HAWAIIAN CAVE BIOLOGY: STATUS OF CONSERVATION AND MANAGEMENT

Fred D. Stone, Ph.D.
B.P. Bishop Museum
Hawaii Cave Conservation Task Force
Cave Conservancy of Hawai`i
Honolulu, Hawai`i

Francis G. Howarth, Ph.D.
B.P. Bishop Museum
Honolulu, Hawai`i

Abstract

Caves on the main Hawaiian Islands support diverse communities of obligate cave-adapted species. First discovered in 1971, currently over 75 species of troglobites are recognized, including planthoppers, crickets, moths, beetles, spiders, pseudoscorpions, millipedes, centipedes, isopods, and others, with new species still being discovered. Efforts to protect these species began soon after their discovery, and are on-going. Systematics research using morphology, behavior, and molecular techniques is revealing much greater diversity among cave populations than assumed. Within some groups, each cave supports one or more distinct populations or species differing from neighboring cave populations in form, behavior, and DNA. Roots provide important food base for the ecosystem, and identification of plant roots in caves and management of the surface environment are essential for habitat protection. Management of the surface includes restoration of native vegetation where needed and removal of invasive alien plants, ungulates, and other harmful introduced species. Control of threats includes prevention of pollution by garbage, sewage, and chemical contamination. The Hawai`i State Cave Protection Law was developed to extend these protections to all caves statewide. Many significant caves occur in protected areas including national parks, national wildlife reserves, military reserves, Hawaii Natural Area Reserves, Nature Conservancy reserves, and other private protected land. Cave resource inventories and development of management plans with the necessary monitoring is on-going in many of these protected areas. Finally, two cave species facing imminent threat of extinction have been listed as endangered species, with delineation of critical habitats, and establishment of protected areas. Currently, the Cave Conservancy of Hawai`i and expansion of private, state, and federal protected lands are extending protection of Hawai`i's unique cave species.

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What cave species occur in Hawai`i, and where are they found?

Since the discovery of cave adapted invertebrates in Hawai`i Volcanoes National Park by Howarth in 1971, over 75 species of troglobites have been discovered on all the main Hawaiian islands. Counter to standard theories of cave species evolution, the youngest islands in the chain have the greatest number of species. Over 44 species occur on Hawai`i Island, the youngest at less than one million years old. Maui, at one to two million years old, has 19 species. Moloka`i, one to two million

