)	Products
1	Fumarole	A- High temperature	Sublimation	> 100	Elementary sulfur, oxides, hydroxides
		B- Low temperature	Deposition from aerosols and vapors	100 ÷50	Sulphates, halides
2	Solution		Evaporation	100 ÷10	Sulphates, halides
3	Alteration		Oxidation, hydration-dehydration, ionic exchange	100 ÷0	Si-, Al-, Fe oxides-hydroxides, sulphates
4	Karst		Diffusion	40 ÷0	Carbonate
5	Biogenic activity		Digestion, dissolution-precipitation, double exchange	40 ÷0	Phosphates, Nitrates, Sulphates, Halides
6	Phase change		Freezing	< 0	Ice

Table 2 (Forti). The ten most important volcanic caves from the mineralogical point of view.

Cave	Location	Peculiarity	Reference
Algar do Carvão	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)	First cave where several genetic mechanisms have been studied	Forti *et al*. 1994
Kitum	Mt. Elgon (Kenya)	Silicate minerals related to meteoric waters action	Forti *et al*. 1999, in press
Skipton	Mt.Widderin (Australia)	First description of some new cave phosphates	Webb 1997
Grillid	Surtsey (Iceland)	Single cave reference for 5 different new cave minerals	Jacobsson *et al*. 1992
Togawa-Sakaidani-do	Kyushu (Japan)	First description of coralloid made by diatoms	Kashima *el Al*. 1987
Hibashi	(Saudi Arabia)	Noticeable variety of rare organic compounds even related to guano-firing	Forti *et al*. 2003, in press
Dangcheomul	Jeju island (Korea)	Best display of different calcite speleothems within a volcanic cave	Woo *et al*. 2000
Abrigo de el Manzano	Rio Grande (Argentina)	Phosphates and sulphates related to bird guano	Benedetto *et al*. 1998

Dt. Höhlen- u. Karstforsch, 46 (1/2): p. 37-41.
Hill C.A., Forti P. 1997. *Cave minerals of the World*. Nat. Spel. Soc., Hintsville: 464 pp.

An Unusual Lava Tube Cave with an Incipient Hornito

William R. Halliday
Honorary President, IUS Commission on Volcanic Caves,
6530 Cornwall Court, Nashville, TN USA 37205.
bnawrh@webtv.net

The 1919 "Postal Rift" lava flow in Hawaii's Kilauea caldera contains a few typical mature lava tube caves and about 200 caves of other types. These include hollow tumuli, drained lava rise and flow lobe caves, immature lava tube caves and complexes. One is a complex cave in a long sequence of subcrustal injection features 2-3 km from the vent. Its main passage is overlain by a small, partially hollow hornito. A puckered cupola is present in the cave ceiling beneath the hornito. The main passage continues as a featureless immature lava tube sloping retrograde to the flowfield, and other unusual features are present. Alternative interpretations of this and other unusual injection structures of Kilauea Volcano will be discussed.

O Papel Estratégico do Centro de Interpretação Subterrâneo da Gruta "Algar do Pena", No Uso Sustentado do Património Espeleológico do Parque Natural das Serras de Aire e Candeeiros

Olímpio Martins
Parque Natural das Serras de Aire e Candeeiros.
cisgap@oninet.pt

O Centro de Interpretação Subterrâneo da Gruta Algar do Pena (CISGAP) é uma infraestrutura do PNSAC, vocacionada para a valorização do património espeleológico cársico.

O CISGAP deve a sua existência à descoberta de uma importante cavidade, em 1985, pelo Sr. Joaquim Pena, na sequência do desmonte de uma bancada de calcário para produção de pedra para calçada.

A Gruta Algar do Pena - assim denominada em honra do seu descobridor - é uma cavidade muito interessante do ponto de vista paisagístico, integrando a maior sala subterrânea actualmente conhecida em Portugal. (125 000 m^3 de volume aproximado).

Inaugurado em 1997, o funcionamento do CISGAP assenta em 4 vertentes:

1. Apoio à Investigação Científica e ordenamento do território no domínio da Espeleologia.
2. Divulgação alargada, do meio espeleológico cársico e fenómenos associados, com especial relevo para o público escolar.
3. Apoio às estratégias desenvolvidas pelo Parque, no domínio do turismo e desporto de natureza.
4. e finalmente como estrutura de apoio à formação de espeleólogos.

No decurso dos quatro anos que antecederam a sua abertura ao público, foram desenvolvidos vários estudos prévios destinados a caracterizar a cavidade do ponto de vista biofísico, os quais posteriormente serviram de base ao estabelecimento do regime de visitas e das medidas minimizadoras de impactes provocados pela visitação.

São catorze, as principais medidas minimizadoras de impactes negativos exercidos sobre a Gruta:

1. Estabelecimento da capacidade de carga.
2. Escalonamento de visitas.
3. Posicionamento do Poço do Elevador.
4. Uso de meios de descontaminação.
5. Estanquecidade do acesso artificial à cavidade.
6. Uso de estruturas "transparentes" de apoio à visita, em materiais não oxidáveis e removíveis.
7. Uso de uma área mínima dedicada à circulação de visitantes no interior da gruta.
8. Ausência de fontes de luz branca, exceptuando as auto-transportadas.
9. Uso de iluminação fixa de "vapor de sódio".
10. Aplicação de penumbra nas zonas de maior pressão.
11. Uso de um sistema de controle climático e monitorização, das alterações climáticas provocadas pelos visitantes.
12. Limitação do tempo de permanência dos visitantes na gruta.
13. Estabelecimento de períodos de repouso da gruta.
14. Proibições várias de carácter genérico.

Para os grupos mais numerosos, por forma a minimizar o efeito de espera de visita à gruta, dada a sua baixa capacidade de carga – 12 pessoas por sessão de visita – foram criadas, várias actividades pedagógicas e de lazer, desenvolvidas no edifício de apoio e nos espaços exteriores.

Assim, os visitantes poderão optar, por participar em jogos de orientação e simulação de uma exploração espeleológica completa, actividades que permitem a interpretação biofísica dos carsos típicos.

Na visita à gruta, o enquadramento de visitantes è efectuado por "guias", com formação espeleológica de base. O apoio à progressão e interpretação de base científica dos fenómenos observados, está assegurado pelo uso de sistemas automáticos de telecomentário. Os vários programas de visita visam sempre a integração da cavidade no contexto geológico e geográfico regional.

Mas o CISGAP possui outras atribuições no domínio da espeleologia, é a infra estrutura de apoio à equipa de espeleologia do PNSAC, o centro do cadastro espeleológico do PNSAC, funcionando ainda como centro de apoio à rede de medição dos recursos hídricos desta Área Protegida.

O CISGAP, é no seu género, uma estrutura impar e sem precedentes no nosso país, contribuindo também para a inovação futura, participando na edificação de outras estruturas interpretativas singulares nesta Área Protegida, o futuro CARSOESCÒPIO, Centro Ciência Viva do Alviela.

Underground Life in Macaronesia: Geological Age, Environment, and Biodiversity

Pedro Oromí
Depto. Biología Animal, Universidad de La Laguna,
38206 La Laguna, Tenerife, Canary Islands. poromi@ull.es

The Macaronesian islands (Azores, Madeira, Canary Islands and Cape Verde Islands) are of volcanic origin but are at different stages of eruption and erosion. Their ages and especially those of their surface rocks affect the existence of caves, especially lava tubes.

Availability of caves for hypogean-adapted life is linked to the stage of ecological succession, which in turns depends on the age of terrains and on the local climate. The existence of the Mesovoid Shallow Substratum (MSS) also permits development of adapted fauna in terrains and even islands lacking volcanic caves.

Since all troglobites on islands must have evolved after local epigean species, biogeographical conditions and faunal diversity of each island are important in the final composition of underground faunas. The wellknown disharmony of island faunas provides new and different evolutionary opportunities toward troglomorphism, so animal groups unexpected in these latitudes have colonized the underground.

An outline of known hypogean animal diversity in Macaronesian archipelagos is presented, relating it to their biogeographical and environmental conditions. A comparison with such faunas of distant volcanic archipelagos (e.g. Hawaii or the Galapagos islands) is also made.

Oral Session I— Vulcanospeleology of the Azores Islands

"Gruta do Carvão" (Carvão Cave) in the Island of S. Miguel (Azores) and Environmental Education

Teófilo Braga
Amigos dos Açores, Ecological Association
(Speleology Working Group), Avenida da Paz, 14,
9600-053 Pico da Pedra, S. Miguel, Azores.
teobraga@hotmail.com

During the first International Meeting on Vulcanospeleology of the Atlantic Islands in 1992, the author presented a pioneer initiative for the Azores: a videotape about "Gruta do Carvão".. Its main objectives were to provide teaching material in the field of volcanology (where there was a lack of such material) and also to promote environmental education.

The present work is intended to provide a brief history of the "Amigos dos Açores" Association in publicizing the value of "Gruta do Carvão" as well as describing its activities since 1992. Main focus has been to demonstrate the importance of that volcanic cave for the purpose of environmental education, namely to create a knowledgeable public with necessary information, ability, mindsets and motivation to work to solve environmental problems.

In addition to environmental workshops in various schools (primarily for grades 5 to 12) and intended to arouse environmental consciousness, between 1998 and 2003 the Association led 41 guided visits to Carvão Cave for 1,441 students.

Ranking Azorean Caves Based on Management Indeces

João P. Constância[1,5], Paulo A.V. Borges[2,4] ,
Manuel P. Costa[3], João C. Nunes[2,5], Paulo Barcelos[4],
Fernando Pereira[4], and Teófilo Braga[5]
[1] Museu Carlos Machado, Natural History Department,
Convento de St. André, 9500 Ponta Delgada, S. Miguel, Azores.
constancia@mail.telepac.pt
[2] Universidade dos Açores, Dep. Ciências Agrárias & Dep.
Geociencias, Angra do Heroísmo & Ponta Delgada, Azores
[3] Direcção de Serviços da Conservação da Natureza, Edificio
Matos Souto, Piedade, 9930 Lajes do Pico, Pico, Azores
[4] "Os Montanheiros", Rua da Rocha,
9700 Angra do Heroísmo, Terceira, Azores
[5] "Amigos dos Açores", Avenida da Paz, 14,
9600-053 Pico da Pedra, S. Miguel, Azores

The Azorean Speleological Inventory (IPEA) is a data base with information about all known Azorean volcanic caves and pits. 86 caves are known on Pico, 67 on Terceira, 27 on São Miguel, 18 on São Jorge, 11 on Graciosa, 9 on Faial, 5 on Santa Maria, and 2 on Flores (Fig. 1). About 60 of these 225 caves have been mapped, with a total of 41,122 m of passages. About 71% are lava tube caves, 10% are pits, 7% are erosional caves, 4% are crevice caves and the others are multiprocess or undetermined types. To date, about 65% of these caves are unsatisfactorily studied, in particular its biological and geological features.

IPEA includes a classifying system which relies on objective sets of criteria which yield logical, coherent and reliable results. Its multi-criteria sets also can provide complex classifications which can be used as managing tools. IPEA incorporates six major classification topics: scientific value, potential for tourism, access, surrounding threats, available information and conservation status. Each topic is assigned

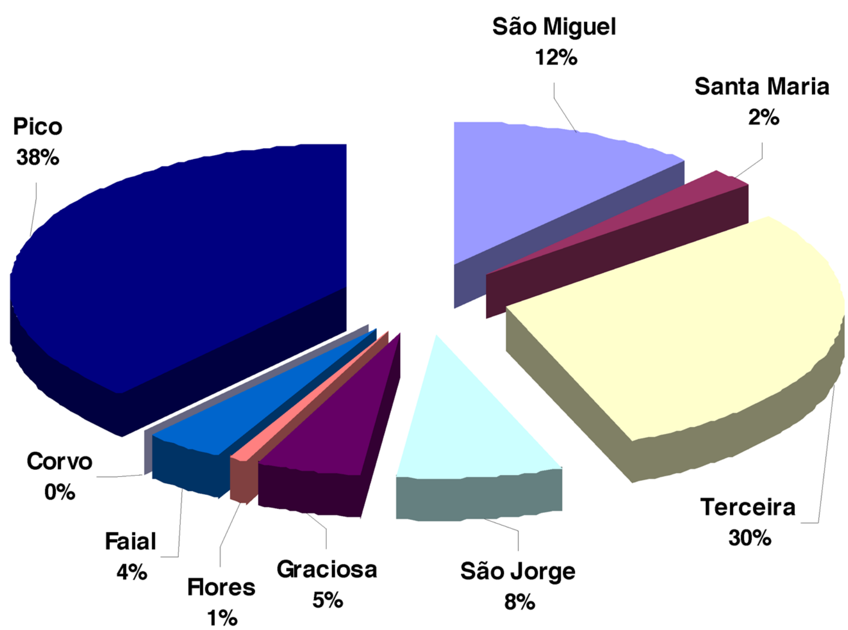


Figure 1 (Constância, et al.). Distribution of volcanic caves in the Azores (total = 225).

Table (Constância, et al.). Ranking most significant Azorean caves, according to three classification issues.

SCIENTIFIC VALUE	TOURISTIC POTENTIAL	CONSERVATION
Água de Pau S. Miguel Island	**Agulhas** Terceira Island	**Água de Pau** S. Miguel Island
Agulhas Terceira Island	**Algar do Carvão** Terceira Island	**Agulhas** Terceira Island
Algar do Carvão Terceira Island	**Branca Opala** Terceira Island	**Algar do Carvão** Terceira Island
Balcões Terceira Island	**Carvão** S. Miguel Island	**Cabras II** Pico Island
Cabras II Pico Island	**D'Água** Terceira Island	**Chocolate** Terceira Island
Canárias Pico Island	**Furna do Enxofre** Graciosa Island	**Furna do Enxofre** Graciosa Island
Chocolate Terceira Island	**João do Rego** S. Miguel Island	**Montanheiros** Pico Island
Frei Matias Pico Island	**Montanheiros** Pico Island	
Furna do Enxofre Graciosa Island	**Natal** Terceira Island	
Henrique Maciel Pico Island	**Ribeira do Fundo** Pico Island	
Montanheiros Pico Island	**Santana** Santa Maria Island	
Natal Terceira Island	**Torres** Pico Island	
Ribeira do Fundo Pico Island	**Túmulos** Pico Island	
Soldão Pico Island		
Torres Pico Island		

by an index (from I to V), based on weighted factors for biological components, geological features, accessibility, singularity and beauty, safety, caving progress, threats, integrity, and available information. Each factor was quantified from 0 (zero) to 5. Lack of information is quantified as zero and the other figures (1 to 5) are objective statements that describe the cave characteristics within the factor.

An initial analysis based on a multi-criterion approach yielded the Table:

1. using positive weighting for geological features, biological components, singularity and beauty, available information, and integrity, 15 caves were found to have especially high scientific values;

2. using positive weighting for geological features, accessibility, singularity and beauty, safety, caving progress, available information, and integrity, and a negative weighting for biological components, 13 caves were found to have great touristic potential;

3. using positive weighting for geological features, biological components, available information, threats, and integrity, 7 caves were found to merit high conservation status.

Algar do Carvão Volcanic Pit, Terceira Island (Azores): Geology and Volcanology

Victor H. Forjaz[1], João C. Nunes[1], and Paulo Barcelos[2]
[1] Universidade dos Açores, Departamento Geociências, Rua Mãe de Deus, 9501-801 Ponta Delgada, Azores.
vhforjaz@notes.uac.pt
[2] "Os Montanheiros", Rua da Rocha, 9700 Angra do Heroísmo, Terceira, Azores

The Algar do Carvão pit is an impressive volcanic conduit located in the Basaltic Fissural Area, in central Terceira island. Initially it was included in a Geologic Natural Reserve (Regional Legislative Decree nr. 13/87/A, of July 21). Recently it was reclassified as a Regional Natural Monument due to unique volcanic features and additional ecological and conservation importance. Among this features are siliceous speleothems (stalactites and stalagmites of amorphous silica), refusion walls, obsidian dripstones, a lake, vegetation around the vent and along the pit walls, and a troglobitic fauna.

In general terms, the pit had a two-phase genesis. It partially corresponds to the volcanic conduit of a scoria cone previously dated at 2,115 years BP. Also a significant part of Algar do Carvão is developed on older trachytic domes and/or *coulées* related to the silicic polygenetic volcano of Pico Alto.

^{14}C age determinations in charcoal trunks collected near the lake level and on trachytic formations inside the Algar do Carvão gave ages of 3,200 ± 40 years BP. Similar radiometric dating analysis on charcoal found beneath the basaltic lava flow of Algar do Carvão gave ages of 1730 ± 40 years BP for that lava flow. The site of the latter ^{14}C sample was close to the main road and outside the pit. It also should be emphasised that another ^{14}C analysis done on a Pico Alto Volcano pumice deposit, NE of Algar do Carvão's scoria cone gave an age of 2,610 ± 70 years BP.

Together with field studies done in the area and in the pit, these age determinations allowed us to conclude that Algar do Carvão initially formed in trachytic flows about 3,200 years ago. Subsequently, other silicic eruptions occurred on the Pico Alto volcanic centre, with extrusion of lava flows and pumice, one of which occurred about 2,600 years ago. More recently (about 1,700 to 2,100 years ago), several (?) basaltic eruptions occurred in the area with extrusion of flooding lava flows. Along last days of one of these basaltic eruptions, and due to tectonic stress, the very fluid lava retreated inside the conduit of the scoria cone and allowed the formation of Algar do Carvão pit as it exists today.

The Project for the Visitors Center Building of the Gruta das Torres Volcanic Cave, Pico Island, Azores

Inês Vieira da Silva and Miguel Vieira
Direcção Regional do Ambiente,
Rua Cônsul Dabney, Colónia Alemã, Apartado 140,
9901 Horta, Faial, Azores. inesvs@hotmail.com

Gruta das Torres is a notable volcanic cave in the parish of Criação Velha, municipality of Madalena on the island of Pico in an agricultural landscape.

This paper presents the project for a Visitors Center building for this cave (Table) developed from two primary standpoints: 1) to enclose the access skylight, to control the entrances and provide security; 2) to provide support and information services to the visitor.

To response simultaneously to these two standpoints, a stone wall 1.80 meters high is planned to surround the skylight entrance (Figure) and at the same time to allow the drawing of the building to emerge from it.

Outside the building, will be a small courtyard with a reflecting pool. Visitors will be able to buy entry tickets and wait for the guided tour in a Waiting Room, then proceed to an Auditorium for a briefing. Helmets, electric hand lamps and other necessary equipment will be available in the Auditorium.

Entry into the cave will be by a stairway already built with local pahoehoe slabs. It will continue inside the cave where an overpass 40 m long will allow visitors to avoid existing breakdowns, without the need to remove this debris. Tours will be about 400 m long, 200 m in each direction.

After each tour, visitors will returns to the Waiting Room, through the same stairway and by way of a ramp which bypasses the Auditorium. Thus, several groups of visitors can tour the cave simultaneously without crossing each other.

The building's structure will consist of reinforced concrete, built on a rail, also of reinforced concrete. This solution avoids the use of foundations, believed to cause excessive vibrations in the surrounding area and also being subject to puncture.

The Visitors Center building is continuous with the stone wall protecting the skylight (Figure), not only because both elements were created from a single formal gesture, but because different techniques for emplacement of the local materials will be used. Thus, the wall will consist of stone mortar and the whole south facade of the building will be made in stone and employing the local construction technique known as "currais de figueiras". The latter allows light to enter all along the wall of the building. The remaining facades will be covered by a black waterproof surface that resembles the texture of the glassy lava in the cave.

Vegetation in the area is most impressive on the edge of the skylight and just inside (Figure). Thus, the building and the wall around the skylight just reinforce the whole ensemble, incorporating this vegetation into an architectural unit within an agricultural landscape. Even bearing in mind that the building is itself a constructed architectonic volume.

Oral Session II— Vulcanospeleology of the World

Rare Cave Minerals and Features of Hibashi Cave, Saudi Arabia

John J. Pint
thepints@saudicaves.com

Ghar al Hibashi, located 300 kms SE of Jeddah in the Nawasif-Buqum lava field is the longest lava tube so far mapped in Saudi Arabia (565 m long). Lava levees, stalactites and stalagmites are found throughout the cave and it has a lava channel 13 m long. A bed of loess, up to 1.5 m thick covers the floor and its age is now being determined by OSL. Coprolites from hyenas, sheep, wolves and foxes are found in many parts of the cave and may be very old. Two areas are covered with burnt bat guano and samples taken from one of these areas were found to contain a number of rare cave minerals. A human skull found in the cave has been carbon dated at 450 years BP and shows possible evidence of foul play.

Researchers working with the Field and Space Robotics Lab at MIT to develop microrobots for cave exploration on Mars recently requested permission to use photos of Hibashi Cave to illustrate the possible interior conditions of lava tubes on Mars.

Two large bat guano deposits in this cave caught fire in the past, possibly affecting "bio-stalactities": soft, yellowish concretions thought to be formed of bat urine. Nineteen minerals were detected in samples collected, mostly related to the mineralization of bones and guano deposits.

Hibashi Cave is occasionally visited by local people and is in need of protection from vandalism.

Table. Main characteristics of the project.

Name	Visitors Center of the “Gruta das Torres” volcanic cave
Location	Criação Velha, Madalena, Pico Island, Azores
Client	Direcção Regional do Ambiente - Secretaria Regional do Ambiente
Architects	Inês Vieira da Silva, Miguel Vieira
Structural Engineer	Rui Borges Pereira
Electrical Engineer	Projectangra - Helena Vargas

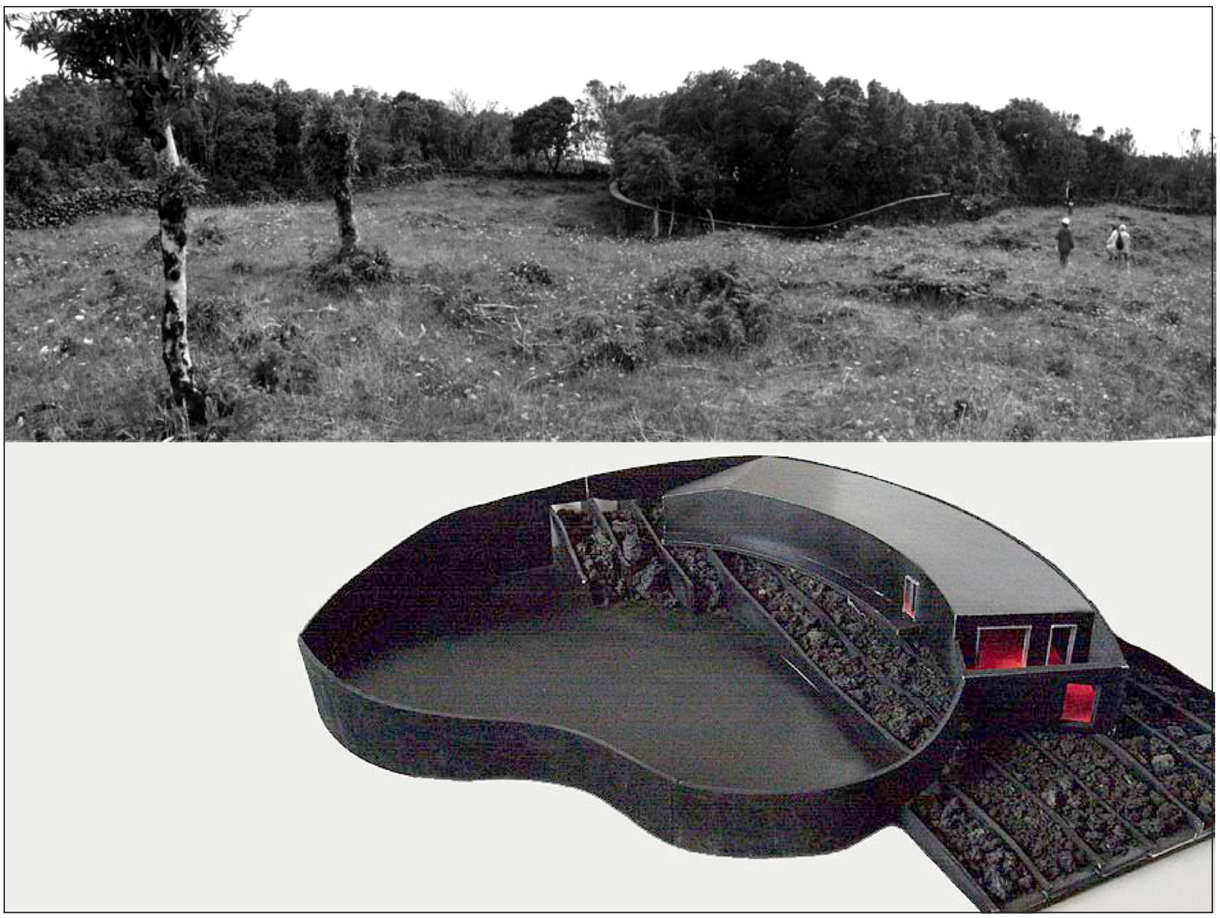


Figure. Visitors Center building projected for the Gruta das Torres volcanic cave (bottom) and present day surroundings (top).

Illustrations for Vieira da Silva and Vieira.

A Digital List of Non-Karstic Caves in Hungary

István Eszterhás and George Szentes
Alte Frankfurter Str. 22B, 61118 Bad Vilbel, Germany.
szentesg@aol.com

The Volcanspeleological Collective has carried out the study and cataloguing of non-karstic caves in Hungary since 1983. They have compiled descriptions, surveys and photographs from each recorded cave. The cave documentation fills more than twenty volumes, mainly as manuscript notes. However, access to this documentation is restricted. We decided to compile an easily accessible, standard list, of non-karstic caves in Hungary, where changes and updates can be easily made. We decided that a digital list would be the most suitable format.

We began to compile the register in 2002. We have listed each known non-karstic cave and located their positions on a map. Cave surveys and photographs, accompanied by short descriptions were also included in the list . Eighteen regions are represented where non-karstic caves occur. Index Maps were prepared for most of the regions. These are linked to the detailed maps with tabular summaries. The language of the list is Hungarian with an English translation, mainly to facilitate the use of the homepage.

The digital presentation of non-karstic caves was carried out using Arcview GIS as well as available digital map material. Detailed Maps and Index Maps with different scales were developed for specific regions as project files (apr). Layout Maps were then prepared. The layout maps were exported in jpg file format. This enables further utilization and handling. The dbf database was filled with cave data and other data to generate regional data sheets. The digital data from the non-karstic cave list facilitates its use by various presentation software programs and allows transfer of the cave registry to other formats.

The final summary of the non-karstic caves in Hungary is to be found on the Home Page of the cave list. All relevant data has been compiled in htm and html file format.

The Hibashi Lava Tube: The Best Site in Saudi Arabia for Cave Minerals

Paolo Forti[1], Ermanno Galli[2], Antonio Rossi[2], John Pint[3], and Susana Pint[3]
[1] Italian Institute of Speleology, University of Bologna, Italy.
forti@geomin.unibo.it
[2] Geological Department, University of Modena and Reggio Emilia, Italy
[3] Saudi Geological Survey, Jeddah, Saudi Arabia

Systematic exploration of lava tube caves in Saudi Arabia started only recently, but several large examples have been now explored and mapped in various lava fields around that country.

One of the largest examples in Saudi Arabia is Hibashi Cave, located in Harrat Nawasif-Buqum lava field, 200 km east of Jeddah. It primarily consists of a huge rectilinear gallery (over 400 m long and 15 m wide) accessed down a breakdown slope in a wide collapse which gives entrance to a side corridor. The cave floor consists of uncemented, locally thick loess.

Table (Forti et al.). Identified cave minerals of the Hibashi lava tube (Saudi Arabia).

1 - Anhydrite	$CaSO_4$
2 - Aphthitalite	$(K, Na)_3Na(SO_4)_2$
3 - Arnhemite	$(K,Na)_4Mg_2(P_2O_7) \cdot 5H_2O$
4 - Arcanite	$K_2(SO_4)$
5 - Archerite	$(K, NH_4)H_2PO_4$
6 - Biphosphammite	$(NH_4, K) H_2 (PO_4)$
7 - Calcite	$CaCO_3$
8 - Carbonate- hydroxylapatite	$Ca_5(PO_4,CO_3)_3(OH)$
9 - Chlorapatite	$Ca_5(PO_4)_3Cl$
10 - Halite	NaCl
11 - Hydroxylapatite	$Ca_5(PO_4)_3(OH)$
12 - Niter	KNO_3
13 - Opal-C	$SiO_2{\cdot}nH_2O$
14 - Palygorskite	$(Mg,Al)_2Si_4O_{10}(OH){\cdot}4H_2O$
15 - Pyrocoproite	$(K,Na)_2Mg(P_2O_7)$
16 - Pyrophosphite	$K_2Ca(P_2O_7)$
17 - Quartz	SiO_2
18 - Urea	$CO(NH_2)_2$
19 - Whitlockite	$Ca_9(Mg,Fe)(PO_4)_6[PO_3(OH)]$

The cave was utilized long ago as shelter by wild animals including bats, hyena, wolf and fox. Many bones and coprolites are scattered throughout the floor. Large guano deposits also are present. Some of the guano has caught fire, partially burning overlying bones. The only true speleothems consist of a few small translucent yellow stalactites hanging from the ceiling.

Three different expeditions were conducted in 2003. A few samples of secondary mineral deposits were collected for analysis. Despite the paucity of the samples, 14 different minerals already have been detected (Table). Most are related to biogenic mineralization of bones and guano deposits.

Besides other rare but well understood cave minerals (like arcanite and archerite), pyrocoproite, pyrophosphate, and arnhemite are extremely rare organic compounds strictly related to combustion of guano. Previously these had been observed only in a few caves in Africa. In this paper the SEM images of these minerals are reported for the first time.

As a result of these findings, the Hibashi Cave must be considered the most important volcanic cave in Saudi Arabia and, by far, the richest mineralogical shelter in this Country.

Final remark: This research was made within the MIUR 2002 Project "*Morphological and Mineralogical Study of Speleothems to Reconstruct Peculiar Karst Rnvironments*", resp. Prof. Paolo Forti.

Investigation of the Discharge Mechanism of Hachijo-fuketsu Lava Tube Cave, Hachijo-jima Island, Japan

Tsutomu Honda
Mt. Fuji Volcano-Speleological Society, Tokyo.
hondat@itergps.naka.jaeri.go.jp

Hachijo-fuketsu lava tube cave is located on Hachijo-jima Island south of Tokyo in the Pacific Ocean. This cave is believed to have been formed by the eruption of Hachijo-nishiyama volcano 1100 years BP. Its lava flow is basaltic, with silica content of 50.5%. Hachijo-fuketsu is the second longest lava tube cave in Japan. Despite good accessibility, it is well preserved. Its upper and middle sections have moderate slopes. Its lower end is flat and horizontal.

In modelling the discharge mechanism of this type of lava tube we used an inclined circular tube model for the sloping sections of the cave. For the flat, horizontal section in which the lava flow is driven by hydrodynamic head, we modelled a flattened circular tube. The yield strengths obtained from these two models were similar and comparable to those of other lava flows.

Regarding the inclined circular pipe case, the discharge mechanism of lava tube caves already has been established, based on Bingham characteristics of intratubal lava flow (Honda 2000, 2001a). A simple model of steady state isothermal laminar flow in inclined circular pipes and in flatten circular pipes were used for analyses. Comparison studies were based on the configuration of Hachijo-fuketsu.

Flow characteristics were studied as a function of parameters such as tube radius, viscosity, yield strength of lava and slope inclination. A critical condition was determined for the discharge parameters in which the yield strength plays a dominant role. Existing observational data were introduced to the critical condition. This model was applied to lava tube cave of Mt. Fuji, Mt. Etna, Mount St. Helens, Suchiooc volcano, Kilauea volcano and others. Some deduced yield strengths of lava of the caves in these areas were found to be in good accordance with yield strength as estimated by other methods (Honda 2001b).

General flow equation of Bingham fluid can be shown as

$$f(t)=(t-f_B)/v_B \quad (t>f_B, \text{ or } r>r_B),$$
$$f(t)=0 \quad (t<f_B, \text{ or } r<r_B).$$

Here, f_B is Bingham yield strength, v_B is Bingham viscosity, which takes specific value depending on the materials. t is shearing stress at r.

For laminar flow model in circular tube on the slope, the equation of the distribution of flow speed u of Bingham fluid are shown as follows:

For tw =(d g sin a)R/2>f_B,

$$u=(R-r_B)^2(d\ g\ \sin a)/4v_B \quad (r<r_B),$$
$$u=[R^2-r^2-2r_B(R-r)]\ (d\ g\ \sin a)/4v_B \quad (r>r_B).$$

For tw= (d g sin a)R/2<f_B, u=0.

Here, tw is shearing stress at wall, a is angle of slope or inclination of tube, d: density of the fluid, g: gravity acceleration, R: radius of the tube, r_B :radius of the flowing position where Bingham yield stress takes f_B.

Here, (d g sin a)R/2=f_B is the critical condition to determine if the fluid in the tube can be drained out. For given and known relation between slope angle and diameter (height) of the tube, this critical condition can give the yield strength f_B. This critical condition means that when the yield strength f_B of Bingham fluid is higher than the shear stress at the wall, there is no flow of fluid, as a consequence, no discharge of fluid from the tube. From Table 1, $f_B=2.5\times10^4$dyne/cm^2 can be obtained for Hachijo-fuketsu.

The above model is, however, valid only for flow in inclined tubes. For perfectly flat lava tubes (0 degree), the effect of inertial as driving force due to the head of the flow must be considered, if the flow is continuous together with the inclined

Tables for Honda.

Table 1. Relation between slope angle and height of Hachijo-Fuketsu lava tube cave of sloped configuration

Location of lava cave	Slope angle(a)	Height(2R)
Upper reaches	4.5 degree	~5m
Intermediate reaches	14 degree	~2m
(Lower reaches)	(0 degree)	(~1m)

Table 2. Relation between head and length at horizontal location of Hachijo-Fuketsu lava tube cave of horizontally flat configuration for 2R=1m

Location of lava cave	Head(H)	Length(L)
Upper reaches	25m	33m
Intermediate reaches	85m	80m
Lower reaches	115m	150m

Table 3. Yield strength obtained from the critical condition

Name of volcano	SiO_2 fraction of lava	Obtained yield strength	References
Hachijo-nisiyama	50.4~50.5%*	2-2. 5x10^4dyne/cm^2	*M.Tsukui et al(2002)
Mt. Fuji	49.09~51.3%*	2.5~5x10^4dyne/cm^2	*H.Tsuya(1971)

tube (Honda 2003). Very rough relation between drained tube length and mean head of the flow can be obtained as $(d\ g\ R)H/2L=f_B$ by replacing (sin a) by (H/L). From Table 2, $f_B=2x10^4$ dyne/cm^2 was obtained for Hachijo-jima.

In summary, obtained basaltic yield stress from slope angle and height of some lava caves (Table 3) are reasonable values as compared with the yield stress obtained for Mt. Fuji.

References:

Honda, T. 2000. *On the formation of Subashiri-Tainai cave in Mt. Fuji*. The 26th Annual Meeting of the Speleological Society of Japan, August: p. 64.

Honda, T. 2001a. *Investigation on the formation mechanism of lava tube cave*. The 27th Annual Meeting of the Speleological Society of Japan, August: p. 11.

Honda, T. 2001b. *Formation mechanism of lava tube caves in Mt. Fuji*. The 2001 Fall Meeting of the Volcanological Society of Japan, October: p. 66.

Honda, T. 2003. *Formation mechanism of lava tube caves of Hachijo-fuketu in Hachijo-jima*. The 2003 Fall Meeting of the Volcanological Society of Japan, 0ctober; p. 160.

Lava Caves of Jordan

Stephan Kempe[1], Ahmad Al-Malabeh[2],
and Horst-Volker Henschel[3]
[1] University of Technology, Institute of Applied Geosciences, Schnittspahnstr 9, D-64287 Darmstadt, Germany.
kempe@geo.tu-darmstadt.de
[2] Hashemite University, Department of Earth and Environmental Sciences, P.O. Box 150459, Zarka 13115, Jordan
[3] POB 110661, D-64221 Darmstadt, Germany

The central section of Jordan is covered by young alkalic olivine basaltic lava flows: the Harrat Al-Jabban volcanics. These are part of the large intracontinental Harrat Al Scham volcanic field. The origin of these lavas may be connected to the existence of a continental intraplate hot spot plume. Its eruptive site should appear to move southward as the Arabian Plate moves northward due to the opening of the Red Sea. The top most and therefore youngest flows, are ca. 400,000 years old (Tarawneh et al., 2000).

In these lavas we explored, surveyed and studied four natural lava tunnels (Abu Al-Kursi, Beer Al-Hamam, Al-Howa Cave and Dabie Cave) and two other lava caves (Azzam Cave and Dahdal Cave) in September 2003 and March 2004 (Table). The two smaller caves are most probably pressure ridge caves formed by the buckling-up of the upper layers

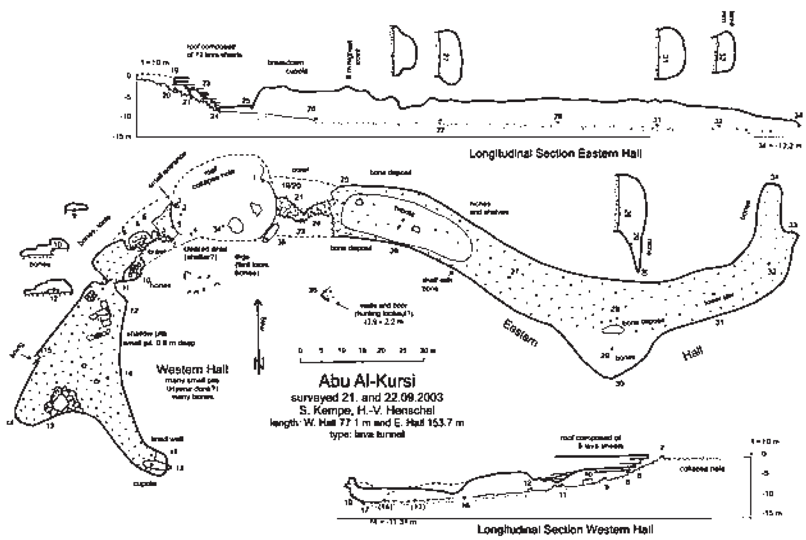


Figure 1 (Kempe et al.). Survey of the Abu Al-Kursi lava tube cave, in Jordan.

Table (Kempe et al.). Data of Jordan lava caves (locations WGS 84).

