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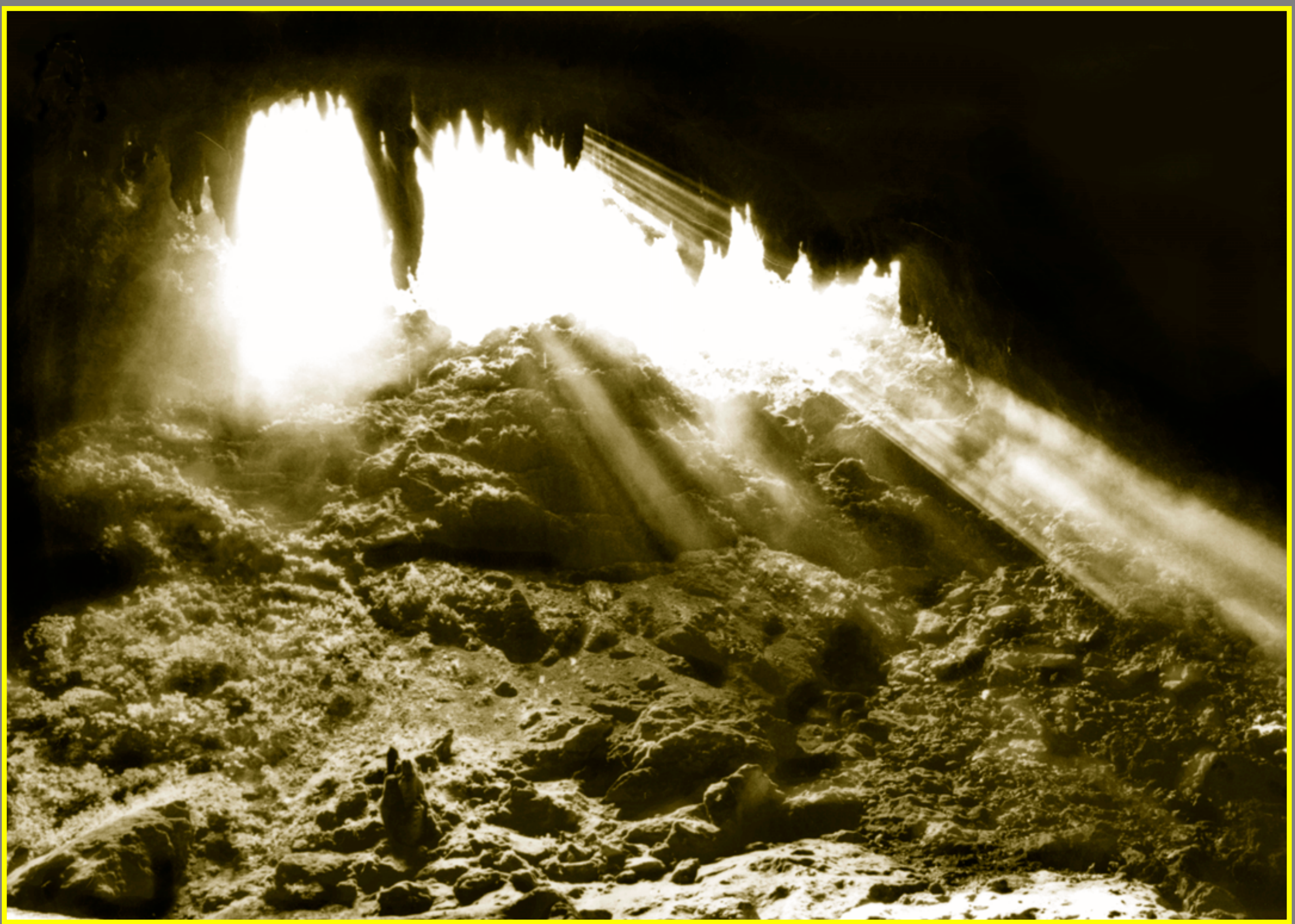

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Front cover: Main entrance of Clara Cave, Río Camuy Cave Park. See Nieves-Rivera, p. 22.

Stewart B. Peck and Margaret K. Thayer - The Cave-inhabiting rove beetles of the United States (Coleoptera; Staphylinidae; excluding Aleocharinae and Pselaphinae): Diversity and distributions. *Journal of Cave and Karst Studies, v. 65*, n. 1, p. 3-8.

THE CAVE-INHABITING ROVE BEETLES OF THE UNITED STATES (COLEOPTERA; STAPHYLINIDAE; EXCLUDING ALEOCHARINAE AND PSELAPHINAE): DIVERSITY AND DISTRIBUTIONS

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A taxonomic listing is given for new records of 66 species of staphylinid beetles (excluding Aleocharinae and Pselaphinae) collected in caves in the contiguous United States. Most species are judged to be either accidentals or infrequent troglophilic inhabitants of caves. Nine species are classed as frequent troglophiles. When added to the 6 frequent troglophile species of aleocharine staphylinids, this yields a total of 15 species of staphylinid beetles (excluding Pselaphinae) frequently found in US cave ecosystems. No troglobitic species are known from US caves. Troglobitic staphylinids (excluding Pselaphinae) elsewhere in the world are few (some 30 species). They are briefly considered and discussed. Worldwide, troglobitic staphylinids are taxonomically, geographically, and geologically concentrated in the Canary Islands (in volcanic lava tube caves) and in nearby Spain and northwestern Africa.

Worldwide, caves are most frequently and abundantly occupied by beetles in the families Carabidae, Leiodidae, and Staphylinidae. The first two of these families contain a great many cave-specialized and cave-restricted (troglobitic) genera and species in many parts of the world, mostly in Europe (Casale *et al*. 1998; Giachino *et al*. 1998). In contrast, very few cave-specialized or cave-restricted (troglobitic) staphylinid beetles are known. Jeannel and Jarrige (1949) summarized data on about 150 species of Staphylinidae from over 1000 caves worldwide and considered very few of these species to be troglobites. Recent reviews by Bordoni and Oromi (1998) and Outerelo *et al*. (1998) list only 30 troglobitic species worldwide, and most of these are from Europe and North Africa. None are from the USA.