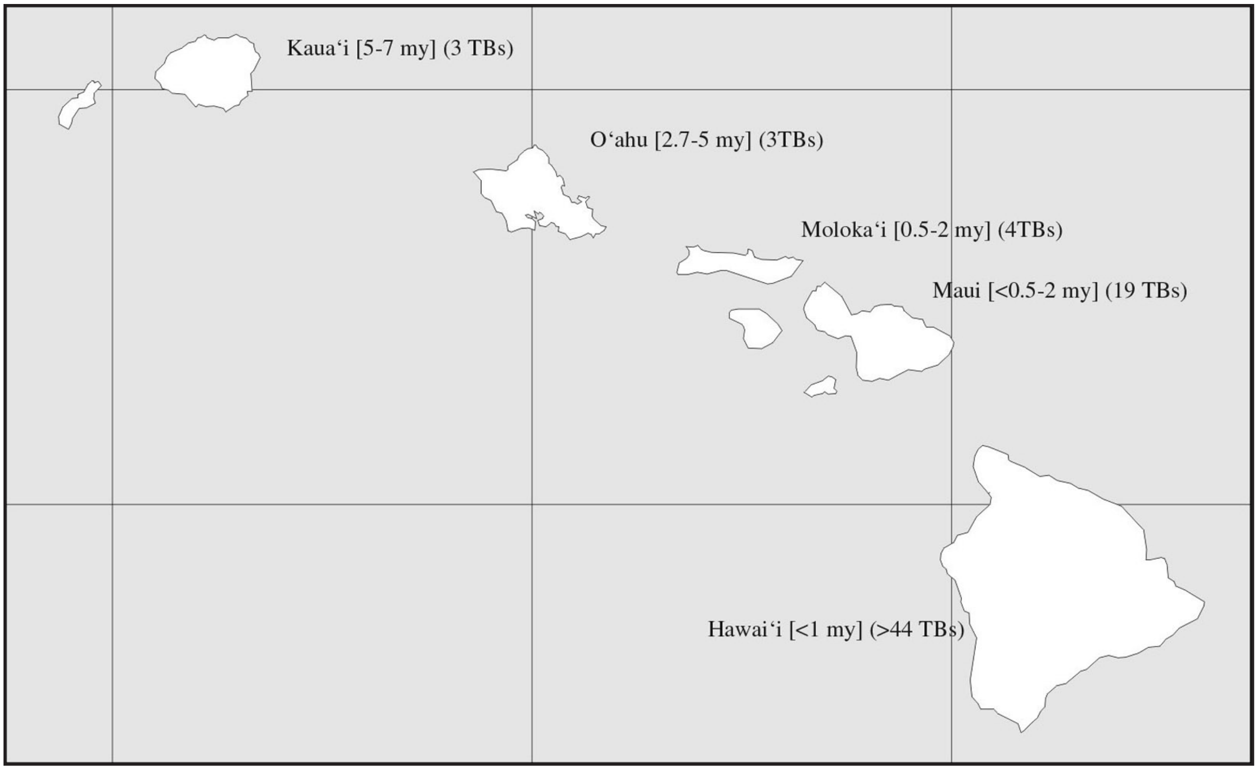

Figure 1. Map of main Hawaiian Islands with ages of major island building lava flows in brackets and numbers of terrestrial troglobites in parentheses.

years has four species, O`ahu, three to five million, and Kaua`i, five to seven million, have three species each. (Figure 1 and Table 1)

New cave species are still being discovered, and many cave species remain to be described. Furthermore, recent taxonomic studies using DNA, morphology, and behavior have shown that even those described in the past may include more than one species (Otte, 1994; Hoch and Howarth, 1993). Therefore, the number of species will continue to rise. In this paper, we will treat only the terrestrial species, but Hawai`i also has cave adapted aquatic species, mostly crustaceans, living in flooded interstices in lava and limestone near the coast. In the future additional marine, anchialine, and fresh water aquatic cave species will no doubt be discovered. Conservation and management of these coastal subterranean habitats raise similar issues as the terrestrial realm, but there are some unique concerns (Brock and Kam, 1997).

Like troglobites elsewhere, Hawaiian cave species live in an environment characterized by having calm air saturated with water vapor. This environment usually occurs only in deeper cave passages and intermediate-sized voids (mesocaverns) in cavernous rock deposits. The degree of cave adaptation and the diversity of species present are correlated better with the size of suitable habitat rather than age of the cave as had been assumed (Howarth, 1993; Hoch and Howarth, 1999). Hawai`i Island with its recent lava flows provides a vast subterranean system for cave life. Maui Island is intermediate in age and still has extensive areas of young lava. The older islands contain only relict caves, and few species persist. Most caves in Hawai`i are lava tubes (Peterson and others, 1994), but a few limestone caves occur on O`ahu, where there are raised coral reefs, and on Kaua`i in cemented coral sand dunes.

Why are cave-adapted species important?

Since the early 1970s, there has been a revolution in cave biology following the rediscovery of the lava tube fauna in Japan; the discovery of lava cave faunas in Hawai`i, Galapagos, Canary Islands, North America, and elsewhere; and the discovery of similar faunas in fractured rock terrains of diverse types, and of course in the tropics (Ueno, 1971; Howarth, 1983a; Juberthie, 1983). These faunas provide systems to independently test the evolutionary theories developed from the pioneering historic biospeleological studies done in temperate limestone caves (for example: Barr, 1968; Culver, 1982).

The Hawaiian Islands are an evolutionary laboratory ideally suited for study of troglobite evolution. (1) Cave species have evolved in a tropical, volcanic, oceanic island chain for which the ages of the islands are known. Evolution has occurred independently on each island (once cave adapted, cave species cannot survive on the surface, and movement between islands is impossible). (2) Closely related surface species are often extant in neighboring habitats, allowing comparison of epigean and cave adapted sibling species. (3) Lava flows reach from mountain ridges to the sea, and new lava flows and lava tubes continually form, allowing comparison of species at different elevations and in various lava tube ages. That is, troglobites occur in lava tubes from 2,400 meters elevation to the sea and from less than a year old to greater than 2 million years old. (4) Volcanoes of different ages and sizes occur on Hawai`i Island. The islands formed in sequence over the moving Pacific Plate, and are successively older to the northwest (Decker and others, 1987), allowing comparison of evolutionary processes among the islands. At least 12 taxonomic groups have independently adapted to cave life on more than one island, indicating that cave adaptation is a general process analogous to the adaptive shifts displayed by epigean species in the islands (Hoch and Howarth, 1999; Howarth and Hoch, 2005).