Name of Cave	Latitude	Longitude	Stations	Length	Stations	Depth	Direction	Type
Abu Al-Kursi W	32°15.401'	36°39.442'	2 to 18	77.1 m	2 to 18	8.1 m	N-S	Lava Tunnel
Abu Al-Kursi E	32°15.401'	36°39.442'	20 to 34	153.7 m	1 to 34	12.2 m	W-E	Lava Tunnel
Azzam Cave	32°17.104'	36°36.594'	13 to 25	44.1 m	1 to 25	4.2 m	NWN-SES	Pressure Ridge
Beer Al-Hamam	32°07.91'	36°49.42'	32 to 23	445.0 m	1 to 23	17.2 m	NW-SE	Lava Tunnel
Dahdal Cave	32°17.344'	36°35.718'	5 to 12	28.9 m	1 t0 12	0.0 m	SW-NE	Pressure Ridge
Al-Howa	32°18.536'	36°37,240'	6-9,6-16	100 m	2-7	11.0 m	NW-SE	Lava Tunnel
Dabié Cave	n.d.	n.d.	0-14	197 m	-	1 m	N-S	Lava Tunnel

Fig. 2: View of Eastern Hall of Abu Al-Kursi.

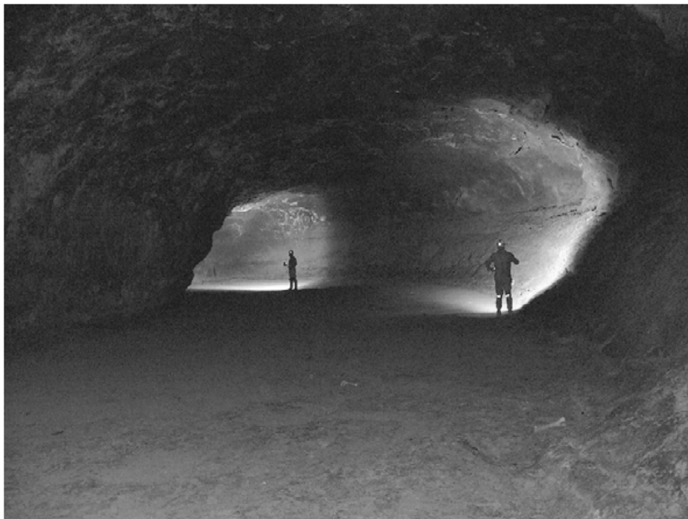
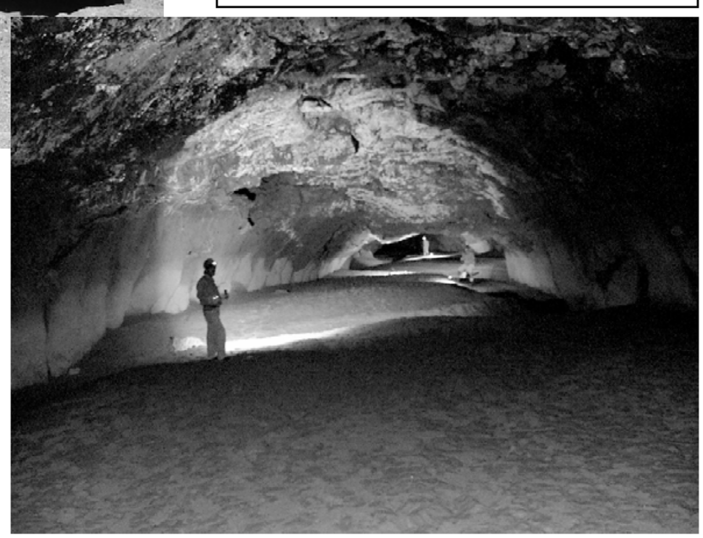


Fig. 3: Camel bones, possibly a former hyena den (note bones with missing ends).

Fig. 4: Entrance to Beer Al-Hamam, a ca. 6 m deep collapse hole in roof of a lava tunnel.

Fig. 5: An upslope view of the lower part of Beer Al Hamam (note sediment floor with channel).



Figures for Kempe et al..

of pahoehoe flowing down from nearby Al-Qu'ays volcano, while they were still hot and plastic. Abu Al-Kursi (Figs. 1, 2, 3) and Beer Al-Hamam (Fig. 4, 5) are large lava tunnels, up to 15 m wide and 8 m high. Al Howa is the section of a medium-sized lava tunnel while Dabie Cave is the smallest of these conduits, less then 4 x 2 m in cross section. These tunnels served to transport lava subterraneously over long distances, i.e. in case of the large caves possibly over several tens of kilometres. Now they are accessible through ceiling collapses, which allow studying the structure of their roofs. These consist of uninterrupted sets of lava sheets which show that these natural tunnels did not form by over-crusting of lava channels, but by repeated under-flowing and inflating of initial lava deltas. In this way lava flows build forward only at the tip, while the rest of the flow is stationary apart from the lava flowing in the tunnel inside. These processes have been studied in Hawaii (e.g., Kempe, 2002) and now can be used to interpret findings elsewhere. The existence of these tunnels shows that the basaltic lava must have been very hot upon eruption, and that it was piped through the tunnels over long distances, thus allowing flow over terrain at slopes at or less than 2°, comparable to the distal slopes of Hawaiian volcanoes. In fact, there should be many subparallel tunnels in these youngest flows.

The age of these flows is much greater than those ages on the Island of Hawai'i. Thus it came as a surprise that such lengths of the tunnels still are accessible. Dahdal Cave, Abu Al-Kursi, Beer Al-Hamam and Dabié Cave contain thick sediment deposits. In the case of the three latter caves, this sediment causes their terminations. During torrential rains, the stream in a wadi washes surface sediment into Beer Al-Hamam. The lower part of the cave ponds during such rains, producing a large reservoir of water. Signs of rapidly flowing water are seen in the sediment surface in the upper part of the cave. The sediments were sampled at a profile. They are mostly silts with some fine sand. Quartz, calcite, plagioclase, illite and koalinite (in decreasing order of amount) compose most of the sediment. That indicates a wind-blown origin, possibly a glacial loess. In the upper centimetres the sediment also contain large concentrations of ammonium nitrate. This is derived from pigeon droppings. In both sections of Abu Al-Kursi, the floor is smooth and covered with a thin layer of fines, laid down by occasional floods that pond at the end of the cave. No sign of flowing water is seen.

All these caves were known locally. Until recently, Azzam Cave was used as a sheep pen. Its entrance was excavated recently, and a nearby sediment pile contains pot shards. Black drippings caused by the use of plastic irrigation pipes as makeshift torches reveal visits by adventurous explorers in Abu Al-Kursi. Visiting Beer Al-Hamam requires climbing down an overhanging pit 5 m deep, but it must have been visited in the past because we found stone cairns inside. Dahdal Cave contains a stone wall so it, too, was visited in the past. Some of these visits, however, may have been in prehistoric times: numerous flint tools (possibly neolithic) were found in the neighbourhood of Dahdal Cave and in two digs in the entrance of Abu Al-Kursi. Dahdal Cave, both sections of Abu-Al-Kursi and Dabié Cave contain camel bones and were used as dens by hyenas (Fig. 3). Shallow circular pits are seen throughout Abu Al-Kursi. They do not appear to be anthropogenic since no excavated material is present. Possibly they are hyena or wolf sleeping pits. The mandible of a wolf or jackal was collected in this cave. A mummified hyena was found in Dabié Cave. Considering the age of these caves, they could contain very valuable deposits of faunal fossils covering a large section of the Pleistocene.

References:

Kempe, S. 2002. Lavaröhren (Pyroducts) auf Hawai'i und ihre Genese. In: W. Rosendahl & A. Hoppe (eds.): *Angewandte Geowissenschaften in Darmstadt - Schriftenreihe der deutschen Geologischen Gesellschaft*, **15**: 109-127.

Tarawneh, K., Ilani, S, Rabba, I., Harlavan, Y., Peltz, S., Ibrahim, K., Weinberger, R., Steinitz, G. 2000. Dating of the Harrat Ash Shaam Basalts Northeast Jordan (Phase 1). Nat. Res. Authority; Geol. Survey Israel.

Caverns in Volcanic Terrains in Costa Rica, Central America

Raúl Mora[1,2], Guillermo Alvarado[1,2,4], and Carlos Ramírez[1,2,3]

[1] Red Sismológica Nacional. raulvolcanes@yahoo.com.mx

[2] Escuela Centroamericana de Geología, Universidad de Costa Rica

[3] Centro reinvestigaciones Geofísicas (CIGEFI), Universidad de Costa Rica

[4] Instituto Costarricense de Electricidad

Costa Rica is located in an evolved volcanic arc (< 30 ma), which is a product of the subduction of the Cocos plate under the Caribbean plate. This country contains many diverse volcanic landforms, developed during the last 200 Ma of its geologic history. This report presents the first classification of caverns and grottos in volcanic areas of Costa Rica, together with a preliminary inventory:

a) volcanic caverns

The majority of its caverns of volcanic origin are small caves or grottos within lava flows (lava fields of Cervantes and Los Angeles). Also included are possible collapsed lava tubes of lava or "jameos", and a grotto which forms part of a crater in Turrialba volcano. All these are less than 11,000 years BP.

b) caverns of marine origin (littoral caves)

These are small caves mostly located in areas frequented by tourists. Thus they are comparatively well known. Most of them are located in cliffs and platforms of marine abrasion developed in oceanic basaltic complexes (ophiolites *s.l.*) These rocks are part of an accreted Cretaceous-Eocene complex located along the Pacific Coast. Comparatively well developed littoral caves also exist at Bajamar-Guacalillo beach in cliffs of Lower Pleistocene epiclastic rocks (debris flows and debris avalanches). These are comparatively large caverns, some of which are interconnected. They are adjacent to sandy beaches, and usually are visited by tourists at the low tide. In addition, submarine and subaerial littoral caverns exist on Cocos Island in the Pacific Ocean. This island is the only subaerial exposure of the submarine Cocos volcanic range.

c) caverns of fluvial erosion

This type of cave is uncommon in Costa Rica and is less known than the others. An example is present in Late Pliocene

Figure (Mora et al.). Grotto that forms part of a volcanic crater in Turrialba volcano.

lava on the left margin of Peñas Blancas River, and a small grotto known as Cave of Death is present on the left bank of the Toro River. It contains lethal concentrations of CO_2. Probably the best known and most spectacular example is a natural bridge formed in Middle Pleistocene ignimbrite called Puente de Piedra (Bridge of Stone). It provides a vehicular crossing of a creek in a town named Tacares of Greece.

d) anthropogenic grottos

The most important of these are pre-Columbian shelters excavated in pyroclastic flows (2.0–0.6 Ma) in the northern part of the country. These include the Indian Cave in Cañas and a cave in Salitral of Bagaces.) Other grottos are present on pumice fall deposits dated of 0.30 ma (the Tibás layer), in the Central Valley of Costa Rica. In general terms, all the caves and grottos are located on Upper Quaternary age formations and were inhabited by humans or were used for rituals.

Because of their small size, those investigated to date have low speleological potential. Some of them, however, have a local tourism potential as well as geoarchaeological value not yet investigated nor exploited. In particular, caves of the spectacular Bajamar-Guacalillo beach have obvious value in geological tourism.

Not yet investigated are a probable natural lava tunnel at Turrialba volcano and a reported erosional tunnel at Liberia River.

The Lava Tubes of Shuwaymis, Saudi Arabia

John J. Pint
Consultant, Saudi Geological Survey.
thepints@saudicaves.com

Kahf Al Shuwaymis, located 204 km N of Medina in the Ithnayn lava field, is the second longest lava tube (513 m) so far mapped in Saudi Arabia. The lava source is Hazim al Khadra volcano, which is characterized by a series of large collapses terminating with the entrance to Kahf Al Shuwaymis. Several fumaroles are active on the slopes of this volcano, one of which emanates from inside a shelter cave. A small pressure-ridge cave was also noted in the area.

Dahl Romahah is located 168 kms N of Medina in the Khaybar lava field. This lava tube is 202 m long and is well decorated with flowstone and speleothems composed of secondary minerals which have leaked through the ceiling and walls. The cave contains a large cache of bones as well as coprolites from wolves, hyenas and foxes. The radon level in Dahl Romahah is considerably higher than in other Saudi lava tubes. In bygone days, this cave was used as a water reservoir by local people, who built a long wall on the surface to channel water into the cave.

Aerial photographs, maps and other reports suggest that many other lava tubes will be found south of these two caves.

Discovery and Survey of Hulduhellir, a Concealed (Entranceless) Lava Cave in the Hallmundarhraun, W. C. Iceland

Chris Wood[1], Paul Cheatham[1], Heli Polonen[1], Rob Watts[1], and Sigurður S. Jónsson[2]
[1] Environmental and Geographical Sciences Group, School of Conservation Sciences, Bournemouth University, Talbot Campus, Poole BH12 5BB, UK. cwood@bournemouth.ac.uk
[2] Icelandic Speleological Society (Hellarannsóknafélag Íslands), PO Box 342, 121 Reykjavik, Iceland

Research undertaken on the Hallmundarhraun in 2000 to ascertain the effectiveness of different geophysical methods in the detection and mapping of cavities in basaltic lava flows revealed the possibility of a concealed continuation of the cave Stefánshellir. The 2000 survey by magnetometer and ground penetrating radar (GPR) indicated that the roof of the main passage of Stefánshellir lifted on other side of the 20m long lava seal that closed the upflow end of the known cave. A further survey in 2001 confirmed this finding and revealed over 350m of cave passage. In 2003 the team were interested in confirming the relationship between the Hallmundarhraun's chain of 20 or more shatter rings (or collapsed tumuli) and the Surtshellir-Stefánshellir lava tube cave system and extended the survey to embrace the three nearest shatter rings.

The results were quite remarkable, showing that the concealed cave - now given the Icelandic name Hulduhellir (Hidden Cave) - passed directly beneath the shatter rings, over a distance of approx. 1.2km from the upflow end of Stefánshellir. The geopysical data infers that Hulduhellir is in places a large diameter passage, although the form that it takes beneath the shatter rings is not clear. In order to better understand the pattern of magnetic anomalies around the cave, a comparable geophysical survey was made over the accessible, large main passage of Surtshellir, while attempts are also being made to replicate anomaly patterns with specialist modelling software.

Oral Session III— Biospeleology of Volcanic Caves

Long-term Study of Population Density of the Troblobitic Azorean Ground-Bettle *Trechus terceiranus* at Algar do Carvão Show Cave: Implications for Cave Management

Paulo A.V. Borges[1,2] and Fernando Pereira[2]
[1] Universidade dos Açores, Dep. Ciências Agrárias, CITA-A, 9700-851 Angra do Heroísmo, Terceira, Azores.
pborges@angra.uac.pt
[2] "Os Montanheiros", Rua da Rocha, 9700 Angra do Heroísmo, Terceira, Azores

Trechus terceiranus Machado (Coleoptera, Carabidae) is the commonest trogobitic insect species in several lava –tube caves and pits and in the Mesovoid Shallow Substratum (MSS) on Terceira (Azores). One of the sites where this ground beetle reaches highest densities is the show cave "Algar do Carvão", an impressive volcanic pit. The troglobitic fauna in this cave is particularly rich, with at least two endemic spider species occurring only in this site.

Cave arthropods were sampled once per month for three years (2001-2003) using baited pitfall traps. All collected specimens were counted and stored for later identification with the exception of the abundant *Trechus terceiranus*, which were counted and returned to their environment.

We found that adults are common all year-round, with some activity-density peaks in months between March and September. The most notable finding was an overall decrease in activity-density of *T. terceiranus* from year to year. The hours of artificial light in this cave also increased during these three years and this could have caused this decrease. We discuss the implications for management of the cave.

Indicators of Conservation Value of Azorean Caves Based on Arthropod Fauna

Paulo A.V. Borges[1,2], Fernando Pereira[2], and João P. Constância[3]
[1] Universidade dos Açores, Dep. Ciências Agrárias, CITA-A, 9700-851 Angra do Heroísmo, Terceira, Azores.
pborges@angra.uac.pt
[2] "Os Montanheiros", Rua da Rocha, 9700 Angra do Heroísmo, Terceira, Azores
[3] "Amigos dos Açores", Avenida da Paz, 14, 9600-053 Pico da Pedra, S. Miguel, Azores

All Azorean lava tubes and volcanic pits known to contain hypogean fauna (37 cavities) were evaluated for species diversity and rarity, based on arthropod populations. To produce an unbiased multiple-criteria index (*importance value for conservation,* IV-C) incorporating diversity and rarity based indices and geological and management based indices, an iterative partial multiple regression analysis was performed. In addition, an irreplaceability index and the complementarity method (using heuristic methods) were used to select the most important caves for conservation management.

Most hypogean endemic species have restricted distributions; some are known from only one cave. It was concluded that several well-managed protected caves per island are necessary to preserve an adequate fraction of endemic arthropods. For presence/absence data, suboptimal solutions indicate that protection of at least 50% lava-tubes with known hypogean fauna is needed if the goal is representation of 100% of endemic arthropod species in a minimum set of reserves.

The most diverse arthropod assemblages occur in large (and beautiful) caves; thus cave size plays an important role in explaining the faunal diversity of arthropods in the Azores. Based both on the uniqueness of species composition and/or high species richness, conservation efforts should be focused on the following unmanaged caves: Algar das Bocas do Fogo (S. Jorge); Gruta dos Montanheiros, Gruta da Ribeira do Fundo, Furna de Henrique Maciel, Gruta do Soldão and Furna das Cabras II (terra) (Pico); Gruta das Anelares and Gruta do Parque do Capelo (Faial); Gruta dos Balcões, Gruta das Agulhas and Gruta do Chocolate (Terceira); Água de Pau (S. Miguel).

Indicators of Conservation Value of Azorean Caves Based on Its Bryophyte Flora at Cave Entrances

Rosalina Gabriel[1], Fernando Pereira[2], Paulo A.V. Borges[1,2], and João P. Constância[3]
[1] Universidade dos Açores, Dep. Ciências Agrárias, CITA-A, 9700-851 Angra do Heroísmo, Terceira, Azores.
rgabriel@angra.uac.pt
[2] "Os Montanheiros", Rua da Rocha, 9700 Angra do Heroísmo, Terceira, Azores
[3] "Amigos dos Açores", Avenida da Paz, 14, 9600-053 Pico da Pedra, S. Miguel, Azores

Cave entrances in the Azores are particularly humid habitats. These provide opportunities for the colonization of a diverse assemblage of bryophyte species. Using both published data and new field sampling, we evaluated species diversity and rarity of bryophytes at the entrance of all known Azorean lava tubes and volcanic pits with such flora. Most frequent species includes the liverworts *Calypogeia arguta*, *Jubula hutchinsiae*, *Lejeunea lamacerina*, and the mosses *Epipterygium tozeri*, *Eurhynchium praelongum*, *Fissidens serrulatus*, *Fissidens viridulus*, *Isopetrygium elegans*, *Lepidopilum virens*, *Tetrastichium fontanum*.

Several rare Azorean bryophyte species appear with dense populations at some cave entrances (e.g. *Archidium alternifolium*; *Asterella africana*; *Plagiochila longispina*), which highlights the importance of this habitat in terms of conservation of these plants.

To produce an unbiased multiple-criteria index (*importance value for conservation*, IV-C), several indices were calculated (based on bryophyte diversity and rarity, and also on geological and management features) and an iterative partial multiple regression analyses was performed.

Preliminary data sows that three pit caves are particularly diverse in bryophytes (e.g. Algar do Carvão, Bocas do Fogo and Furna do Enxofre). This indicates the importance of shaded and humid openings. Lava tubes with a diverse troglobitic fauna also are diverse in terms of bryophyte species (e.g., Algar do Carvão, Gruta dos Montanheiros, Gruta da Agostinha, Furna do Henrique Maciel). We also evaluate the utility of several cave management indices as surrogates of bryophyte diversity in Azorean volcanic cavities.

On the Nature of Bacterial Communities from Four Windows Cave, El Malpais National Monument, New Mexico, USA

Diana E. Northup[1], Cynthia A. Connolly[2], Amanda Trent[1], Penelope J. Boston[3], Vickie Peck[4], and Donald O. Natvig[1]
[1] Biology Department, University of New Mexico.
dnorthup@unm.edu
[2] Socorro High School
[3] Earth and Environmental Science Department,
New Mexico Tech
[4] Sandia National Laboratory

One of the striking features of some lava tubes is the extensive bacterial mats that cover the walls. Yet, despite their prominence in lava tubes, little is known about the nature of these bacterial communities. To rectify this situation we have investigated the bacterial mats that cover the walls of Four Windows Cave, a lava tube in El Malpais National Monument, New Mexico (see Figure). These bacterial mats, which occur in the twilight zone adjacent to algal mats, and in dark zone of the lava tube, cover from 25-75% of the wall. Their macroscopic and microscopic visual appearance suggests that these bacterial mats are composed of actinomycetes, bacteria that commonly inhabit caves. Actinomycetes are a group of Gram-positive bacteria that break down complex organic matter and thrive in environments where nutrients are sparse and conditions extreme. With a temperature of 0-2°C and seeping organic matter for nourishment, Four Windows provides an excellent habitat for these bacteria. Some types of actinomycetes are medicinally and agriculturally significant because they excrete antibiotic products to repel invaders. Cave bacterial mats may have such antibiotic properties. Vacuuming of the bacterial mats and the adjacent algae, demonstrated the presence of collembola and mites on the algae and no invertebrates on the bacterial mats.

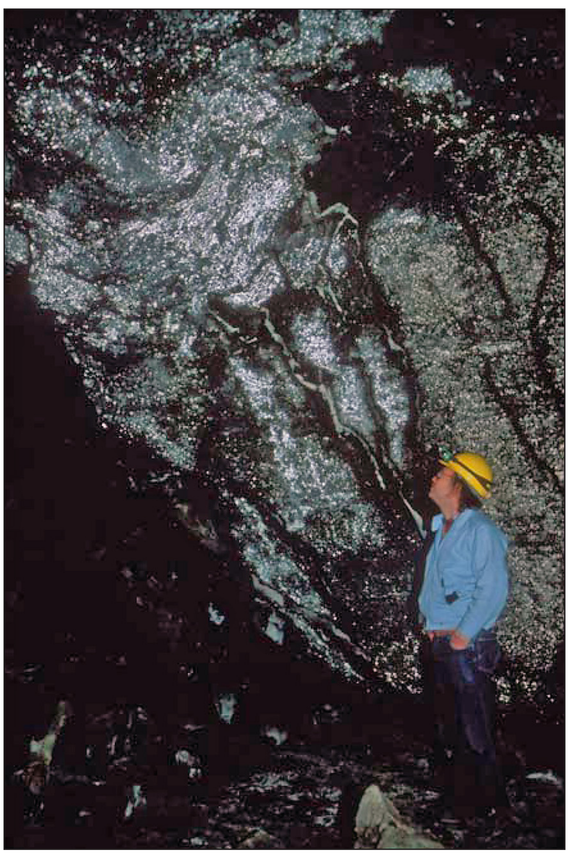


Figure (Northup, et al.). Mats of actinomycete bacteria spread across wall of Four Windows Cave, El Maplais National Monument. During some seasons the bacterial mats are hydrophobic and the walls appear "silvered" when light is shown upon them.

In an effort to phylogenetically characterize bacterial colony members, we extracted DNA from wall rock communities, using a soil DNA extraction technique developed at Los Alamos National Laboratories. The DNA was purified, the 16S rRNA gene was amplified using PCR, amplification products were cloned, and thirty clones were sequenced in their entirety. A restriction fragment length polymorphism (RFLP) analysis of 11 clones exhibited unique banding, an indicator of genetic diversity. Comparison of our sequences with those in the Ribosomal Database II revealed that the Four Windows bacterial sequences are most closely related to actinomycetes, as suspected. Some clones also showed similarities to environmental soil strains. Other clones are related to genera such as *Nocardia* and *Frankia*, although not closely. These results reveal a diverse community of bacteria and the presence of several novel bacterial species.

To investigate the degree to which the actinomycetes had adapted to the lava tube environment, we also investigated the ability of bacteria cultured from these mats to withstand the effects of ultraviolet (UV) radiation. Bacteria from the mats and from the surface rocks above the lava tube were cultured on R2A medium on-site in Four Windows Cave, were allowed to grow for 24-hours in the cave environment, and were then transported to the laboratory where they were grown at 2°C in an incubator. We subjected twelve isolates from the lava tube to one dose (100 seconds) and a half dose (50 seconds) of UV radiation. For controls, we subjected six isolates from the cave surface to the same radiation treatments and also allowed replicates of all the isolates to grow without any radiation. The results showed a general trend in which microbes isolated from the lava tube were much more UV sensitive than the microbes isolated from the surface. However, all of the microbes tested displayed at least slight sensitivity to UV radiation. Based on the results, the bacterial colonies currently inhabiting the Four-Windows lava tube appear to be at least somewhat cave-adapted.

Our studies of the actinomycete communities in Four Windows Cave reveal a diverse community of bacteria that may produce secondary compounds that make them unpalatable to invertebrates. These bacteria appear to have become at least somewhat cave-adapted as evidenced by their loss of UV resistance.

Large Invertebrate Diversity in Four Small Lava Tubes of Madeira Island

Elvio Nunes[1], D. Aguín-Pombo[1,2], Pedro Oromí[3], and R. Capela[1,2]
[1] Department of Biology, University of Madeira, Campus Universitário da Penteada, 9000 390 Funchal, Madeira. panama@net.sapo.pt
[2] CEM, Centre for Macaronesian Studies, Campus Universitário da Penteada, 9000-390 Funchal, Madeira
[3] Depto. Biología Animal, University of La Laguna, 38206 La Laguna, Tenerife, Canary Islands

The epigean fauna of Madeira is well known, highly diversified and very rich in endemic species. In contrast, its cave-dwelling fauna was not very well known. Madeira is a comparatively old island (5 My) with few modern lavas and therefore only a comparatively small number of lava tube caves are known: 21 volcanic caves have been reported. Of these, some already have been destroyed and others (e.g. São Vicente caves), have been heavily modified for tourism. To date, only two significant complexes of lava tubes have been studied: São Vicente (Cardais Caves) and Machico (Cavalum Caves). The Machico lava tubes are under serious pressure because of frequent visitation but still represent the best preserved group of lava tubes in Madeira. Yet their cave-dwelling fauna is little known. Although a few reports have been published, they have dealt only with few taxa. Further, these were reported merely from the complex as a whole without indication of which individual species was noted in which cave. At present, its fauna is at special risk because of current plans for construction of a tunnel. The resulting urgent need for detailed information led us to study biodiversity in four of its five small caves.

Invertebrates were sampled by sight and by 32 baited pitfall traps set during a seven months period. Of 8,497 sampled specimens, 14.3% were Phoridae, representing 9 species. This family was excluded from further consideration.

The remaining specimens belong to 69 taxa. Of these, 8 were known endemisms, 5 were new species and 1 was a new record to Madeira. Previously only 18 species were known from these caves, and 8 of these were not found in this study. The estimated number of species in this complex is 79. For a small cave complex with less than 300 m in total length, this is a considerable number. Cavalum II had the greatest number of species. Although many species were present in more than one cave, some were found in only one. For example the endemic spider *Centromerus sexoculatus* was sampled only in Cavalum I, the pseudoescorpion *Microcreagrina madeirensis* in Cavalum III and the carabid *Trechus fulvus maderensis* in Landeiros Cave.

This sampling thus demonstrated that protective measures are urgently needed.for the cave-dwelling fauna of the Machico complex.

Oral Session IV— Theoretical Studies, Conservation, and Management of Caves

Speleothemic Minerals Deposited as Condensates from Vapors, 1919 Lava Flow, Kilauea Caldera, Hawaii, USA

William R. Halliday
Honorary President, IUS Commission on Volcanic Caves, 6530 Cornwall Court, Nashville, TN USA 37205.
bnawrh@webtv.net

Few publications acknowledge the existence of cave minerals deposited from fumes and/or steam. The 1919 "Postal Rift" lava flow in Kilauea Caldera contains about 200 caves. Included are lava tube caves, hollow tumulus caves, drained flow lobe caves and others. While a single body of magma is believed to underlie the entire caldera, significant differences in the fumes of different areas are readily detected by human senses, on and beneath the surface. A significant minority of its caves is at least intermittently hyperthermal, with varied patterns of steam and fume emissions and varied mineral deposition along hot cracks and in other locations on ceilings, walls, floors, and lava speleothems.

Working conditions include up to 100% relative humidity and temperatures up to 130 degrees F, but as a result of thermostratification, temperatures as high as about 175 degrees F can be measured in speleothemic areas. Sulfates, chlorides and (rarely) elemental sulfur are believed to be present. An initial project of mineral identification foundered with the termination of the position of Cave Specialist at Hawaii Volcanoes National Park. A new project is strongly indicated.

Climate Modeling for Two Lava Tube Caves at El Malpais National Monument, New Mexico, USA

Kenneth L. Ingham[1], Diana E. Northup[2], and Calvin W. Welbourn[3]
[1] Kenneth Ingham Consulting, LLC. ingham@i-pi.com
[2] Biology Department, University of New Mexico
[3] The Florida Department of Agriculture and Consumer Services

Reliable data concerning cave microclimate benefits those who manage caves for human visitation, protection, and the conservation and restoration of bat roosts. Both published and unpublished information about cave climates is limited, however. Mathematical models of cave climate are even more limited, and for lava tube caves, these appear to be totally lacking. Because they are simpler than many limestone caves (thus making the task of modelling tractable) we tested the use of lava tube caves as laboratories in which to do climate modeling.

We present the results of investigating temperature and humidity in two lava tube caves at El Malpais National Monument, New Mexico, USA. One cave was a single-entrance cave with an ice sheet, the other a tube with detectable airflow to/from cracks on the surface. In these two tubes, we collected 1.5 years of temperature and humidity data with Onsett

Hobo™ dataloggers. Using the data, we investigated how temperature and humidity change with season and distance from the entrance, and we now propose mathematical models to predict future temperatures based on heat flow from the surface as well as advection.

Our models show a good fit to the equation

$$T(t) = a1 + a2\cos[(t2\pi)/365.24] + a3\sin[(t2\pi)/365.24] + a4\cos(t2\pi) + a5\sin(t2\pi).$$

This implies that, at least in these lava tube caves, accurate prediction of temperature is possible.

Pa'auhau Civil Defense Cave, Mauna Kea Volcano, Hawai'i: A Lava Tunnel ("Pyroduct") Modified by Water Erosion

Stephan Kempe[1], Ingo Bauer[1], and Horst-Volker Henschel[2]
[1] University of Technology, Institute of Applied Geosciences, Schnittspahnstr 9, D-64287 Darmstadt, Germany.
kempe@geo.tu-darmstadt.de
[2] POB 110661, D-64221 Darmstadt, Germany

Pa'auhau Civil Defense Cave was surveyed and geologically inspected by the authors in 2001. It is located on the heavily eroded eastern flank of Mauna Kea volcano, in the Hamakua volcanics (200-250 to 65-70 ka). It is the largest lava tunnel ("pyroduct", "lava tube") known on this volcano. Typical morphologic elements of natural lava tunnels are present, including secondary ceilings, linings, base sheets, lava falls, and lava stalactites. The cave has only a moderate width and the cross section of the lava flowing in it did not exceed 1-2 m^2. The cave has a dendritic passage pattern and is only a section of a once longer system (Fig. bottom). The present entrance is situated at the downhill end of the cave. It looks out into a modern canyon (Kahawaili'ili'i Gulch). Upslope, the Alpine Stream Passage of the cave ends in breakdown at the wall of the same gulch. The Main Passage ends at a lava choke, and Mudcrawl and other side passages end in mud and sand chokes. The presence of casts of large trees shows that the cave lava transgressed a forested terrain. Plunge pools expose a diamict which contains large blocks in a fine-grained matrix with a red top layer underlying the cave lava. The Table lists some of the morphometric characteristics of the cave.

Water of the gulch entered the cave upslope and traversed much but not all of the cave modifying it substantially (see Fig. top). It left polished walls and ceilings, large plunge pools, stream potholes, scallops, flutes, gravel, rounded blocks, sand and mud. At high water it partially ponded, flooding high elevation passages which then fed water back to the main gallery. It excavated four large plunge pools, cutting through the dense base sheet of the lava and exposing underlying strata. Polished ceilings show where the water sumped in several places. When in flood the speed of the water was enough to create potholes and to remove blocks of the lava from the cave's margins and grind them to rounded boulders and gravel. Even though dripwater presently collects in the cave and flows along some sections of the floor, no water has flowed out of the cave for a long time. The presence of charcoal shows that nearly all the cave's passages were visited by ancient Hawaiians. They left numerous piles of stones, cairns, and stone rings, and also placed stones on the walls. The purpose of this is unknown. The presence of caves eroded by flowing water in the lavas of Hawai'i offers a new view of deep-seated watercourses in volcanic edifices.

Table (Kempe et al., Civil Defense Cave). Morphometric characteristics of the cave.

	Stations	Measurements m	Horizontal m
Main survey line	1 to 74	579.6	573.4
Side passages sum:		420.9	415.5
Sum:		1000.5	988.9
End to end (horizontal)			502.6
Sinuosity main passage			1.14
Vertical	1 to 74	48.9	
Slope ($\tan^{-1}$ 48.93/573.3)			4.87°
Slope ($\tan^{-1}$ 48.93/502.62)			5.56°
Main passage/side passage ratio			1.37
Secondary ceiling ratio			0.11

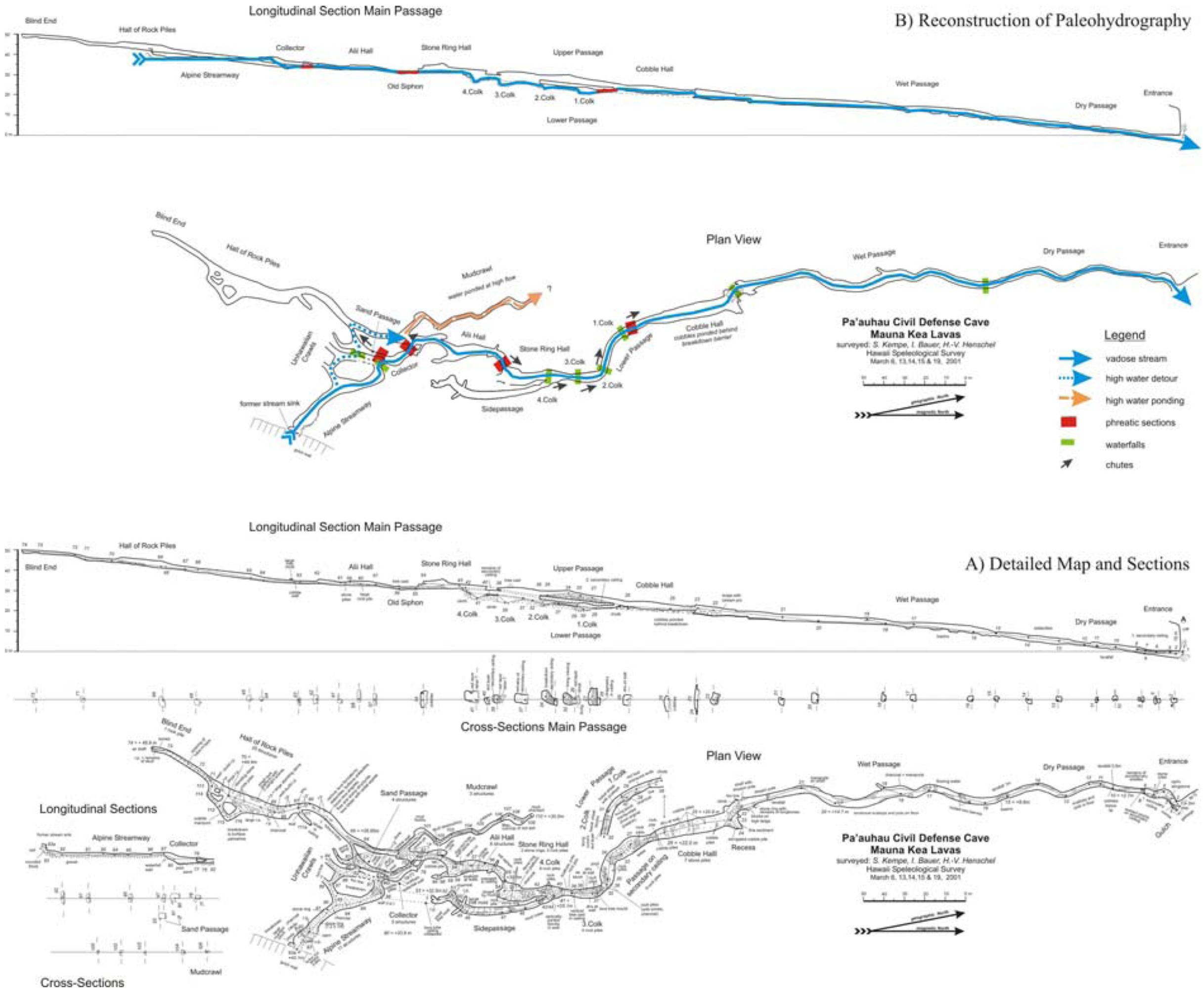
Kuka'iau Cave, Mauna Kea, Hawai'i: A Water-Eroded Cave (A New Type of Lava Cave in Hawai'i)

Stephan Kempe[1], Marlin S. Werner[2], and Horst-Volker Henschel[3]
[1] University of Technology, Institute of Applied Geosciences, Schnittspahnstr 9, D-64287 Darmstadt, Germany.
kempe@geo.tu-darmstadt.de
[2] P.O. Box 11509, Hilo, Hawaii 96721-6509, USA
[3] POB 110661, D-64221 Darmstadt, Germany

From 2000 to 2002, Kuka'iau Cave (alias ThatCave/ThisCave) was explored, traversed from end to end for the first time, surveyed and inspected geologically. It is located on the heavily eroded eastern flank of Mauna Kea, Hawai'i in the Hamakua volcanics (200-250 to 65-70 ka). Together with Pa'auhau Civil Defense Cave (a natural lava tunnel) it is one of the first substantial caves described in detail in lavas of Mauna Kea volcano. Furthermore, we assert that it is the first cave known in Hawai'i which owes its existence entirely to stream erosion.

Kuka'iau Cave is ca. 1,000 m long. It is used by an episodic river that enters the cave by a series of waterfall pits. The resurgence of the stream is 108 m lower than its insurgence: thus the average slope is 9.8° (Fig. 1). 200 m before the exit the intermittent stream passes through a sump where it flows upward over a series of gravel chutes into a vadose passage which follows the dip of the strata (Fig. 2 a-d).