Most staphylinid beetles are distinctive in their appearance, with an exceptionally elongate and flexible body form and very short elytra (front wing covers) over their hind wings (Figs. 1–6). Their English common name, "rove beetle," comes from their behavior of rapidly running about in many directions. Some species in the family are eyeless and without flight wings, but other than the few cave species, these are mostly small to minute litter- or soil-inhabiting species. This beetle family is one of the world's largest, with some 4100 species recorded in the USA and Canada, and over 47,000 species known to science worldwide (Newton *et al*. 2000). Recently, the traditional beetle families Scaphidiidae and Pselaphidae have been combined with the family Staphylinidae, and each is now treated as a subfamily (Kasule 1966; Newton & Thayer 1995). These two groups are not included in the following discussions, which are restricted to the subfamilies traditionally placed in the Staphylinidae. Pselaphines are known from many caves, especially in the USA (Chandler 1992; Chandler & Reddell 2001) and Europe (Poggi *et al*. 1998). Some 53 species of them in 8 genera are considered to be troglobites in the USA (Peck 1998; Chandler & Reddell 2001). We are not aware of any cave records for scaphidiines, which are strictly mycophagous as far as known (Leschen & Löbl 1995), and they seem unlikely to be cave-associated.

Staphylinid beetles occur frequently and commonly in caves in the United States. The published records of staphylinids from US caves are many and scattered in numerous regional and state cave faunal reports. These have been summarized by Roth (2001). After many years of faunal surveys of many caves by many people, no troglobitic species (outside Pselaphinae) have been found in the USA. It now seems most likely that none will be found in the future.

Identification of species in this very large beetle family is difficult and time consuming, even for the specialist, and since troglobitic species are not known from the US, staphylinid beetles have often received little or no specific attention in surveys of cave insect diversity. For these reasons, we have a very scattered and incomplete knowledge of which species of staphylinid beetles are frequent inhabitants of US caves and components of cave ecosystems.

Klimaszewski and Peck (1986) presented a comprehensive systematic report on the cave-inhabiting aleocharine staphylinids of the USA. The aim of this paper is to complement that report and the literature summary of Roth (2001). We present a systematic summary of new records of authoritatively identified species of Staphylinidae (excluding Aleocharinae and Pselaphinae) from cave localities throughout the USA. This documentation of the species diversity and distribution of these staphylinid beetles helps to complete an understanding of this previously poorly known part of the fauna of US caves.

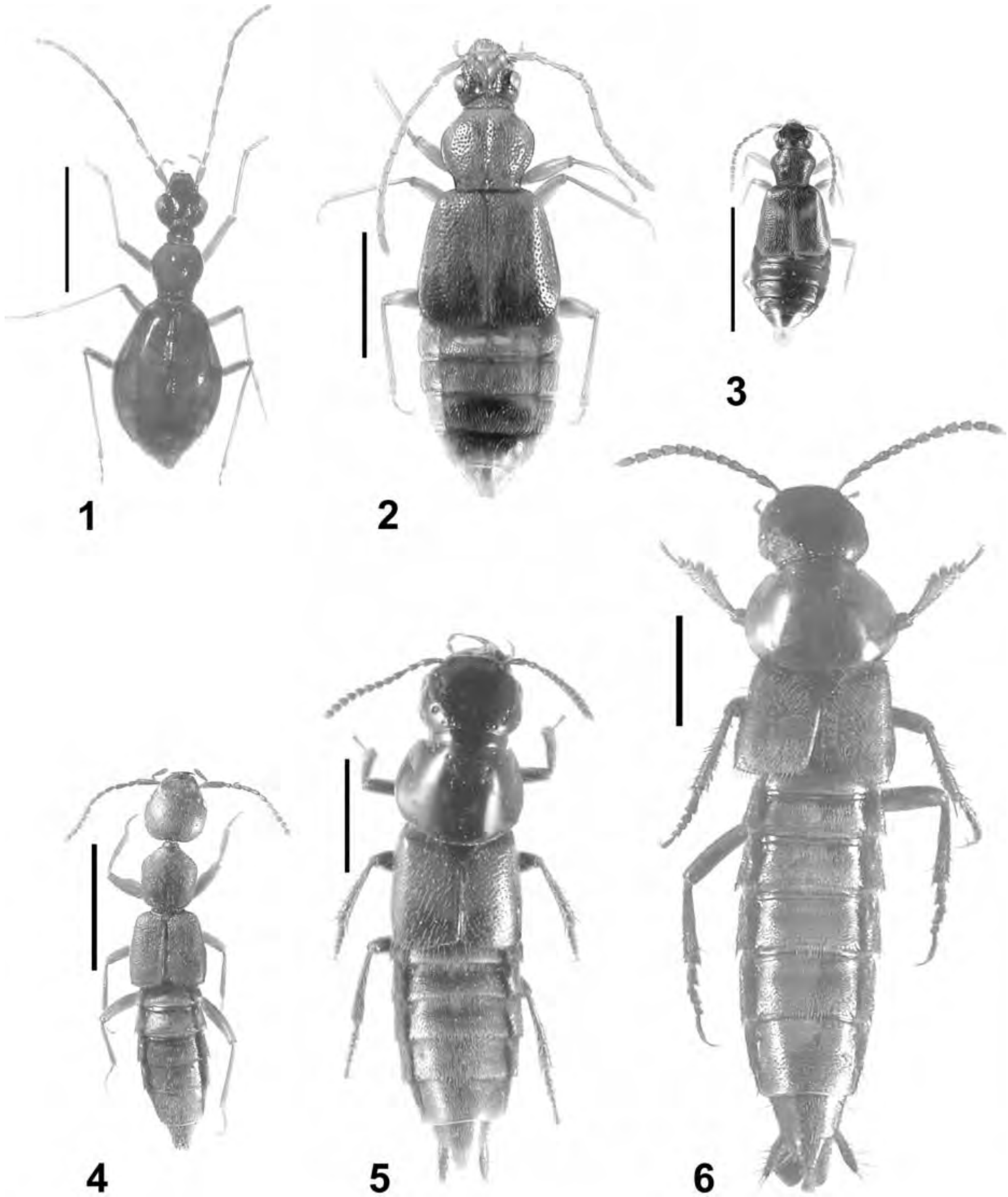

Figure 1. ***Brathinus nitidus.***

Figure 2. ***Geodromicus brunneus.***

Figure 3. ***Lesteva pallipes.***

Figure 4. ***Eustilicus condei.***

Figure 5. ***Quedius erythrogaster.***

Figure 6. ***Quedius spelaeus.***

All scale lines are 2.0 mm.