Howarth developed a bioclimatic model to explain the occurrence and evolution of cave species (Howarth, 1980). Five zones can be characterized by their abiotic and biotic environments: Entrance, Twilight, Transition, Deep Cave, and Stagnant Air Zones (Howarth, 1993). The extent of each zone is governed by the location, size, and shape of the entrances and passages; however, the boundaries between the zones are dynamic. The deep cave and stagnant air zones are usually found only deep within caves or beyond a passage constriction such as an n- or u-shaped deadend passage, which trap water vapor and carbon dioxide. Only a few caves extend into the stagnant air zone, but it is hypothesized that this is the environment characteristic of the mesocaverns (Howarth and Stone 1990). In both limestone and lava caves, obligate cave species are almost universally restricted to the two deeper zones, where the air remains saturated with water vapor. Many are found only in deadend passages beyond tortuous crawlways. The mesocaverns provide a large habitat for troglobite survival and dispersal.

Threats to cave species

Threats to cave species occur both on the surface and below the surface in the caves and mesocaverns. Surface alterations are caused by loss of native vegetation through land clearing, fires, and lava flows, introduced ungulates (feral pigs, goats, sheep, cattle) and other animals, alien invasive plants and diseases, mineral mining and quarrying, and other land use changes. Surface modification can also affect water resources in caves (for example: changes in drainage, impoundments, and stream channel changes). Subsurface alterations are caused by removal of entire caves, opening entrances, and alteration of cave entrances and passages that change the cave microclimate. Surface and underground pollution from human and animal waste, fertilizer, and pesticides can affect cave animals. Introduced species (rats, cane toads, cockroaches, millipedes) have invaded caves and prey on or compete with native species. People entering caves can disrupt the ecosystem by introducing toxins (for example, smoke) and other foreign materials, modifying passages to gain access thereby changing airflow, and damaging tree roots and other food resources Howarth, 1983b).

What is being done?

The problems of conserving Hawaiian cave adapted species were recognized from the time of their discovery in 1971 (Howarth, 1972; 1983b; Howarth and Stone, 1982). In 1978, Howarth initiated a proposal to protect two cave animals on Kaua`i, the no-eyed, big-eyed wolf spider (*Adelocosa anops*) and the terrestrial amphipod (*Spelaeorchestia koloana*) under the United States Endangered Species Act. The two species were formally listed in 2000. Stone presented a resolution supporting conservation of Hawaiian caves to the National Speleological Society Board of Governors in 1982, and this was followed by the establishment of the Hawai`i Cave Conservation Task Force (Howarth and Stone, 1982). Existing federal and state legislation protects native Hawaiian burials. Recently, a task force composed of native Hawaiians, cave owners, and cave scientists working with the Office of Historic Affairs under the Department of Land

and Natural Resources jointly developed a draft Hawai`i Cave Protection Act, which was passed by the state legislature after they strengthened the land owner section to require a written permission before cavers could enter caves.

Ideally, conservation of cave resources requires protection of the land overlying the caves through direct purchase by private conservancies or public agencies followed by elimination of introduced plant and animal species and restoration of the native vegetation. Cave management can then be based on the specific needs and threats to each cave, depending on the environment. For example on Kaua`i, limestone caves in fossil coral sand dunes were threatened by quarrying. The dune with the most important cave is now protected and quarrying was stopped. Non-native trees are being removed and native species (determined by a paleontological survey of the cave sediments) are being replanted. A few cave reserves have been established on private lands through conservation agreements.

Effective conservation programs are based on sound science developed through research. First, one needs to understand the systematics of the inhabitants; that is, how they are related to other animals. Systematics research determines whether a species is an alien invader or native, and if native, whether it is widely distributed in many caves or whether each population is distinct. Obviously, conservation actions should be based on such understanding. In fact, conservation biology programs can only be as good as the systematics upon which it is based. Clearly, conservation priorities differ according to whether troglobites are widespread in many caves across an island or separate species occupy each cave. The recognition that many Hawaiian cave adapted animals are restricted to a small area means that a variety of caves in as many areas as possible need to be protected to perpetuate the maximum level of biodiversity.

Research is also underway to develop effective management plans for protecting cave resources. A unique aspect of this research is to develop protocols to manage the surface environment to enhance the cave habitat below. The reason for this strategy is the fact that the main energy source for the ecosystem is plant roots that penetrate deep underground to obtain water and nutrients. In Hawaiian rainforests, the roots of native *`ohi`a lehua* trees (*Metrosideros polymorpha)* provide a major food source for cave species. A few other plant species are locally important, and a critical aspect for effective restoration is to identify plant roots in caves. In addition, monitoring protocols are being developed to determine long-term trends of sensitive cave populations.

Control of threats to caves and cave life that lie outside reserves is more difficult. These include prevention of garbage dumping and pollution of the caves and ground water by sewage and chemical contamination, and minimizing damage to caves from unrestricted entry by recreational cavers. These problems can be reduced through legislation and education. There is a dilemma posed with developing strategies for protecting cave resources: on one hand, one needs to make the resources known so that they will be less likely to be destroyed through ignorance during land use changes; however, publicizing the resources can lead to increased visitation and subsequent increased rate of destruction.