The cave is essentially erosional in origin. We concluded this from the geology of the strata exposed in the cave, from its morphology and from the lack of typical lava tunnel features (such as pahoehoe sheets of the primary roof, secondary ceilings, lava falls, glazing, etc.). At the upper entrance the cave is located in a thick series of 'aa. The lower section was created by removing 'aa and diamict layers, thus excluding the possibility that the cave developed from a precursor lava tunnel ("pyroduct"; "lava tube"). Also, in its phreatic sump section, the cave makes several right angle turns and moves upward through a series of pahoehoe sheets, unlike any lava tunnel. Furthermore, the major section of the upper cave has



Map for Kempe et al. Civil Defense Cave.

developed along a red paleosoil which forms a base layer. Allophane and halloysite (minerals produced by weathering) helped in sealing the primary porosity of this base layer causing a locally perched water table. Water moved along this base layer on a steep hydraulic gradient through the interstices in ‘aa and through small pahoehoe tubes. This exerted a high pressure on the porous diamict of the lower cave, causing its removal by erosion. These observations of water-eroded caves in lavas in Hawai‘i offer a new perspective on deep-seated water courses in volcanic edifices.

Feasibility of Public Access to Þríhnúkagígur

Árni B. Stefánsson
Kambsveg 10, 104 Reykjavík, Iceland.
gunnhildurstef@simnet.is

Þríhnúkagígur was fully surveyed in two field trips in-Spring 1991. Public access to this tremendous volcanic bottle-shaped chimney subsequently has been proposed and discussed several times.

A tunnel to the bottom of the vault has been considered repeatedly. That proposal is not attractive. Although the vault is impressive from the bottom, the view basically is of bare country rock devoid of its original lava coating and formations, for tens of meters upward. This is not especially exciting, nor is standing on the pile of fallen rock at the bottom. Because of weathering of the uppermost part of the shaft and because of falling snow, ice and other debris, danger from rockfall and shatter exists within a radius of 10m from the center line. The possibility of additional rockfall from the overhanging sides of the shaft has not been investigated.

A spiral stairway down the shaft would damage notable lava formations in the narrow funnel at the top. It also would spoil the view of the impressive crater opening at the top of the cinder cone. For the vault to be enjoyed, a spiral ladder hanging from the top would have to be 65m long. Its construction would not be feasible, nor for most persons to descend and ascend it.

A few months ago, a new idea came to the author. At about -60 m, the shaft could be accessed through a 200 m tunnel. With reflection and study of our maps, the idea became even more attractive. At that level, a grid view balcony under the closed NE vent would be under an overhang of solid rock

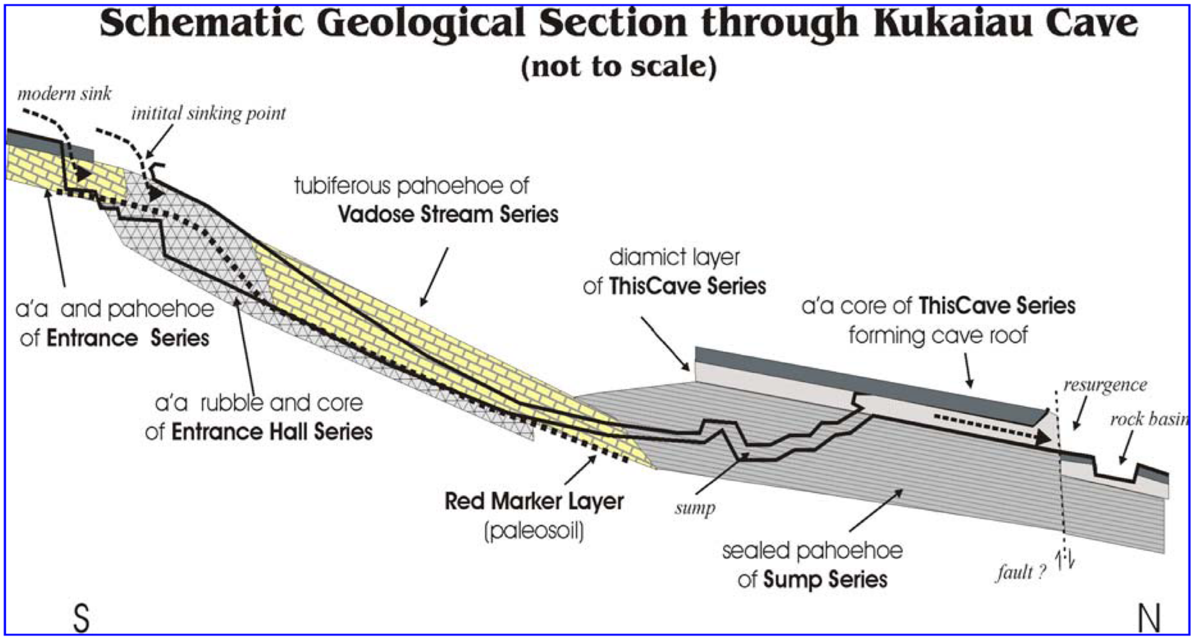


Fig. 1: Schematic geological section through Kuka'iau Cave, showing its complex course through a variety of different rock layers and illustrating the upward movement of water in the sump-section.

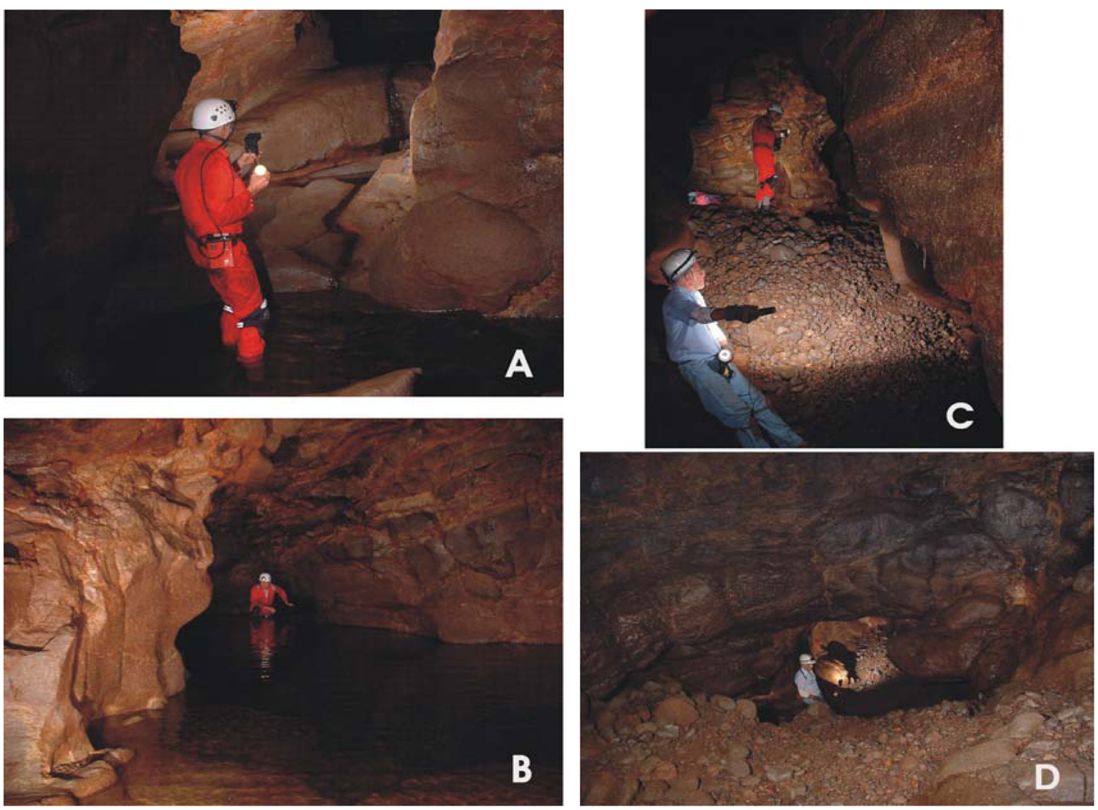


Fig 2: Sump Section: A) Natural rock dam maintaining water level in Echo Lake, a permanent lake even when the sump is empty; B) Echo Lake, which separates the upper and lower parts of the cave. It was first passed in June 2002; C) Chute above Echo Lake. Here, gravel is moved uphill when the cave floods; D) View down the last chute. When the cave floods, the water wells up from this point into the vadose lower section of the cave under a pressure of up to 6 bar.

Figures for Kempe et al. Kuka'iau Cave

where the shaft widens. Thus it would be sheltered from falling rock and snow. Intact lava formations are impressive at this level, and would be in no danger of damage. The sight downward into the widening chamber is as if one were standing on the top of a 20-story building inside a mountain. Two such buildings would fit in this space, side by side. The openings of two tunnels about 4 x 4 m would occupy only about 1:1000 of the wall space. Between such tunnels, a balcony for lighting would do trivial damage to the walls. A light, stable chain fence around the opening at the top would suffice for protective work, thus making the awesome pit accessible and conserving it at the same time.

Whether or not this engineering project can really be done has not been decided, but preliminary work has begun. The author would welcome constructive input.

Volcanic and Pseudokarstic Sites of Jeju Island (Jeju-do), Korea: Potential Features for Inclusion in a Nomination for the World Heritage List

Kyung S. Woo[1] and S.-Y. Um[2]
[1] Cave Research Institute of Korea, Dep. of Geology, Kangwon National Univ., Chuncheon, Kangwon 200-701, Korea.
wooks@kangwon.ac.kr
[2] Information Management Division, Cultural Properties Administration, Daejeon, 302-701, Korea

Scientific research has been conducted on various features of Jeju Island, looking toward a nomination as a World Heritage Site. The Island contains a variety of volcanic landforms and more than 100 lava tube caves of geological and speleological significance. It essentially consists of one major shield volcano, Hallasan (Mt. Halla), with satellite cones around its flanks. Especially notable features include maar (Sangumburi), parasitic cones (Geomunoreum and Seongsan-Ilchubong), giant lava tubes (Bengdwi Cave, Manjang Cave, Gimnyeonsa Cave, Dangcheomul Cave and Susan Cave), an exposure of columnar jointing at Daepodong, a volcanic dome (Mt. Sanbang) and the Suwolbong tuff deposits. Especially notable are the lava tube caves, which show a complete flow system and display perfectly preserved internal structures despite their age of 0.2-0.3 Ma BP. Dangcheomul Cave contains calcareous speleothems of superlative beauty.

Four aspects are identified which demonstrate the congruence of specific features to criteria for World Heritage status:

1) The volcanic exposures of these features provide an accessible sequence of volcanogenic rocks formed in three different eruptive periods between 1 million and a few thousands years BP. The volcanic processes that made Jeju Island were quite different from those for adjacent volcanic terrain;

2) The listed features include a remarkable range of internationally important volcanic landforms that contain and provide significant information on the history of the Earth. The environmental conditions of the eruptions have created diverse volcanic landforms;

3) The largest and most spectacular lava tube caves are located in the western and north eastern parts. With a length of 7.416 km, Manjang Cave is one of the longest and most voluminous. Its single passage contains two (locally three) levels. Other, shorter caves (i.e., 4.481 km Bengdwi Cave) are more complex in form. Susan Cave is a beautifully formed classical lava tube with 4.393 km in length;

4) Of great significance are the abundant carbonate speleothems seen in some low elevation lava tube caves. This phenomenon is very uncommon, and the spectacular caves in which it occurs on Jeju Island are generally acknowledged to be world's leading examples. Dangcheomul Cave can be considered to be the world's most beautiful lava tube cave containing calcareous speleothems.

Closed Depressions on Pahoehoe Lava Flow Fields and Their Relationship with Lava Tube Systems

Chris Wood, Rob Watts, and Paul Cheatham
Environmental and Geographical Sciences Group,
School of Conservation Sciences, Bournemouth University,
Talbot Campus, Poole BH12 5BB, UK.
cwood@bournemouth.ac.uk

Closed depressions have long been recognised as significant features of basaltic pahoehoe lava flows, but their origin has been greatly misinterpreted. Many depressions have been classified as collapse features, while some scientists deny the presence of collapse forms and regard all such features as lava rise pits. In their study of Icelandic pahoehoe lava flow fields the present authors recognise the presence of five different types of closed depressions, which they classify as: open skylights in the roofs of lava caves, conical depressions caused by surface collapse into underlying voids, lava rise pits, shallow sags from the draining of lava rises, shatter rings or collapsed tumuli.

This paper will describe examples of the different types of depressions from the Laki lava flow field (Skaftáreldahraun) and the Hallmundarhraun, and will discuss the role of lava tubes in their formation. It will be seen that an understanding of the forms of closed depressions assists interpretation of the style of emplacement of historic and ancient lava flow fields.

Poster Presentations

GESPEA: Working Group on Volcanic Caves of the Azores

Manuel P. Costa[1], Fernando Pereira[2], João P. Constância[3], João C. Nunes[3,4], Paulo Barcelos[2], and Paulo A.V. Borges[2,4]
[1] Direcção de Serviços da Conservação da Natureza, Edificio Matos Souto, Piedade, 9930 Lajes do Pico, Pico, Azores. paulino.costa@mail.telepac.pt
[2] "Os Montanheiros", Rua da Rocha, 9700 Angra do Heroísmo, Terceira, Azores
[3] "Amigos dos Açores", Avenida da Paz, 14, 9600-053 Pico da Pedra, S. Miguel, Azores
[4] Universidade dos Açores, Dep. Geociencias & Dep. Ciências Agrárias, Ponta Delgada & Angra do Heroísmo, Azores

In 1998, the Regional Government of the Azores established a working group (called GESPEA) to be in charge of studying volcanic caves of the archipelago. This was done because of the rich geological and biological resources and values of the volcanic caves of this region, and their uniqueness. This group is developing a data base and a classification system intended to gather all available information on these caves. It also intends to streamline management of Azorean caves and pits for tourism as well as scientific study.

The various volcanic caves the Azores jointly form a distinct entity. As a whole they provide a diversified geological, biological and aesthetic patrimony that must be publicized and protected in ways consistent with each of these factors. In addition to developing the data base and classification system, the GESPEA is working on policies for overall protection, and on specific legislation where special needs exist.

Analysis of Iron Speciation Microstructures in Lava Samples from Hawaii by Position Sensitive X-Ray Absorption Spectroscopy

Stephan Kempe[1], G. Schmidt[2], M. Kersten[2], and B. Hasse[3]
[1] University of Technology, Institute of Applied Geosciences, Schnittspahnstr 9, D-64287 Darmstadt, Germany. kempe@geo.tu-darmstadt.de
[2] Geosciences Institute, Gutenberg University, Becherweg 21, D-55099 Mainz, Germany
3 DESY-HASYLAB, Notkestr 85, D-22603 Hamburg, Germany

As a result of rapid cooling and solidification of liquid lava after eruption, many volcanic rocks are fine-grained and homogeneous. However, many of them contain fragmented minerals which formed before the eruption and are evident as comparatively large particles within a fine matrix. Also the rock may contain numerous vesicles formed by gases expanding within the melt.

Iron is a common element in volcanic rocks. It may be present in different states of oxidation, depending on the time and speed of oxidation processes during and after cooling. Hematite is specifically noticeable in the form of a thin, shiny bluish-grey layer on surfaces of natural lava tunnels, which have been active for a long time. This shiny layer is commonly called "glaze".

X-ray absorption fine structure spectrometry (XAFS) has become a powerful, widely-used method of speciation analysis. It allows direct, non-destructive determination of chemical bonding forms of selected elements, provided that they are present in sufficiently high concentration and suitable reference data are available. Analysis of the near-edge structure (XANES) of the absorption spectrum provides information about the valence state and coordination geometry. The valence determines the exact location of the absorption edge on the energy axis, called the edge energy (E0). The coordination influences the shape of the absorption edge.

The standard application of XAFS is bulk analysis of homogenized samples. If a sample contains several different species of the selected element, it may be possible to identify all components from the resulting absorption spectrum although without gaining any information on their spatial distribution. Spatial XAFS analyses of metal speciation in solid samples at the micrometer scale have been largely limited to spot analyses, using a microfocussed beam directed at a few pre-elected spots on the sample. The investigation of entire sample areas by this method is not practicable because a spot-by-spot collection of absorption spectra is extremely time-consuming. Only a few attempts have been made to perform XAFS imaging experiments by parallel detection (Kersten and Wroblewski, 1999, Mizusawa and Sakurai, 2004).

Lava glaze samples from Three Fingers Mauka Cave, Mackenzie State Park, Hawaii were analyzed. The rocks which form these lava tubes are known to contain different ratios of FeO / Fe_2O_3, depending on their location (Kempe, 2003). In thin sections, some particles up to 1 mm in diameter were visible within the fine matrix. Details of the analyses will be presented.

The micro XAFS experiments were conducted at HASYLAB Beamline G3. A spatially resolved image of the sample area penetrated by the monochromatic beam (approx. 10 mm wide and 5 mm high) was recorded directly on the X-ray sensitive CCD chip of the camera

(Hamamatsu C-4880, chip dimension 13 x 13 mm, pixel resolution 13 μm, cooled down to 65 °C). The shutter was synchronized with the readout of the CCD and the ionization chambers (I0 in front of the sample, I1 behind it) so the exposure time could be optimized by normalizing it to the I1 reading. The energy range was from 7000 to 7400 eV with incremental steps of 1 eV, so each scan contained a sequence of 401 images along with the readings from the ionization chambers. The monochromator was stabilized electronically.

The image sequences were processed using specific IDL routines and the remote sensing software ENVI. After creating a stack of absorption coefficient images, the Minimum Noise Fraction (MNF) transformation was calculated for an energy range of 100 eV around the absorption edge. Thus the areas on the sample with the most evident differences in the image range around the absorption edge were found. Then classes of different XAFS spectra were identified by selecting specific features from a scatter plot created from two eigenimages. The according spectra were obtained by summarizing the absorption spectra of all pixels which were assigned to the same class. E0 was defined as “halfway up the absorption edge”.

The varying shape and height of the absorption edges reflect the inhomogeneous distribution of iron in the sample with a clear resemblance of the map to the visible structures. The E0 values obtained from the average of three scans are 7117.73 eV for class 1 and 7118.15 eV for class 2. These must be interpreted with some caution. A precise calibration of the monochromator was not possible, and since energy steps of 1 eV were used, the difference between the E0 of classes 1 and 2, which is less than 1 eV, may not be significant. However, each scan showed the same E0 with only negligible variation, and the same difference between classes 1 and 2: thus it is believed that the average can be trusted quite well. The edge energy of trivalent iron species is known to be approximately 2 eV above E0 of divalent species.

The results of the present study suggest that the samples contain an inhomogeneous mix of different iron species with slightly different valence states. Pyroxenes and/or olivines are the most likely components, and some hematite particles also may be present, although they could not be seen in the sample. Due to the lack of calibration and the small difference between the absorption edges, a more definite identification of species is not possible at this point. For this purpose, a better signal to noise ratio is needed so that the full EXAFS spectra can be analyzed, not just the XANES region.

With this setup, position sensitive x-ray absorption spectroscopy is possible at about 10μm spatial resolution. By detailed examination of the XANES spectra, information about differences in Fe concentration and oxidation state between areas was obtained. Future efforts will focus on samples with clearly visible hematite glazing while avoiding the presence of holes in the samples. With an improved setup, we will seek to make the full EXAFS range usable for analysis.

References:

Kersten, M., Wroblewski, T. 1999. Two-dimensional XAFS Topography of amorphous oxyhydroxide layers in Mn/Fe-nodules. In: W. Laasch et al. (eds.): *HASYLAB Annual Report* 1998.

Mizusawa, M, Sakurai, K. 2004. XAFS imaging of Tsukuba gabbroic rocks: area analysis of chemical composition and local structure. *J. Synchrotron Rad.*, 11: 209-213.

Kempe, K. 2003. Lavaröhren (Pyroducts) auf Hawai’i und ihre Genese. In: W. Rosendahl & A. Hoppe (eds.): *Angewandte Geowissenschaften in Darmstadt - Schriftenreihe der deutschen Geologischen Gesellschaft,* 15: 109-127.

New Data on the Probable Malha Grande Lava Flow Complex Including Malha, Buracos, and Balcões Caves, Terceira, Azores

Fernando Pereira[1,2], Paulo Barcelos[1], José M. Botelho[1], Luis Bettencourt[1], and Paulo A.V. Borges[1,2]

[1] “Os Montanheiros”, Rua da Rocha, 9700 Angra do Heroísmo, Terceira, Azores. fpereira@notes.angra.uac.pt

[2] Universidade dos Açores, Dep. Ciências Agrárias, CITA-A, 9700-851 Angra do Heroísmo, Terceira, Azores

Located in the Malha Grande lava field, Gruta dos Balcões is the longest cave on Terceira island. The current length of its mapped passages is 4.421 km.

Recent field surveys have shown that two other nearby lava tube caves are probably isolated segments of the principal tube of Gruta dos Balcões: Gruta dos Buracos and Gruta da Malha Grande. This would make the total length of Gruta dos Balcões system about 5.021 km. Further, other lava tube caves north of Gruta dos Balcões (e.g. Terra Mole, Cascata, Principiantes, Opala Branca and Chocolate) are in the same flow field and probably also belong to the same complex. If this is true, the total length of the Gruta dos Balcões Complex is around 6 km. This would make Gruta dos Balcões the longest lava tube system in the Azores, surpassing the Gruta das Torres lava tube system on Pico island.

The Malha Grande lava tubes are believed to have been formed by the eruption of Pico do Fogo volcano 240 years ago. Its caves are occasionally visited by local people and need protection from vandalism above and below ground. Moreover, the presence of cattle is creating some disturbance in and around entrances to some of the caves. We recommend that this notable area of large and beautiful caves be specifically managed to protect and preserve its extraordinary underground resources.

2004 SYMPOSIUM PAPERS

Rare Cave Minerals and Features of Hibashi Cave, Saudi Arabia

John J. Pint

thepints@saudicaves.com

Abstract

Ghar Al Hibashi is a lava tube situated in a field of vasicular basaltic lava flows located 245 km east of Makkah (Mecca) Saudi Arabia. The cave has 581 m of mainly rectilinear passages containing a bed of loess up to 1.5 m deep, OSL-dated at 5.8±0.5 ka bp at its lowest level, as well as many bones and the desiccated scat of hyenas, wolves, foxes, bats, etc., well preserved due to a temperature of C 20-21° and humidity of 48%. Phytoliths have been found inside plant material preserved in samples of this scat. A human skull, 425 years old and the remains of an old wall indicate a potential for historical or archaeological studies. The loess bed is under study for testing microrobotic designs to navigate inside lava tubes on Mars.

Two large bat guano deposits in this cave caught fire in the past, possibly affecting "bio-stalactites" : soft, yellowish, accretions, c. 4 cm long by 1 cm wide, thought to be formed of bat urine. Nineteen minerals were detected in samples collected, mostly related to the biogenic mineralization of bones and guano deposits. Three of them, pyrocoproite, pyrophosphite and arnhemite are extremely rare organic compounds strictly related to the guano combustion, observed until now only in a few caves in Africa. Hibashi Cave may be one of the richest mineralogical shelters of the Arabian Peninsula, and has been included in the list of the ten mineralogically most important lava caves in the world.

Introduction

In the year 2001, the Saudi Geological Survey initiated subproject 4.1.3 "Mapping of underground cavities (caves) in Phanerozoic rocks." Studies of caves located in the Phanerozoic limestone belts of the country demonstrated that some contained artifacts, bones, etc. of historic, environmental and archeological value (Pint, 2003), while others were judged aesthetically and structurally suitable for purposes of tourism (Forti et al, 2003, Cigna, 2004). In light of these studies, the investigation of cavities in Saudi Arabia was broadened to include lava caves in order to determine their possible value for scientific and touristic purposes.

Saudi Arabia has approximately 80,000 kms^2 of lava fields, known as Harrats (Fig.1). In late 2001 and early 2002, a preliminary survey for lava-tube caves was carried out in Harrat Kishb, a young basaltic lava field with an area of 5, 892 kms^2 centered circa 270 km northeast of Jeddah. Six lava caves were located, three of which were mapped. These three caves were found to contain items of historical, geological and archeological interest (Roobol et al, 2002).

From November 2002 to the present writing, other lava caves were located in Harrats Ithnayn, Buqum-Nawasif and northern, central and southern areas of Harrat Khaybar. Two of these caves, Dahl Romahah and Kahf Al Shuwaymis, are briefly described in Pint, 2004 and are still under study.

Hibashi Cave appears to be deserving of special attention due to the wealth of mineralogical data which has come to light from the analyses of speleothems found in it. It has, in fact, recently been included in the list of the ten mineralogically most important lava caves in the world (Forti, 2004). In addition, the floor of Ghar Al Hibashi is covered with a layer of loess or fine silt, up to 1.5 m in depth, of considerable interest to sedimentologists as well as scientists studying the lava tubes of Mars, whose surface is covered with a similarly fine sediment, according to NASA, 2004. Hibashi Cave is also the site of two extensive guano fires, which have rarely been described in speleological publications (Martini, 1994b) and whose effect on secondary cave minerals is of interest to speleo-mineralogists.

The casual discovery of a human skull and a man-made wall inside Hibashi Cave give hope that archeologists and historians could carry out fruitful studies in this cave. In addition, the considerable quantities of bones, guano and animal scat inside the cave may shed light on the past flora and fauna of the Arabian Peninsula. In particular, phytoliths found in plant fibers inside wolf and hyena scat from Hibashi Cave may be of value in studying the desertification of Saudi Arabia.

It is hoped that this publication will confirm the importance of Hibashi Cave and will be of use to government authorities in protecting the cave from vandalism and intrusions.

Geology of Harrat Nawasif-Buqum

Ghar Al Hibashi is located in Harrat Nawasif-Buqum, a group of lava flows encompassing about 11,000 km^2 and roughly situated between the towns of Turubah and Ranyah, E of Makkah, Saudi Arabia. The origin of the basalts in Harrat Nawasif-Buqum is attributable to the period of magmatic eruptions that began in the Miocene and continued until historic times. These basalts can be classified as Upper Tertiary and Quaternary. They are primarily titaniferous olivine basalts, including alkali basalts, basanites and nepheline-basanites, occasionally interlayered with pyroclastics. Hotzl et al (1978) took two samples

Figure 1. Map of Saudi Arabia showing all major laval fields. Hibashi Cave is located in Harrat Nawasif-Boqum.

of Harrat Nawasif-Buqum basalts for potassium-argon age-dating, yielding ages of 3.5±0.3 million years for the older basalts and 1.1±0.3 million years for the younger. Because of the relatively unweathered condition of the basalt in which it is found, it can be assumed that Ghar Al Hibashi lies within one of the younger flows, However, it should be noted that the younger sample dated by Hotzl et al (1978) was taken from the area of Sha'ib Hathag, some 63 kms NE of Ghar Al Hibashi. Arno et al (1980) report ages of 22.8, 15.8, 7.3, 4.4 and 2.8 million years for samples taken from the flows of this harrat, leaving the exact age of the basalt in which Hibashi was formed, very much in question.

Ziab and Ramsay, 1986, state that the Buqum basalt is between 20 and 25 m thick in the Turubah area but much thinner farther north. The depth of Ghar Al Hibashi (about 22 meters from the surface to the cave floor) suggests that the cave may lie within the basalt studied by Ziab and Ramsay, which they describe as gray to dark gray, vesicular, medium grained and prophyritic, containing phenocrysts of olivine, titanaugite, plagioclase and opaque minerals. They further state that it has an SiO_2 content ranging from 42 to 47 percent, high TiO_2 (1.42-2.79 percent), and high P2O5 (0.32-0.67 percent). Almost all the rocks they studied were undersaturated, with 0.3 to 7.8 percent nepheline, 8-21 percent olivine and no quartz in the norm. All the rocks were highly sodic and normative alibite exceeded normative orthoclase, typically by a factor of approximately five.

Figure 2 is an aerial photograph showing the flat-lying undeformed, unmetamorphosed basaltic lava flows and cinder cones in the vicinity of Ghar Al Hibashi. Lava flows from what appear to be at least four different events can be seen within one km distance from the cave entrance. While steep-walled scoria cones less than 200,000 years old lie less than two kms from the cave, the entrance to Ghar Al Hibashi appears to be located in an older flow.

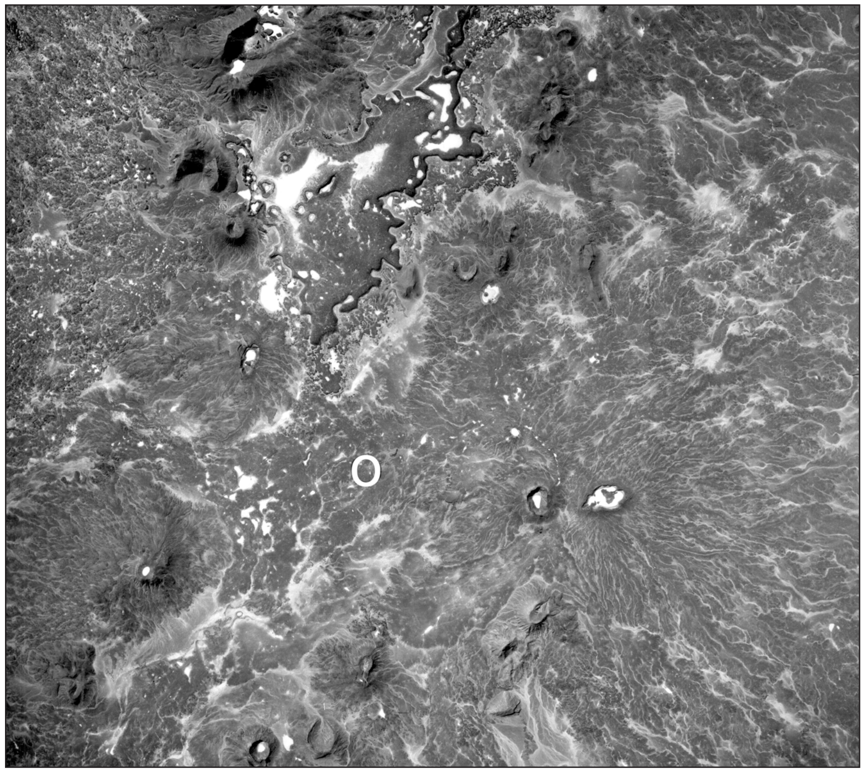


Figure 2. Aerial photograph of the flat-lying undeformed, unmetamorphosed basaltic lava flows and cinder cones in the vicinity of Ghar al Hibashi. located in the circle.

Description of Ghar al Hibashi

The exact location of Hibashi Cave is given in Pint, 2001, where it is registered as Cave number 180. The cave is located approximately in the center of Harrat Nawasif-Buqum inside a vasicular basaltic area, in a slightly raised portion of a major basaltic flow emanating from a large crater to the southeast. The cave lies approximately 22 m below the surface and contains 581 m of passages. The main passage is mainly flat and runs east and west, intersected by a side passage running NW-SE, downsloping from an entrance collapse to the floor of the main passage. Plan and Profile maps of the cave are shown in Figure 3 and the cave entrance in Figure 4.

Secondary Minerals of the Cave. During three different expeditions

Figure 4. The entrance to Ghar al Hibashi. No rigging is required to visit the cave.

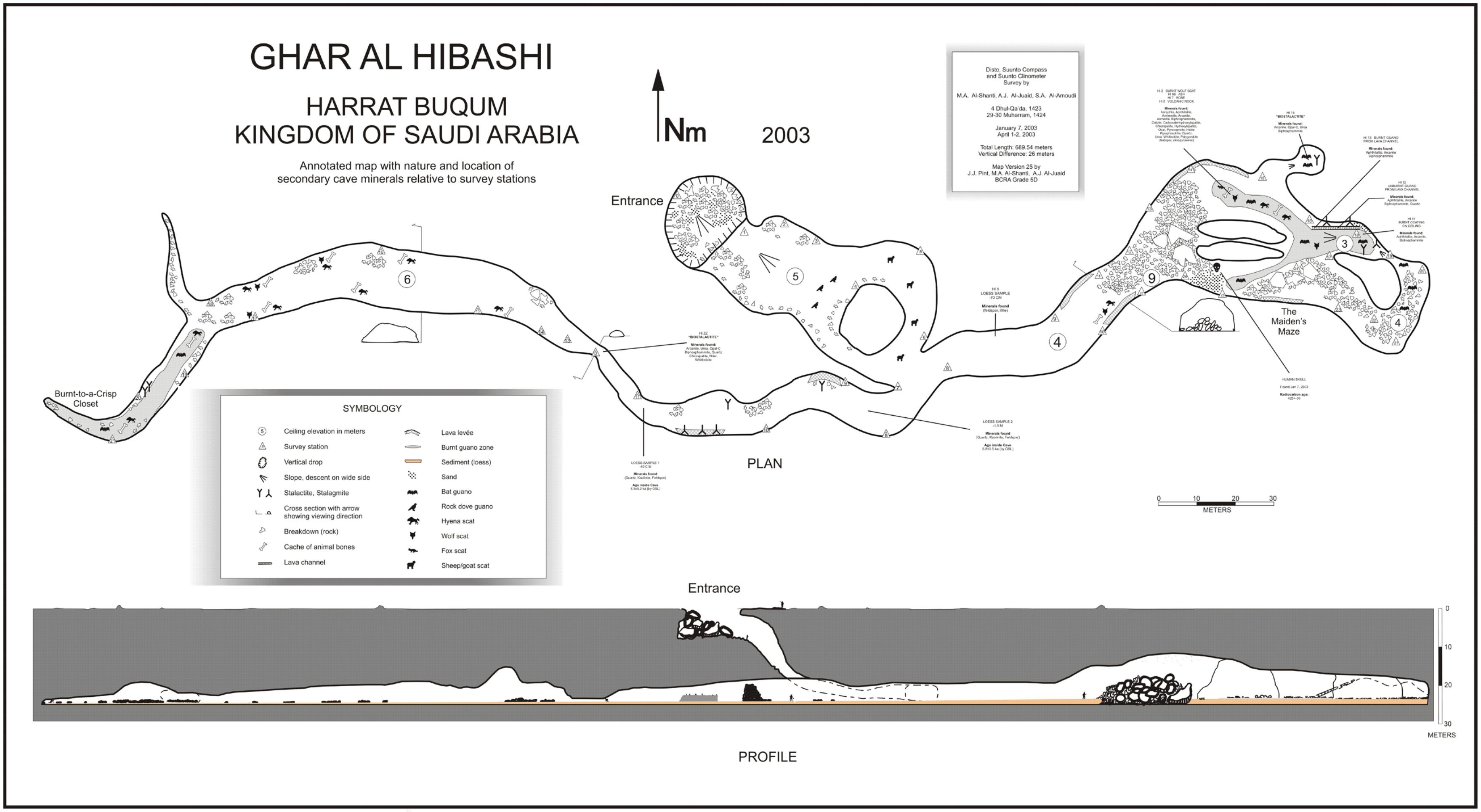


Figure 3. Map of Ghar al Hibashi. A larger version of this map is included in the supplementary material on the CD.

carried out in 2003, a few samples of secondary chemical deposits were collected inside Ghar Al Hibashi to be analysed from the mineralogical point of view. This research was carried out as part of the MIUR 2002 Project "Morphological and Mineralogical Study of speleothems to reconstruct peculiar karst environments" under the direction of Prof. Paolo Forti and is described in detail in Forti et al, 2004. The minerals detected in samples from Hibashi cave are listed in table 1.

Mineralogical importance of Ghar Al Hibashi. A great variety of minerals developed within the cave environment thanks to the peculiar conditions which in time made it possible for different minerogenetic mechanisms to become active. Among these the one related to guano combustion is quite unusual and allows a better description of some very rare cave minerals, which were observed until now only in a few caves of Namibia.

Thanks to these findings, Hibashi lava tube has been referred to as the most important volcanic cave of Saudi Arabia and the richest mineralogical shelter of the country (Forti et al, 2004). For this reason, Hibashi cave has been inserted in the "top ten volcanic caves" for hosted minerals (Forti, 2004). This research is a further confirmation of the recently advanced opinion that amongst the different cavern environments, the volcanic one is the most favourable for the development of minerogenetic mechanisms and consequently of cave minerals.

Loess Floor Cover. To date, six volcanic caves located in Saudi Arabia have been studied and mapped by speleologists. In each of these, sediment covers most, if not all of the original basalt floors. Mud and a phosphate-rich compound were found in lava caves on Harrat Kishb (Roobol et al, 2002) while sand, mud and dust cover the floor of Kahf al Shuwaymis in Harrat Ithnayn and wet and dry mud lies on the floor of Dahl Romahah in Harrat Khaybar. In addition, eight lava caves surveyed in Jordan show similar characteristics (Kempe, 2004). The sediment in Saudi Arabia's Ghar Al Hibashi, however, seems to consist mainly of a thick (up to 1.5 m deep) layer of powdery silt. In order to better understand the nature of the Hibashi sediment, researchers participating in the SGS Loessic Silt Project were invited to visit the cave.

Collection of samples. Two samples of silt were taken on August 31, 2003, in each case from the very lowest level possible, immediately above the original cave floor. Holes were dug by shovel in order to access the bottom of the sediment layer. A pressurized water sprayer

Table 1. Identified cave minerals and their distribution within the cavity: Hi2: burnt wolf scat; Hi6b: ash from burnt zone; Hi7: bone from burnt zone; Hi8: volcanic rock from burnt zone; Hi9: dirt sample from –70 cm below floor; Hi10: nest of insect larvae; Hi12: content of lava channels; Hi13: lower extreme content of lava channel; Hi14: burnt coating on ceiling; Hi15: sticky stalactite between stations 18w-19w; HiZZ: sticky stalactites near station 12w. The following, detrital and/or not cave-related, minerals have been also detected: calcite (Hi2), dolomite (Hi2), feldspar (Hi2, Hi7, Hi8, Hi9, HiZZ), illite (Hi9) and pyroxene (Hi8); no minerals at all have been detected in Hi10.