MATERIALS AND METHODS

Staphylinid beetles are usually collected in caves by general searching and hand collecting, or by setting bait stations and baited pitfall traps. The beetles usually feed as generalized predators on small terrestrial invertebrates and are most frequently found at or near decaying organic matter, which attracts their prey items. Most of the records reported here have been collected by the first author over many years of field work in US caves. Many additional records are included which were made by many other collectors, and these people are thanked in the acknowledgments. This paper reports on 611 collections and 2185 specimens. All specimens reported here have been seen by one of the authors and most specimens are in the collections of the Field Museum of Natural History, Chicago, IL, USA; the American Museum of Natural History, New York, NY, USA; or the Canadian National Collection of Insects, Agriculture Canada, Ottawa, Ontario, Canada.

Identifications were made by the authors, J.M. Campbell, A. Smetana, A. Davies, and A.F. Newton. The species records are arranged in putative phylogenetic sequence by subfamily, tribe, and subtribe following Newton *et al*. (2000, which also provides authorities for generic and family group names) and alphabetically by genus and species. Only records that have been determined to species by a staphylinid taxonomist are given, with names updated where needed, following Herman (2001; all except Paederinae) and an unpublished database maintained by A.F. Newton. There are additional unidentified specimens in the above and other collections, especially the Illinois Natural History Survey, but it is unlikely that they contain any additional species of frequently occurring troglophiles not listed here. Full label data such as date of collection, name of collector and other label information are available as Access or other digital files from the authors. Frequently, a species has been taken many times in a cave and by the same or other collectors on many separate occasions. Such duplicate records are not indicated.

Frequency of association of the species with cave habitats is given as (1) "accidental" (for which there about 5 records or fewer and there is no apparent or regular association with cave habitats) or (2) as "troglophile" (having an apparently regular association with dark-zone cave habitats, and for which there are usually more than 5 records). The troglophiles are further divided into the subcategories of (2A) "infrequent troglophiles" (with ~5-10 cave records) and (2B) "frequent troglophiles" (for which there are generally many >10 cave records). These categorizations are subjective, and may be modified by the accumulation of additional data; in particular, more records may elevate some infrequent troglophile species into the category of frequent troglophiles. Supplementary data available at http://www.caves.org/pub/journal/Peck-Thayer Appendix.rtf include a brief summary of the general distribution of the species, microhabitat associations of the species in caves when known or suspected, and, for species previously reported from caves, a list of state abbreviations as a summary of previous records (see Roth 2001).

RESULTS

No cave-limited or cave-evolved species (troglobites) have been found in caves in the contiguous USA. In a world list of troglophilic Staphylinidae, Bordoni and Oromi (1998) list 44 species, 8 of which are from the USA. From the data reported here, 9 species of staphylinids (excluding Aleocharinae and Pselaphinae) are considered to be regularly occurring or frequent troglophiles in US caves. Adding these to the data on the 6 frequently occurring troglophilic species of Aleocharinae (from Klimaszewski & Peck 1986) and that presented in Roth (2001), 15 species of frequently occurring troglophile staphylinids are now known from US caves. Their names and general geographical distributions in caves are in Table 1. Species judged to be infrequent troglophiles or accidentals in US caves are listed in Table 2. Full data on cave names for all specimen records are at
http://www.caves.org/pub/journal/Peck-Thayer Appendix.rtf

It is interesting to note that of the species in Table 1, *Quedius fulgidus* and *Quedius mesomelinus* were probably accidentally introduced into North America (Smetana 1971). They are, thus, historically recent additions to the fauna of US caves. At present, they seem to be geographically and ecologically peripheral in US cave ecosystems, although at least the last species is also troglophilic in Europe (Outerelo *et al*. 1998), with some populations possibly being subtroglobitic (Hennicke & Eckert 2001). The total taxonomic and numerical abundance of terrestrial predators in US cave ecosystems would have been less before the accidental introduction of these species into North America. It is evident that these species have found niche space in US cave habitats, but there is no present evidence that they displaced other terrestrial predators from US caves. Rather, they have slightly enriched the diversity of terrestrial insect predators in US cave ecosystems.

DISCUSSION

Staphylinids in caves. Staphylinids are an ecologically very diverse group of beetles.

Nevertheless, most occupy habitats that are moist and have very low light levels. This general preference would seemingly preadapt them for life in caves. However, in view of the great number of species known from the USA, comparatively few have actually been found to establish populations in caves. This may be because they are somehow restricted by microhabitat requirements, by food types, by competition with already-established species, or perhaps by a need for environmental temperature fluctuations. Alternatively, those that do occur regularly in caves might do so because (1) they are more omnivorous or tolerant of the limited foods available in caves, or (2) caves present suitable extensions of the microhabitats they favor in non-cave environments, or (3) they are tolerant of the dark, humidity, and relatively constant temperatures of caves.

Distributional patterns. A few of the records represent new state records for the species, which is not unexpected in a group of beetles that has not been well studied. Some troglophiles appear to be more prevalent in caves in the southern part of their ranges than in the northern parts. It is assumed that this is because more southerly caves offer cooler and moister habitats than are generally found outside of caves, and the troglophiles use caves more frequently in the south as environmental refuges. This pattern is present in at least *Brathinus nititdus*, *Lesteva pallipes*, *Quedius erythrogaster* and *Q. fulgidus* and may occur in other troglophilic staphylinids, but distributional data are not adequate to demonstrate its generality.