Howarth, Stone, and colleagues, working through B.P. Bishop Museum and within the auspices of the Hawai`i Cave Conservation Task Force have worked on cave inventories and management plans for a number of public and private land areas. These included military reservations on several islands, state Natural Area Reserves, National Parks, The Nature Conservancy of Hawai`i, and other private land. Following a detailed survey, a major cave on the island of Hawai`i was removed from the Agricultural Lots and re-zoned in conservation land. Cave inventories have also been conducted through the state and federal Environmental Assessment and Environmental Impact Statement processes, including an important biological and cultural cave threatened by geothermal development.

Additional cave surveys have been conducted by the Hawai`i Speleological Survey and the Hawai`i Grotto of the National Speleological Society. Recently the Hawai`i Cave Conservancy has purchased land containing a major cave on the island of Hawai`i.

Protection of land areas on the major Hawaiian Islands

Kaua`i is the oldest of the main Hawaiian Islands, and as already noted, has two endangered cave species. The U.S. Fish and Wildlife Service is developing a Recovery Plan for these species. Howarth has worked with private landowners to assist in establishment of three preserves protecting seven caves on 30 acres. Another cave entrance is being successfully protected as a "cave trap" in the middle of a golf course. The lithified coral sand dune at Mahualepu is being protected and native vegetation restored, as mentioned above.

On O`ahu several caves with cave species occur on military reserves, and Howarth has worked with the military to inventory the caves and make management recommendations. In one area, there are limestone caves in a raised coral reef.

Moloka`i and Maui have caves with cave species in the national parks, military reserves, state natural area reserves, and private land, including some owned or under lease by The Nature Conservancy. Surveys of the biology and paleontology have been conducted and management recommendations completed.

Hawai`i has the most caves and the longest lava tubes of any of the Hawaiian islands, and it also has the most cave species. These occur in national parks, national wildlife refuges, military reserve, state natural area reserves, state forest land, conservation zoned land, private land under control of the Cave Conservancy of Hawai`i, The Nature Conservancy, Kamehameha Schools, and numerous other land owners. Cave inventories, biological surveys, and management plans have been completed for Hawai`i Volcanoes National Park, Pohakuloa Military Training Area, Manuka Natural Area Reserve, and Kiholo Bay State Park among others.

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TABLE 1: NUMBERS OF TERRESTRIAL TROGLOBITES IN HAWAI`I

TAXA	HA	MA	MO	OA	KA
Crustacea: Amphipoda					
Talitridae (sandhoppers) *Spelaeorchestia*					1
Crustacea: Isopoda: Philosciidae (sowbugs)					
Hawaiioscia & Littorophilophiloscia	1	1	1	1	1
Arachnida: Acari (mites)					
Rhagidiidae: *Foveacheles*	1		1		
Arachnida: Araneae:					
Linyphiidae (sheetweb spiders) *Meioneta & Erigone*	>7	1			
Lycosidae (wolf spiders) *Lycosa & Adelocosa*	1				1
Oonopidae (six-eyed spiders) *Oonops*	1				
Theridiidae (cobweb spiders) *Theridion*	2	1			
Arachnida: Pseudoscorpionida: Chthoniidae					
Tyranochthonius		1		1	
Vulcanochthonius	3				
Myriapoda: Chilopoda					
Lithobiidae (rock centipedes) *Lithobius*	>1	1	1		
Myriapoda: Diplopoda					
Cambalidae (millipedes) *Nannolene*	>2	1			
Insecta: Collembola					
Hypogastruridae (springtails) *Neanura*	1				
Entomobryidae (springtails) *Sinella & Hawinella*	1	3		1	
Insecta: Orthoptera: Gryllidae (true crickets)					
Oecanthinae (tree crickets) *Thaumatogryllus*	2	2			
Nemobiinae (rock crickets) *Caconemobius*	>4	1			
Insecta: Dermaptera (earwigs)					
Carcinophoridae *Anisolabis*	1				
Insecta: Heteroptera					
Mesoveliidae (water treaders) *Cavaticovelia*	1				
Reduviidae (thread-legged bugs) *Nesidiolestes*	2				
Insecta: Homoptera: Cixiidae (planthoppers)					
Oliarus	>5	3	1		
Insecta: Coleoptera					
Carabidae (ground beetles) *Blackburnia & Tachys*	2	3			
Staphylinidae (rove beetles) *Nesomedon*	2				
Insecta: Lepidoptera					
Noctuidae (moths) *Schrankia*	>2	1			
Insecta: Diptera					
Phoridae (scuttle flies) *Megaselia*	2				
TOTALS	>44	19	4	3	3