Sample	Mineral	Formula	Characteristics
Hi7, Hi8	**1** - Anhydrite	$CaSO_4$	Orthorhombic - milky-white small earthy subspherical grains
Hi6b, Hi7, Hi12, Hi13, Hi14	**2** - Aphthitalite	$(K, Na)_3Na(SO_4)_2$	Trigonal – Honey yellow to dark brown subspherical grains and/or vitreous fragment mixed with **6** and/or **4**
Hi8	**3** - Arnhemite	$(K,Na)_4Mg_2(P_2O_7) \cdot 5H_2O$	Hexagonal – Soft uncemented white dull material mixed with **13** and **16**.
Hi6b, Hi7, Hi12, Hi13, Hi14, Hi15, Hizz	**4** - Arcanite	$K_2(SO_4)$	Orthorhombic – Emi-transparent to lemon yellow vitreous crust, mixed with **9, 13, 15 e 16** or plastic microcrystalline honey yellow small aggregates mixed with **2** e **6**
Hi7, Hi8	**5** - Archerite	$(K, NH_4)H_2PO_4$	Tetragonal – pale gray glassy luster coralloids mixed with **15** and **16**.
Hi12, Hi13, Hi14, Hi15, Hizz	**6** - Biphosphammite	$(NH_4, K) H_2 (PO_4)$	Tetragonal – Honey yellow to transparent subspherical grains and/or vitreous crusts or plastic microcrystalline honey yellow to dark brown and black masses with rare thin elongated prismatical crystals . Often mixed with **2**, **4**, **6** and **18.**
Hi7	**7** - Calcite	$CaCO_3$	Trigonal- Very rare as insulated crystals or aggregates of elongated crystals
Hi6b, Hi7	**8** - Carbonate-hydroxylapatite	$Ca_5(PO_4,CO_3)_3(OH)$	Hexagonal – honey yellow vitreous semi-transparent hard material
Hi6b, Hi7, Hizz	**9** - Chlorapatite	$Ca_5(PO_4)_3Cl$	Monoclinic – Cream white microcristalline hard material with rare aggregates of small dumpy fibrous prismatic crystals
Hi7	**10** - Halite	$NaCl$	Cubic – Rare semi-transparent pale blue coralloid grains strictly associated with **9** and **14**.
Hi6b, Hi7	**11** - Hydroxylapatite	$Ca_5(PO_4)_3(OH)$	Hexagonal – Porous to compact fragments within bone partially transformed into **19**.
Hizz	**12** - Niter	KNO_3	Orthorhombic – Similar and always strictly mixed to **6**
Hi6b, Hi7, Hi8, Hi15, Hizz	**13** - Opal-C	$SiO_2{\cdot}nH_2O$	Tetragonal – Semi-transparent to pale yellow viteous globular or coralloid crusts mixed with **15**, **16** and **17**.
Hi7	**14** - Palygorskite	$(Mg,Al)_2Si_4O_{10}(OH){\cdot}4H_2O$	Monoclinic/Orthorhombic – Soft tuft of snow-white thin, bent, fibrous crystals
Hi6b, Hi7, Hi8	**15** - Pyrocoproite	$(K,Na)_2Mg(P_2O_7)$	Monoclinic – Semitransparent to pale grey vitreous globular saccaroidal crusts or pale green elongated pseudo-fibres. Often mixed with **16**.
Hi6b, Hi7, Hi8	**16** - Pyrophosphite	$K_2Ca(P_2O_7)$	Monoclinic – colourless to snow-white vitreous saccaroidal crusts. Nearly always mixed with **15**.
Hi6b, Hi7, Hi8, Hi12, Hizz	**17** - Quartz	SiO_2	Trigonal – crust or insulated grains without the characteristic prismatic habit often associated with **13**, **15** and **16**.
Hi7, Hi8, Hi15, Hizz	**18** - Urea	$CO(NH_2)_2$	Tetragonal – small colourless to pale yellow transparent prismatic tabular crystals or radial aggregates
Hi6b, Hi7, Hi8, Hizz	**19** - Whitlockite	$Ca_9(Mg,Fe)(PO_4)_6[PO_3(OH)]$	Trigonal – Milky white spongy material or small vitreous pinkish crystals over bone fragments

Figure 5. Measuring the depth of the loess bed at the second sampling point.

was used to strengthen the side walls as the holes were dug and also to minimize the amount of dust in the air. Sample number one was taken from a point 4 m SE of station 11W, in the middle of the passage. The sediment was 40 cm deep at this point. The sample was forced into a heavy-duty PVC tube which was then sealed with tight-fitting end caps. Desiccated hyena scat, twigs and fragments of basalt were found lying on the original floor of the cave. The second sample was taken from the bottom of a hole dug halfway between stations 8W and 9W, equidistant from the walls of the passage. At this location, 60 meters closer to the cave entrance than the first sampling point, the sediment was found to be 1.5 m deep (Fig. 5).

Analyses of loess content. The results of analyses carried out on these samples will be reported in Vincent and Kattan, 2005. Below we briefly summarize comments on the Hibashi sediment communicated to the chief author by Dr. Peter Vincent.

A laser granulometer indicates that this sediment is loess with a mean particle size of about 10 microns. It is a fine silt dominated by quartz, feldspar and kaoline, as determined by XRD analysis. The kaoline indicates that it was derived from deep weathering because it is an end-product clay mineral that now only forms in humid tropical conditions. The quartz is almost certainly derived from the deeply weathering laterites which are filled with eroded quartz grains. There is abundant evidence that deep weathering of the Shield took place in Miocene times after the uplift, releasing the quartz silt. Because the silt could not have come from the basalt in the area (which is a basic rock and quartz poor), it is not a local fluvial deposit, but must be related to the weathering underneath the local basalt or must come from further afield. It was almost certainly carried into the cave by air (Vincent, 2004).

Age dating of Hibashi loess. Optically Stimulated Luminescence (OSL) was used to date the two samples from Ghar Al Hibashi. The procedures were carried out during a six-month period in 2003 at Oxford University, U.K., using a Danish instrument from Riso. The age of sample 1 (depth: 40 cm, circa 150 m from the cave entrance) was found to be 4.5±0.2 ka while the age of sample 2 (depth: 150 cm, circa 90 m from the entrance) is 5.8±0.5 ka. Both of these dates are post-Holocene wet-phase (7 ka bp) and presumably relate to the onset of aridity and more frequent windstorms (Vincent, 2004).

Role of Hibashi loess for design of microrobots for Mars. A joint project by the Field and Space Robotics Laboratory of MIT (Massachusetts Institute of Technology) and the Cave and Karst Studies Program at New Mexico Tech. (NM Institute of Mining and Technology) is using Hibashi Cave as a model for lava tubes on Mars. This project, funded by the NASA Institute for Advanced Concepts (NIAC) is looking at microrobotic technology for accessing such systems in extraterrestrial locations (Dubowsky et al., 2003).

Interest in lava tubes on other bodies including Mars and the Moon for future space missions has been suggested by a number of investigators (Boston, 2003, Frederick, 1999, Horz, 1985). A detailed NIAC study over four years has produced a set of enabling technologies that will allow robotic and ultimately human use of Martian lava-tube caves. One of those identified technologies, i.e. the need for highly capable miniature robotics for ground-based detection, reconnaissance, and mapping of lava-tube structures, has led to the most recent project.

Mars has many lava tubes of great size that are quite conspicuous on orbital imaging data from various Mars mission instruments. The NMT team has identified numerous instances of these. Because of the large amount of very fine surface material that is globally distributed on Mars by planet-scale dust storms occurring at fairly regular intervals, the NMT workers have hypothesized (Boston, 2004) that such materials would sift into lava tubes and create a flat floor of such unconsolidated deposits. The Hibashi system is filled with such material and presents a perfect analog for such a situation. According to Boston, 2004, the detailed map of the system, shown in Figure 3, has been invaluable in producing robotic motion simulations created by the MIT team to test the capabilities of the candidate microrobotic designs to navigate into and around such a challenging environment. The project is continuing with a Phase II proposal to be submitted to NASA in the near future.

Animal and avian excreta in Ghar al Hibashi

The arid climate of Saudi Arabia results in relatively low humidity within most of the country's caves and, therefore, the preservation of much of the caves' contents which, under wetter conditions, would be destroyed by decomposition or water movement. The humidity of Hibashi Cave, for example, is typically 48%.

Animal and avian excreta introduced into the cave environment have been remarkably well preserved in Hibashi Cave and merit study, as will be explained below. In contrast, so little evidence of the presence of fauna has been found inside most of the world's caves, that the official List of Cave Symbols of the International Union of Speleology (UIS) has only one symbol for excreta, a v-shaped drawing which represents the guano of bats or birds. Hibashi Cave, however, contains the desiccated excreta of at least six species in such quantity that they are useful not only as landmarks, but also for understanding the history, climate, flora and fauna of the area, both inside and outside the cave.

Figure 6. The three types of animal feces most frequently found in Saudi caves. From left: hyena, fox, and wolf.

Unlike typical coprolites, this dry scat can easily be broken apart and its contents examined.

By far the most frequently found type of scat is tan, sometimes white, in color, less than 4 cm long and less than 2 cms wide, sometimes tapered at one end. Benischke found large quantities of similar scat in B7 (or Murubbeh) Cave, located on Saudi Arabia's Summan Plateau. Toothmarks on bones found near these droppings led experts in Austria to identify them as hyena scat (Benischke et al, 1988). Although hyenas are not normally found in most parts of Saudi Arabia today, they can still be seen in the southwestern part of the kingdom where they are considered unwelcome predators. In 1998, speleologists observed the body of a recently killed hyena hanging in the air near Al Jawah village, approximately 103 kms SSW of Hibashi Cave. The great amount of hyena scat found in caves all over Saudi Arabia (Pint and Pint, 2004; Pint, 2000; Roobol et al., 2002; Al-Shanti et al., 2003) indicates that these animals were more prevalent in the past than they are today. Larger, cylindrically shaped scat, brownish in color, is less frequently found in Hibashi Cave. This is thought to be wolf scat, based on the opinions of local people regarding scat of similar size, shape and color found in other Saudi limestone and lava caves (Al-Shanti et al., 2003). Figure 6 shows the three types of animal feces most frequently found in Saudi caves. Hyena scat is seen on the left and wolf scat on the right. It seems likely that the scat in the middle is from a fox. Similar scat was found in Black Scorpion cave where foxes were observed outside the cave, at night. Live foxes were also seen near and inside Murubbeh/B7 cave where the desiccated body of an Arabian Red Fox (Vulpes vulpes arabica) was found. Carbon dating indicated the remains to be 1890±45 years old, suggesting that foxes have long lived deep inside caves in Saudi Arabia.

Mounds of rock-dove guano are found between stations 3 and 4 and probably once covered a much larger part of the sun-lit portion of the cave, but have been destroyed, probably by human traffic.

Researchers at Oxford University, U.K. have discovered phytoliths in plant fibers found in hyena scat from Hibashi cave. According to Mulder and Ellis (2000), plant opal-phytoliths are of great value for the study of aridification, desertification, wind patterns, etc. Phytoliths are microscopic bodies that occur in the leaves, roots, etc. of plants. They are composed of opaline silica or calcium oxalates and have unique shapes that act as signatures for the plants that produced them.

In Ghar Al Hibashi, the age of phytoliths may be determined from the vertical position of the scat in the bed of loess or by carbon-dating scat samples. Since plant fibers are commonly found in hyena and wolf scat (Fig. 7), caves in Saudi Arabia and Hibashi Cave in particular, may provide a sufficient source of phytoliths for the study of climate change and desertification on the Arabian peninsula.

Observations on a human skull found in Ghar al Hibashi

Parts of a human skull were found in Ghar Al Hibashi by SGS geologist Abdulrahman Al-Jouid on January 7, 2003. The two pieces were lying at the edge of a patch of sand 8 m NE of station 26 near the far eastern end of the cave. Because human skulls previously had been stolen from Murubbeh-B7 cave (see Forti et al, 2003, pp 18-19) and because Hibashi Cave has no gate and is occasionally visited by the general public, as indicated by graffiti at the cave entrance and inside, it was decided to remove the skull parts from the cave for safekeeping.

Photographs of the skull parts (Fig. 8) were shown to Donald A. McFarlane, Associate Professor at the W. M. Keck Science Center, Claremont Colleges, California. He stated (McFarlane, 2003) that both pieces were obviously human and appeared to be in quite good condition, even though the parietal and occipitals of the cranium were missing. He identified the smaller fragment as the back of the cranium, the hole being the magnum foramen into which the spinal column connects. McFarlane noted the cranium had apparently split off along the coronal and squamosal sutures, possibly suggesting a relatively young (adult) individual, since these sutures increasingly fuse with age. He also noted that the skull appeared to have only seven teeth per quadrate. The 3 molar which typically develops between 15 -21 years of age appeared to be un-erupted. Since the second molar

Figure 7. Broken scat showing plant fibers.

Figure 8. The skull found in Ghar al Hibashi. It is approximately 425 years old.

Figure 9. The upper portion of the skull appears to have been removed with the help of a flat blade, such as from a sword or axe, suggesting the possibility of foul play in the death of this individual.

comes through at about 11-12 years, McFarlane was of the opinion that the individual had been about 14-18 years old at the time of death.

Photographs of the teeth were also shown to Dr. Erik Bjurström, dental consultant, who noted (Bjurström, 2003) that in this skull the canines were not fully erupted and baby tooth 5 was still in place. Bjurström estimated that the skull belonged to a person 12 to 14 years old, using norms that apply to modern man.

In 2003, samples were taken from the larger skull piece and sent to the Gliwice Radiocarbon Laboratory at the Institute of Physics of the Silesian University of Technology, Gilwice Poland. Collagen was successfully extracted from the sample and a radiocarbon age of 425±30 years BP was established.

As may be noted in Fig. 9, the upper portion of the skull appears to have been removed with the help of a flat blade, such as from a sword or axe, suggesting the possibility of foul play in the death of this individual.

Conclusions and recommendations

A number of rare and unusual secondary cave minerals were found in Ghar Al Hibashi in a small number of samples taken mainly from one area of the cave. It is recommended that similar studies be carried out on samples from the extreme western end of the cave. In like manner, a thorough study could be made of the cave silt and of the phytoliths contained in fibers found in the animal scat.

To date, no attempts have been made to dig for artifacts nor to study the bones, horns and other primate remains scattered throughout the cave. The subsurface may yield further finds of possible interest to historians, archeologists and perhaps paleontologists.

Although Hibashi Cave as been declared of world-class importance, it is, at present, not protected by a gate or a fence and is occasionally visited by the general public, as indicated by several layers of graffiti on its walls, both near the entrance and deep inside. If the cave cannot be preserved exclusively for scientific studies, it would seem useful to control the spontaneous tourism now going on there. Visitors might be restricted to certain areas of the cave and a walkway might be built (perhaps of native basalt cobbles) to reduce the dispersion of loess into the air. Such a walkway might benefit both tourists and scientists.

Ghar Al Hibashi appears to be an unusual and important cave and it is hoped that studies of this lava tube will continue.

References

Al-Shanti, M.A., Pint, J.J., Al-Juaid, A.J., and Al-Amoudi, S.A., 2003: Preliminary survey for caves in the Habakah region of the Kingdom of Saudi Arabia: Saudi Geological Survey Open-File Report SGS-OF-2003-3, 32 p., 43 figs.

Arno, V., Bakashwin, M.A., Bakor, A.Y., Barberi, F., Basahel, A., Di Paola, G.M., Ferrara, G., Gazzaz, M.A., Giuliani, A., Heikel, M., Marinelli, G., Nassíef, A.O., Rosi, M., and Santacroce, R., 1980. Recent volcanism within the Arabian plate – preliminary data from Harrats Hadan and Nawasif-Al Buqum, in Geodynamic evolution of the Afro-Arabian rift system: Atti dei convegni lincei (Accademia Nazionale Dei Lincei, Rome) no. 47, p. 629-643.

Benischke, R., Fuchs, G., Weissensteiner, V., 1988, Karstphenomena of the Arabian Shelf Platform and their Influence on Underground Aquifers, Second Report, Volume 1, Speleological Investigations in the Shawyah-Ma'aqla Region, Eastern Province, Saudi Arabia. Austrian Academy of Sciences-KFUPM, pp. 49-50.

Boston, P.J., 2004. Email sent to J. Pint on November 24, 2004 from Dr. Penelope J. Boston, Director, Cave and Karst Studies Program, Assoc. Prof. Earth and Environmental Sciences Dept., New Mexico Institute of Mining and Technology.

Boston, P.J. 2003. Extraterrestrial Caves. Encyclopedia of Cave and Karst Science. Fitzroy-Dearborn Publishers, Ltd., London, UK.

Bjurström, L., 2003. Email sent to J. Pint on Jan 16, 2003 from Erik Bjurström, Dental Consultant, formerly of King Faisal Specialist Hospital, Riyadh.

Cigna, A., 2004. Development of show caves in the Kingdom of Saudi Arabia. Report submitted to Saudi Geological Survey, summarising the results obtained during Dr. Cigna's visit to Saudi Arabia from 15 to 25 March, 2004.

Dubowsky, S., Iagnemma, K., and Boston, P.J. 2004. Microbots for Large-scale Planetary Surface and Subsurface Exploration. Phase I Final report for NIAC CP. 02-02. http://www.niac.usra.edu/files/studies/dubowsky.

Forti, P., Pint, J.J., Al-Shanti, M.A., Al-Juaid, A.J., Al-Amoudi, S.A., and Pint, S.I., 2003. The development of tourist caves in the Kingdom of Saudi Arabia, Saudi Geological Survey Open-File Report SGS-OF-2003-6, 32 p., 51 figs. 1 table, 2 apps.

Forti P., 2004. Minerogenetic processes and cave minerals in volcanic environment: an overview. XI Int. Symp. on Vulcanospeleology, Pico Island, Azores; now in press for the Journal of Cave and Karst Studies, National Speleological Society

Forti P., Galli, E., Rossi, A., Pint, J., Pint, S., 2004. Ghar Al Hibashi lava tube: the richest site in Saudi Arabia for cave minerals. Manuscript accepted for publication in Acta Carsologica, December 2004

Frederick, R.D., 1999. Martian lava tube caves as habitats. Second Annual Mars Society Convention, Boulder, CO, Aug. 12-15, 1999.

Horz, F., 1985. Lava tubes: Potential shelters for habitats. In, W. Mendell, ed., Lunar Bases and Space Activities of the 21st Century. pp. 405-412. Lunar and Planet. Inst., Houston, TX.

Hotzl, H., Lippolt, H.J., Maurin, V., Moster, H. And Rauert, W., 1978. Quarternary Studies on the recharge area situated in crystalline rock regions, In: S.S. Al-Sayari and J.G. Zotl (eds.), "Quarternary period in Saudi Arabia," pp. 230-239. Springer Verlag.

Kempe, S., 2004. Email sent to J. Pint on November 16, 2004 by Prof. Dr. Stephan Kempe, Institute for Applied Geosciences, Technical University of Darmstadt, Germany.

Martini J.E.J., 1994b. The Combustion of Bat Guano – A Poorly Known Phenomenon. South African Speleological Association Bulletin 33, p.70-72.

McFarlane, 2003. Email sent to John Pint on Feb. 10, 2003 from Donald A. McFarlane, Associate Professor, W. M. Keck Science Center, The Claremont Colleges, 925 North Mills Avenue, Claremont, CA 91711-5916 USA.

Mulder, C., Ellis, R.P., 2000. Ecological Significance of South-West African Grass Leaf Phytoliths: A Climatic Response of Vegetation Biomes to Modern Aridification Trends. - In: S.W.L. Jacobs & J. Everett (eds.), Grasses: Systematics and Evolution. - Proceedings of the Second International Conference on the Comparative Biology of the Monocotyledons (MONOCOTS II: Sydney) CSIRO: Melbourne

Pint, J.J., 2000, The Desert Cave Journal 1998-2000, NSS NEWS, October 2000, pp. 276-281.

Pint, J. 2001, Master list of GPS coordinates for Saudi Arabia caves (updated to October 31, 2004): Saudi Geological Survey Confidential Data File SGS-CDF-2001-1, pp. 1-12

Pint J., 2003. The Desert Caves of Saudi Arabia. Stacey International, London, 120 pp.

Pint J., 2004. The lava tubes of Shuwaymis , Saudi Arabia. XI International Symposium on Vulcanospeleology, Pico Island, Azores.

Pint, J. and Pint, S., 2004, The Caves of 'Ar 'Ar, NSS NEWS, March 2004, pp. 68-73.

Roobol, M.J., Pint, J.J., Al-Shanti, M.A., Al-Juaid, A.J., Al-Amoudi, S.A. and Pint, S., with the collaboration of Al-Eisa, A.M., Allam, F., Al-Sulaimani, G.S., and Banakhar, A.S., 2002: Preliminary survey for lava-tube caves on Harrat Kishb, Kingdom of Saudi Arabia: Saudi Geological Survey Open-File report SGS-OF-2002-3, 35 p., 41 figs., 1 table, 4 apps., 2 plates.

Vincent, P., 2004. Email sent to J. Pint on November 10, 2004 by Dr. Peter Vincent, Geography Dept., Lancaster University, U.K.

Vincent, P. and Kattan, F., 2005: Loessic alluvial silts on the Arabian Shield. Manuscript in preparation for publication by Saudi Geological Survey, Jeddah, Saudi Arabia.

Ziab, A.M. and Ramsay, C.R., 1986. Explanatory notes to the Geologic Map of the Turabah quadrangle, Sheet 21E, Kingdom of Saudi Arabia, Ministry of Petroleum and Mineral Resources, Deputy Ministry for Mineral Resources, Jeddah.

Biospeleology in Macaronesia

Pedro Oromí

Dept. of Animal Biology, University of La Laguna, Tenerife, Canary Islands

Geographical and speleological background

In the biogeographical sense Macaronesia is a subregion of the Western Palaearctic which includes southwest continental Portugal, part of the coastal zone of south Morocco, and the Atlantic archipelagos of the Azores, Madeira, Selvagens, Canaries and Cape Verde. Since the establishment of the term in the 19th century by the British botanist P.B. Webb, much has been discussed about the validity of Macaronesia as a biogeographic unit, about its appropriate space and boundaries, and about its different meaning for vegetal and animal organisms. Two continental areas and five volcanic archipelagos have generally been identified within Macaronesia. The islands are of oceanic origin with no surface connection with other land since they emerged from the sea bottom. Independently to other biogeographic considerations, in this text we only pay attention to the strictly volcanic Macaronesian archipelagos, which constitute an insular geographic reality very different to that of the continental Macaronesian enclaves. From a political point of view the Azores, Madeira and Selvagens belong to Portugal, the Canary Islands to Spain, and the Cape Verde form an independent country, though with a strong Portuguese character for obvious historical reasons.

The Macaronesian archipelagos have common geological features mainly derived from their volcanic origin. All the islands have been built up from the sea bottom by successive accumulation of volcanic materials that finally emerged over the marine surface along the Tertiary and Quaternary. Actually the volcanism is still active on the Azores, the Canaries and the Cape Verde islands. Almost all the rocks forming these archipelagos are volcanic. However, in some of the Canary Islands (i.e. La Palma, La Gomera and Fuerteventura) there are plutonic rocks that belonged to their original basements, were uplifted over the sea level and are now exposed on the surface by the effects of erosion. On other islands like Santa Maria (Azores) and Porto Santo (Madeira) some limestone rocks of marine origin have been formed and are actually emerged because of eustatic movements of the sea level. These non volcanic rocks are anyway very scarce, and have developed such a slight karstification that true caves are not found at all inside them. Therefore, in the Macaronesian islands the caves enough developed as to be considered of speleological interest occur only in volcanic terrains.

Such particular cavities have a genesis, morphology and a life span very different than limestone caves. The main types of volcanic caves are lava tubes and volcanic pits, each with their variants depending on the type of speleogenesis (see Montoriol, 1973).

The lava tube caves are formed only in fluid basaltic lavas, never occurring in viscous acidic lava flows of trachytic nature. They originate after more or less permanent lava channels that consolidate by cooling of the peripheral layers, and are finally roofed when significant speed differences are established between the inner and the surface flow. The inner temperature of the tube allows the lava to keep flowing inside until the emission stops, the liquid empties totally and the system becomes a hollow tube. These caves are therefore usually shallow and follow parallel to the surface topography at the moment of being formed. Great accumulation of further new lavas on that containing the cave, and changes on the relief by important erosive effects can alter this parallelism between lava tubes and the actual surface upon them.

A particular type of lava tubes are those originated by the emptying of a dyke. They usually have a different morphology and since their origin are located much deeper below surface than the so called rheogenetic lava tube caves (Socorro & Martín, 1992). These dyke caves do not necessarily follow the surface topography, and normally open to outside at cliffs and other steep terrains due to erosion. Some examples of this kina of caves are Gruta dos Anjos (Santa Maria), Gruta do Inferno (Selvagem Grande) or Cueva de la Fajanita (La Palma).

The volcanic pits often derive from the emptying of volcanic chimneys when the eruption stops and the remaining lava contracts. The spatter cones are hollows with limited dimensions, while other volcanic pits can exceed 100 m deep, like Algar do Montoso, in São Jorge (Azores). They are usually bell-shaped, though they often show more complex structures with connected cavities and multiple vents. The geysers and the vents of gaseous phreatomagmatic eruptions can originate remarkable pits, like that of Sima de Tinguatón in Lanzarote. Some times the retraction cracks originated after cooling trachytic, viscous lavas can also originate remarkable pits, like the 70 m deep Sima Vicky (Tenerife).

Also lava tubes can be combined with volcanic pits in a single but complex cavity with several levels at different depths, like it occurs in Sima de Las Palomas (El Hierro) and Cueva del Sobrado (Tenerife).

Speleogenesis and ecological succession on volcanic terrains

Besides their peculiar speleogenesis when compared to karstic caves, lava tube caves have a geological cycle and an ecological succession also very different (see Howarth, 1996). The formation of a lava tube is very quick, sometimes just a few days, and immediately starts its evolution towards definitive destruction as a cave, which will take place within a period of 100,000 to 500,000 years depending on the local climate and erosion (Howarth, 1973). Volcanic pits, however, can last longer time. The cycle of lava tubes is very short in geological terms, compared to that of limestone caves (millions of years) which needed at least 100,000 years to initiate its formation. On the other hand, lava tube caves usually have much less permanent water than limestone caves (which need it for their formation and is only absent in fossil, inactive caves), and are in general much shallower so that the roots of surface plants often reach and invade the cave.

A recently formed lava tube starts with a juvenile phase characterized by its dependence on the outside climate due to the network of cracks of the lava, easily connecting the cave to the exterior. As ecological succession goes on over the lava, the soil seals the surface, shallower passages retain moisture and the cave enters in a mature phase with the subsequent climatic isolation (temperature and humidity). Thus, there is a simultaneous ecological succession inside and outside the cave, which is very important to determine the living community inhabiting this environment (Ashmole *et al*., 1992). There is a particular way to accelerate this process when a thick layer of small-sized pyroclasts (cinder and lapilli) are deposited upon the recent lavas, which isolate the cave from outside temperatures, keep the moisture and allow many plants to grow up and provide roots to the cave. Many caves in recent or very dry areas of the Canary and the Cape Verde islands have good conditions for troglobites thanks to be covered by ash fields. As time goes by the erosion leads the cave to a senile stage, in which silting of the network of cracks and voids in the surrounding lava isolates the system, the inner space of the cave can be even stuffed up by clay deposits, and internal collapses finally destroy the cavity. Volcanic pits usually have a much longer senile stage due to their larger volume and their vertical shape and more solid architecture. Thus volcanic pits last much longer than lava tube caves, reaching a few million years and being the only caves in the oldest terrains of the islands (Oromí *et al*., 1985).

In the lava tube caves ecological succession typically progresses upwards (Howarth, 1996) in such way that deep levels reach maturity before the upper levels, which need better soil cover on the surface to maintain ideal conditions for troglobites. For example Cueva de Todoque (La Palma, Canary Is.) formed in the lavas of San Juan eruption (1949) some troglobites have been found in the deepest passages, while lavicolous species are the only inhabitants in the rest of the cave (Ashmole et al., 1992; Martín, 1992). In limestone caves instead, the oldest habitats are closer to the surface and ecological succession progresses downwards.

The older is a lava tube, the higher probability to be covered by further lava flows, which keep the cave away from surface. In such conditions the roots do not reach the cave, and provision of organic matter by percolating water is more difficult. Consequently, lava tubes occurring under many lava flows hold a poor fauna or are even abiotic, as it also happens in dyke caves.

Animal communities in volcanic caves

When a lava tube has attained maturity, its environmental conditions are similar to that of limestone caves: absence of light, temperature stability, humidity close to saturation. Scarcity of organic matter is also severe, with lesser provision by water than in limestone caves but frequently compensated by the presence of roots (if there are). In the Macaronesian islands bat colonies are very few inside the caves, therefore the guano is negligible.

Volcanic pits are usually richer in food because they operate as pitfall traps for many organisms; on the contrary, in lava tubes the input of energy through the entrance only affects a few metres inside, and hardly progresses into the cave.

Adaptations to cave life are the same for volcanic and limestone troglobites: depigmentation, eye reduction, elongation of body and appendages, slow metabolism, starving resistance, longer life span, inability to live outside the cave, *k* reproductive strategies (more limited but successful offspring), etc. Higher tolerance to temperature changes has been observed in island troglobites with respect to temperate continental species, both in the nature and in laboratory experiences (Izquierdo, 1997); this could be related to the shallower lava tubes to which they are adapted, and maybe also to the less marked seasonal differences in oceanic islands.

In these volcanic hypogean communities the root-feeding species are particularly abundant with respect to other trophic categories. It is remarkable the richness of sap-sucking plant-hoppers (Cixiidae and Meenoplidae) on three of the archipelagos, while in Europe and North Africa these groups are unknown in the caves. It is also peculiar of these island cave-dwelling communities the presence of troglobitic species belonging to taxonomical groups absent in caves of the nearby mainland, and even very rare all over the world. This is the case for landhoppers (Amphipoda: Talitridae), earwigs (Dermaptera) and thread-legged bugs (Hemiptera: Reduviidae) which have troglomorphic species only in the Canary Islands and in Hawaii. The diversity and abundance of troglobitic cockroaches (Blattaria) in the Canaries contrasts with the absence of these insects in caves of the whole Palaearctic.

Troglobitic species are unable to survive outside their hypogean environment, and therefore they cannot colonize other islands. This implies that all troglobites in Macaronesia are always endemic to a single island. The presence of a troglobite in two islands could only be explained when these islands had been connected in relatively recent past times due to regressions of the sea level (for example Pico and Faial in the Azores; Fuerteventura and Lanzarote in the Canaries).

Types of caves and biological richness

It is very common to find a troglobitic species in different, distant caves formed in separated lava flows within an island. This is due to the existence of the so called Mesovoid Shallow Substratum (MSS: Juberthie, 1983; Culver, 2001), an extensive network of cracks and voids connecting large areas, which is suitable to be occupied by many troglobites. There is a particular type of MSS in volcanic islands made up by the lava clinker covered by a thin soil (Oromí et al., 1986), which has provided a rich adapted fauna in places without caves on the Canary and the Azores islands (Medina & Oromí, 1990 and 1991; Borges, 1993).

Actually troglobites occupy the extensive network of spaces in the appropriate underground, either good caves, crevices or MSS. In general they often prefer small tubes and cracks than proper "caves" that are for us just windows to reach the hypogean habitat. But in

Table I. Types of caves and animal richness.

Type of cave	Troglobites	Other species
Lava tubes	rich	moderate
Chimney pits	moderate	rich
Big crevices	poor	poor
Drained dykes	poor	poor
Erosion caves	none	poor

general the abundance of cavities is a good indicator to the richness of well adapted fauna in an area, especially lava tube caves which are found in basaltic terrain, the best for a good network of spaces.

Besides the stage of ecological succession and the geographic situation of a cave, the animal communities occurring in it also depends on its morphology and depth. Mature lava tubes are more isolated from the surface than volcanic pits concerning direct input through the entrance. Thus the pits can hold a richer fauna with many epigean species, while in the tubes the community is poorer but with much higher proportion of troglobites. The dyke caves are usually very poor because of their location very deep underground, where neither roots nor percolating water with organic matter arrive easily. Most of the dyke caves we have studied had a scarce fauna and always close to the entrance. Other pits like big crevices are also poor because they are usually formed in acidic lavas, which are more impermeable and unconnected to the Mesovoid shallow substratum (MSS), an important reservoir of the hypogean fauna in volcanic terrains without lava tubes. The erosion caves generally formed close to the sea shore are very often also dyke caves, and lack an adapted hypogean fauna.

Main features of the terrestrial cave fauna in Macaronesia

Island faunas are always peculiar because of their disharmony, with many absent animal groups that are found in the continent. This is also the same concerning to cave animals, in such way that these lacking species are partially replaced by other species preadapted to hypogean life, very often belonging to unusual taxonomic groups in the continental cave faunas. This is due to the inability for some of these groups to colonize oceanic islands, being their potential hypogean niches occupied by other groups that commonly don't do it in the mainland.

All Macaronesian troglobites have evolved locally, in such way that all species are endemic to a single island with the exceptions above mentioned. This implies allopatric speciation and many independent colonisations of the underground. However, some genera include various related troglobitic species in one island (3 *Trechus* spp. in Pico, 5 *Cixius* spp. in La Palma, 11 *Loboptera* spp. and 8 *Dysdera* spp. in Tenerife, etc.) In some of these cases two or more congeneric species are found together, but they have different epigean sister species, which also implies independent invasions of the underground. Moreover, many of the epigean sister species are actually occurring on the surface in the same area to their corresponding hypogean sister species, what means that the latter have evolved by parapatric speciation. This is a common situation in Macaronesian islands and agrees with the adaptive shift hypothesis for the origin of troglobites (Rouch & Danielopol, 1987; Howarth, 1987). However, there are also troglobites with no epigean relatives at all on their island and even on the whole archipelago. This is the case for the thread-legged bugs *Collartida anophthalma* (from El Hierro) and *Collartida tanausu* (from La Palma), several species of the pseudoscorpion genus *Tyrannochthonius* and the planthopper genus *Meenoplus*. Some of the species belong to endemic genera, like the harvestman *Maiorerus randoi* from Fuerteventura, the ground beetles *Spelaeovulcania canariensis* from Tenerife and *Pseudoplatyderus amblyops* from La Gomera, with no related species elsewhere in the world. It is difficult to say that these species evolved according to the classical climatic relict hypothesis proposed for the troglobites from Europe and North America (Vandel, 1964; Barr, 1968), since glaciations didn't affect these islands of the mid Atlantic. Maybe their relict condition was due to secondary climatic changes derived from glaciations (drought, forest withdrawal).

Azores Islands

This is the western and northernmost archipelago, being located on the Midatlantic ridge. This implies interesting geologic consequences, with predominance of Hawaiian type volcanism and therefore basaltic rocks, very suitable for the formation of lava tubes. Its geographical situation divides the archipelago in two groups of islands, one at west (Flores and Corvo) and the other at east (rest of the islands) of this ridge, in such way that the former shift westwards together with the ocean floor, and the second group move eastwards towards Europe. The age of each island varies depending on the distance to the ridge, the youngest being those of the central group (Faial, Pico and São Jorge) and the oldest one Santa Maria. The greatest abundance on lava tube caves is in general in the youngest islands, though older islands can be also rich in such caves whenever recent volcanism (in geological terms) have took place and have modern terrains, like for instance São Miguel. On the contrary, modern islands like Flores (2.16 Ma) but lacking recent eruptions, are poor in such caves. All the Azores islands are rather rich in lava tube caves except Corvo, Flores and Santa Maria, and at least some troglobitic species are so far known from all the rest except Graciosa (see Table II).

The studies on cave biology had been very sporadic before the 1980's, and only a few freshwater species occurring in pools at the bottom of pits were known. The knowledge on the terrestrial fauna started in 1987, when an expedition by researchers from Edinburgh University (UK) and La Laguna University (Canary Islands) financed by National Geographic Society and with the valuable collaboration of Os Montanheiros members (Angra do Heroísmo) studied the cave fauna from Terceira, Pico, and São Jorge, and discovered the first cave-dwelling species (see Oromí *et al*., 1990). The same team visited again the archipelago in 1989, also joining the first Azorean biospeleologist (Paulo Borges)

Table II. Islands of the Azorean archipelago. Ages in million years (after França et al., 2004). Presence or absence of volcanic caves with apparent conditions to hold troglobitic fauna. Presence or absence of troglobites.

	Corvo	Flores	Faial	Pico	Graciosa	S.Jorge	Terceira	S.Miguel	S.Maria
age	0.7	2.1	0.7	0.2	2.5	0.5	3.5	4.0	8.1
caves	-	-	+	+	+	+	+	+	-
troglobites	-	-	+	+	+	+	+	+	-

for the study of caves in São Miguel, where they also were helped by the local caver Teófilo Braga (Amigos dos Açores). They also visited Pico, São Jorge, Faial and Graciosa, and found new troglobitic species in all except Graciosa (Oromí *et al*., 1990; Oromí & Borges, 1991; Mahnert, 1990; Merrett & Ashmole, 1989). Since then the biospeleologist team created in Universidade dos Açores at Terceira, has continued the research on cave fauna from the different islands, and now they have an advanced knowledge on the Azorean hypogean fauna, both from caves and from the MSS. The BALA Project carried out in 1998-2001 and directed by Prof. Paulo Borges provided a remarkable improve on the knowledge of the Azorean fauna (Borges *et al*., 2005a, 2005b).

Actually 20 species of troglobites have been found on the archipelago, belonging to eight different orders of arthropods (Borges & Oromí, 1994 and in press). All of them are endemic to a single island, except a few which are found both in Pico and Faial, This is difficult to explain unless a land connection existed between the two islands in the past allowing troglobites to move to each other, separated by less than 50 m depths (see Eason & Ashmole, 1992); however, this hypothesis is controversial since the western part of Pico is extremely recent, probably younger than the descent of sea level during the last glaciation (João C. Nunes, pers. comm.). The hypogean species from the Azores have a moderated degree of troglomorphism, with an obvious reduction of eyes but never reaching the eyeless condition, and never with a very marked lengthening of appendages. The most remarkable case of splitting is found in the genus *Trechus* which includes seven different cave-dwelling species in the archipelago (see Oromí & Borges, 1991; Borges & Oromí, 1991 and in press; Borges *et al*., 2004).

Madeira Islands

The archipelago of Madeira is located at latitude of 33ºN and is formed by two main islands, Madeira and Porto Santo, and the Desertas islets. Porto Santo is an old island (15 Ma), without lava tube caves and troglobitic fauna known so far. Madeira is younger (5.5 Ma) but with scarce recent volcanism, and therefore with few caves. However, the island had often been visited by entomologists which sporadically entered the caves and discovered a few troglobitic species of woodlice (Vandel, 1960), spiders (Wunderlich, 1992) and beetles (Erber, 1990; Serrano & Borges, 1995). In 2000 the GIET team from the University of La Laguna organized a research expedition to Madeira and visited Grutas do Cavalum (Machico) and Grutas de São Vicente, but it has been after 2002 when Dora Aguín and Elvio Nunes, from Universidade da Madeira, who carried about for the first time an accurate study of Machico caves, and discovered several unknown troglobites (Nunes *et al*., 2003).