The problem of defining a troglobitic staphylinid. In a world list of 29 species of troglobitic Staphylinidae, Bordoni and Oromi (1998) note that categorizing a staphylinid as a troglobite is not as easy or clear-cut as for some other groups of cave insects. Outerelo *et al*. (1998) add one additional

Table 1. Staphylinidae frequently occurring as troglophiles in US caves. Additional supportive data are at http://www.caves.org/pub/journal/Peck-Thayer Appendix.rtf and also available from the NSS library and NSS archives (see masthead for NSS address).

Omaliinae: Anthophagini
- *Geodromicus brunneus* (Say, 1823): eastern-central USA; from VA and IL south to OK and GA. Fig. 2.
- *Lesteva pallipes* LeConte, 1863: eastern-central USA; from IA and MD south to AR and GA. Fig. 3

Aleocharinae
- Aleocharini
  - *Aleochara* (*Echochara*) *lucifuga* (Casey, 1893): eastern-central USA; PA and IA to VA and AL.
- Athetini
  - *Aloconota laurentiana* Blatchley, 1910, (reported as *Aloconota insecta* (Thomson, 1856) in Klimaszewski and Peck (1986), by Gusarov 2001): eastern-central USA; NY and IL to MO, VA, and AL.
  - *Atheta* (subgenus undetermined) *annexa* Casey, 1910: eastern-central USA; IA and VA to MO, GA, and FL.
  - *Atheta* (*Dimetrota*? subgenus uncertain) *lucifuga* Klimaszewski and Peck, 1986: eastern-central USA; MO and KY to GA and FL.
  - *Atheta* (*Dimetrota*) *troglophila* Klimaszewski and Peck, 1986: eastern-central USA; PA and IA to AR, GA, and FL.
- Oxypodini
  - *Blepharrhymenus illectus* (Casey, 1911): central to south eastern USA; MO to TN and AL.

Paederinae: Paederini: Stilicina
- *Eustilicus condei* (Jarrige, 1960): southwestern USA; TX and NM. Fig. 4.

Staphylininae: Staphylinini
- Quediina
  - *Quedius erythrogaster* Mannerheim, 1852: OR, CA, and eastern states; IL to NY and south to TN and AL. Fig. 5.
  - *Quedius fulgidus* (Fabricius, 1792): eastern USA; IL to PA and south to AL and AR.
  - *Quedius mesomelinus* (Marsham, 1802): northcentral-north eastern USA; MN to PA south to IA and VA
  - *Quedius spelaeus* Horn, 1878: widespread eastern-central and western USA; MN to NY and south to MO and VA; also WA to WY and south to CA and UT. Fig. 6.
- Philonthina
  - *Belonuchus aphaobius* Smetana, 1995: southwestern USA; central TX.
  - *Belonuchus troglophilus* Smetana, 1995: southwestern USA; AZ, OK, TX.

species (*Anotylus subanophthalmicus*) to bring the total to 30 species. Some of these species may actually be endogeans (species whose primary habitat is in either soil or deep rock cracks and crevices or the superficial subterranean zone). For such species, caves are only secondary habitats. Many eyeless and wingless endogean species are known worldwide. They frequently occur in regions with Mediterranean-type climates and are most often collected by soil-washing techniques (Campbell & Peck 1990). Because of their limited dispersal abilities, many endogean species may be useful indicators of past regional biogeographic history. For example, Campbell and Peck (1990) suggest that the eyeless and flightless endogean species *Omalonomus relictus* is evidence that the Cypress Hills of southern Alberta and Saskatchewan, Canada, were not ice-covered during times of Pleistocene glaciations.

Where do troglobitic staphylinids occur? The distributions of the 30 species of supposed troglobites listed by Bordoni and Oromi (1998) and Outerelo *et al.* (1998) are as follows: Canary Islands and Madeira Island, 12; Morocco, 7; Spain, 4; Algeria, 2; Italy, 1; Romania, 1; Galapagos Islands, 1; Mexico, 1; and India, 1. There are 3 notable patterns of species concentration in this list. The first is the *taxonomic* concentration of 15 species in the genera *Domene* and *Apteranopsis* in the Canary Islands and nearby Spain and northwestern Africa (see below). The second is the *geographic* concentration of 25 species in the Canary Islands and the western Mediterranean region of Spain and North Africa. The third is the *geologic* concentration of 13 species in lava tube caves on oceanic volcanic islands of the Canaries, Madeira, and the Galapagos. Statistically, there is a much higher frequency of troglobites in volcanic cave habitats than would be normally expected, since volcanic caves on islands are certainly much rarer habitats than are solution caves in limestone on continents. Additionally, volcanic (lava tube) caves are thought to be much younger than limestone solution caves. While this may be true on a cave by cave basis, we would argue that volcanic landscapes themselves may generally be as old as limestone karst landscapes as sites for origins of troglobitic species.

What is the evolutionary origin of troglobitic staphylinids? About half of the troglobitic staphylinids are scattered in various genera. Thus, these troglobites have evolved independently from several ancestral stocks in several different regions, and probably at different times. But there may have been some general or common adaptive theme in their cave specialization. The species in the western Mediterranean region may represent subterranean occupation by diverse ancestors in response to regional Pleistocene interglacial climatic change and increasing aridity, as is widely thought for so many troglobitic arthropods. This explains multiple adaptations to subterranean habitats in many different ancestral lines. However, 2 taxonomic patterns are also present. The paederine genus *Domene* is represented by 9 troglobitic species in Spain, the Canary Islands, and Morocco, and the aleocharine genus *Apteranopsis* by 6 species in the Canary Islands. These 2 genera have been the most successful in penetrating and speciating in cave habitats. Secondly, a total of 11 of these species are in the Canary Islands. This concentration must be meaningful. Seemingly these isolated, oceanic, and volcanic islands have a different ecological structure or history in their subterranean habitats that collectively allowed more formation of troglobitic species of staphylinids than any other region in the world.

Perhaps the abundance of carabid beetle predators elsewhere in the world has suppressed the evolution of troglobitic staphylinids; that is, the niche of troglobitic predatory beetles may be filled by carabids nearly worldwide. But at least 4 species of troglobitic trechine carabids are known from the Canary Islands (Casale *et al*. 1998), so this cannot be the full answer. Additionally, the relative proximity of these islands to

Table 2. Staphylinidae judged to be infrequent troglophiles or accidentals in US caves. Additional supportive data are at http://www.caves.org/pub/journal/Peck-Thayer Appendix.rtf and also available from the NSS library and NSS archives (see masthead for NSS address).

Subfamily Omaliinae
Tribe Omaliini
Omalium rivulare (Paykull, 1789), accidental.
Tribe Anthophagini
Brathinus nitidus LeConte, 1852, infrequent troglophile. Fig. 1.
Lesteva cribratula (Casey, 1894), infrequent troglophile.
Olophrum obtectum Erichson, 1840, accidental.
Orobanus ?simulator LeConte, 1878, accidental.
Subfamily Proteininae
Megarthrus americanus Sachse, 1852, accidental.
Subfamily Tachyporinae
Tribe Deropini
Derops divalis (Sanderson, 1947), infrequent troglophile.
Tribe Tachyporini
Coproporus laevis LeConte, 1863, accidental.
Nitidotachinus horni (Campbell, 1973), accidental.
Nitidotachinus scrutator (Gemminger & Harold, 1868), accidental.
Sepedophilus crassus (Gravenhorst, 1802), accidental.
Sepedophilus littoreus (Linnaeus, 1758), accidental.
Sepedophilus opicus (Say, 1832), accidental.
Tachinus canadensis Horn, 1877, accidental.
Tachinus fimbriatus Gravenhorst, 1802, accidental.
Tachinus frigidus Erichson, 1839, accidental.
Tachinus fumipennis Say, 1832, accidental.
Tachyporus jocosus Say, 1832, accidental.
Tribe Mycetoporini
Lordithon obsoletus (Say, 1832), accidental.
Subfamily Trichophyinae
Trichophya pilicornis (Gyllenhal, 1810), accidental.
Subfamily Oxytelinae
Tribe Deleasterini
Deleaster trimaculatus Fall, 1910, accidental.
Tribe Oxytelini
Anotylus exiguus (Erichson, 1840), accidental.
Anotylus insignitus (Gravenhorst, 1806), accidental.
Anotylus tetracarinatus (Block, 1799), accidental.
Oxytelus nimius Casey, 1894, accidental.
Subfamily Steninae
Dianous chalybeaus LeConte, 1863, accidental.
Stenus (*Tesnus*) *alacer* Casey, 1884, accidental.
Stenus (*Stenus*) *bilentigatus* Casey, 1884, accidental.
Stenus (Stenus) *renifer* LeConte, 1963, accidental.
Subfamily Paederinae
Tribe Paederini
Subtribe Lathrobiina
Lathrobium (*Tetartopeus*) *angulare* LeConte, 1863, accidental.
Lathrobium (*Apteralium*) *brevipenne* LeConte, 1863, accidental.
Lobrathium gnoma (Casey, 1905), accidental.
Subtribe Scopaeina
Orus (*Leucorus*) *rubens* (Casey, 1905), accidental.
Subtribe Stilicina
Eustilicus tristis (Melsheimer, 1844), infrequent troglophile.
Rugilus dentatus Say, 1831, accidental.
Rugilus opaculus (LeConte, 1880), accidental.
Subtribe Cryptobiina
Homaeotarsus badius (Gravenhorst, 1802), accidental.
Homaeotarsus bicolor (Gravenhorst, 1802), accidental.
Homaeotarsus capito (Casey, 1884), accidental.
Homaeotarsus carolinus (Erichson, 1840), accidental.
Homaeotarsus cinctus (Say, 1830), accidental.
Homaeotarsus pimerianus (LeConte, 1863), accidental.
Subtribe Paederina
Paederus littorarius Gravenhorst, 1806, accidental.
Subfamily Staphylininae
Tribe Xantholinini
Neohypnus obscurus (Erichson, 1839), accidental.
Stenistoderus rubripennis (LeConte, 1880), accidental.
Tribe Staphylinini
Subtribe Quediina
Heterothops campbelli Smetana, 1971, accidental.
Quedius capucinus (Gravenhorst, 1806), accidental.
Quedius laticollis (Gravenhorst, 1802), accidental.
Quedius montanicus (Casey, 1915), accidental
Subtribe Philonthina
Erichsonius nanus (Horn, 1884), accidental.
Erichsonius patella (Horn, 1884), accidental.
Erichsonius pusio (Horn, 1884), accidental.
Gabrius micropthalmus (Horn, 1884), accidental.
Hesperus baltimorensis (Gravenhorst, 1802), accidental.
Neobisnius paederoides (LeConte, 1863), accidental.
Neobisnius sobrinus (Erichson, 1840), infrequent troglophile.
Philonthus caeruleipennis (Mannerheim, 1830), accidental.
Philonthus thoracicus (Gravenhorst, 1802), accidental.

continental sources of colonist species also seems important–e.g., no troglobitic staphylinids are found in the Hawaiian Islands. Another potentially important factor is the availability of suitable habitats outside of caves. If the habitats are highly suitable for staphylinids, there would be less selective pressure for staphylinids to occupy and become isolated in cave environments. This might well be important because of the general aridity of the islands and areas which do posses troglobitic staphylinids. Increasing regional aridity would tend to make caves distinctly more "attractive" to moisture-loving insects such as staphylinid beetles.