The cave-dwelling fauna from Madeira is not very rich in species, which have a little marked degree of troglomorphism (Serrano & Borges, in press). This is the only archipelago in Macaronesia where no cave-adapted planthoppers have ever been found. Not a single genus of arthropods includes various troglobitic species, which probable indicates that its limited underground environment has not promoted the radiative evolution in this habitat.

Selvagens Islands

This very small and isolated archipelago is between Madeira and the Canaries, at 30° N. It originated some 24 Ma but it after remained under the sea level for a long time, when new eruptions emerged again the islands between 12 and 8 Ma. They are low islands (less than 150 m) and only Selvagem Grande has one cave, formed in a dyke by marine erosion when it was at the sea level (now the cave is higher up). It was recently visited by a biologist from La Laguna who was looking for cave fauna. The conditions are not good for trogobites, and just a troglophilic spider was collected (*Spermopohorides selvagensis* Wunderlich) (Arechavaleta *et al*., 2001).

Canary Islands

This is the larger archipelago and the closest to the mainland (110 km from Fuerteventura to the Sahara coast), being situated between 27° and 29° N. Their ages rank from 21 Ma (Fuerteventura) to less than 1 Ma (El Hierro), in such way that the age decreases from east to west (see Table III). The origin of the Canaries is not related to the mid-Atlantic ridge like the Azores but to a hotspot model with the peculiarity that the older islands still continue with volcanic activity (Carracedo *et al*., 1998). This has allowed the presence of modern lavas on all the islands except La Gomera where no eruptions have occurred along the last 3 Ma (Cantagrel *et al*., 1984). The islands with more volcanic caves are Lanzarote, Tenerife, La Palma and El Hierro. The lava tube caves in Lanzarote are large and abundant, but the aridity of the climate and the scarce soil covering the lavas prevents the existence of the necessary humidity for the existence of a true troglobitic fauna. The islands containing more troglobites are Tenerife, La Palma and El Hierro. In Fuerteventura they are also rare because of the dry climate, but there are two species. In Gran Canaria there are few caves, but recent research points to the presence of an adapted fauna. A similar situation occurs on La Gomera, where there are no caves at all but a few hypogean species inhabit the MSS in the humid forest.

The studies on the underground fauna in the Canaries early started in 1892 when the crab *Munidopsis polymorpha* was described from the anchialine cave Jameos del Agua (Lanzarote), together with some other adapted species (Koelbel, 1892). The animal community of this cave and the neighbouring Túnel de la Atlántida has been intensively studied along the last century, and as much as 25 species adapted to this particular habitat are so far known (Oromí & Izquierdo, 1994, in press). It is remarkable the existence of *Speleonectes ondinae*, the only Remipede crustacean known from the oriental part of the Atlantic.

The first terrestrial troglobite to be described was *Collartida anophthalma*, discovered in the early 80's by catalan cavers in El Hierro (Español & Ribes, 1983). At this time was created the Grupo de Investigaciones Espeleológicas de Tenerife (GIET) from the University of La Laguna (Tenerife), which has been regularly studying the hypogean fauna with a remarkable success (Oromí & Izquierdo, 1994, in press). In the Museo de Ciencias Naturales de Tenerife also the late J.J. Hernández Pacheco was active on cave research up to his death in 1993 (Hernández Pacheco *et al*., 1995), and in La Palma island members of the G.E. Benisahare caving club also studied many caves with discoveries of many interesting hypogean species (García & Oromí, 1996; Machado, 1998).

The organization in 1992 of the 10th Int. Symposium of Biospeleology in Tenerife by the GIET team, and the 7th Int. Symposium on Vulcanospeleology in 1994 in La Palma by Junonia and GIET groups, show the intense activity and the relevance of their studies. Between 1999 and 2001 this team from La Laguna carried out a research LIFE-Nature project on the cave fauna from the Canary Islands and its conservation.

Table III. The islands of the Canary archipelago set from west to east according to their geographic position. Ages in million years. Presence of caves apparently suitable to hold terrestrial adapted fauna. Number of troglobitic species.

	Hierro	LaPalma	Gomera	Tenerife	G.Canaria	Fuerteventura	Lanzarote
age	0.8	2	12	12	14	21	15.5
caves	+	+	-	+	+	+	-
troglobites	19	31	8	64	4	2	-

The hypogean fauna from the Canaries is the richest in Macaronesia, 132 of terrestrial troglobitic and 57 aquatic stygobiont (either freshwater or anchialine) species having been found so far. This is also the fauna with the most advanced degree of troglomorphism among these Atlantic islands, including some species such as the thread-legged bug *Collartida anophthalma* (Hemiptera, Reduviidae) and the rove-beetle *Domene vulcanica* (Coleoptera, Staphylinidae) easily comparable to the most troglomorphic species from the Palaearctic. The most adapted fauna to the underground occurs in the modern terrains of Tenerife, while the hypogean species from the western islands (La Palma and El Hierro) are usually more ambimorphic with some exceptions.

Various genera having undergone radiative evolution on the Canaries are also represented in the underground fauna, like the spiders *Dysdera* (9 spp.) and *Spermophora* (5 spp.). In other genera such as the cockroaches *Loboptera* (Blattaria), the planthoppers *Meenoplus* (Hemiptera) and the beetles Domene and *Wolltinerfia* (Coleoptera) this radiation has originated only troglobitic species(see Table IV). There are also hypogean species with no relatives on the surface, neither belonging to the same nor to close genera, for which they can be considered as relict species whose epigean ancestors disappeared from the islands after originating the actual hypogean forms. In this sense they are remarkable the cases of *Tyrannochthonius* and *Lagynochthonius* (Pseudoscorpiones

Table IV. Arthropod polyspecific genera with troglobites in the Canary Islands. The islands where each species occurs are indicated (H: El Hierro; P: La Palma; G: La Gomera; T: Tenerife; F: Fuerteventura).

GENERA	TOTAL NO. SPECIES	HYPOGEAN SPECIES	ISLANDS
Dysdera (Araneae)	44	9	P, T
Spermophora (Araneae)	24	5	H, P, T, F
Porcellio (Isopoda)	19	1	T
Dolichoiulus (Diplopoda)	43	4	H, P, T
Lithobius (Chilopoda)	11	4	H, P, G, T
Loboptera (Blattaria)	12	11	H, P, T
Cixius (Hemiptera)	7	6	H, P
Meenoplus (Hemiptera)	3	3	H, P
Trechus (Coleoptera)	12	2	H, P
Wolltinerfia (Coleoptera)	3	3	T
Licinopsis (Coleoptera)	6	2	H, P
Alevonota (Coleoptera)	10	6	P, T
Ocypus (Coleoptera)	7	2	T
Domene (Coleoptera)	5	5	T, G, P
Laparocerus (Coleoptera)	>100	4	H, P, G

Chthoniidae), *Maiorerus* (Opiliones Laniatores), *Collartida* (Hemiptera Reduviidae) or *Spelaeovulcania* and *Canarobius* (Coleoptera Carabidae).

One of the most interesting features of the Canary hypogean fauna is the presence of unexpected groups in such faunas of the neighbouring mainland. The cave-adapted cockroaches are unknown in the whole Palaearctic, while landhoppers (Amphipoda Talitridae), earwigs (Dermaptera) and thread-legged bugs (Hemiptera Reduviidae) have troglobitic species only in the Canary Islands and in Hawaii.

Cape Verde Islands

The Cape Verde Islands are the southernmost in Macaronesia, being located some 500 km west of Dakar, in Senegal. They form a double arch of islands, the windward islands (Ilhas de Barlavento) and the leeward islands (Ilhas de Sotavento) with ages decreasing from east to west. The easternmost islands (Sal, Boavista and Maio) are low and rather flat, with an arid climate and very few caves due to erosion in such old terrains. Santo Antão, São Vicente, São Nicolau, and Santiago are mountainous but with hardly any recent volcanism for which lava tubes are also scarce: only a few unexplored caves in Santo Antão and the clay-silted Gruta do Lázaro in Santiago are known. But in Fogo island there is an active recent volcanism (last eruption in 1995) with abundant basaltic lavas which have originated abundant caves, though never as large as those from the Azores and the Canary Islands. The relatively recent lava tube caves related to the main volcano (both in Chã das Caldeiras and on the eastern slopes of the island) are better preserved than those in older terrains of the rest of the island.

Knowledge and popularization of caves has been scarce in Cape Verde. Besides some popular believes (the so called "grutas de Lázaro" on Santiago, where supposedly this Robin Hood like bandit hid his treasures) and a few references in modern tourist guides (Schleich & Schleich, 1995), very little is published about this subject. The serious surveying of lava tubes started with the Espeleo Clube de Torres Vedras expedition in 1997, and in 1999 the GIET team from La Laguna University carried out a biological study in eight caves, discovering for the first time the presence of an adapted fauna on this archipelago. Troglobites were found only in caves above 2000 m from the sea level, being remarkable for their adaptations the planthopper *Nysia subfogo* (Hemiptera, Meenoplidae), a Cryptopidae centipede and two still undescribed spiders (Hoch *et al*., 1999).

The aridity of Cape Verde prevents most of its caves to be inhabited by troglobites, since the inner environment is highly influenced by the climate outside. Only in Fogo the Chã das Caldeiras caves covered by a thick layer of cinders are isolated and keep humidity enough for the development of true cave-dwelling species. More visits and research are needed to better know this adapted fauna, which is probably richer than the few species so far discovered.

The hypogean fauna from Macaronesia is abundant in spite of being recently studied, it is varied and has a special interest for the peculiarities due to the insular condition. All troglobitic species are endemic to reduced areas, since they are almost always exclusive to a single island. They are the result of local processes of speciation, with the appearance of troglomorphic characters in groups often unexpected in other parts of the world. But they are often threatened species as well, since the fragility of their environment is remarkable. Many caves on the Azores are silting up due to transformation of forest in pastureland, the few caves in Madeira are absolutely spoiled for tourist use without any sensibility by the owners (case of Grutas de São Vicente) or very damaged by uncontrolled visits and vandalism (case of Grutas do Cavalum); and many caves on the Canary Islands are more and more severely polluted by sewage (case of Cueva del Viento and other lava tubes in Icod de los Vinos), stupidly transformed as show-caves in spite of the presence of protected species (case of Cueva del Llano in Fuerteventura and the endangered *Maiorerus randoi*), or spoiled by uncontrolled visits. The troglobitic fauna has a low resistance to environmental changes and they can easily disappear from the caves.

References

ARECHAVALETA, M., N. ZURITA & P. OROMÍ. 2001. Nuevos datos sobre la fauna de artrópodos de las Islas Salvajes. *Revista Academia Canaria Ciencias*, 12 (3-4) (2000): 83-99.

ASHMOLE, N.P., P. OROMÍ, M.J. ASHMOLE & J.L. MARTIN. 1992. Primary faunal succession in volcanic terrain: lava and cave studies in the Canary Islands. *Biological Journal Linnean Society,* 46: 207-234.

BARR, T.C. 1968. Cave ecology and the evolution of troglobites. *Evolutionary Biology,* 2: 35-102.

BORGES, P.A.V., C. AGUIAR, J. AMARAL, I.R. AMORIM, G. ANDRÉ, A. ARRAIOL, A. BAZ, F. DINIS, H. ENGHOFF, C. GASPAR, F. ILHARCO, V. MAHNERT, C. MELO, F. PEREIRA, J.A. QUARTAU, S. RIBEIRO, J. RIBES, A.R.M. SERRANO, A.B. SOUSA, , R.Z. STRASSEN, L. VIEIRA, V. VIEIRA, A. VITORINO, & J. WUNDERLICH. 2005a. Ranking protected areas in the Azores using standardized sampling of soil epigean arthropods. *Biodiversity and Conservation*, 14: 2029-2060.

BORGES, P.A.V., R. CUNHA, R. GABRIEL, A. F. MARTINS, L. SILVA, & V. VIEIRA, (eds.). 2005b. *A list of the terrestrial fauna (Mollusca and Arthropoda) and flora (Bryophyta, Pteridophyta and Spermatophyta) from the Azores*. Direcção Regional do Ambiente and Universidade dos Açores, Horta, Angra do Heroísmo and Ponta Delgada, 318 pp.

BORGES, P.A.V. 1993. First records for the Mesocavernous Shallow Stratum (MSS) from the Azores. *Mémoires Biospéologie*, 20: 49-54.

BORGES, P.A.V. & P. OROMÍ. 1991. Cave-dwelling ground beetles of the Azores (Col., Carabidae). *Mémoires Biospéologie,* 18: 185-191.

BORGES, P.A.V. & P. OROMÍ. 1994. The Azores. In C. Juberthie & V. Decu (Eds.) *Encyclopaedia Biospeologica*, vol. I. Soc. Biospéologie, Moulis and Bucarest, 605-610.

BORGES, P.A.V. & P. OROMÍ. In press. The Azores. In C. Juberthie & V. Decu (Eds.) *Encyclopaedia Biospeologica*, vol. I. Soc. Biospéologie, Moulis and Bucarest, in press.

BORGES, P. A. V., A. R. M. SERRANO & I.R. AMORIM. 2004. New species of cave-dwelling beetles (Coleoptera: Carabidae: Trechinae) from the Azores. *Journal of Natural History*, 38: 1303-1313.

CANTAGREL, J. M., A. CENDRERO,

J.M. FUSTER, E. IBARROLA & C. JAMOND. 1984. *Bulletin Volcanology*, 47 (3): 597-609.

CARRACEDO, J.C., S.J. DAY, H. GUILLOU, E. RODRÍGUEZ BADIOLA, J.A. CANAS & F.J. PÉREZ TORRADO. 1998. Hotspot volcanism close to a passive continental margin: the Canary Islands. *Geological Magazine*, 135 (5): 591-604.

CULVER, D.C. 2001. Subterranean ecosystems. *Encyclopedia of Biodiversity*, 5: 527-540.

ERBER, D. 1990. *Thalassophilus pieperi* n.sp., a new cavernicolous carabid beetle from Madeira. *Bocagiana*, 140: 1-12.

ESPAÑOL, F. & J. RIBES. 1983. Una nueva especie troglobia de Emesinae (Heteroptera, Reduviidae) de las Islas Canarias. *Speleon*, 26/27: 57-60.

GARCÍA, R. & P. OROMÍ. 1996. *Laparocerus zarazagai* n.sp., un nuevo coleóptero microftalmo de Canarias (Curculionidae, Mylacini). *Vieraea*, 25: 153-157.

HERNÁNDEZ, J.J., P. OROMÍ, A. LAINEZ, G. ORTEGA, A.E. PEREZ, J.S. LOPEZ, A.L. MEDINA, I. IZQUIERDO, L. SALA, N. ZURITA, M. ROSALES, F. PEREZ & J.L. MARTÍN. 1995. *Catálogo espeleológico de Tenerife*. Cabildo de Tenerife, Santa Cruz de Tenerife, 168 pp.

HOCH, H., P. OROMÍ & M. ARECHAVALETA. 1999. *Nisia subfogo* n.sp., a new cave-dwelling planthopper from the Cape Verde Islands (Hemiptera: Fulgoromorpha: Meenoplidae). *Revista Academia Canaria Ciencias,* 11 (3-4): 189-199.

HOWARTH, F.G. 1973. The cavernicolous fauna of Hawaiian lava tubes, 1. Introduction. *Pacific Insects*, 15 (1): 139-151

HOWARTH, F.G. 1987. The evolution of non-relictual tropical troglobites. *International Journal Speleology*, 16: 1-16.

HOWARTH, F.G. 1996. A comparison of the ecology and evolution of cave-adapted faunas in volcanic and karstic caves. *Abstracts 7th Int. Symposium Vulcanospeleology,* Los Libros de la Frontera, Sant Climent de Llobregat, Barcelona, pp. 63-68.

IZQUIERDO, I. 1997. *Estrategias adaptativas al medio subterráneo de las especies del género Loboptera Brunner W. (Blattaria, Blattellidae) en las Islas Canarias*. Tesis Doctoral (unpublished), Universidad de la Laguna, Tenerife, 324 pp.

JUBERTHIE, C. 1983. Le milieu souterrain: étendue et composition. *Mémoires Biospéologie,* 10 : 17-65.

KOELBEL, K. 1892. Beitrage zur Kenntnis der Crustacean der Kanarischen Inseln. *Ann. K.K. Naturhistorische Hofmuseums*, 7: 1-105.

MACHADO, A. 1998. Un nuevo *Parazuphium* Jeannel anoftalmo de La Palma, Islas Canarias. *Vieraea*, 26: 163-167.

MAHNERT, V. 1990. Deux nouvelles espèces du genre *Pseudoblothrus* Beier, 1931 (Pseudoscorpiones, Syarinidae) des Açores (Portugal). *Vieraea*, 18: 167-170.

MARTÍN, J.L. 1992. *Caracterización ecológica y evolución de las comunidades subterráneas en las islas de Tenerife, El Hierro y La Palma*. Unpublished Doctoral Thesis, University of La Laguna, 342 pp.

MEDINA, A.L. & P. OROMÍ. 1990. First data on the superficial underground compartment on La Gomera (Canary Islands). *Mémoires Biospéologie*, 17: 87-91.

MEDINA, A.L. & P. OROMÍ. 1991. *Wolltinerfia anagae* n.sp., nuevo coleóptero hipogeo de la isla de Tenerife (Coleoptera, Carabidae). *Mémoires Biospéologie*, 18: 215-218.

MERRETT, P. & N.P. ASHMOLE. 1989. A new troglobitic Theridion (Araneae: Theridiidae) from the Azores. *Bulletin British arachnological Society*, 8 (2): 51-54.

MONTORIOL, J. 1973. Sobre la tipología vulcanoespeleológica. *Com. III Simp. Espeleologia, Mataró*: 268-272.

NUNES, E., D. AGUIN-POMBO, P. OROMÍ & R. CAPELA. 2003. A preliminary analysis of the cave-dwelling fauna from Machico lava tubes (Madeira island). *Abstracts II Symposium of Island Ecosystems, Funchal*.

OROMÍ, P. & P.A.V. BORGES. 1991. New Trechodinae and Trechinae from the Azores (Col., Carabidae). *Bocagiana*, 145: 1-11.

OROMÍ, P., J.J. HERNANDEZ, J.L. MARTIN & A. LAINEZ. 1985. Tubos volcánicos en Tenerife (Islas Canarias). Consideraciones sobre su distribución en la isla. *Actas II SimposiumRegional Espeleología, Burgos*: 85-93.

OROMÍ, P. & I. IZQUIERDO. 1994. Canary Islands. In C. Juberthie & V. Decu (Eds.) *Encyclopaedia Biospeologica*. Soc. Biospéologie, Moulis and Bucarest, 631-639.

OROMÍ, P. & I. IZQUIERDO. In press. Canary Islands. In C. Juberthie & V. Decu (Eds.) *Encyclopaedia Biospeologica*. Soc. Biospéologie, Moulis and Bucarest, in press.

OROMÍ, P., J.L. MARTIN, N.P. ASHMOLE & M.J. ASHMOLE. 1990. A preliminary report on the cavernicolous fauna of the Azores. *Mémoires Biospéologie*, 17: 97-105.

ROUCH, R. & D.L. DANIELOPOL. 1987. l'origine de la gaune aquatique souterraine, entre le paradigme du refuge et le modèle de la colonisation active. *Stygologia*, 3 : 345-372.

SCHLEICH, H.H. & K. SCHLEICH. 1995. *Cabo Verde Kapverdischen Inseln*. Verlag Stephanie Naglschmid, Stuttgart, 197 pp.

SERRANO, A.R.M. & P.A.V. BORGES. (1995). A new subspecies of *Trechus fulvus* Dejean, 1831 (*Trechus fulvus madeirensis* n. ssp.) from the Madeira Island with some biogeographical comments. *Proceedings of the First Symposium "Fauna and Flora of the Atlantic Islands, Boletim do Museu Municipal do Funchal*, Suppl. no. 4: 663-670.

SERRANO, A. R. M. & P. A. V. BORGES (in press). The Madeira archipelago. *In*. C. Juberthie & V. Decu (Eds.) *Encyclopaedia Biospeleologica. Tome Ia Amérique et Europe*. pp. ???. Sociétè de Biospéleologie, Moulis.

SOCORRO, J.S. & J.L. MARTIN. 1992. The Fajanita Cave (La Palma, Canary Islands): a volcanic cavity originated by partial draining of a dyke. *Proceedings 6th International Symposium Vulcanospeleology*: 177-184.

VANDEL, A. 1960. Les Isopodes terrestres de l'archipel Madérien. *Mémoires du Muséum d'Histoire naturelle*, 12 (1): 3-148.

VANDEL, A. 1964. *Biospéologie. La Biologie des Animaux Cavernicoles*. Paris, Gauthier-Villars Éditeur.

WUNDERLICH, J. 1992. Die Spinnen-Fauna der makaronesischen Inseln. Taxonomie, Ökologie, Biogeographie und Evolution. *Beiträge zur Araneologie*, 1: 1-619.

Investigation of the Discharge Mechanism of Hachijo-Fuketsu Lava Tube Cave, Hachijo-jima Island, Japan

Tsutomu Honda

Mt. Fuji Volcano-Speleological Society; tsutomuh@jx.ejnet.ne.jp

Abstract

Bingham fluid model by using inclined and flat circular tube are applied for the investigation of Hachijo-fuketsu lava tube cave in Japan. From the size and configuration of Hachijo-fuketsu lava tube cave such as tube length, inclination angle, tube diameter(height), the yield strength of the lava was obtained. The obtained yield strength was compared with other lava which formed lava caves and found to have a reasonable value as basaltic.

Introduction

Hachijo-fuketsu lava tube cave is located on Hachijo-jima island south of Tokyo in the Pacific Ocean. Hachijo-jima island, located on the volcanic front of the izu-Ogasawara(Bonin) arc, consist of two stratovolcanoes: Nisiyama and Higasi-yama. Nishiyama is a scarcely dissected cone called "Hachijo-fuji". Nishiyama began its volcanic activities about 10000 years ago. Many lateral volcanoes exist around Nishiyama. Hachijou-fuketsu is believed to have been formed by the eruption of Hachijo-nishiyama volcano 1100 years BP[1]. Its lava flow is basaltic, with silica content of 50.5%[2]. Hachijo-fuketsu is the second longest lava tube in Japan. Despite good accessibility, it is well preserved as shown in Fig. 1. As shown in Fig. 2, its upper and middle sections have moderates slopes and its lower end is flat and horizontal[3].

Modelling, Assumption and Analysis

In modelling the discharge mechanism of this type of lava tube, we used an inclined circular tube model for the sloping section of the cave as shown in Fig. 3. For the flat horizontal section in which the lava flow is driven by hydrodynamic head, we modeled a flat circular tube as shown in Fig. 4. The yield strengths obtained from these two models were similar and comparable to those of other lava flows.

Regarding the inclined circular pipe case, the discharge mechanism of lava tube caves already has been established, based on Bingham characteristics of intratubal lava flow[4,5]. A simple model of steady state isothermal laminar flow in inclined circular pipes and in flatten circular pipes were used for analyses. Comparison studies were based on the configuration of Hachijo-fuketsu.

Flow characteristics were studied as a function of parameters such as tube radius, viscosity, yield strength of lava and slope inclination. A critical condition was determined for the discharge parameters in which the yield strength plays a dominant role. Existing observational data were introduced to the critical condition. This model was applied to lava tube cave of Mt.Fuji, Mt.Etna, Mount St.Helens, Suchiooc volcano, Kilauea volcano and others. Some deduced yield strength of lava of the caves in these areas were found to be in good accordance with yield strength as estimated by other methods[6].

General flow equation of Bingham fluid can be shown as,

$$f(\tau)=(\tau-f_B)/\eta_B \quad (\tau>f_B, \text{ or } r>r_B),$$
$$f(\tau)=0 \quad (\tau<f_B, \text{ or } r<r_B).$$

Here, f_B is Bingham yield stress, η_B is Bingham viscosity, which takes specific value depending on the materials. τ is sharing stress at r.

For laminar flow model in circular tube on the slope, the equation of the distribution of flow speed u of Bingham fluid are shown as follows:

For $\tau_w = (\varrho g \sin\alpha)R/2 > f_B$,

$$u=(R-r_B)^2(\varrho g \sin\alpha)/4\eta_B \quad (r<r_B),$$
$$u=[R^2-r^2-2r_B(R-r)]\,(\varrho g \sin\alpha)/4\eta_B \quad (r>r_B).$$

For $\tau_w = (\varrho g \sin\alpha)R/2 < f_B$, u=0.

Here, α is angle of slope or inclination of tube, ϱ: density of the fluid, g: gravity acceleration, R: radius of the tube, r_B: radius of the flowing position where Bingham yield stress takes f_B.

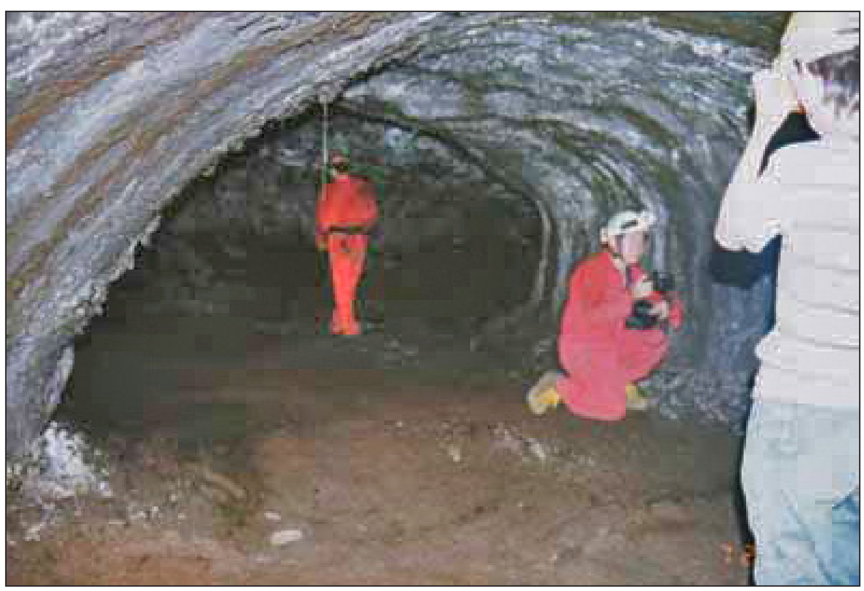


Figure 1. Inside of Hachijou-Fuketsu (photo by T. Honda).

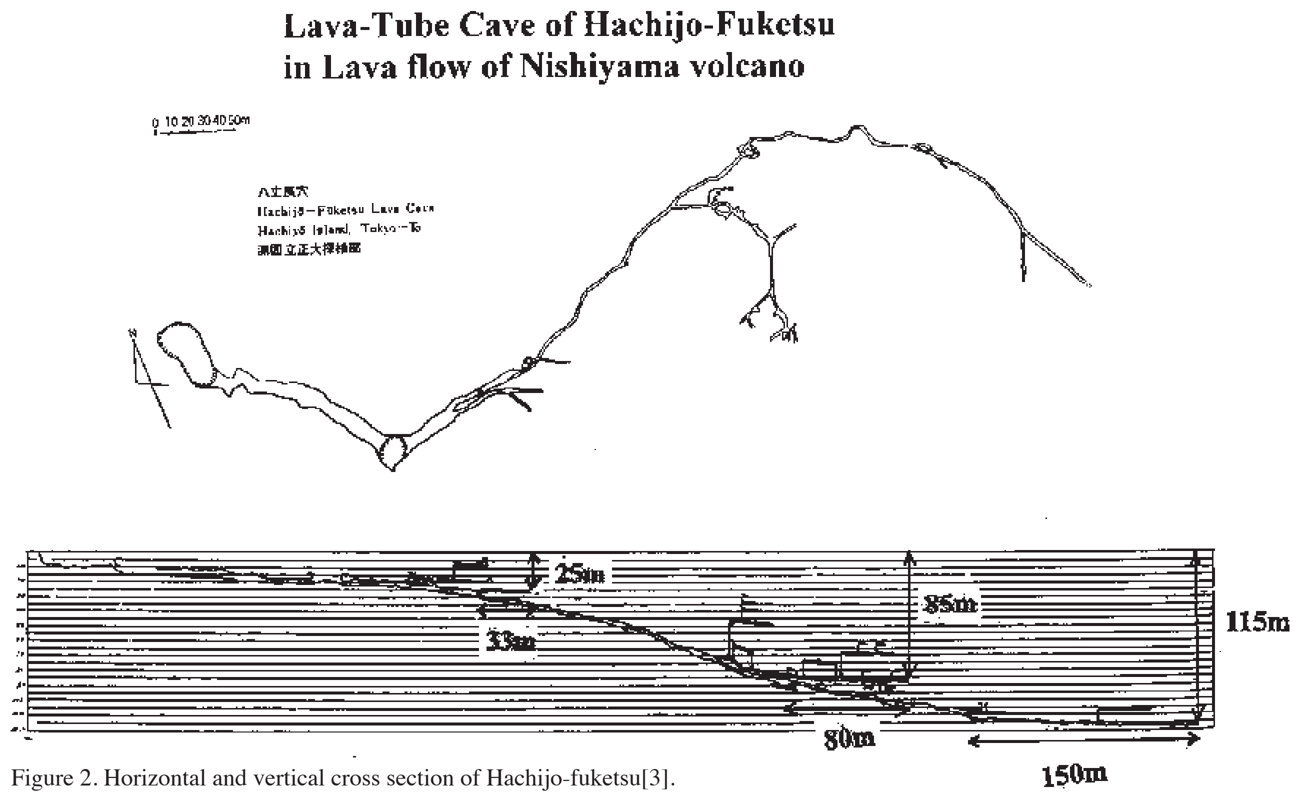


Figure 2. Horizontal and vertical cross section of Hachijo-fuketsu[3].

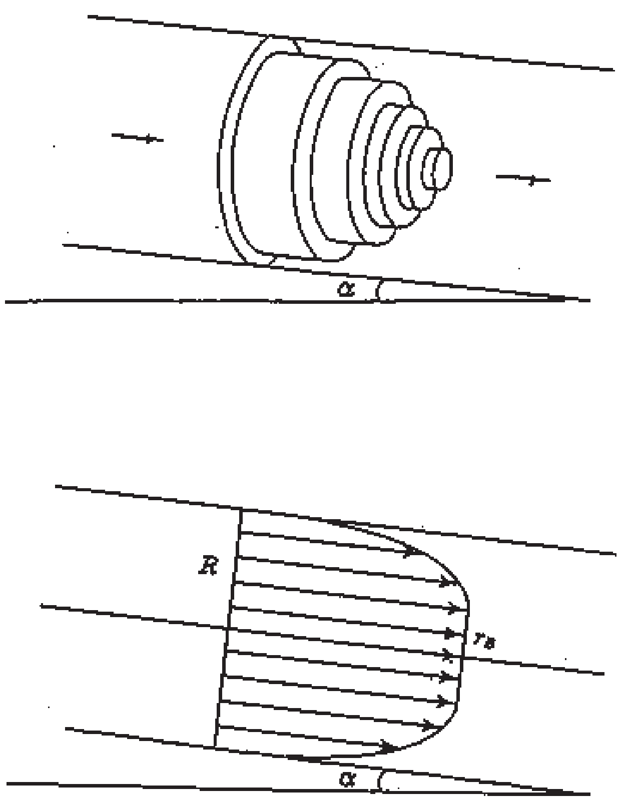


Figure 3. Bingham fluid model of inclined tube.

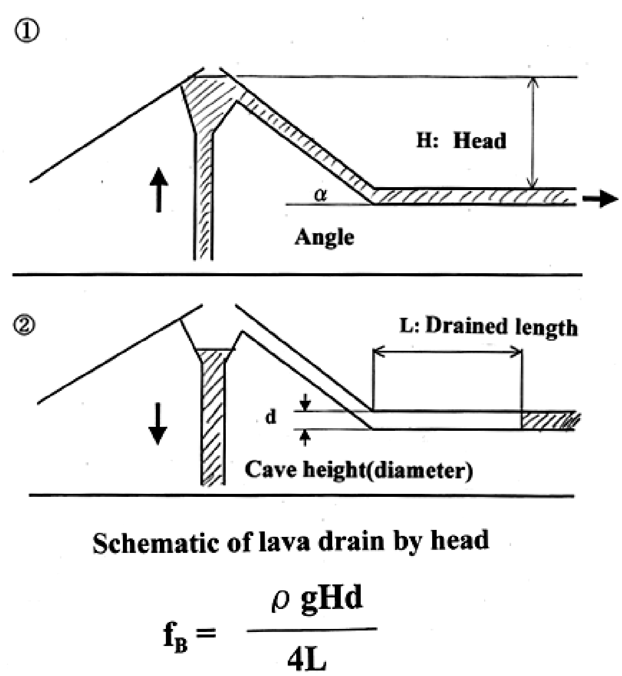


Figure 4. Simplified model of Hachijo-fuketsu.

Table 1. Relation between slope angle and height of Hachijo-fuketsu lava tube cave of sloped configuration.

Location of lava cave	Slope angle(α)	Height(2R)
Upper reaches	4.5 degree	~5m
Intermediate reaches	14 degree	~2m
(Lower reaches)	(0 degree)	(~1m)

Table 2. Relation between head and length at horizontal location of Hachijo-fuketsu lava tube cave of horizontally flat configuration for 2R=1m.

Location of lava cave	Head(H)	Length(L)
Upper reaches	25m	33m
Intermediate reaches	85m	80m
Lower reaches	115m	150m

Table 3. Yield strength obtained from the critical condition.

Name of volcano	SiO_2 fraction of lava	Obtained yield strength	References
Hachijo-nishiyama	50.4~50.5%*	$2.0 \sim 2.5 \times 10^4$ dyne/cm^2	*M.Tsukui et al (2002)[2]
Mt.Fuji	49.09~51.3%*	$2.5 \sim 5.0 \times 10^4$ dyne/cm^2[5]	*H.Tsuya(1971)[8]

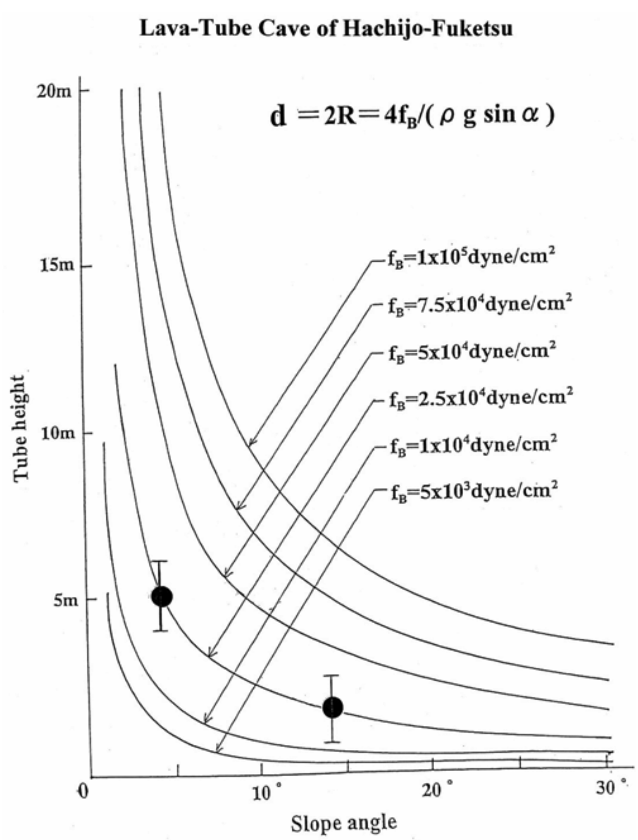


Figure 5. Relation between Slope angle and Tube height in sloped area.

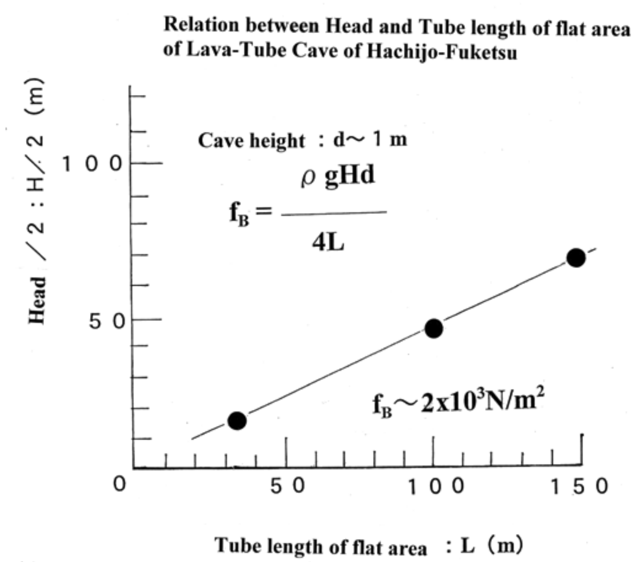


Figure 6. Relation between Head and tube length of flat area.

Here, $(\varrho g \sin\alpha)R/2=f_B$ is the limiting condition to determine if the fluid in the tube can be drained out. For given and known relation between slope angle and diameter(height) of the tube, this critical condition can give the yield strength f_B as shown in Fig. 5. This critical condition means that when the yield strength of Bingham fluid is higher than the shear stress at the wall, there is no flow of fluid, as a consequence, no drainage of fluid from the tube. From Table 1, $f_B=2.5 \times 10^4$dyne/cm^2 can be obtained for Hachijo-fuketsu.

The above model is, however, valid only for flow in inclined tubes. For perfectly flat lava tube(0 degree), the effect of inertial as driving force due to the head of the flow must be considered, if the flow is continuous together with the inclined tube[7]. Very rough relation between drained tube length and mean head of the flow can be obtained as $(\varrho g R)H/2L=f_B$ by $(\sin\alpha)$ by (H/L). From Table 2, $f_B=2 \times 10^4$dyne/cm^2 was obtained for Hachijo-jima as shown in Fig. 6.

In summary, obtained basaltic yield stress from slope angle and height of some lava caves(see Table 3)are reasonable values as compared with the yield stress obtained for Mt. Fuji[7].

Conclusions

As a results of this study, Bingham fluid model seems to be well applied for an explanation of formation process of lava tube cave. Further application of this model to other lava tube caves will be necessary and interesting for confirmation. Though the yield strength only plays a main role in this steady state model, for a future study, the analysis by using time dependent transition equation should be performed. In this case, the viscosity of lava will be involved.

References

[1] S.Sugihara and S.Shimada(1998): Stratigraphy and Eruption Ages of Deposits at the Southeast Side of Nishiyama Volcano, Hachijo Island during the Last 2500 Years. Journal of Geography 107(5) p695-p712, 1998.

[2] M.Tsukui and K.Hoshino(2000): Magmatic Differentiation of Hachijo-Nishiyama Volcano,Izu Island,Japan. Bulletin of the Volcanological Society of Japan, Vol.47, No.2, p57-p72.

[3]T.Ogawa(1980): The lava caves and lava tree-molds of Mt.Fuji. The journal of the Association of Japanese Cavers, Vol.2, No.3, August 1980.

[4]T.Honda(2000): On the formation of Subashiri-Tainai cave in Mt.Fuji. The 26th Annual Meeting of the Speleological Society of Japan, August; p.64.

[5] T.Honda(2001): Investigation on the formation mechanism of lava tube cave. The 27th Annual Meeting of the Speleological Society of Japan, August; p.11.

[6] T.Honda(2001): Formation mechanism of lava tube caves in Mt.Fuji. The 2001 Fall Meeting of the Volcanological Society of Japan, October; p.66.

[7]T.Honda(2003): Formation mechanism of lava tube caves of Hachijo-fuketsu in Hachijo-jima. The 2003 Fall Meeting of the Volcanological Society of Japan, October; p.160.

[8] H.Tsuya(1971): Geography and Geology of Mt.Fuji. Study on Mt.Fuji. puplished by Fuji-kyu,1971.

Indicators of Conservation Value of Azorean Caves Based on its Arthropod Fauna

Paulo A.V. Borges [1,2], Fernando Pereira [2], and João P. Constância [3]

[1] Universidade dos Açores, Dep. Ciências Agrárias, CITA-A, 9700-851 Angra do Heroísmo, Terceira, Açores; pborges@mail.angra.uac.pt.
[2] "Os Montanheiros", Rua da Rocha, 9700 Angra do Heroísmo, Terceira, Açores.
[3] "Amigos dos Açores", Avenida da Paz, 14, 9600-053 Pico da Pedra, S. Miguel.

Abstract

All Azorean lava-tubes and volcanic pits with fauna were evaluated for species diversity and rarity based on arthropods. To produce an unbiased multiple-criteria index (*importance value for conservation*, IV-C) incorporating arthropod species diversity based indices and indices qualifying geological and management features (e.g. diversity of geological structures, threats, accessibility, etc.), an iterative partial multiple regression analysis was performed. In addition, the complementarity method (using heuristic methods) was used for priority-cave analyses. Most hypogean endemic species have restricted distributions, occurring only in one cave. It was concluded that several well-managed protected caves per island are absolutely necessary to have a good fraction of the endemic arthropods preserved. For presence/absence data, suboptimal solutions indicate that at least 50% lava-tubes with known hypogean fauna are needed if we want that 100% of endemic arthropod species are represented in a minimum set of reserves. Based both on the uniqueness of species composition and/or high species richness and geological value of the caves, conservation efforts should be focused on the following caves: Gruta da Beira, Algar das Bocas do Fogo (S. Jorge); Montanheiros, Henrique Maciel, Soldão, Furna das Cabras II and Ribeira do Fundo (Pico); Algar do Carvão, Balcões, Agulhas and Chocolate (Terceira); Água de Pau (S. Miguel); Anelares and Parque do Capelo (Faial).

Introduction

Caves as islands are isolated entities, and, as a consequence, they lack the "rescue effect": only "source" species can be maintained in ecological and evolutionary time (Rosenweig 1995). Thus, cave species could be considered as very restricted in distribution due to their low dispersal abilities and cave isolation. However, cave-adapted species could disperse between cave systems throughout the MSS ("Milieu souterrain siperficiel" or "Mesovoid Shallow Substratum" sensu CULVER, 2001). This is the case of *Trechus terceiranus*, a troglobian species found in many caves from Terceira island (Azores) but also in the MSS (Borges 1993). Than, it is important to investigate how widespread are cavernicolous fauna to better conserve it.

The conservation of the rich Azorean cave-adapted fauna (Borges & Oromí 1994) is urgent but the resources are not enough to protect all caves. Consequently, there is a need to set priorities for conservation. The aim of this study was to examine the faunistic relative value of a set of well sampled lava tubes and volcanic pits in the Azorean islands as a management tool to improve the conservation of Azorean cave-adapted arthropod biodiversity. We examined the following hypotheses:

(a) Using an iterative partial regression analyses to produce a multiple-criteria index incorporating diversity and rarity based indices, at least one cave per island will be highly ranked. This follows the assumption that the dispersal rates of species are low and consequently there is a high level of island-restricted endemism.

(b) The restricted distribution of endemic species will imply that most caves are unique and largely irreplaceable. Consequently, most caves will be needed to ensure each species is included at least one time in a complementary based approach.

Methods

Sites and data. This study was conducted in the Azores, a volcanic Northern Atlantic archipelago that comprises nine islands, as well as several islets and seamounts distributed from Northwest to Southeast, roughly between 37° and 40° N and 24° and 31° W. The Azorean islands extend for about 615 km and are situated across the Mid-Atlantic Ridge, which separates the western group (Flores and Corvo) from the central (Faial, Pico, S. Jorge, Terceira and

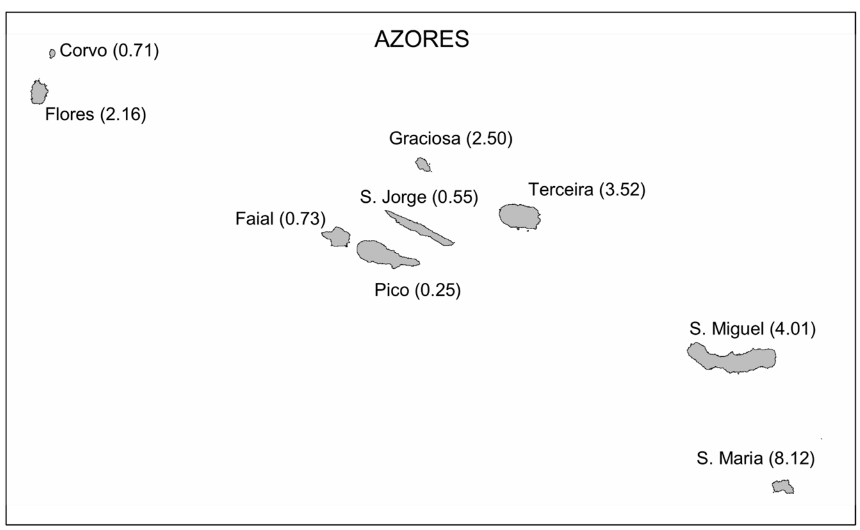


Figure 1. The nine Azorean islands with indication of their geological age based on data from Nunes (1999).

Graciosa) and the eastern (S. Miguel and S. Maria) groups (Figure 1). All these islands have a relatively recent volcanic origin, ranging from 8.12 Myr B.P. (S. Maria) to 250 000 years B.P. (Pico) (Nunes 1999).

In this study a total of 37 volcanic cavities distributed on six of the nine Azorean islands (excluding S. Maria, Flores and Corvo) were surveyed and are listed in Table 1. Some of those caves were surveyed intensively during 1988 and 1990 with two expeditions of "National Geographic" under the supervision of Pedro Oromí (Univ. de La Laguna) and Philippe Ashmole (Univ. de Edinburg) (see Oromí *et al*. 1990). However, many of the caves were also sampled by investigators of the University of the Azores and "Os Montanheiros" (see Borges & Oromí 1994). Part of the arthropod data on the presence/absence in the caves is unpublished and resulted from recent surveys performed by PB and FP. Arthropods were classified to one of three colonization categories: natives, endemics and introduced. In cases of doubt, a species was assumed to be native. Moreover, following information available in Borges & Oromí (1994) all the species were also classified as cave-adapted (troglobites) and non cave-adapted.

Data analysis. For prioritizing the 37 caves two techniques were used: i) indices for scoring conservation priorities based on comparative analyses; ii) the complementarity method.

i) Scoring method. Due to its simplicity a scoring approach was used with 9 different indices, incorporating arthropod species diversity based indices, but also indices qualifying cave geological and management features (data from IPEA database, Constância et al. 2004). (see Table 2). However, as the several indices give quite different ranking of the caves results a multiple criteria index was applied.

Multiple criteria Index: Importance Value for Conservation (IV-C). When different values or criteria are combined in a single index, it is difficult to know what the single value obtained from it represents (see Borges et al. 2005). Moreover, the different indices used to describe a cave value may not be unrelated, thus leading to the possibility of giving a higher weighting to a given feature in the construction of the complex index. To avoid possible problems of collinearity we have used partial regression analysis techniques (Legendre & Legendre 1998, see also Borges et al. 2005), which allow the separation of the variability of a given predictor that is independent (i.e., non related) from the variability of another variable, or set of variables. To do this, we applied generalised linear models (GLM) with natural logarithm link functions, in which the predictor is regressed against this variable, or group of variables, and the resulting residuals are retained as the independent term of the variable. In this particular case, we have developed iterative partial regression analyses, each time extracting the variability of a predictor that is independent of the formerly chosen indices. That is, after selecting a first index (A), which is used without any transformation in the Importance Value for Conservation (IV-C) calculations, we regressed the second one (B) against A, obtaining its residuals (rB). In successive steps, each index (e.g., C) is regressed against the formerly included (in this case, A and rB) in a multiple regression analysis, obtaining its residuals (rC). The first selected index to be used without any transformation was the total number of endemic species ($S_{trogl.}$), since cave-adapted species richness was considered to be of major importance to cave conservation. The other indices entered in the model by decreasing order of their r^2 values of a GLM regression of each index with $S_{trogl.}$. Thus, the final Importance Value for Conservation (IV-C) composite index is as follows:

$$
\begin{aligned}
\text{IV-C} = [& (S_{trogl.} / S_{trogl.}\ \text{max}) \\
& + (RS_{end.} / RS_{end.}\ \text{max}) \\
& + (\text{RShow} / \text{RShow max}) \\
& + (\text{RSrare} / \text{RSrare max}) \\
& + (\text{RGEO} / \text{RGEO max}) \\
& + (\text{RDif.Expl.} / \text{RDif.Expl. max}) \\
& + (\text{RIntegrity} / \text{RIntegrity max}) \\
& + (\text{RThreats} / \text{RThreats max}) \\
& + (\text{RAccess.} / \text{RAccess max})] / 9
\end{aligned}
$$

in which for a reserve the value of the residual variance (R) of each of the additional indices is divided by the maximum value (max) obtained within all reserves. For instance, the residuals of "Show" were obtained after the following polynomial model:

$$\text{Show} = a + b\, S_{trogl.} + c\, RS_{end.}$$

This composite index has a maximum value of 1 (see also Borges et al. 2005).

ii) Complementarity. To obtain the minimum set of caves that combined have the highest representation of species we applied the complementarity method (Williams 2001). We used a heuristic suboptimal simple-greedy reserve-selection algorithm in an Excel Spreadsheet Macro. First, the cave with the highest species richness was selected. Then, these species are ignored and the cave with the highest complement of species (that is, the most species not represented in the previous selected cave), and so on, until all species are represented at least once. This method was applied to a dataset comprising only presence-absence data for the cave-adapted arthropods, to have the minimum set of caves to represent all species at least once.

Results

We recorded 35 species of endemic arthropods in the 37 caves (see Appendix 1). From those species, 19 (54%) are

Table 1. List of the lava tubes (LT) and volcanic pits (VP) investigated.

Island	Cave	Type
Faial	Furna Ruim	VP
Faial	Gruta das Anelares	LT
Faial	Gruta do Cabeço do Canto	LT
Faial	Gruta do Parque do Capelo	LT
Graciosa	Furna do Enxofre	VP
Pico	Furna da Baliza	LT
Pico	Furna de Henrique Maciel	LT
Pico	Furna do Frei Matias	LT
Pico	Furna dos Vimes	LT
Pico	Furna Nova I	LT
Pico	Furnas das Cabras II (terra)	LT
Pico	Gruta da Agostinha	LT
Pico	Gruta da Ribeira do Fundo	LT
Pico	Gruta das Canárias	LT
Pico	Gruta das Torres	LT
Pico	Gruta do Mistério da Silveira I	LT
Pico	Gruta do Soldão	LT
Pico	Gruta dos Montanheiros	LT
S. Jorge	Algar das Bocas do Fogo	VP
S. Jorge	Gruta da Beira	LT
S. Miguel	Fenda do Pico Queimado	VP
S. Miguel	Gruta de Água de Pau	LT
S. Miguel	Gruta do Enforcado	LT
S. Miguel	Gruta do Esqueleto	LT
S. Miguel	Gruta do Pico da Cruz	LT
Terceira	Algar do Carvão	VP
Terceira	Furna de Santa Maria	LT
Terceira	Gruta da Achada	LT
Terceira	Gruta da Madre de Deus	LT
Terceira	Gruta da Malha	LT
Terceira	Gruta das Agulhas	LT
Terceira	Gruta do Caldeira	LT
Terceira	Gruta do Chocolate	LT
Terceira	Gruta do Coelho	LT
Terceira	Gruta do Natal	LT
Terceira	Gruta dos Balcões	LT
Terceira	Gruta dos Principiantes	LT

Table 2. The list of indices used to rank the caves.

Code	Index		Explanation
Strogl	**S trogobites**		The number of cave-adapted species
Send	**S endemics**		The number of endemic species
Srare	**S rare**		The number of rare species (those that occur in only one cave)
Show	**Show cave index**	0	No information available
		1	Small cave (less than de 100 x 2 m).
		2	Small and simple cave but with at least 100 m and less than 200m
		3	Size between 200 and 500m but few interesting structures
		4	Large size caves (more than 500m) and with diversity of structures
		5	Large size caves (more than 1000m) and with diversity of structures
GEO	**Geology index**	0	No information available
		1	Relevant geological structures not present
		2	Presence of very common geological structures (e.g. lava stalactites)
		3	Presence of common geological structures (e.g. benches, striated walls)
		4	Presence of rare geological structures (e.g. Secondary deposits, levees, different levels of tunnels, etc.)
		5	Presence of very rare geological structures (e.g. Gas bubbles, stalagmite, columns)
DIF.Expl.	**Difficulty of**	0	No information available
	Exploration Index	1	Lava tube or pit of difficult exploration due to difficulty of progression
		2	Lava tube or pit of difficult exploration in some parts due to difficulty of progression
		3	Cavity with some obstacles
		4	Presence of some obstacles but easy to transpose
		5	No obstacles - all people could visit the cave
Integrity	**Integrity index**	0	No information available
		1	More than 50% of the cavity destroyed
		2	some evidences of destruction (< 50% of he length)
		3	More than 90% of the lenght well preserved but presence of Human alterations or disturbance
		4	Well preserved and few signals of Human alterations or disturbance
		5	Very well preserved
Threats	**Treats index**	0	No information available
		1	The cavity has destroyed parts due to epigean land-use changes and disturbance
		2	Well known epigean Human activities are identified and could cause near-future disturbance
		3	Well known epigean Human activities are identified and could cause future disturbance
		4	Well known epigean Human activities are identified but with non potential threat to the cavity
		5	Non occurrence of Human activity or threats in the area of the cave
Acess.	**Acessibility index**	0	No information available
		1	Very difficult to access - no roads or tracks available
		2	Difficult access, far from near locality and more than 45 m walk
		3	Difficult access, far from near locality or need of special permission of the property owner
		4	Easy access, with available public transport
		5	Easy access, easy to locate, near a locality

cave-adapted species. Most hypogean endemic species have restricted distributions, occurring only in one cave (Fig. 2).

Table 3 shows that the first ten caves using the multiple criteria index (IV-C) belong to four out of the six studied islands. No caves from Graciosa and Faial were included in the top ranked list. On the other hand, Pico and Terceira have the highest number of cavities elected in the top ten cavities. The 10 top caves include both large caves (e.g. Montanheiros, Balcões, Henrique Maciel) and small caves. Three currently protected caves, also used as Show-caves, (Algar do Carvão, Torres, Furna do Enxofre), are not listed in the top 10, but Algar do Carvão (Terceira) and Torres (Pico) are 11th and 13th, respectively.

Using presence/absence data, heuristic (suboptimal) solution show that only 9 caves are needed to have all cave-adapted species represented at least once (Table 4). Moreover, five out of the six islands have at least one cave represented in the minimum complementary set of caves (Table 4).

Table 3. Ranking of the 37 caves in terms of the multiple criteria index, Importance Value for Conservation (IV-C).

Cave	Island	IV-C
Gruta dos Montanheiros	**Pico**	**0.63**
Gruta de Água de Pau	**São Miguel**	**0.62**
Gruta das Agulhas	**Terceira**	**0.58**
Gruta do Chocolate	**Terceira**	**0.56**
Algar das Bocas do Fogo	**S. Jorge**	**0.55**
Gruta dos Balcões	**Terceira**	**0.53**
Furna de Henrique Maciel	**Pico**	**0.53**
Gruta do Soldão	**Pico**	**0.51**
Furnas das Cabras II (terra)	**Pico**	**0.51**
Gruta da Ribeira do Fundo	**Pico**	**0.50**
Algar do Carvão	Terceira	0.47
Furna Nova I	Pico	0.46
Gruta das Torres	Pico	0.43
Gruta da Beira	S. Jorge	0.43
Gruta das Anelares	Faial	0.42
Gruta da Achada	Terceira	0.42
Gruta da Madre de Deus	Terceira	0.42
Furna do Frei Matias	Pico	0.42
Gruta do Pico da Cruz	São Miguel	0.42
Gruta do Coelho	Terceira	0.42
Gruta da Malha	Terceira	0.41
Furna do Enxofre	Graciosa	0.41
Gruta das Canárias	Pico	0.41
Furna de Santa Maria	Terceira	0.41
Gruta do Natal	Terceira	0.41
Gruta do Mistério da Silveira I	Pico	0.41
Furna Ruim	Faial	0.41
Gruta do Caldeira	Terceira	0.41
Gruta da Agostinha	Pico	0.39
Gruta do Enforcado	São Miguel	0.39
Gruta do Cabeço do Canto	Faial	0.38
Gruta dos Principiantes	Terceira	0.37
Furna dos Vimes	Pico	0.36
Fenda do Pico Queimado	São Miguel	0.35
Gruta do Esqueleto	São Miguel	0.35
Furna da Baliza	Pico	0.34
Gruta do Parque do Capelo	Faial	0.33

Conclusions

In this study we aimed to quantify the relative value of Azorean caves using both arthropods and cave geological features. Interestingly, data from this study shows that a regional conservation approach, which value at least one cave per island, will be required to conserve arthropod biodiversity in the Azores (see Tables 3 and 4).

Remarkably, Gruta dos Montanheiros was ranked first using two completely different selection approaches, which highlight the importance of this beautiful lava tube located in the island o Pico.

Using a single criterion may not allow us to cover all conservation goals. Therefore, based both on the uniqueness of species composition and/or high species richness and geological value of the caves (Tables 3 and 4), conservation efforts should be focused on the following caves: Gruta da Beira, Algar das Bocas do Fogo (S. Jorge); Montanheiros, Henrique Maciel, Soldão, Furna das Cabras II and Ribeira do Fundo (Pico); Algar do Carvão, Balcões, Agulhas and Chocolate (Terceira); Água de Pau (S. Miguel); Anelares and Parque do Capelo (Faial).

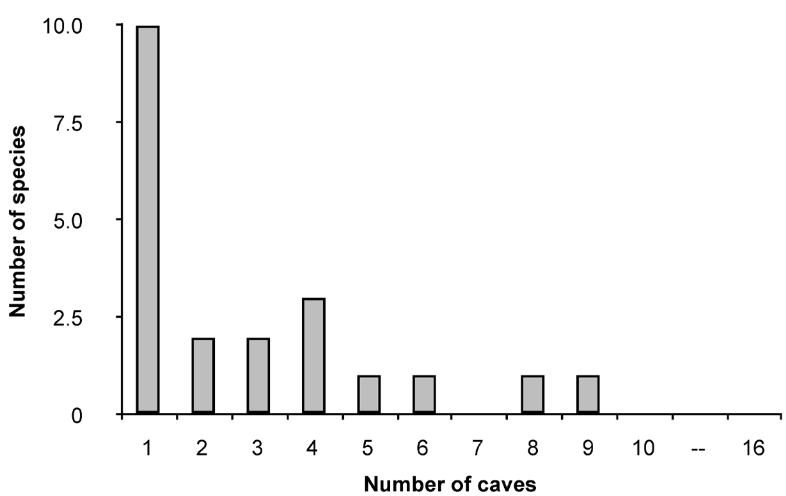


Figure 2. Frequency distribution of Azorean troglobitic species in volcanic caves.

Acknowledgements

We wish to thank to Azorean Government for supporting our trip to Pico to participate on the XInd International Symposium on Vulcanospeleology (Madalena, Pico, May 2004).

References

Borges, P.A.V. (1993). First records for the Mesocavernous Shallow Stratum (MSS) from the Azores. *Mémoires de Biospéologie*, 20: 49-54.

Borges, P.A.V., Aguiar, C., Amaral, J., Amorim, I.R., André, G., Arraiol, A.,. Baz A., Dinis, F., Enghoff, H., Gaspar, C., Ilharco, F., Mahnert, V., Melo, C., Pereira, F., Quartau, J.A., Ribeiro, S., Ribes, J., Serrano, A.R.M., Sousa, A.B., Strassen, R.Z., Vieira, L., Vieira, V., Vitorino, A. and Wunderlich, J. (2005). Ranking protected areas in the Azores using standardized sampling of soil epigean arthropods. *Biodiversity and Conservation*, 14: 2029-2060.

Borges, P.A.V. & Oromí, P. (1994). The Azores. *In*. C. Juberthie & V. Decu (Eds.) *Encyclopaedia Biospeleologica*.

Table 4. Minimum complementarity set of caves to have all troglobian species represented at least once.

Step	Cave	Island	S	S Accumulated
1	Gruta dos Montanheiros	Pico	5	5
2	Algar do Carvão	Terceira	5	10
3	Gruta da Beira	S. Jorge	2	12
4	Gruta das Agulhas	Terceira	2	14
5	Gruta das Anelares	Faial	1	15
6	Gruta do Parque do Capelo	Faial	1	16
7	Furnas das Cabras II (terra)	Pico	1	17
8	Algar das Bocas do Fogo	S. Jorge	1	18
9	Gruta de Água de Pau	S. Miguel	1	19

Tome I . pp. 605-610. Sociétè de Biospéleologie, Moulis.

Constância, J.P., Borges, P.A.V., Costa, M.P., Nunes, J.C., Barcelos, P., Pereira, F. & Braga, T. (2004). Ranking Azorean caves based on management índices. Abstract book of the XIth International Symposium on Vulcanospeleology (Pico, Açores).

Culver, D.C. (2001). Subterranean Ecosystems, in S. Levin (ed.) *Encyclopaedia of Biodiversity*, Volume 5, pp. 527-540, Academic Press.

Legendre, P. & Legendre, L. 1998. *Numerical Ecology,* Second english edition edn. Elsevier, Amsterdam.

Nunes, J.C. (1999). *A actividade vulcânica na ilha do Pico do Plistocénico Superior ao Holocénico: mecanismo eruptivo e Hazard vulcânico*. Ph.D Thesis, Universidade dos Açores, Ponta Delgada.

Oromí, P., Martin, J.L., Ashmole, N.P. & Ashmole, M.J. (1990). A preliminary report on the cavernicolous fauna of the Azores. *Mémoires de Biospéologie*, 17: 97-105.

Rosenzweig M.L. (1995). Species diversity in space and time. Cambridge University Press, Cambridge.

Whittaker, R.J. (1998). Island Biogeography – Ecology, Evolution and Conservation. Oxford University Press, Oxford.

Williams P. 2001. Complementarity. In: Levin S. (ed.), Encyclopaedia of Biodiversity, Volume 5. Academic Press, pp. 813-829.

Appendix 1. List of the species endemic species recorded in the Azorean caves. The cave-adapted species are also marked (C).

List of species	Taxonomic group	Troglobian
Calyptophthiracarus maritimus	ACARI-Oribatei	
Damaeus pomboi	ACARI-Oribatei	
Dorycranosus angustatus	ACARI-Oribatei	
Galumna rasilis	ACARI-Oribatei	
Galumna sp. (n sp.)	ACARI-Oribatei	
Hermanniella sp. 1 (n sp.)	ACARI-Oribatei	
Hermanniella sp. 2 (n.sp)	ACARI-Oribatei	
Nothrus palustris azorensis	ACARI-Oribatei	
Phthiracarus falciformis	ACARI-Oribatei	
Tritegeus (n. sp.)	ACARI-Oribatei	
Xenillus discrepans azorensis	ACARI-Oribatei	
Turinyphia cavernicola n. sp.	ARANEAE	C
Lepthyphantes acoreensis	ARANEAE	
Porrhomma n.sp.	ARANEAE	C
Rugathodes acoreensis	ARANEAE	
Rugathodes pico	ARANEAE	C
Lithobius obscurus azoreae	CHILOPODA	C
Lithobius obscurus borgei	CHILOPODA	
Thalassophilus azoricus	COLEOPTERA	C
Trechus jorgensis	COLEOPTERA	C
Trechus montanheirorum	COLEOPTERA	C
Trechus picoensis	COLEOPTERA	C
Trechus terceiranus	COLEOPTERA	C
Trechus oromii	COLEOPTERA	C
Trechus pereirai	COLEOPTERA	C
Onychiurus sp.	COLLEMBOLA	C
Pseudosinella ashmoleorum	COLLEMBOLA	C
Pseudosinella azorica	COLLEMBOLA	
Gen. sp. indeterminado	CRUSTACEA	C
Macarorchestia martini	CRUSTACEA	C
Orchestia chevreuxi	CRUSTACEA	
Cixius azopicavus	HOMOPTERA	C
Cixius cavazoricus	HOMOPTERA	C
Pseudoblothrus oromii	PSEUDOSCORPIONES	C
Pseudoblothrus vulcanus	PSEUDOSCORPIONES	C

Indicators of Conservation Value of Azorean Caves Based on its Byrophyte Flora at the Entrance

Rosalina Gabriel [1], Fernando Pereira [2], Paulo A.V. Borges [1,2], and João P. Constância [3]

[1] Universidade dos Açores, Dep. Ciências Agrárias, CITA-A, 9700-851 Angra do Heroísmo, Terceira, Açores, Portugal; rgabriel@notes.angra.uac.pt.
[2] "Os Montanheiros", Rua da Rocha, 4-8, 9700 Angra do Heroísmo, Terceira, Açores, Portugal.
[3] "Amigos dos Açores", Avenida da Paz, 14, 9600-053 Pico da Pedra, S. Miguel, Açores, Portugal.

Abstract

Cave entrances in the Azores are particularly humid habitats. These provide opportunities for the colonization of a diverse assemblage of bryophyte species. Using both published data and new field sampling, we evaluated species diversity and rarity of bryophytes at the entrance of all known Azorean lava tubes and volcanic pits with such flora. Frequent species include the liverworts: *Calypogeia arguta*, *Jubula hutchinsiae* or *Lejeunea lamacerina*, and the mosses: *Epipterygium tozeri*, *Eurhynchium praelongum*, *Fissidens serrulatus*, *Isopterygium elegans*, *Lepidopilum virens* and *Tetrastichium fontanum*. Several rare Azorean bryophyte species appear at some cave entrances (e.g. *Archidium alternifolium*; *Asterella africana*; *Plagiochila longispina*), which reinforces the importance of this habitat for the regional conservation of these plants. To produce an unbiased multiple-criteria index (*Importance Value for Conservation*, IV-C), several indices based on bryophyte diversity and rarity, and also geological and management features, were calculated for each cave, and an iterative partial multiple regression analyses was performed. Data sows that three pit caves are particularly diverse in bryophytes (Algar do Carvão, Terceira Island, Bocas do Fogo, S. Jorge and Furna do Enxofre, Graciosa). Lava tubes with a diverse troglobitic fauna also are diverse in terms of bryophyte species (e.g., Algar do Carvão, Gruta dos Montanheiros, Gruta da Agostinha, Furna do Henrique Maciel). We also evaluate the utility of several cave management indices as surrogates of bryophyte diversity in Azorean volcanic cavities.

Table 1. List of the Azorean lava tubes (LT), volcanic pits (VP) and other type (OT) of cavities investigated for bryophytes in this article.

Island	Cave number	Cave	Type
Graciosa	1	Furna do Enxofre	VP
Pico	2	Furna de Henrique Maciel	LT
Pico	3	Furna do Frei Matias	LT
Pico	4	Furna dos Vimes	LT
Pico	5	Gruta da Agostinha	LT
Pico	6	Gruta das Torres	LT
Pico	7	Gruta do Soldão	LT
Pico	8	Gruta dos Montanheiros	LT
S. Jorge	9	Algar das Bocas do Fogo	VP
S. Maria	10	Anjos	OT
S. Miguel	11	Fenda do Pico Queimado	VP
S. Miguel	12	Gruta da Batalha	LT
S. Miguel	13	Gruta do Enforcado	LT
S. Miguel	14	Gruta do Esqueleto	LT
S. Miguel	15	Gruta do Pico da Cruz	LT
S. Miguel	16	Gruta de Ponta Delgada	LT
Terceira	17	Algar do Carvão	VP
Terceira	18	Gruta do Chocolate	LT
Terceira	19	Gruta dos Balcões	LT

Introduction

The study of the Azorean bryophyte flora started with two expeditions of the "National Geographic Foundation" (1988, 1990), under the co-supervision of Pedro Oromí (Univ. de La Laguna) and Philippe Ashmole (Univ. of Edinburgh) and with the support of the speleological Azorean group "Os Montanheiros" (see Oromí et al. 1990, González-Mancebo *et al*. 1991). After those two expeditions, the University of the Azores and "Os Montanheiros" performed most of the bryophyte survey work in the Azores (e.g. Gabriel & Dias 1994, Gabriel & Bates 2005).

Bryophytes include mosses (Class Bryopsida), liverworts (Class Marchantiopsida) and hornworts (Class Anthocerotopsida), all of which are small, non-vascular, primitive plants that occupy a wide variety of habitats and substrates. Bryophytes assume an important functional role in the ecosystems where they occur, performing water interception, accumulation of water and their mineral contents, decomposition of organic matter and physical protection of soils (Longton, 1992). Many bryophyte species are used as bioindicators, and their presence is associated with atmospheric and aquatic purity (e.g. Hylander, Jonsson, & Nilsson 2002).

When air flows into a cave, it carries micro-organisms, leaves, seeds, spores, small arthropods, etc. Some will survive (mainly algae, fungi, ferns and bryophytes), modifying the bare rock. Some will form an important part of the food chain for cave dwelling organisms. In most places, the species found at the caves (either in entrances or areas above) are common species. However, these species add greatly to the diversity of the plant species at the caves and the scenic value of the rocks and rocky outcrops.

Four hundred and thirty eight bryophyte species are given to the Azores (Gabriel *et al*. 2005), but few data are available concerning their relative importance in the Azorean cave environment.

The aims of this manuscript are:

a) To evaluate species diversity and rarity of bryophytes at the entrance of the known Azorean lava tubes and volcanic pits with such flora;

b) To evaluate the utility of several cave management indices as surrogates of bryophyte diversity in Azorean volcanic cavities.

Methods

Sites and data. All main literature for the Azorean cave bryophytes was surveyed, and data was updated using the Herbarium of the University of the Azores

(AZU). Besides, during the summer of the year 2000, 18 Azorean caves were prospected for bryophytes by FP, searching the main substrata available: rock and soil. Only part of this data was identified. However, the quality of the data only allowed to perform statistical analysis for the 19 caves listed on Table 1.

Data analysis. For prioritizing the 19 caves we used a multiple criteria index: Importance Value for Conservation (IV-C) (based on Borges et al. 2005). The multiple criteria index was built using 9 different indices (see Table 2), based on the diversity and rarity of bryophytes, but also on geological and management features of the caves (data from IPEA database, Constância et al. 2004). We also used the total number of cave-adapted arthropods in caves based on information obtained from Borges et al. (2007, this volume).

To avoid problems of collinearity we have used partial regression analysis techniques (Legendre & Legendre 1998, see also Borges et al. 2005), which allow the separation of the variability of a given predictor that is independent (i.e., non related) from the variability of another variable, or set of variables. To do this, we applied generalised linear models (GLM) with natural logarithm link functions, in which the predictor is regressed against this variable, or group of variables, and the resulting residuals are retained as the independent term of the variable. In this particular case, we have developed iterative partial regression analyses, each time extracting the variability of a predictor that is independent of the formerly chosen indices. The first selected index to be used without any transformation was the total number of bryophyte species ($S_{Bryo.}$), since total species richness was considered to be of major importance to cave conservation. The other indices entered in the model by decreasing order of their r^2 values of a GLM regression of each index with $S_{Bryo.}$. Thus, the final Importance Value for Conservation (IV-C) composite index is as follows:

$$\begin{aligned}\text{IV-C} = [&(S_{Bryo} / S_{Bryo}\ \max)\\ &+ (R\_S_{ECCB} / R\_{}_{ECCB}\ \max)\\ &+ (R\_SBryo_{end} / R\_SBryo_{end}\ \max)\\ &+ (R\_S_{trogl} / R\_S_{trogl}\ \max)\\ &+ (R\_Show / R\_Show\ \max)\\ &+ (R\_GEO / R\_GEO\ \max)\\ &+ (R\_Integrity / R\_Integrity\ \max)\\ &+ (R\_Threats / R\_Threats\ \max)\\ &+ (R\_Access / R\_Access\ \max)] / 9\end{aligned}$$

in which for a cave, the value of the residual variance (R) of each of the additional indices is divided by the maximum value (max) obtained within all caves. For instance, the residuals of "$SBryo_{end}$" were obtained after the following polynomial model:

$$SBryo_{end} = a + b\, S_{Bryo} + c\, R\, S_{ECCB}$$

in which "a" is the value of the intercept, "b" is the value of the slope of the first variable and "c" is the value of the slope of the second variable.

This composite index has a maximum value of 1 (see also Borges et al. 2005).

Results and discussion

The majority of bryophytes found at the cave entrances may be found elsewhere in the Azorean islands, and there are no known exclusive cave species. However it is remarkable that 151 species out of the 438 Azorean bryophytes (34.5%) have been recorded for this habitat. For an updated list of bryophytes present at the Azorean caves see Pereira et al. (2006, in press). Among the most frequently recorded moss species are: *Eurhynchium praelongum*, *Fissidens bryoides s. l.*, *F. serrulatus*, *Tetrastichium fontanum* and *T. virens* while among the most recorded liverworts there may be found *Calypogeia arguta*, *Jubula hutchinsiae* ssp. *hutchinsiae*, and

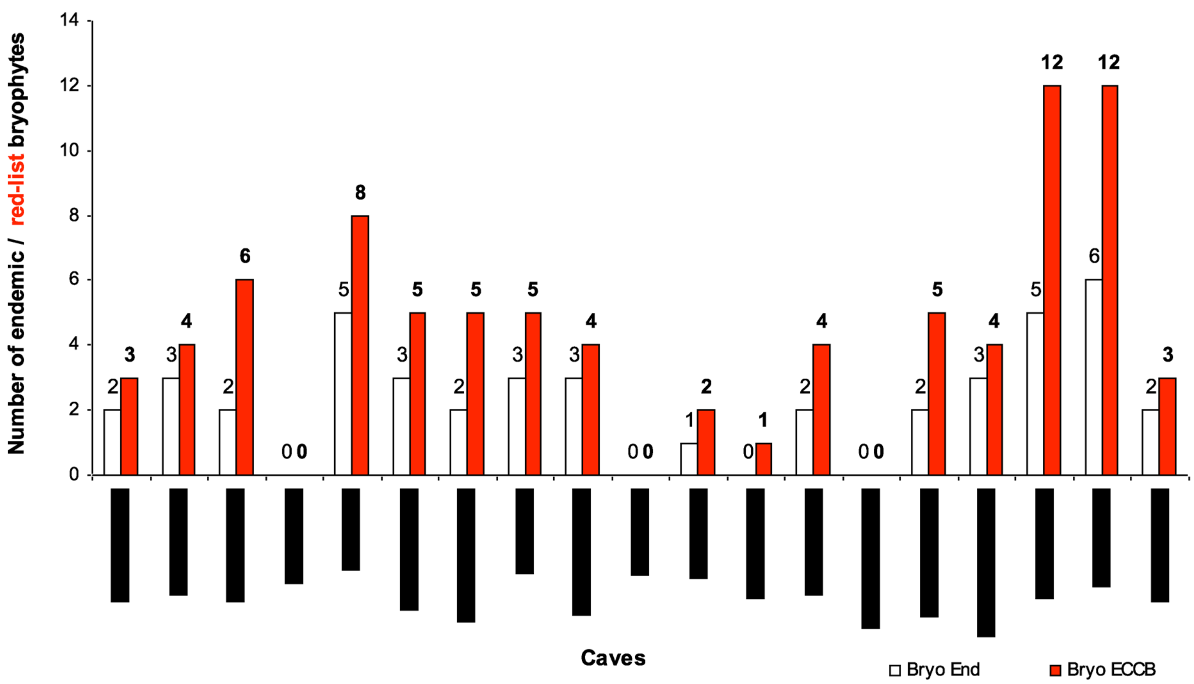


Figure 1. Number of endemic (Azores, Macaronesia) or red-listed (ECCB, 1995) bryophyte species present at the entrances of the studied Azorean caves.

Table 2. Explanation of the list of indices used to rank the Azorean caves.

Code	Index		Explanation
SBryo	S bryophytes		The number of bryophyte species
SECCB	S ECCB		The number of rare bryophyte species based on ECCB, 1995
SBryo.end	S endemic bryophytes		The number of endemic bryophyte species from the Azores and Macaronesia
Strogl	S troglobites		The number of cave-adapted arthropod species
Show	Show cave index	0	No information available
		1	Small cave (less than de 100 x 2 m).
		2	Small and simple cave, at least with 100 m but less than 200m
		3	Size between 200 and 500 m but few interesting structures
		4	Large size cave (more than 500 m) and with a wide diversity of structures
		5	Large size cave (more than 1000 m) and with a wide diversity of structures
GEO	Geology index	0	No information available
		1	Relevant geological structures not present
		2	Presence of very common geological structures (e.g. lava stalactites)
		3	Presence of common geological structures (e.g. benches, striated walls)
		4	Presence of rare geological structures (e.g. secondary deposits, levees, different levels of tunnels, etc.)
		5	Presence of very rare geological structures (e.g. gas bubbles, stalagmite, columns)
Integrity	Integrity index	0	No information available
		1	More than 50% of the cavity destroyed
		2	Some evidence of destruction (< 50% of the length)
		3	More than 90% of the length well preserved but evidence of human alterations or disturbance
		4	Well preserved and few signals of Human alterations or disturbance
		5	Very well preserved
Threats	Threats index	0	No information available
		1	The cavity has destroyed parts due to epigean land-use changes and disturbance
		2	Well known epigean human activities are identified and could cause near-future disturbance
		3	Well known epigean human activities are identified and could cause future disturbance
		4	Well known epigean human activities are identified but with no potential threat to the cavity
		5	Non occurrence of human activity or threats in the area of the cave
Access.	Accessibility index	0	No information available
		1	Very difficult to access, without roads or tracks available
		2	Difficult access, far from near locality and more than 45 min walk
		3	Difficult access, far from near locality or need of special permission of the property owner
		4	Easy access, with available public transport
		5	Easy access, easy to locate, near a locality

Lejeunea lamacerina.