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A CONSERVATION FOCUSED INVENTORY OF SUBTERRANEAN INVERTEBRATES OF THE SOUTHWESTERN ILLINOIS KARST

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In 1998-1999 The Nature Conservancy conducted a bioinventory of caves in Monroe and St. Clair counties in southwestern Illinois. This karst area comprises a small section of the Ozark Plateau isolated from the Missouri Ozarks by the Mississippi River. In the 71 sites that were sampled, 41 species thought to be globally rare were found and were assigned state (S) and global (G) ranks of rarity for conservation use. The list includes 10 species considered to be new to science and 12 species previously unreported from Illinois. Twenty four taxa were classified as obligate subterranean species, including four endemic species: the pseudoscorpion Mundochthonius cavernicolus, *the amphipod* Gammarus acherondytes, *the milliped* Chaetaspis *sp. (undescribed), and the dipluran* Eumesocampa *sp. (undescribed).* Gammarus acherondytes, *recently listed as an endangered species, was found in six previously unsampled caves. All sites were rank-ordered according to the number of global and state rare species. The greatest single site diversity was found in Fogelpole Cave with 18 global and 20 state rare species. The highest subterranean drainage system diversity was found in the Danes/Pautler Cave System with 20 globally rare species. Fogelpole Cave also had the highest number of troglobites with 14 species. The Danes/Pautler Cave System again had the highest number of troglobites found in a groundwater system with 16 species.*

In 1978 S.B. Peck and J.J. Lewis presented the first comprehensive list of subterranean invertebrates in Illinois. This list was the result of fieldwork done by Peck from 1966-1968, and Lewis from 1972-1976. In 1976 Lewis' work for the Illinois Natural Areas Inventory recommended several caves from the western Illinois "sinkhole plain karst" (SHPK) for conservation. This eventually became a reality with the creation of Fogelpole Cave and Stemler Cave nature preserves, the Armin Krueger Speleological Preserve, and Illinois Caverns State Natural Area. Despite these efforts, progressive urbanization of the SHPK due to the proximity of St. Louis, Missouri, was having an increasing impact on the caves and subterranean fauna of the area. With the growth in human population, groundwater contamination had become a growing reality, leading to several projects to define the kinds, sources and spatial relationships of groundwater contamination in the western Illinois karst (Panno *et al.* 1996, 1997, 1998, 1999; Taylor *et al.* 2000). Extensive dye tracing was also conducted to delineate the recharge areas of springs in the area (Aley & Aley 1998; Aley *et al.* 1999).

Much attention was drawn to the SHPK by the listing of the Illinois cave amphipod, *Gammarus acherondytes*, as an endangered species. Webb's (1995) report on the status of this unique amphipod, the only troglobitic species of *Gammarus* currently described in North America, became the foundation for its listing in 1998. We suspected that some other troglobitic species were present, but yet undetected in the area, and that others known to be present were more widespread than had been demonstrated, possibly including *Gammarus acherondytes*. In 1998 The Nature Conservancy initiated a bioinventory project to gather more data on the status of cave invertebrates in Monroe and St. Clair counties (Lewis *et al*. 1999). The goal of this paper is to present the results of this bioinventory to support cave and karst conservation efforts in Illinois.

PROJECT AREA

The SHPK (Fig. 1) consists of an area of the Salem Plateau section of the Ozark Plateau physiographic province isolated through dissection by the Mississippi River, which left this island of karst east of the river (Willman *et al.* 1975). In St. Clair and Monroe counties, just southeast of St. Louis, a well developed karst is present with three somewhat distinct subunits. These are the: (1) Columbia, (2) Waterloo, and (3) Renault karst areas.

The Columbia karst is the most isolated, with the separation visible on topographic maps as a swath of land devoid of sinkholes. This area coincides with the Waterloo-Dupo Anticline. Stemler Cave as well as dozens of smaller caves occur in this area just to the northeast of Columbia.

The Waterloo karst area includes the Pautler Cave System (includes the recently connected Pautler and Danes caves, with 8.3 kilometers of mapped passage) that resurges via Icebox