Besides, there are noteworthy occurrences on the Azorean Caves, of either endemic (Azores and Macaronesia) or European red-listed species, and some caves harbour more than 10 classified species according to the ECCB (1995) (see Figure 1). Caves such as "Gruta do Frei Matias" and "Gruta das Torres" (both in Pico) or "Algar do Carvão" and "Gruta dos Balcões" (both in Terceira) contain more than five red-listed bryophytes and only three of the 19 analysed caves ("Furna dos Vimes", "Gruta dos Anjos" e "Gruta de Ponta Delgada") have no classified bryophyte species (see Figure 1, Pereira et al. 2006, in press).

Among the most interesting species that may be found at cave entrances, are the bryophytes *Aphanolejeunea teotonii*, *Asterella africana*, Cephalozia crassifolia, *Echinodium renauldii*, *Plagiochila longispina* and *Radula wichurae*. These European vulnerable species occur at cave entrances at different islands, and for instance *Asterella africana* has not been referred outside that habitat in the Azores, recently. The endemic moss *Echinodium renauldii*, an epilithic species, which is generally found at lower altitudes (below 500 m), has also been referred for at least three caves ("Furna do Henrique Maciel", "Furna da Agostinha" e "Gruta das Torres" – all in Pico Island). Thus, caves may serve as a refuge to some species that otherwise would not be present at that particular altitude and these data highlight the importance of the habitat for the regional conservation of these plants.

A statistical significant relationship was observed between the diversity of cave-adapted arthropods and the species richness of bryophytes in the Azorean cave entrances ($r = 0.59$; $p = 0.008$) (Figure 2). In spite of the fact that the relationship is not perfect, there are some caves that are diverse both in troglobitic fauna and bryophyte species (e.g., Algar do Carvão, Gruta dos Montanheiros, Gruta da Agostinha, Furna do Henrique Maciel). Bryophyte richness could, with caution, be used as an indicator of the diverse cave adapted arthropods.

The ranking obtained with the multiple criteria index, Importance Value for Conservation (IV-C) for the 19 caves may be observed in Table 3. Eight caves, have IV-C values equal or above 0.50 (maximum value is 1.00). All of these caves are located in Pico, Terceira and Graciosa Islands.

Considering the present state of speleological and biospeleological knowledge of the Azores, none of the most interesting caves are to be found on S. Miguel Island, the largest and most populated island of the Azorean archipelago. Cave entrances in S. Miguel are highly disturbed, mainly due to land use changes in the surrounding areas.

Also in view of the calculated index, none of the top five caves are show-caves, at the present. This indicates that there are other caves with potential for tourism exploitation, and that their biological value should be highlighted. Care should be taken when developing show-cave projects, in order to preserve their biological and geological features.

Conclusions

Unlike other cave entrances, Azorean caves bear an exquisite and wonderful bryophyte flora. Many species commonly found in this habitat are endemic or red-listed and their populations are important to the survival of the species in the Azores. These species add greatly to diversity of the plant species at the caves and the scenic value of the rocks and rocky outcrops.

In the Azores, the importance of cave entrances to bryophytes is twofold: i) since these are particularly humid, sheltered habitats, they support a diverse assemblage of bryophyte species; in fact circa 35% of the Azorean bryophytes is referred to this habitat and ii) species, either endemic or referred in the European Red List (ECCB 1995) due to their vulnerability or rarity (19 species).

Bryophyte diversity was shown to be a surrogate of cave adapted arthropods, indicating that well preserved caves have a global importance for both the organisms living inside the cave system and to those adapted to cave entrances, hence bryophytes.

In view of the calculated conservation index (IV-C), none of the top five caves are show-caves, at the present. This indicates that there are other caves with potential for tourism exploitation, and that their biological value should be highlighted. Care should be taken when developing show-cave projects, in order to preserve their biological and geological features.

Table 3. Ranking of the 19 caves using the multiple criteria index, Importance Value for Conservation (IV-C).

Cave	Island	IV-C
Furna de Henrique Maciel	Pico	0.57
Gruta dos Balcões	Terceira	0.55
Gruta dos Montanheiros	Pico	0.54
Gruta da Agostinha	Pico	0.53
Gruta do Chocolate	Terceira	0.52
Gruta das Torres	Pico	0.51
Gruta do Soldão	Pico	0.50
Furna do Enxofre	Graciosa	0.50
Algar do Carvão	Terceira	0.46
Gruta do Pico da Cruz	S. Miguel	0.45
Algar das Bocas do Fogo	S. Jorge	0.44
Furna do Frei Matias	Pico	0.39
Gruta da Batalha	S. Miguel	0.38
Gruta de Ponta Delgada	S. Miguel	0.36
Gruta do Esqueleto	S. Miguel	0.36
Furna dos Vimes	Pico	0.32
Fenda do Pico Queimado	S. Miguel	0.31
Gruta do Enforcado	S. Miguel	0.30
Gruta dos Anjos	S. Maria	0.20

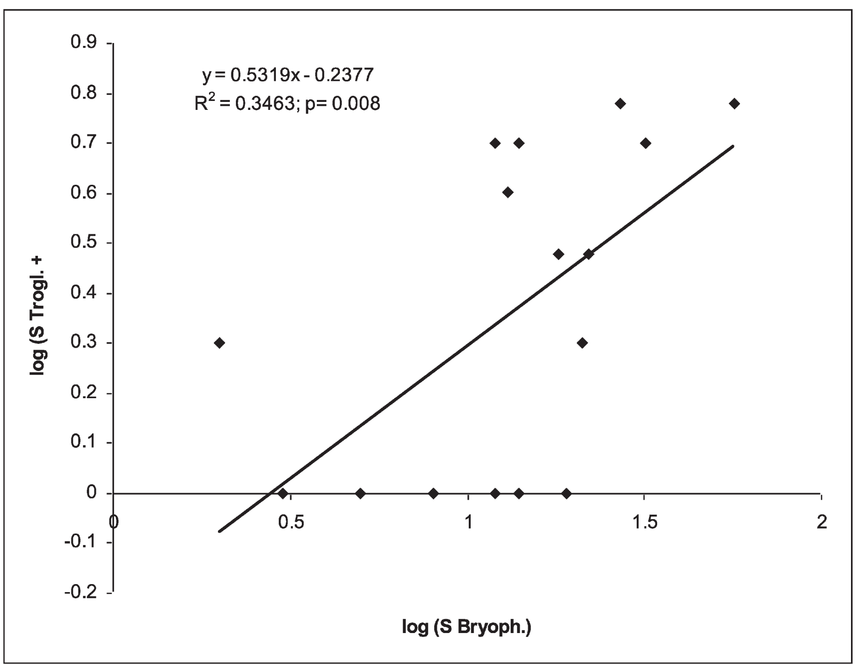


Figure 2. Relationship verified between the logarithm of the number of troglobian arthropod species (S Trogl) and the logarithm of the number of bryophyte species (S Bryoph) found at the entrance of caves.

Acknowledgements

We wish to thank to Azorean Government for supporting our trip to Pico Island to participate on the XI[nd] International Symposium on Vulcanospeleology (Madalena, Pico, Açores, Portugal. May 2004).

We wish to acknowledge "Centro de Investigação e Tecnologia Agrária dos Açores (CITAa/UAçores)" for supporting our fieldwork in Pico Island (2000).

References

Borges, P.A.V., Aguiar, C., Amaral, J., Amorim, I.R., André, G., Arraiol, A.,. Baz A., Dinis, F., Enghoff, H., Gaspar, C., Ilharco, F., Mahnert, V., Melo, C., Pereira, F., Quartau, J.A., Ribeiro, S., Ribes, J., Serrano, A.R.M., Sousa, A.B., Strassen, R.Z., Vieira, L., Vieira, V., Vitorino, A. and Wunderlich, J. (2005). Ranking protected areas in the Azores using standardized sampling of soil epigean arthropods. *Biodiversity and Conservation*, 14: 2029-2060.

Borges, P.A.V., Pereira, F. & Constância, J.P. (2007). Indicators of conservation value of Azorean caves based on its arthropod fauna. Proceedings of the Xth, XIth and XIIth International Symposium on Vulcanospeleology.

Constância, J.P., Borges, P.A.V., Costa, M.P., Nunes, J.C., Barcelos, P., Pereira, F. & Braga, T. (2004). Ranking Azorean caves based on management índices. Abstract book of the XIth International Symposium on Vulcanospeleology (Pico, Açores).

ECCB (1995). *Red data book of European bryophytes*. European Committee for the Conservation of Bryophytes. Trondheim.

Gabriel, R. & Bates, J.W. (2005) Bryophyte community composition and habitat specificity in the natural forests of Terceira, Azores. *Plant Ecology*, 177, 125-144.

Gabriel, R. & Dias, E. (1994). First approach to the study of the Algar do Carvão flora (Terceira, Azores). in: Actas do 3º Congresso Nacional de Espeleologia e do 1º Encontro Internacional de Vulcanoespeleologia das Ilhas Atlânticas (30 de Setembro a 4 de Outubro de 1992), pp. 206-213. Angra do Heroísmo.

Gabriel, R., Sjögren, E., Schumacker, R., Sérgio, C., Frahm, J.-P. & Sousa, E. (2005) List of bryophytes In *A list of the terrestrial fauna (Mollusca and Arthropoda) and flora (Bryophyta, Pteridophyta and Spermatophyta) from the Azores* (eds P.A.V. Borges, R. Cunha, R. Gabriel, A.M.F. Martins, L. Silva, & V. Vieira). pp. ???, Direcção Regional de Ambiente e do Mar dos Açores and Universidade dos Açores, Horta, Angra do Heroísmo and Ponta Delgada.

González-Mancebo, J.M., Losada-Lima, A. & Hérnandez-Garcia, C.D. (1991). A contribution to the floristic knwoledge of caves on the Azores. *Mémoires de Biospéologie*, 18: 219-226.

Hylander, K., Jonsson, B. G. & Nilsson, C. 2002. Evaluting buffer strips along boreal streams using bryophytes as indicators. *Ecological Applications*, 12 (3): 797-806.

Legendre, P. & Legendre, L. 1998. *Numerical Ecology*, Second English edition. Elsevier, Amsterdam.

Longton, R. E. 1992. 2. The role of bryophytes and lichens in terrestrial ecosystems. in: Bates, J. & Farmer, A. (eds.) 1992. *Bryophytes and Lichens in a changing environment*. pp.: 32-76. Claredon Press. Oxford.

Oromí, P., Martin, J.L., Ashmole, N.P. & Ashmole, M.J. (1990). A preliminary report on the cavernicolous fauna of the Azores. *Mémoires de Biospéologie*, 17: 97-105.

Pereira, F, Borges, P A V, Costa, M P, Constância, J P, Nunes, J C, Barcelos, P Braga, T & Gabriel, R (2006, in press). Catálogo das cavidades vulcânicas dos Açores (grutas lávicas, algares e grutas de erosão marinha). Direcção Regional do Ambiente, Horta, 286 pp.

The Nature of Bacterial Communities in Four Windows Cave, El Malpais National Monument, New Mexico, USA

Diana E. Northup[1], Cynthia A. Connolly[1], Amanda Trent[1], Vickie M. Peck[1], Michael N. Spilde[2], W. Calvin Welbourn[3], and Donald O. Natvig[1]

[1] Biology Department, University of New Mexico.
[2] Institute of Meteoritics, University of New Mexico.
[3] The Florida Department of Agriculture and Consumer Services, Division of Plant Industry.

Abstract

One of the striking features of some lava tube caves is the extensive bacterial mats (a.k.a. lava wall slime) that cover the walls. Despite their prominence little is known about the nature of these bacterial communities. We have investigated the bacterial mats on the walls of Four Windows Cave, a lava tube in El Malpais National Monument, New Mexico, USA. These bacterial mats in the twilight zone adjacent to algal mats, and in the dark zone of the lava tube, cover from 25–75% of the wall. Their macroscopic and microscopic visual appearance suggests that these bacterial mats are composed of actinomycetes, bacteria that commonly inhabit caves. Vacuuming of bacterial mats and the adjacent algae revealed collembola and mites on the algae but no invertebrates were recovered from the bacterial mats. DNA was extracted from wall rock communities, purified, the 16S rRNA gene was amplified using PCR, cloned, and approximately 1000 bases were sequenced from thirty clones. Comparison of Four Windows bacterial sequences with the Ribosomal Database II revealed that some were most closely related to actinomycetes. Others grouped with members of the *Chloroflexi*, the *Verrucomicrobia*, and the *Betaproteobacteria*. Closest relatives of two of the clones were from Mammoth Cave samples. The latter appear to be novel bacterial species. The ability of bacteria cultured from these mats to withstand the effects of ultraviolet (UV) radiation revealed the microbes isolated from the lava tube were much more UV sensitive than the microbes isolated from the surface. However, all of the microbes tested displayed at least slight sensitivity to UV radiation. Based on the results, the bacterial colonies currently inhabiting the Four-Windows lava tube appear to be at least somewhat cave-adapted. Our studies of the actinomycete communities in Four Windows Cave reveal a diverse community of bacteria that appear to be unpalatable to invertebrates.

Introduction

A revolution in microbiology occurred with the introduction of 16S ribosomal methodology to discover the great diversity and distribution of life through genetic sequences. Standard culturing techniques used to cultivate microorganisms from caves, have met with limited success (Amann et al. 1995; Hugenholtz et al. 1998). Culture-independent molecular phylogenetic techniques allow us to reveal the diversity present in many varied environments (Pace 1997). Many novel prokaryotic species have been detected as a result of this new technology. Bacteria have been found in some of the most extreme areas including deep-sea thermal vents, within rock cores, and in caves. These microorganisms are important participants in the precipitation and dissolution of minerals, in caves (Northup and Lavoie 2001) and on the surface (Ehrlich 1999). However, we have barely begun to characterize the microbial diversity of caves and the roles of microorganisms in the subsurface.

Humid lava tube caves contain highly visible mats of bacteria and other microorganisms , nicknamed "lava wall slime," (Figure 1), but they have received even less attention than limestone caves (Northup and Welbourn 1997). These microbial mats do contain fungi and aerobic bacteria and serve as a habitat for arthropods that feed on nutrients captured in the slimes, e.g. springtails (Insecta: Collembola), mites (Arachnida: Acari), fly larvae (Insecta: Diptera), earthworms (Oligochaeta), a water treader (Insecta: Hemiptera), and carabid beetles (Insecta: Coleoptera) (Howarth, 1973, 1981). Stone and Howarth (Howarth, 1981) also have suggested that the slimes are important sites of nutrient recycling (e.g. nitrogen).

Ashmole et al. (1992) have found slimes present in humid caves in the Canary and Azore Islands, but never in dry caves. In the Northwestern USA (Washington) lava tube slimes consist of different species of bacteria, including actinomycetes in the genus *Streptomyces* (Staley and Crawford 1975). Staley and Crawford (1975) observed two main types: a white slime that is occurs alone, is hydrophobic, and occurs in warmer areas (>6 degrees C), and an orange slime that underlies the white slime and is seen in colder areas. Associated with the slime, Staley and Crawford (1975) found fly larvae (Diptera: Mycetophilidae), overwintering harvestmen (Arachnida: Opiliones), a troglobitic harvestman, *Speleonychia* sp. (Opilionides: Travuniidae), and a millipede (Diplopoda: Polyzoniidae).

We remain almost completely ignorant of the nature of these bacterial mats due to the lack of culture-independent studies. Thus, this study was undertaken using culture-independent methods to characterize the nature of the lava wall slime in Four Windows Cave. We also investigated the sensitivity of cultured isolates to ultraviolet (UV) radiation to determine whether the bacteria of lava tubes have lost resistance to UV radiation in comparison to their surface bacteria. Previous studies of the sensitivity of deep subsurface bacteria found no differences in sensitivity between deep subsurface and surface bacteria (Arrage et al. 1993a,1993b). Most cave animals lose non-essential traits as they adapt to the subsurface environment, but this has never been investigated in bacteria inhabiting caves.

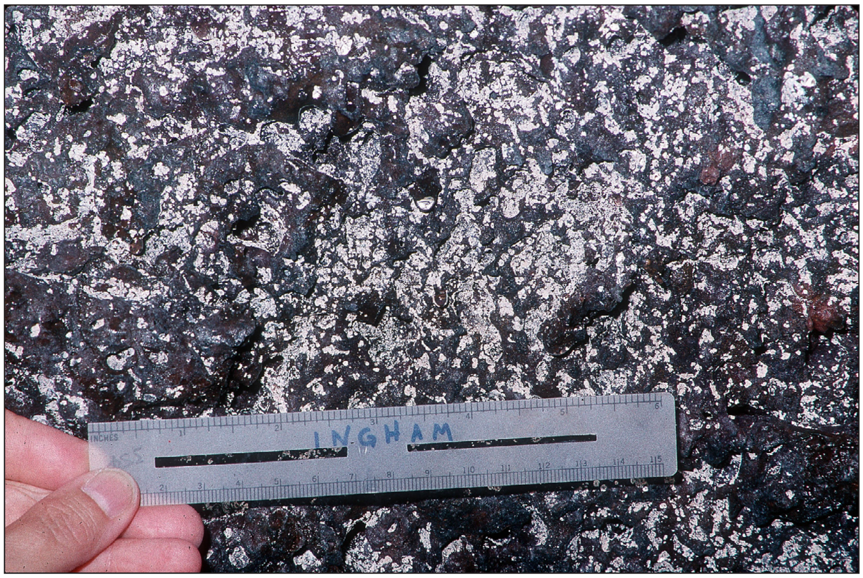


Figure 1. Close-up view of the bacterial colonies on the walls of Four Windows Cave. Photo by Kenneth Ingham.

During a previous investigation of the arthropod community inhabiting Four Windows Cave (Northup and Welbourn 1997), we noted the presence of mites on the algal mats on the walls of the twilight zone, but not on the bacterial mats. A more systematic vacuuming experiment was undertaken to document this anecdotal observation that might suggest that the bacterial mats are distasteful or toxic to invertebrates.

These preliminary studies of the microbial mats present in one lava tube, Four Windows Cave, will allow us to more fully understand the lava tube ecosystem and will lay the groundwork for future studies in other lava tubes.

Experimental Methods

Cave Description

Four Windows Cave, located in El Malpais National Monument, New Mexico, USA is a moderately long lava tube with four skylights that give the cave its name. An extensive invertebrate community exists in the moss garden growing under the skylights. These skylights provide light for the moss garden directly below them and the algal communities on the walls of the twilight zone, both of which support moderately diverse invertebrate communities. Four Windows is cold, ranging from -2 to +2° C with ice stalagmites form in the winter. During the rainy season (July and August), moisture seeps into the cave through cracks and supplies moisture and organic matter for the microbial and invertebrate communities.

The walls and ceiling of Four Windows Cave have extensive deposits of bacterial mats. The distribution of bacterial colonies is patchy (Figure 1), but appears to be most dense in areas of lower light and possibly where moisture enters the cave through cracks. Mat coverage ranges from isolated, individual colonies to dense mats several mm thick (Lavoie and Northup 1994). The visible color of both individual and massed colonies was predominately whitish-tan, but a few gold colored colonies and veins of colonies occur. Observation shows that colonies are hydrophobic, with water or secreted fluids beading up on the surface. This water often reflects light, causing the colonies to appear reflective. Senger and Crawford (1984) associate the hydrophobicity to the presence of spores produced by the bacteria.

Sample Collection for DNA Extraction and Invertebrate Study

Small samples of wall rock covered with bacterial slime were collected from Four Windows Cave in July, 1996 under a National Park Service collecting permit. These samples were chipped from the parent wall rock with an ethanol-dipped, flame-sterilized rock hammer. The samples were then caught in a sterile container, sealed, and placed on dry ice for transport. Upon arriving at the lab, the samples were stored in a -80° C freezer.

Both algae and bacteria were vacuumed with an Insect Vac (BioQuip) to examine the invertebrate communities that inhabit each environment. First, the collection tube of the vacuum was cleaned with ethanol and a sterile filter placed inside. Bacteria patches were vacuumed for one minute, the collection chamber was washed thoroughly with ethanol, and its contents repeatedly transferred to an appropriately labeled, sterile tube. The vacuum filter also was caught in this container and sealed. This procedure was repeated on an algae patch adjacent to the bacterial mats. Bacterial and algal washes were analyzed separately microscopically.

Scanning Electron Microscopy

Samples of the lava tube wall rock covered with microbial colonies were

Figure 2. Cal Welbourn sampling invertebrates from algal colonies on the wall of Four Windows Cave. Photo by Kenneth Ingham.

examined on a JEOL 5800 scanning electron microscope (SEM) equipped with an Oxford (Link) Isis energy dispersive x-ray analyzer (EDX). Rock samples with adherent bacterial colonies were mounted directly on an SEM sample stub while in the cave and then coated by evaporation with Au-Pd in the lab prior to imaging.

Molecular Characterization of the Bacterial Community

Extraction of DNA. Nucleic acids were extracted and purified from two 0.5 gm aliquots of sample by using the bead-mill homogenization procedure described by Kuske et al. (1997). Following bead-mill disruption and centrifugation, the supernatant was transferred and the bead pellet was washed once with 1 ml of TE buffer (10 mM Tris [pH 8.0], 1 mM EDTA), re-homogenized for 5 sec, and centrifuged again. This supernatant was pooled with the original supernatant. Nucleic acids were precipitated from the solution by using 0.1 volume of 3 M sodium acetate (pH 5.2) and 2.5 volumes of ethanol, incubated on ice, and centrifuged for 30 min at 12,000 x g. Precipitated nucleic acids were suspended in TE. DNA was purified using Sephadex G-200 spin columns equilibrated in TE, as described previously (Kuske et al. 1997). The clear column eluate containing DNA was precipitated and suspended in TE buffer. Negative control samples were prepared with TENS buffer alone containing no sample addition and were subjected to the same procedures as used with the samples.

PCR amplification of small subunit rRNA genes from environmental DNAs. The forward primer used was 533F and the reverse primer used was the 1492R primer (Lane 1991). Amplification reaction mixtures contained 30 mM Tris-HCL (pH8.3), 50 mM KCl, 1.5 mM $MgCl_2$, 5 μg bovine serum albumin (Boehringer-Mannheim), 200 μM (each) deoxynucleoside triphosphates, 100 pmol of each primer, and 5 U of Taq polymerase (AmpliTaq LD; Perkin-Elmer, Foster City, Calif.) in a final reaction volume of 100 μl. PCR was conducted with a Perkin-Elmer 9600 thermal cycler as follows: 2 min at 94 °C (denaturation), followed by 35 cycles of 60 sec annealing at 48 °C (annealing), 60 sec at 72 °C (extension), and 5 sec at 94 °C (denaturation), with a final 60 sec at 48 °C (annealing) and 5-min at 72 °C (extension) step after cycling was complete. Five microliters of each reaction mixture was analyzed on 1% SeaKem agarose gels and the desired PCR amplification products were ferified by ethidium bromide staining and UV illumination of the gels.

Small-subunit rDNA libraries. A clone library of small subunit rRNA gene copies was generated from the Four Windows sample. PCR products from 533F-1492R amplification reactions were ligated into pGEM-T plasmid vectors (Promega, Madison, Wis.) using T4 DNA ligase and overnight incubation at 4 ºC, according to the manufacturer's protocols. Recombinant plasmids were transformed into *Escherichia coli* JM109 competent cells (Promega), and colonies containing plasmids with inserts were identified by blue/white color selection on LB/ampicillin/IPTG/XGal agar plates.

RFLP. To assist in determining the genetic diversity of the bacterial colony, the 16S ribosomal DNA of seventeen clones were cut with enzymes to produce RFLPs (restriction fragment length polymorphisms): one μl of plasmid DNA, two μl of React Buffer 3, sixteen μl of double distilled water, and one μl of enzyme were used to digest the DNA. Enzymes used were *EcoR1*, *Bstu 1* and *RSA1*, with one enzyme per reaction. Sheared DNA patterns were visualized using a 4% Metaphor (FMC Rockland, Maine) electrophoresis gel in TAE, stained with 1 μl of ethidium bromide and exposed to UV light.

DNA Sequencing. PCR products from 32 clones with inserts of the correct size (approximately 1.0 kb) were purified with a QIAprep plasmid miniprep kit (Qiagen, Inc., Chatsworth, Calif.). 125-300 ng of purified DNA was used as a template in cycle sequencing reactions with thermo sequenase dye terminator cycle sequencing pre-mix kit (Amersham Life Science, Inc., Cleveland, Ohio) and ABI PRISM dye terminator cycle sequencing kit (Perkin-Elmer, Foster City, Calif.) on an ABI 377. Primers used for sequencing were T7 and SP6. Full-length insert sequences were obtained for a subset of clones by using primers for internal sequencing (906F, 907R, and 765F) of the rRNA gene.

Phylogenetic analysis. Each sequence was submitted to the CHIMERA_CHECK program of the Ribosomal Database Project (RDP; Maidak et al. 2001; (http://rdp8.cme.msu.edu/html/)) to detect the presence of possible chimeric artifacts. All sequences were initially analyzed using BLAST (NCBI; Altschul et al. 1997) and SIMILARITY_MATCH (RDPII; Maidak et al. 2001) to identify related sequences available in public databases and to determine phylogenetic groupings of clone sequences. Clone insert representatives of each phylogenetic group identified were sequenced in their entirety. Alignment of the final dataset was accomplished using the RDP II alignment software and manually using the BioEdit editor (http://www.mbio.ncsu.edu/BioEdit/bioedit.html), guided by 16S primary and secondary structure considerations. Identity values were generated by the similarity identity matrix program in BioEdit (http://www.mbio.ncsu.edu/BioEdit/bioedit.html). Distance analyses were performed using PAUP (version 4.0b10, distributed by Sinauer; http://paup.csit.fsu.edu/) with the Jukes-Cantor model. The tree of highest likelihood was found by repeated tree building using random sequence input orders. Bootstrap analyses were conducted on 1000 resampled datasets using PAUP.

UV Sensitivity Experiments

Bacterial inoculation, isolation and growth. To obtain bacterial isolates from the rock walls and surface rocks, we swiped polyester fiber-tipped swabs across the rock and inoculated thirty R2A medium (low-nutrient) plates using the standard streak isolation method. We obtained water samples with sterile 5 ml syringes from a pool of water that had accumulated inside the cave and dispensed 0.2ml of the water onto ten R2A plates, which were spread with a flame-sterilized glass spreader onsite in the cave. Inoculated plates were incubated in the cave for 16 hours before transport to a 3°C incubator in the laboratory where they remained in the dark for two weeks. Surface inoculates were stored for just under three weeks at 37°C. Morphologically unique colonies from both sets of plates were sub-cultured to provide pure cultures for UV experiments. In addition, we sub-cultured the surface colonies onto nutrient-rich LB plates.

UV Radiation Treatment. Once the subcultures were grown, we chose twelve of the most interesting cave colonies and six of the surface colonies to expose to UV light. Interesting was defined as the most morphologically different and slowly growing (likely to be more cave-adapted) colonies. Three replicate plates of colonies per R2A plate were inoculated for each of two treatments plus the control. Immediately after inoculating the plates, we placed the plates, with lids off, under the sterile hood and exposed the plates to a UV light from a germicidal lamp for 100 seconds (1 Dose) or 50 seconds (½-dose plates). After the treatment, we covered the plates, wrapped them in foil to prevent photoreactivation and placed them in the appropriate incubators. The control replicates that were not exposed to UV light were also wrapped in foil and incubated. We monitored the growth of the cultures with visual checks of colony growth for six days, and documented them with a digital camera.

Results

Invertebrate Vacuuming

Visual observation of the bacterial colonies in Four Windows Cave revealed no macroscopically visual invertebrates. Therefore, bacterial and algal mats were vacuumed as described above to more thoroughly investigate the presence of invertebrates. No invertebrates were found within the bacterial mat collection tube. The algal mat collection tube contained fourteen collembola. Eleven of these belonged to the family Hypogasturidae and three belonged to the family Entomobryidae. Previous vacuuming had also yielded Acari (mites) in the Nanorchestidae, and undetermined Oribatida and insects in family Chironomidae (Diptera) were also found.

Scanning Electron Microscopy

Examination by Scanning Electron Microscopy (SEM) of samples of white bacterial mat samples from Four Windows Cave revealed a dense mat of bacteria (Figure 3), some of which were tentatively identified as actinomycetes from their visual appearance. Additional morphologies observed with SEM (not shown) resembled planctomycete-like or *Verrucomicrobium*-like bacteria.

RFLP Analysis and Nucleotide sequences

All eleven RFLP clones examined exhibited unique banding. Several clone sequences appeared to be chimeras and were removed from the analysis. Comparison of our sequences with those in the Ribosomal Database II and Blast revealed that some Four Windows bacterial sequences are most closely related to *Actinobacteria*, as suspected. Other clones grouped with members of the *Chloroflexi*, the *Verrucomicrobia*, and the *Betaproteobacteria*. Two of the closest relatives to our clones were sequenced from Mammoth Cave samples. The latter appear to be novel bacterial species. Figure 4 shows a phylogenetic tree of representative clone sequences and their closest relatives.

UV Sensitivity

Six days after the UV treatments, we scored the UV sensitivity of the different strains based on comparisons with the control strains. Each replicate was rated from one to three, with three being the most sensitive. Overall, every strain showed at least some sensitivity to the 1 dose (100 sec) of UV radiation and all but four strains (all surface) showed some sensitivity to ½ dose (50 sec) of UV. All of the cave strains showed significantly more sensitivity than the surface strains and seven of the cave replicates showed no growth at all with both 1 and ½ doses. All cave bacteria replicates were scored a three. Figures 5 and 6 show the dramatic differences in growth after UV exposure in surface and cave isolates respectively.

Discussion

The lack of invertebrates on the bacterial mats while invertebrates were found on adjacent algal mats suggests that the bacterial mats may contain toxic or distasteful compounds. Scanning electron microscopy and molecular phylogenetic analysis suggest the presence of actinomycete (*Actinobacteria*) bacteria in the bacterial mats. Actinomycetes are a highly varied group of Gram-positive bacteria that have the unusual characteristics of filamentous growth and exospore production. They may make up 10–33% of total soil microbes,

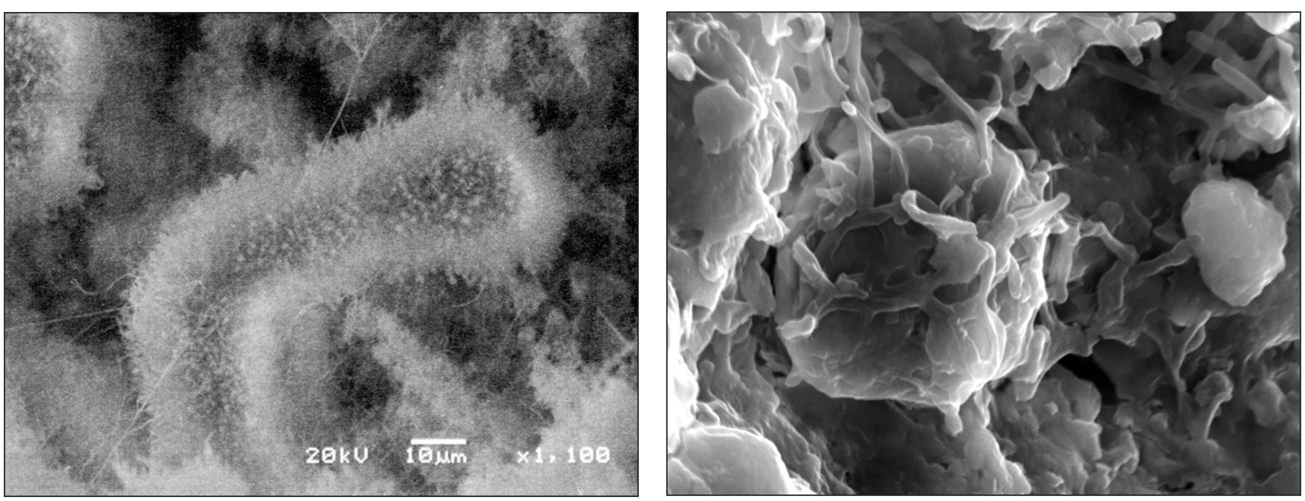


Figure 3. Scanning electron micrographs of sampled white bacterial colonies showing the presence of unusual morphologies (left) and filamentous (right). Photomicrographs by M. Spilde.

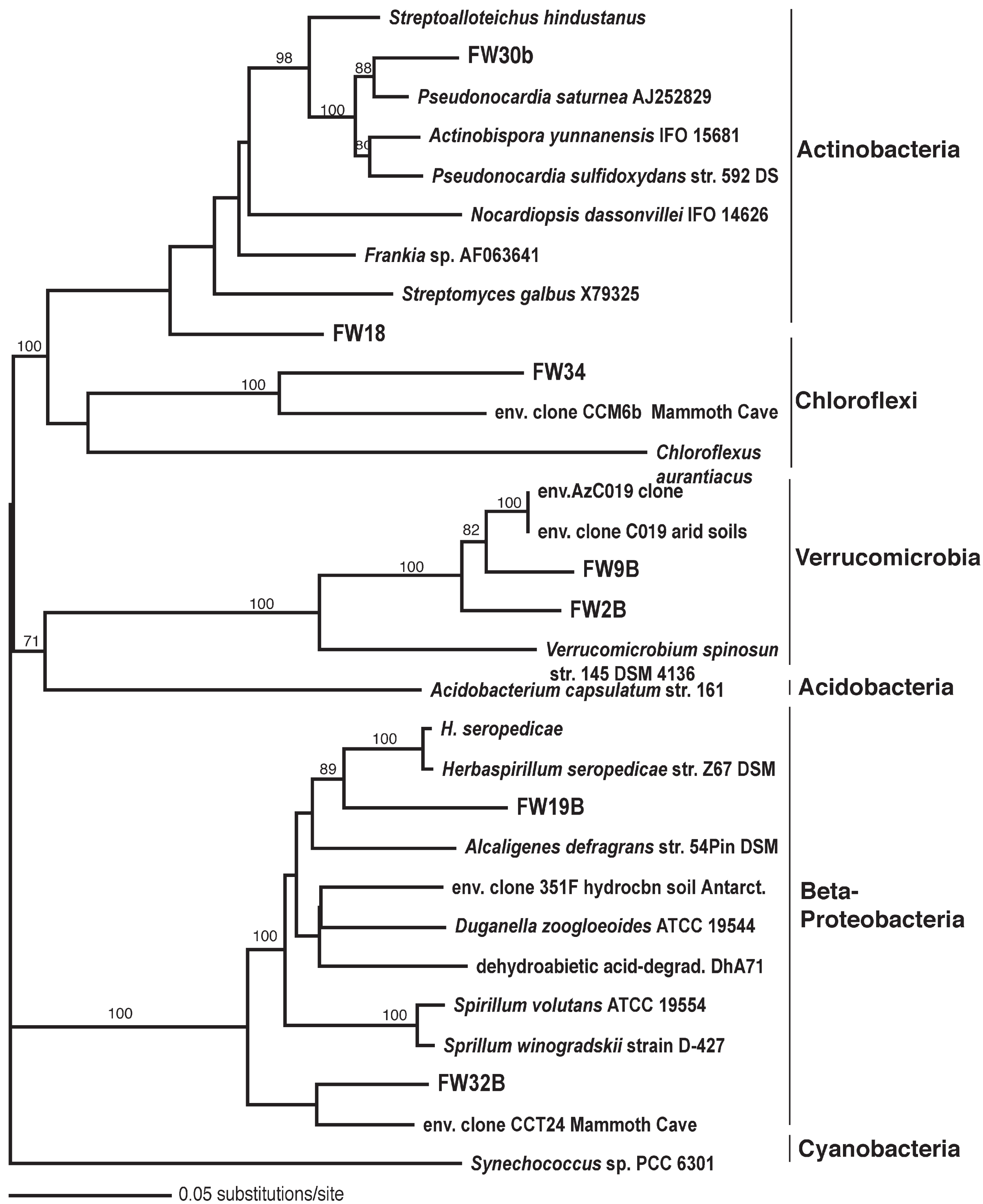


Figure 4. Phylogenetic tree of bacterial rDNA clone sequences from Four Windows Cave lava wall microbial mats. Partial rRNA gene sequences (ca. 1000 nucleotides) from clones (designated "FW" in bold type) were analyzed with most closely related sequences obtained from the databases, as well as other representatives of major bacterial groups. *Synechococcus* sp. PCC 6301 was used as the outgroup. The tree was inferred by maximum likelihood analysis of homologous nucleotide positions of sequence from each organism or clone. Numbers indicate percentages of bootstrap resamplings that support branches in maximum likelihood (above branch) and maximum parsimony (below branch) analyses. Bootstrap results are reported only for those branches that attained >70% support with at least one of the methods used.

with *Streptomyces* and *Norcardia* being the most abundant genera. They are relatively resistant to desiccation, and prefer alkaline or neutral pH environments. Metabolically, their main role in nature is in decomposition of organic matter and they thrive in environments where nutrients are sparse and conditions extreme. Many actinomycetes are known to fix atmospheric nitrogen either in association with some plant roots or as free-living cells. The role of Actinomycetes in nitrogen fixation in caves has not been explored (Lavoie per. comm. 1993). With a temperature of -2 to +2°C and seeping organic matter for nourishment, Four Windows Cave provides an excellent habitat for these bacteria. Some types of actinomycetes are medicinally and agriculturally significant because they excrete antibiotic products to repel invaders. The antibiotic properties of many bacteria species make them interesting to the medicinal industry. The lack of invertebrate life on the bacterial slime communities could be an indicator that the environment may be excreting antibiotic compounds toxic or distasteful to these small animals.