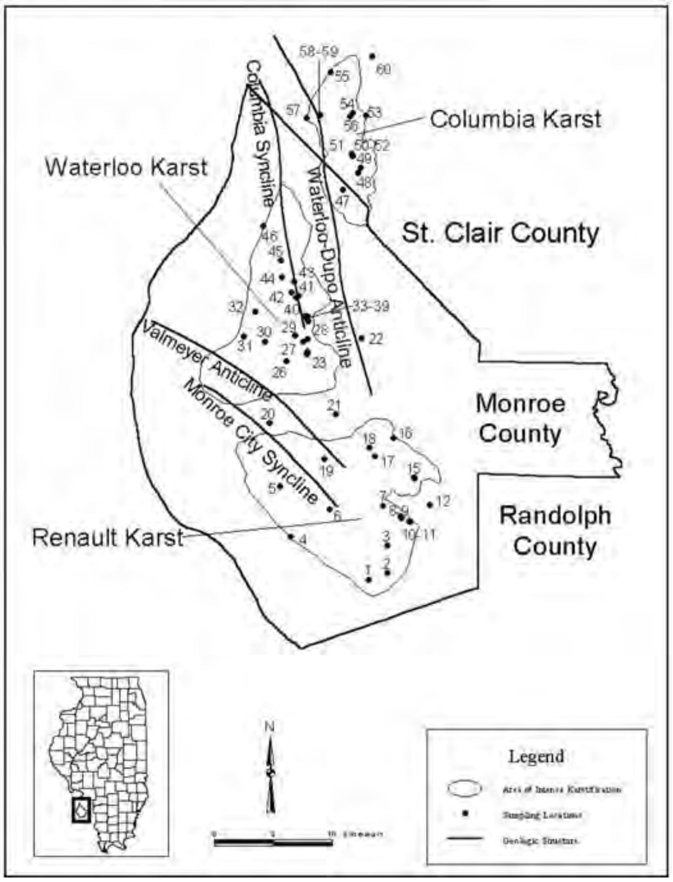

Figure 1. Key to Sampling Locations in the Sinkhole Plain: 1 Couchs Cave; 2 Jacobs Cave; 3 Wannabe Karst Window Cave; 4 Saltpeter Cave; 5 Wandas Waterfall Cave; 6 Juelfs Cave; 7 Fogelpole Cave; **8** Myrons Misery Cave and Bat Sump Cave; **11** Collier Spring and Karst Window; 12 Frees Well; 13 Walsh Seep; 14 Walsh Spring; 15 Walsh Cave; 16 Kelly Spring Cave (Dual Pit); 17 Illinois Caverns; 18 Spider Cave; 19 Metter Cave; 20 Madonnaville Cave; 21 Voelker Well; 22 Belle Fontaine; **23** Danes Cave, Danes Annex Cave, and Dirks Cave; 26 Cedar Ridge Cave; 27 Rose Hole; 28 Pautler Cave; 29 Wednesday Cave; 30 Frog Cave; 31 Trout Hollow Spring 32 Bicklein Cave; **33-38** Camp Vandeventer karst window, Camp Vandeventer Cave = Ice Box Cave, Camp Vandeventer Spring, Connecting Crevice Cave, Hidden Hand Cave, Little Cave, and Fountain Creek pump-well; 40 Antler Cave; **41** Two Row Cave and Antler Cave; 42 Bat Love Cave; 43 Andy's Run Cave; 44 Maya Spring; 45 Schipps Well; 46 Terry Spring; 47 Haney Spring; 48 Browns Cave II; 49 Dashed Hopes Pit; **50-52** Stemler well, Stemler Cave, Stemler Cave (Harres Pit); 53 Spring Valley Spring; 54 WH Spring and Karst Window; 55 Falling Springs; 56 Sparrow Spring; 57 Imbs Station Road Spring; 58 Pipe Spring; 59 Cement Hollow Spring; 60 drain tile.

Note: a **bold** number corresponds to multiple sampling locations on the figure

Cave at the Camp Vandeventer boy scout camp. The Renault karst area encompasses Fogelpole Cave (the longest cave known in Illinois with 24 kilometers of passages mapped), Krueger-Dry Run/Spider/Kelly Spring Cave System (8 kilometers), and Illinois Caverns (8.6 kilometers). Several of these sites were discussed by Bretz and Harris (1961).

FIELD WORK: METHODS

The following list presents collection records from a total of 71 sites, including 39 caves, 20 springs, 5 wells, 4 karst windows and 3 drain tiles (approximate locations are provided in Figure 1). The sampling was conducted between 20 June 1998 and 7 July 1999. The sites were sampled as appropriate using hand collecting, limburger cheese-baited pitfall traps, Berlese extraction of leaf litter, plankton netting of aquatic habitats, and placement of shrimp-baited jar traps in deep water habitats. The collected material was deposited in the institutional collections of the taxonomists identifying the specimens.

ANNOTATED LIST OF FAUNA

For each species the following list provides scientific name and author, ecological classification, common name for species of conservation interest (obligate subterranean species or species of high global rarity), localities and a suggested state and global rank of rarity. Taxa not identified to the species level or felt to be accidentals were eliminated from the list due to their limited conservation value. Our sources and definitions are as follows.

Common names are now required by many agencies and were obtained from published sources if available (e.g., Turgeon *et al*. 1998), suggestions from taxonomists, or coined if otherwise unavailable.

As discussed by Camacho (1992), the literature is replete with nomenclature for the ecological classification of subterranean organisms. Prominent among these are classification schemes using a variety of terms including troglobite (Schiner 1854, Racovitza 1907), stygobite (Thienemann 1925, Motas 1962, Viets 1959), troglomorph (Christiansen 1962), stygobiont (Husmann 1971) and stygicole (Chapman 1986). We have chosen to avoid this nomenclatural chaos by following (Table 1) the simple classification used by Peck and Lewis (1978) until a clearer consensus of classification emerges.

Localities listed are comprehensive, with known records cited, then new records given in alphabetical order by county.

One contribution of this paper intended to facilitate conservation use is the presentation of a suggested state and global rank of rarity (S and G-ranks, respectively). The basis for these ranks is the number of sites from which the species is known (Table 2). The definition of element (species) occurrence must be determined for each animal since barriers to dispersal differ from species to species. Thus, for *Ergodesmus remingtoni*, three sites that are physically separated to human entry (e.g., Danes, Pautler & Icebox caves) are easily connect-

Table 1. The ecological classification of cavernicoles as defined by Barr (1963, 1968) and Peck and Lewis (1978):

Classification	Abbreviation	Brief definition
troglobite	TB	obligate cavernicoles, live/reproduce only in caves
troglophile	TP	facultative cavernicoles, may live/reproduce in caves
trogloxene	TX	cave "visitors", must leave the cave at some point in life cycle
accidental	AC	enter caves only by accident
edaphobite	ED	soil inhabitant that may occur in caves
phreatobite	PB	groundwater animal that may occur in caves
parasite/commensal	PS	an organism that lives obligately in/on another

Table 2. Element occurrence criteria for assigning state and global rarity rankings

Rank	Criteria	Description
S1 – G1	<5 localities in Illinois / globally	critically imperiled
S2 – G2	6-20 localities in Illinois / globally	imperiled
S3 – G3	21-100 localities in Illinois / globally	vulnerable
S4 – G4	>100 localities in Illinois / globally	apparently secure
S5 – G5	widespread and common from many localities	secure
SE	exotic (introduced) species	

ed by the millipeds and thus considered a single element occurrence. After occurences are determined the rank can be modified accordingly if the biotic potential (frequency of reproduction, number of offspring, life span) of the species is particularly high or low. Another common reason for modification of a ranking occurs with analysis of threats, such as loss of known populations due to environmental degradation (e.g., *Gammarus acherondytes*). Animals like the Illinois cave amphipod, with a very restricted range, are more sensitive to localized threats and are afforded a lower ranking. For a few species endemic to the southwestern Illinois karst all of the known sites are listed and the S/G ranks are apparent. For the other more widespread taxa listed, the rank was suggested based on the opinion of the taxonomists identifying the material (including their knowledge of unpublished records) and published sources. In the final analysis ranking remains somewhat subjective and conservation oriented agencies typically develop criteria for ranking based on criteria beyond the scope of this paper. A detailed discussion of ranking criteria is presented by Stein *et al*. (2000).

After the S/G rank a brief narrative is given to present range or occurrence information for each species and citations as deemed appropriate. G5 species are so widespread as to require no further information. Important sources by which S/G ranks could be evaluated were the Illinois cave bioinventories of Peck and Lewis (1978) and Webb *et al*. (1994). Also used were the checklists for cave faunas of Kentucky (Barr 1967), Indiana (Lewis 1983, 1998), Missouri (Gardner 1986), and the Driftless area (Peck & Christiansen 1990). In the interest of conservation of space a telegraphic style has been used in many cases to convey habitat and range information. Much of the information on species of lesser conservation interest has been placed in Table 3.