The molecular phylogenetic analysis of bacteria adhered to the rock walls of Four Windows Cave revealed that the community is not merely actinomycetes, but contains organisms from three other major bacterial groups: *Chloroflexi*, *Verrucomicrobia*, and the *Betaproteobacteria*. None of these relationships are especially close as evidenced by the long branch length for many of the Four Windows Cave clones. The closest relatives are those from Mammoth Cave environmental isolates and other soil environmental isolates, indicating the novel nature of these isolates. Clone FW34 grouped with the *Chloroflexi*, a group of generally phototrophic, filamentous organisms. However, other studies have shown cave bacteria grouping with the *Chloroflexi* (Engel, personal communication 2005), and in this case, the association is not a close one. The closer relative of clone FW34 is an isolate from the soils of Mammoth Cave in Kentucky. The lack of a close relationship to a cultivated bacterial species and the fact that close relatives can have different physiologies does not allow us to draw any conclusions concerning this clone. Several clones, as represented by FW2b and FW9b, group with the *Verrucomicrobia*, a recently proposed division that has been elevated to phylum status within the Bacterial Domain (Schlesner et al. 2001). The genera *Verrucomicrobium* and *Prosthecobacter* within the *Verrucomicrobia* are prosthecate with fimbriae (finger or hair-like appendages) extensions from their tips. Their morphology is similar to some of the morphologies seen in the SEM photomicrographs of Four Windows samples. The *Verrucomicrobia* have been found in a variety of aquatic and terrestrial habitats worldwide. While most cultivated members are heterotrophic, we are just beginning to learn about their physiology. Thus, little can be said about the physiology of the Four Windows clones based on their association with the *Verrucomicrobia*.

The grouping of isolate FW19B with *Herbaspirillum seropedicae* in the *Betaproteobacteria*, probably reveals an isolate from the surface rhizosphere. Bacteria in the *Herbaspirillum* are usually associated with plant roots, often as nitrogen-fixers. Isolate FW32B groups with another Mammoth Cave environmental isolate within the *Betaproteobacteria*.

Overall, the molecular phylogenetic analysis of a small clone library from Four Windows Cave points to the novel nature of the isolates and the need to learn more about their physiology through enrichment culture studies. Of note is the observation that the closest relatives come from another cave, Mammoth Cave in Kentucky. It is tempting to speculate that this is a small bit of evidence for the existence of an indigenous cave microbial community, but much remains to be learned about the microbial diversity of caves.

Our UV sensitivity experiments with cultured isolates from Four Windows Cave showed a marked sensitivity to UV radiation in comparison to surface cultured isolates, showing a different trend than that seen by Arrage et al. (1993b).

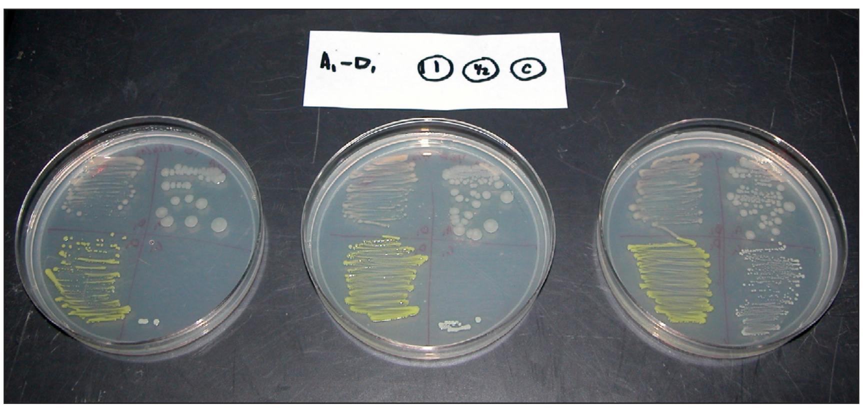


Figure 5. Comparison of replicate 1 surface strains A – D. 1= full UV dose, ½= half UV dose, C= no UV. Replicates 2 and 3 showed similar UV sensitivity (data not shown).

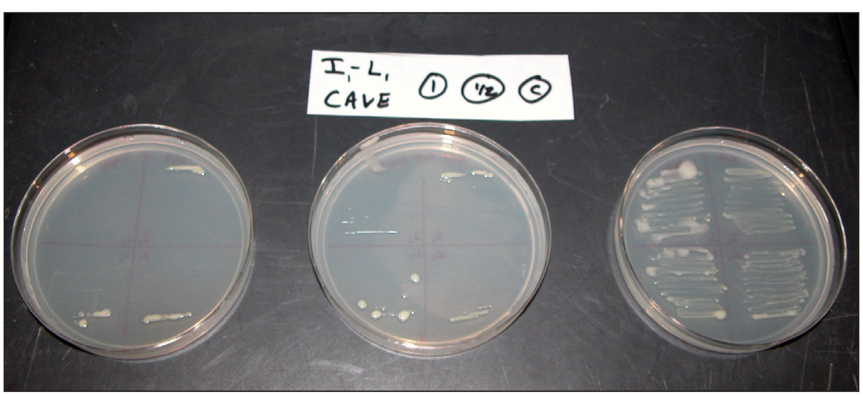


Figure 6. Comparison of replicate 1 cave strains I – L. 1= full UV dose, ½= half UV dose, C= no UV. Replicates 2 and 3 showed similar UV sensitivity (data not shown).

To further test these findings in a more rigorous manner, we are repeating the experiments with isolates from other caves with quantification of the starting inoculum and final growth amounts. If the finding is confirmed, the loss of UV sensitivity may represent an adaptation to the cave environment by bacteria that have no need of UV radiation resistance in the dark environment of the cave. Many of the same genes (*recA*) that control for UV resistance/repair also control repair for other environmental stresses such as desiccation.

This study represents some small steps in adding to our understanding of the bacterial mats that coat the walls of many lava tubes worldwide. We have established that there is a morphologically and genetically diverse community in these mats, that the culturable bacteria are UV sensitive, and that these mats are distasteful to invertebrates who preferentially feed on adjacent algal mats. These studies will hopefully spark interest in these interesting and novel communities, allowing us to further investigate their nature.

References

Altschul SF, Madden TL, Schäffer AA, Zhang J, Zhang Z, Miller W, Lipman DJ. 1997. Gapped BLAST and PSI-BLAST: a new generation of protein database search programs. Nucleic Acids Research 25:3389-3402.

Amann, R. I., Ludwig ,W., and K. Schleifer. 1995. Phylogenetic Identification and In Situ Detection of Individual Microbial Cells without Cultivation. Microbiological Reviews **59**: 143-166.

Arrage, A.A., Phelps, T.J., Benoit, R.E., Palumbo, A.V. and White, D.C. 1993a. Bacterial sensitivity to UV light as a model for ionizing radiation resistance. Journal of Microbiological Methods **18(2)**: 127-136.

Arrage, A.A., Phelps, T.J., Benoit, R.E., Palumbo, A.V. and White, D.C. 1993b. Survival of subsurface microorganisms exposed to UV radiation and hydrogen peroxide. Applied and Environmental Microbiology **59(11)**: 3545-3550.

Ashmole, N. P., Orom, P., Ashmole, M. J., and Martin, J. L. 1992. Primary faunal succession in volcanic terrain: Lava and cave studies on the Canary Islands: Biological Journal of the Linnean Society **46**: 207-234.

Ehrlich, H.L. 1999. Microbes as geologic agents: Their role in mineral formation. Geomicrobiology Journal **16**(2): 135-153.

Howarth, F. G. 1973. The cavernicolous fauna of Hawaiian lava tubes, 1. Introduction. Pacific Insects 15: 139-151.

Howarth, F. G. 1981. Community structure and niche differentiation in Hawaiian lava tubes; pp. 318-336. *In*: Mueller-Dombois, D., Bridges, K. W., and Carson, H. L. (eds.). *Island Ecosystems: Biological Organization in Selected Hawaiian Communities*. US/IBP Synthesis Series 15: Stroudsburg (PA): Hutchinson Ross Publishing Company.

Hugenholtz, P., Goebel, B.M., and Pace, N.R. (1998) Impact of culture-independent studies on the emerging phylogenetic view of bacterial diversity. Journal of Bacteriology **180**:4765-4774.

Kuske, C., Barns, S., and J. Busch. 1997. Diverse uncultivated bacterial groups from soils of the arid southwestern United States that are present in many geographic regions. Applied and Environmental Microbiology **63**: 3614-3621.

Lane DJ. 1991. 16S/23S rRNA sequencing. p. 115-175. *In*: Stackebrandt E., Goodfellow M., (eds.) *Nucleic Acid Techniques in Bacterial Systematics*. New York: John Wiley and Sons.

Lavoie, K.H. and Northup, D.E. 1994. Distributional survey of actinomycetes in a limestone cave and a lava tube cave. pp.44-45. In: Sasowsky I.D., Palmer M.V. (eds.) *Breakthroughs in karst geomicrobiology and redox geochemistry: abstracts and field-trip guide for the symposium held February 16 through 19, 1994 Colorado Springs, Colorado*. Special Pubication **1**. Charles Town, WV: Karst Waters Institute, Inc.

Maidak, B.L., Cole, J.R., Lilburn, T.G., Parker Jr., C.T., Saxman, P.R., Farris, R.J., Garrity, G.M., Olsen, G.J., Schmidt, T.M., Tiedje, J.M. 2001. The RDP-II (Ribosomal Database Project). Nucleic Acids Research **29**:173-174.

Northup, D.E. and Lavoie, K.H. 2001. Geomicrobiology of caves. Geomicrobiology Journal **18**(3): 199-222.

Northup, D.E. and Welbourn, W.C. 1997, Life in the twilight zone: Lava tube ecology. New Mexico Bureau of Mines & Mineral Resources Bulletin **156**: 69-82.

Pace, N.R. 1997. A molecular view of microbial diversity and the biosphere. Science **276**(5313): 734-740.

Schlesner, H., Jenkins, C. and Staley, J.T. 2001. The phylum Verrucomicrobia: A phylogenetically heterogeneous bacterial group. *In*: M. Dworkin et al., eds., *The Prokaryotes: An Evolving Electronic Resource for the Microbiological Community*, 3rd edition, release 3.19, Springer-Verlag, New York, http://link.springer-ny.com/link/service/books/10125/.

Senger, C.M. and Crawford, R.L. 1984. Biological inventory: Mount St. Helens Cave basalt flow area: Final Report. Unpublished report prepared for the Gifford Pinchot National Forest, Mount St. Helens National Volcanic Monument, St. Helens Ranger District. 526 pp.

Staley, J. T. and Crawford, R. 1975. The biologist's chamber: lava tube slime: Cascade Caver **14** (2-3): 20-21.

Acknowledgements

The authors wish to thank Herschel Schultz, El Malpais National Monument, for access to Four Windows Cave and a collecting permit that allowed us to pursue this research. We especially thank Kenneth Ingham for his photo documentation of our study site and methods. Penny and Ariel Boston's help in collecting samples is greatly appreciated. Sandy Brantley provided valuable assistance in the identification of insects collected during the vacuuming experiments. Jessica Snider provided valuable comments on the manuscript.

Climate Modeling for Two Lava Tube Caves at El Malpais National Monument, New Mexico USA

Kenneth L. Ingham[1], Diana E. Northup[2], and W. Calvin Welbourn[3]

[1] Kenneth Ingham Consulting, LLC.; ingham@i-pi.com
[2] Biology Department, University of New Mexico; dnorthup@unm.edu
[3] The Florida Department of Agriculture and Consumer Services, Division of Plant Industry

Abstract

Reliable data on cave microclimate benefits those who manage caves for human visitation, protection, and the conservation and restoration of bat roosts. Information, both published and unpublished, on cave climates is limited. Mathematical models of cave climate are even more limited, and for lava tube caves, these appear to be totally lacking. Because lava tube caves are simpler than many limestone caves (thus making the task of modeling tractable) we tested the use of lava tube caves as laboratories for climate modeling.

We present the results of investigating temperature and humidity in two lava tube caves at El Malpais National Monument, New Mexico, USA. One cave was a single-entrance cave with an ice sheet, the other a tube with detectable airflow to/from cracks on the surface. One and one-half years of data were collected in these two tubes using data loggers. Using these data, we investigated temperature and humidity changes with seasons and distance from the entrance, and propose mathematical models to predict future temperatures based on heat flow from the surface as well as advection.

Our models show a good fit to the equation

$$T(t) = a_1 + a_2 \cos[(t2\pi)/365.24] + a_3 \sin[(t2\pi)/365.24] + a_4 \cos(t2\pi) + a_5 \sin(t2\pi)$$

This implies that, at least in these lava tube caves, accurate prediction of temperature is possible.

Introduction

Cave managers need temperature and humidity data to assess the impact of visitors, conservation and restoration of bat roosts, etc. For example, in an ice cave, the question might arise, "Is human visitation melting the ice?" We show that for some caves, a manager could start by collecting data during a time without visitation. Once the baseline data exists, the predictions can allow the manager to know if the visitation is affecting the cave climate.

This paper presents the results of a cave climate study from October 1993 through August 1995 of two lava tubes at El Malpais National Monument, New Mexico, USA. The original goal was to study the impact of prescribed fire on lava tube caves; however, for political reasons the prescribed fire never occurred. If we had planned to do a cave climate study, we would have placed data loggers differently.

Description of the caves

Both of the lava tubes are located in an open Ponderosa pine forest on El Malpais National Monument, in west-central New Mexico, USA (Figure 1).

Lava Wall cave (also known as Peel Bark cave) is the smaller of the two lava tubes. It has a large wide entrance (Figure 2) approximately 6.5m x 1.5m, and it gets progressively narrower and lower. Within 6m, it turns into a muddy crawl which continues for at least 24m. The crawl shows evidence of repeated flooding and organic input, and a commonly-felt breeze implies that it connects to cracks in a nearby (30m distant) sink. Figure 3 shows an approximate cross-section of the cave. Note that this cave is

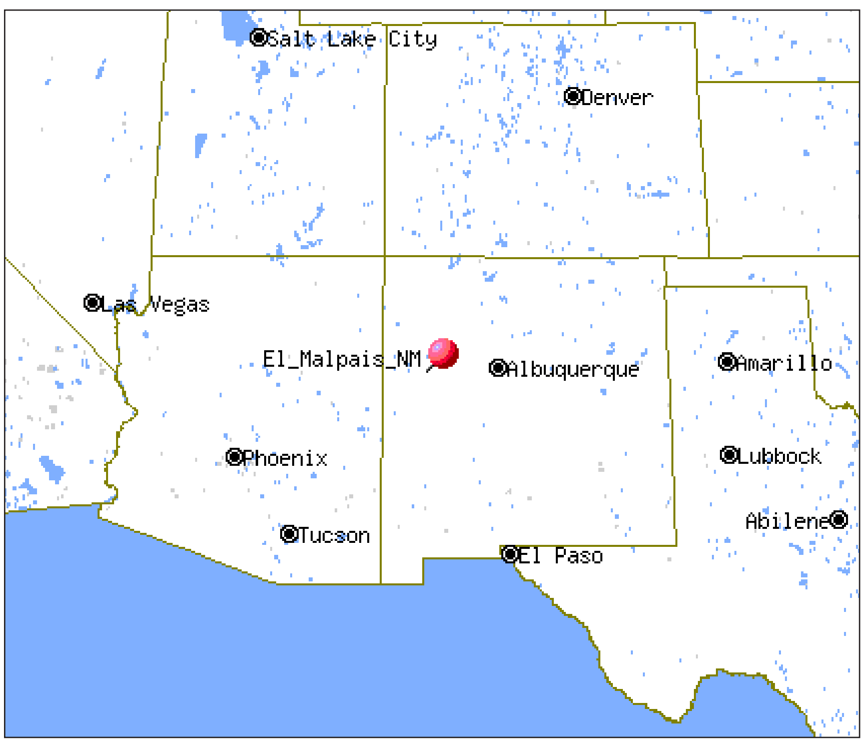


Figure 1. Approximate location of El Malpais National Monument, where the two lava tubes are located.

Figure 2. Entrance of Lava Wall cave.

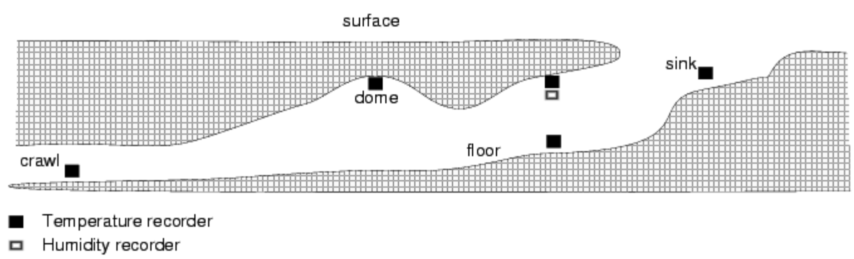


Figure 3. Cross section of Lava Wall cave.

relatively level once you are inside.

Frozen Mat cave is larger, with two rooms and a passage. The small (less than 1 meter square) entrance leads into a breakdown room (about 4m x 9m). Over a breakdown pile is a second room (about 5m x 20m) containing a 5m x 6m ice sheet (Figure 4), covered with up to 2.5cm of water in the summer. The ice is about 3m-4.5m below the entrance and about 20m from the entrance. The ice sheet varies in extent and depth throughout the year and year-to-year. The room extends no more than about 7.5m beyond the ice. Figure 5 shows an approximate cross-section of the cave.

On the left side of the entrance room in Frozen Mat is a low passage that proceeds for at least 13m and appears to pinch out. No airflow was detected through this passage.

Literature Review

Heat drives much of the airflow, and airflow can move heat around. As a result, we review previous work by looking at what is known about heat flow and caves, and then looking at previous studies of airflow.

Heat

Heat is important for two reasons. First, to predict the temperatures inside caves, we need to know from where the heat comes. Second, heat is sometimes responsible for airflow.

Heat in caves comes from three sources:

- the radioactive decay of elements in the Earth's core (geothermal heating).
- surface heat generated by the sun and transported by conduction through the soil and rock.
- surface heat generated by the sun and carried into the cave by air movement (advection).
- heat moved by a stream running through a cave (which does not apply to the caves we studied).

Figure 4. The ice sheet in Frozen Mat cave.

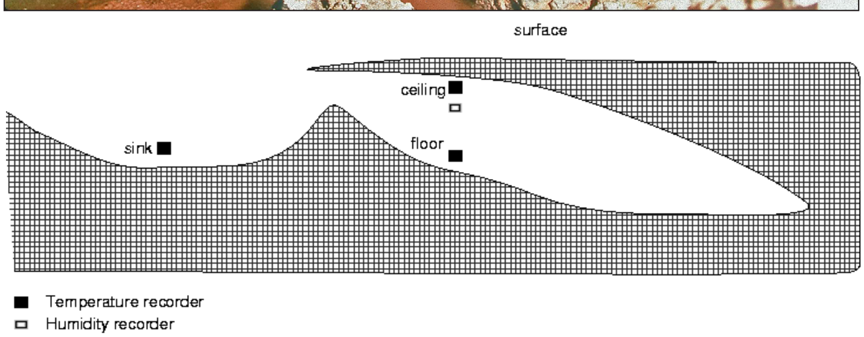


Figure 5. Cross section of Frozen Mat cave.

Geothermal heating. Atkinson, Smart, and Wigley [2] used geothermal heating to explain the difference between the mean annual temperature and the actual measured temperature deep in Castleguard cave in Alberta Canada. Most likely, geothermal heat is omitted from studies because most caves (especially the lava tubes we were studying) are close to the surface, and the other factors dominate their temperature.

Solar heat transported by conduction. Daily variations in temperature in the soil and rock die out about 1m deep [16]. Annual variations in temperature may be observed as deep as 20-24m [16] depending on the rock and soil types. At depths below below where the surface influence is felt, the temperature of a cave should be stable at the mean annual surface temperature [4, 8, 14, 16].

Heat transferred by advection. Advection is the transfer of heat by air movement. In this case, rather than the heat which is being moved causing the movement (as in convection), some other factor is causing the air movement.

Airflow

To know about airflow, we must look at the factors that can cause air to move in caves:

- density differences in air caused by temperature variations,
- the number of entrances a cave has and their relative elevation, and
- differences in air pressure from various factors considered below.

The single most important factor affecting airflow is the number of entrances a cave has and the relative height of these entrances. A cave with multiple entrances where those entrances are not at the same level will nearly always have a breeze blowing through it. When the temperature inside is lower than the temperature outside (as it is in summer), the cool (and therefore denser) air will exit the lower entrance, and the outside, warmer air will enter at the upper entrance. Conditions reverse when the temperature inside is higher than the temperature outside (as it is in winter). During times when the inside and outside temperatures are nearly the same, no breeze may blow or other factors may dominate the airflow. The velocity of the air movement in this chimney effect is directly related to the temperature (and to some extent the humidity) differences between the air inside and outside of the cave. Airflow velocities will also be affected by the volume of the cave as well as the sizes of the entrances.

Wigley and Brown [19] and Atkinson, Smart, and Wigley [2], note that a cave may have extra "entrances" in terms of fractures leading to the surface which may be too small for humans to travel but are large enough to allow air to flow. These airflow routes will cause the chimney effect to occur even in what appear to be single entrance caves. This effect probably occurs in Lava Wall cave.

For caves with a single entrance, airflow is controlled by a complex collection of factors including:

- convection,
- the current barometric pressure and how it is changing, and
- wind blowing across or into an entrance.

Additionally, surface roughness, and the sinuosity of passage affect the airflow by making it more turbulent and hence slowing it down.

Since warm air is less dense that cool air, it will tend to rise or flow along the upper part of the cave. Similarly, cool air will flow along the bottoms of the passages. The slope of the cave and orientation of the entrance will determine if or how convection will cause air exchange with the interior portions of the cave [19]. This convection was the primary air movement discovered at Altimira Cave in Spain by Villar et al. [17]. It also is a part of the airflow at Glowworm Cave in New Zealand [6]. Another example where convection is a major cause of the airflow was investigated by Smithson [15]. He looked at vertical variations of temperature in Poole's Cavern U.K. and saw the effects of convective airflow.

Convection explains why single-entrance caves which slope downward are cold traps. In the winter cold air flows into the cave. In the summer it becomes stagnant, and hence remains cool and in some cases collects ice [3, 8]. In upward-trending caves, the reverse would happen and cooler air would fall out the entrance when it was cooler in the cave than outside [19].

Other than convection, airflow also results whenever the barometric pressure outside is different from the pressure inside. When this difference occurs, the cave will inhale or exhale to equalize the pressure. Lewis [12] and Wigley and Brown [19] noted many factors which affect the atmospheric pressure outside and hence the breathing of a cave:

- weather patterns as high and low pressure systems move across, the cave lags the outside by a small amount as air flows to equalize the pressure.
- atmospheric tides are caused by the atmosphere absorbing heat directly from the sun and from the heat reflected from the earth's surface. A typical tidal curve has two maxima and two minima in 24 hours.
- gravity waves are the atmospheric equivalent of the waves we commonly associate with the ocean. They have periods from about three minutes to three hours.
- infrasound from sources such as the aurora, nuclear blasts, distant storms, waterfalls, the jet stream, volcanic explosions, earthquakes, waves on the ocean, large meteorites, supersonic aircraft.
- cave resonance from wind blowing across an entrance, much like a bottle resonates when blown across its opening.

Wigley and Brown [19] noted that a cave with widely separated entrances which has a strong storm (such as a summer thunderstorm) over one entrance may have a notable difference of pressure between the entrances which causes airflow.

Wind blowing into an entrance can cause airflow as noted by Smithson [15]. In multi-entrance caves, the wind may blow in one entrance and out another. Wind blowing across an entrance will lower the pressure at that entrance which will affect the airflow.

Any of the above mechanisms for airflow can act simultaneously to result in airflow which may be barely detectable (as in the flickering of a candle) all the way up to wind which moves gravel [19].

Temperatures in the cave

When the temperatures are different from the mean annual temperature, it is due to one of the causes mentioned above. First, we note that rock stores heat, and it will release that heat to cooler air or will absorb heat from warmer air [18].

Second, adding humidity to air cools it [7, 18] because of the heat needed to change liquid water to water vapor (about 540 calories/gram, depending on temperature). Therefore unsaturated air (from the surface) moving across a source of water (such as water percolating in from the surface) will cool as the water evaporates into it.

Taking these two factors into consideration, Wigley and Brown [18] develop the following formula to describe the temperature in the cave:

$$T = T_a + (T_0 - T_a)e^{-X} + \frac{L_v}{c_p} w(q_0 - q_a)Xe^{-X}$$

where T_a is the deep cave rock temperature, T_0 is the temperature of the air entering the cave, X is the ratio of the distance from the entrance (x) and the relaxation length (x_0), L_v is the latent heat of vaporization, c_p is the specific heat of air, w is cave wetness which indicates the fraction of the cave wall which is wet, q_0 is specific humidity of the air entering the cave, q_a is the specific humidity of the outside air when it is cooled to T_a.

The relaxation length, $x_0 = 36.44\, a^{1.2} V^{0.2}$, where a is the radius of the cave in cm and V is the velocity of the air moving into the cave in cm/sec. It is the distance it takes the temperature T_a to decay to $T_a e^{-1}$. In some caves it may be easier to calculate this distance rather than measure the airflow [5]. Wigley and Brown [19] found relaxation lengths in the range of 10 to 500m.

Given the equation of Wigley and Brown along with data obtained from monitoring the cave, we can predict the temperatures in the cave based on temperature and humidity outside the cave, current airflow, and amount of moisture on the wall of the caves. Preceding a prescribed fire, the cave should be monitored, a plan suggested by Smithson and Wigley and Brown [13, 19]. These predictions then should be compared with actual conditions observed to determine how the cave varies from predicted. During the prescribed fire, the cave can be monitored and any effects of the fire can be noted as divergence from the predicted values.

Humidity

Humidity is of interest because when water evaporates, it absorbs heat. Conversely, when it condenses, heat is released. So humidity is tied together with heat. Additionally, Howarth [1, 10, 11] states that the key environmental factor that determines the distribution of troglobites is the degree to which the atmosphere is saturated.

As you travel deeper into a lava tube (provided there are not additional entrances), evaporation decreases. Howarth [9] found that the rate of potential evaporation in the deep cave zone was only 8% of that of the twilight zone and hypothesized that the rate within the mesocaverns was much lower still. Cave organisms further take advantage of areas with low evaporation by moving into the small voids, which are often sites of accumulation of organic matter [1].

The degree of saturation of air in lava tubes is dependent on several surface factors and is a dynamic phenomenon. Climate on the surface influences the movement of air in lava tubes. When the temperature is lower outside than inside, as often happens at night in the winter, the vapor pressure of water is higher inside the cave than outside causing moist air to diffuse out of the cave. If the daytime water vapor pressure is still less than that in the cave, the water vapor will continue to diffuse out of the cave in the daytime, resulting in a winter drying of the cave known as the "wintering effect" [1]. When conditions reverse, the cave will gain moisture from the surface air.

The "wintering effect" does not seem to apply to the blind tubes at El Malpais. Frequent snowpacks that remain for days or weeks provide moisture for the lava tubes both in the form of atmospheric moisture and as melting water percolating through cracks. Ice in the lava tubes accumulates over winter, reaching a peak in early spring.

The deeper in to the cave you go, the longer the lag between changes in the surface conditions and the corresponding changes in the cave environment. Similarly, the amount of change becomes less with increasing distance from the entrance [1].

Materials and methods

Onset Hobo (Onset Computer, 470 MacArthur Blvd., Bourne, MA 02532, +1-508-759-9500, http://www.onsetcomp.com/) temperature and humidity data loggers capable of storing 1800 observations were used to collect the data. The recording interval varied from 5.6 minutes to 96 minutes, and was based on our expected return date to download data. During the winter, access to the caves was often impossible. The data loggers themselves were stored in plastic containers to shield them from the elements, with the temperature sensor outside of the container.

Unfortunately, animals destroyed some of the remote sensors. To protect the sensor, we moved the sensor for two data loggers inside the plastic container. This changed the reaction time from two to 40 minutes.

Results

Plotting raw data from the data loggers results in a graph such as the one from Frozen Mat cave (Figure 6). The data from the other data loggers were similar, and all exhibit a diurnal cycle.

A Fast Fourier Transform requires data with equal intervals, a requirement we could not meet due to the varied data collection intervals. We tried a traditional Fourier Analysis, but the resulting spectrums were not helpful in predicting temperatures.

We used a least-squares algorithm to fit sine and cosine to the daily and annual data, specifically:

$$T(t) = a_1 + a_2 \cos(\frac{t2\pi}{365.24}) + a_3 \sin(\frac{t2\pi}{365.24}) + a_4 \cos(t2\pi) + a_4 \sin(t2\pi)$$

By using both the sine and cosine, we are able to represent the annual/diurnal cycles, as well phase information.

The resulting equations for Lava Wall are in Table 1, and for Frozen Mat are in Table 2.

Discussion

Not surprisingly, diurnal cycles are strongly evident in all temperature data. Both caves are small, and have an interaction coupled to the surface temperature. The oscillations diminish as you go deeper in the cave. In Frozen

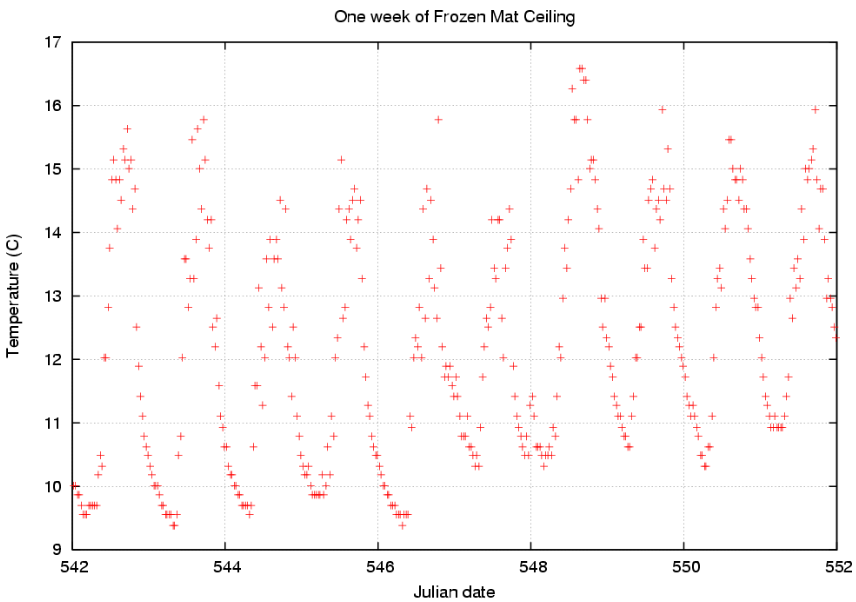


Figure 6. A week of data from the ceiling data logger in Frozen mat cave.

Table 1. Equations fitting the data for the data loggers in Lava Wall cave.

ceiling	$T(t) = 0.0(\pm 0.0) + -10.843922(\pm 0.016795)\cos(\frac{t2\pi}{365.24}) + -14.900744(\pm 0.015138)\sin(\frac{t2\pi}{365.24}) + -0.147362(\pm 0.015631)\cos(t2\pi) + -0.261526(\pm 0.015624)\sin(t2\pi)$
floor	$T(t) = 0.0(\pm 0.0) + -7.237748(\pm 0.016262)\cos(\frac{t2\pi}{365.24}) + -15.836785(\pm 0.013960)\sin(\frac{t2\pi}{365.24}) + -0.129653(\pm 0.014451)\cos(t2\pi) + -0.361877(\pm 0.014440)\sin(t2\pi)$
crawl	$T(t) = 0.0(\pm 0.0) + -1.427401(\pm 0.033754)\cos(\frac{t2\pi}{365.24}) + -10.884780(\pm 0.025210)\sin(\frac{t2\pi}{365.24}) + -0.261690(\pm 0.020269)\cos(t2\pi) + -0.531103(\pm 0.020291)\sin(t2\pi)$
sink	$T(t) = 0.0(\pm 0.0) + -19.417273(\pm 0.016925)\cos(\frac{t2\pi}{365.24}) + -13.317093(\pm 0.016707)\sin(\frac{t2\pi}{365.24}) + 0.625014(\pm 0.016633)\cos(t2\pi) + 0.546246(\pm 0.016627)\sin(t2\pi)$
dome	$T(t) = 0.0(\pm 0.0) + 31.512697(\pm 0.054709)\cos(\frac{t2\pi}{365.24}) + -25.051178(\pm 0.054308)\sin(\frac{t2\pi}{365.24}) + -0.198811(\pm 0.052696)\cos(t2\pi) + -0.744981(\pm 0.052707)\sin(t2\pi)$
relative humidity	$T(t) = 0.0(\pm 0.0) + -16.574255(\pm 0.016254)\cos(\frac{t2\pi}{365.24}) + -36.632496(\pm 0.013953)\sin(\frac{t2\pi}{365.24}) + -1.820918(\pm 0.014438)\cos(t2\pi) + -0.763961(\pm 0.014441)\sin(t2\pi)$

Table 2. Equations fitting the data for the data loggers in Frozen Mat cave.

ceiling	$T(t) = 0.0(\pm 0.0) + -8.430573(\pm 0.012779)\cos(\frac{t2\pi}{365.24}) + -20.716593(\pm 0.011610)\sin(\frac{t2\pi}{365.24}) + -0.368887(\pm 0.012041)\cos(t2\pi) + 0.136714(\pm 0.012025)\sin(t2\pi)$
sink	$T(t) = 0.0(\pm 0.0) + -23.819973(\pm 0.015790)\cos(\frac{t2\pi}{365.24}) + -22.008461(\pm 0.013915)\sin(\frac{t2\pi}{365.24}) + -3.382733(\pm 0.014441)\cos(t2\pi) + -0.264057(\pm 0.014429)\sin(t2\pi)$
floor	$T(t) = 0.0(\pm 0.0) + -8.482291(\pm 0.015796)\cos(\frac{t2\pi}{365.24}) + -17.615507(\pm 0.013921)\sin(\frac{t2\pi}{365.24}) + 0.014079(\pm 0.014441)\cos(t2\pi) + -0.054044(\pm 0.014440)\sin(t2\pi)$
relative humidity	$T(t) = 0.0(\pm 0.0) + -5.646605(\pm 0.015349)\cos(\frac{t2\pi}{365.24}) + -38.756611(\pm 0.013631)\sin(\frac{t2\pi}{365.24}) + 0.471688(\pm 0.014182)\cos(t2\pi) + 0.210453(\pm 0.014171)\sin(t2\pi)$

Mat cave, the ice sheet melting produces nearly constant temperatures until the ice retreats far enough from the data logger. The humidity is lowest mid-afternoon, which corresponds to the high point in the diurnal temperature cycle.

The error values show that the daily plus annual sine and cosine functions fit the data well. This good fit implies that the temperatures in these caves are predictable. Other, simple caves should be as predictable. More complex caves, e.g., those with multiple entrances, may be more difficult to model due to more factors affecting the temperature and/or humidity. Because each cave has a different geometry, airflow, etc., the optimal placement for climate sensors will vary.

Since our data loggers were placed for observing effects of fire, we were unable to test the prediction by Wigley and Brown [18]. To confirm their prediction would have required airflow data and/or additional temperature data in order to determine the relaxation length.

Conclusion

Cave managers can use temperature and humidity predictions for guiding their decisions for cave management. For example, bats require temperature and humidity within certain tolerances in order to use the cave. Ice formations in lava tubes may melt from the heat produced by humans visiting the cave. We have shown that for simple caves, accurate prediction of temperature and humidity is possible.

References

1. G. A. Ahearn and F.G. Howarth. Physiology of cave arthropods in Hawaii. *The Journal of Experimental Zoology*, 222:227-238, 1982.
2. T. C. Atkinson, P. L. Smart, and T. M. L. Wigley. Climate and natural radon levels in Castleguard Cave, Columbia Icefields, Alberta, Canada. *Artic and Alpine Research*, 15(4):487-502, 1983.
3. Alfred Bögli. *Karst hydrology and physical speleology*. Springer-Verlag, 1980.
4. J. B. Cropley. Influence of surface conditions on temperatures in large cave systems. *Bulletin of the National Speleological Society*, 27(1):1-10, January 1965.
5. C. R. De Freitas and R. N. Littlejohn.

Cave climate: assessment of heat and moisture exchange. *Journal of Climatology*, 7:553-569, 1987.

6. C. R. De Freitas, R. N. Littlejohn, T. S. Clarkson, and I. S. Kristament. Cave climate: assessment of airflow and ventilation. *Journal of Climatology,* 2:383-397, 1982.
7. Adolfo Eraso. Tentative nomogram for cave climate calculations. In Dr. Otakar Stecl, CSc., editor, *Problems of the Speleological Research: Proceedings of the International SpeleologicaConference held in Brno June 29-July 4 1964*. Academia, Publishing house of the Czechoslovak Academy of Sciences, 1965.
8. William R. Halliday. Ice caves of the United States. *Bulletin of the National Speleological Society*, 16:3-28, December 1954.
9. Francis G. Howarth. The evolution of non-relictual tropical troglobites. *International Journal of Speleology*, 16:1-16, 1987.
10. Francis G. Howarth. Evolutionary ecology of aeolian and subterranean habitats in Hawaii. *Trends in Ecology and Evolution,* 2(7):220-223, July 1987.
11. Francis G. Howarth. Hawaiian cave faunas: macroevolution on young islands. In E. C. Dudley, editor, *The unity of evolutionary biology: fourth international congress of systematic and evolutionary biology, College Park, Maryland, USA, June 30-July 7, 1990*, volume v1,v2, pages 285-295, Portland, Oregon, April 1991. Dioscorides Press.
12. Warren C. Lewis. Atmospheric pressure changes and cave airflow: a review. *The NSS Bulletin*, 53(1):1-12, June 1991.
13. P. A. Smithson. Temperature variations in Creswell Crags Caves (near Worksop). *East Midland Geographer*, 8:51-64, 1982.
14. P. A. Smithson. Inter-relatonships between cave and outside air temperature. *Theor. Appl. Climatol.*, 44:65-73, 1991.
15. P. A. Smithson. Vertical temperature structure in a cave environment. *Geoarchaeology: An International Journal*, 8(3):229-240, 1993.
16. A. K. S. Thakur and M. Musa Momoh. Temperature variation in upper Earth crust due to periodic nature of solar insolation. *Energy Convers. Mgmt*, 23(3):131-134, 1983.
17. E. Villar, P. L. Fernández, L. S. Quindos, J. R. Solana, and J. Soto. Air temperatures and airinterchanges at Altimira Cave (Spain). *Transactions of the Britsh Cave Research Association*, 11(2):92-98, July 1984.
18. T. M. L. Wigley and M. C. Brown. Geophysical applications of heat and mass transfer in turbulent pipe flow. *boundary-layer meteorology*, 1:300-320, 1971.
19. T. M. L. Wigley and M. C. Brown. *The physics of caves*, chapter 9, pages 329-358. Academic Press, 1976.