PHYLUM PLATYHELMINTHES
CLASS TURBELLARIA
ORDER TRICLADIDA
FAMILY KENKIIDAE

Sphalloplana hubrichti (Hyman) TB Hubricht's cave flatworm

Monroe Co.: Fogelpole, Juelfs, Spider caves, Illinois Caverns (Peck & Lewis 1978); Danes, Frog, Icebox, Jacobs, Kelly Spring, Madonnaville, Walsh Spring, Wandas Waterfall, Wannabe Karst Window and Wednesday caves, Rose Hole, Camp Vandeventer Karst Window; **St. Clair Co**.: Stemler Cave (Peck & Lewis 1978); Dashed Hopes Pit.

S/G-rank: S3/G3; Caves and springs, western Illinois and southeastern Missouri (Kenk 1977, Peck & Lewis 1978).

PHYLUM MOLLUSCA
CLASS GASTROPODA
ORDER NEOTAENIOGLOSSA
FAMILY HYDROBIIDAE

Fontigens antroecetes (Hubricht) TB Eastern Ozark cave snail

St. Clair Co.: Stemler Cave (Peck & Lewis 1978).

S/G-rank: S1/G1; Hershler et al. (1990) from Stemler Cave (type-locality), Cliff Cave, St. Louis Co. and 7 caves in Perry Co., Missouri. Of the Perry Co. sites, only three cave systems are actually involved and two of the sites (Mertz and Schindler caves) are synonyms. The continued presence of the snail in Cliff Cave, in suburban St. Louis is unknown. The population in the type-locality remains extant, but is threatened by pollution from septic systems in subdivisions surrounding Stemler Cave.

ORDER MESOGASTROPODA
FAMILY POMATIOPSIDAE

Pomatiopsis lapidaria (Say) TX

St. Clair Co.: Stemler Cave.

S/G-rank: S5/G5; Calciphilic, semi-aquatic, eastern U.S (Hubricht 1985).

ORDER BASOMMATOPHORA
FAMILY CARYCHIIDAE

Carychium mexicanum Pilsbry TX Southern thorn snail

Monroe Co.: Pautler Cave; **St. Clair Co**.: Dashed Hopes Pit.

S/G-rank: S1/G4; Moist litter of entrance pits, the first Illinois record and a significant range extension; otherwise occurs in the gulf coast states and eastern Mexico (Hubricht 1985).

Table 3. Localities for species of lesser conservation interest.

					Monroe County														
Order	Family	Taxon	Ecological Classification	Rank	Andys Run Cave	Antler Cave	Bat Love Cave	Bat Sump Cave	Belle Fontaine Spring	Bicklein Cave	Camp Vandeventer Karst Wind	Camp Vandeventer Spring	Cedar Ridge Cave	Collier Spring	Couchs Cave	Danes Cave	Danes Annex Cave	Dirks Cave	[cut off]
PHYLUM PLATYHELMINTHES																			
CLASS TURBELLARIA																			
TRICLADIDA	PLANARIIDAE	*Phagocata gracilis* (Haldeman)	TX/TP	S4/G5							L								
PHYLUM MOLLUSCA																			
CLASS GASTROPODA																			
PULMONATA	PHYSIDAE	*Physella sp.* (near *halei?*)	TP/TB	?							L					L			F
MESOGASTROPODA	POMATIOPSIDAE	*Pomatiopsis lapidaria* (Say)	TX	S5/G5															
BASOMMATOPHORA	CARYCHIIDAE	*Carychium exile* Lea	TX	S5/G5													L	L	
STYLOMMATOPHORA	PUPILLIDAE	*Pupoides albilabris* (Adams)	TX	S5/G5															
		Gastrocopta armifera (Say)	TX	S5/G5															
		Gastrocopta contracta (Say)	TX	S5/G5															
		Gastrocopta pentodon (Say)	TX	S5/G5															
	HELICODISCIDAE	*Helicodiscus singleyanus* (Pilsbry)	TX	S4/G4														L	
	LIMACIDAE	*Deroceras laeve* (Muller)	TX	S5/G5									L						L
	ZONITIDAE	*Hawaiia minuscula* (Binney)	TX	S5/G5															
		Zonitoides arboreus (Say)	TX	S5/G5									L						
	POLYGYRIDAE	*Inflectarius inflectus* (Say)	TP	S5/G5			L			L					L				
		Mesodon clausus (Say)	TX	S5/G5															
		Xolotrema fosteri (Baker)	TX	S5/G5									L				L		
PHYLUM ARTHROPODA																			
CLASS CRUSTACEA																			
EUCOPEPODA																			
SUBORDER CYCLOPOIDA																			
	CYCLOPIDAE	*Acanthocyclops brevispinosus* (Herrick)	TX	S5/G5								L							
		Acanthocyclops robustus (Sars)	TX	S5/G5				L											
		Acanthocyclops vernalis (Fischer)	TX	S5/G5				L											
		Acanthocyclops littoralis Petkovski	TX	S5/G5				L											
		Eucyclops agilis (Koch)	TX	S5/G5															
		Macrocyclops albidus (Jurine)	TX	S5/G5				L											
		Mesocyclops edax (Forbes)	TX	S5/G5								L							
		Microcyclops rubellus (Lilljeborg)	TX	S5/G5															
		Orthocyclops modestus (Herrick)	TX	S5/G5				L											
		Tropocyclops prasinus mexicanus Kiefer	TX	S5/G5								L							
SUBORDER HARPACTICOIDA																			
	CANTHOCAMPTIDAE	*Attheyella nordenskioldi* (Lilljeborg)	TX	S5/G5															
ISOPODA																			
SUBORDER ONISCOIDEA																			
	ARMADILLIIDIDAE	*Armadillidium nasatum* Budde-Lund	TX	SE/G5															L
	CYLISTICIDAE	*Cylisticus convexus* (DeGeer)	TX/TP	SE/G5															
	TRICHONISCIDAE	*Haplothalmus danicus* Budde-Lunde	TX/TP	SE/G5															
SUBORDER ASELLOTA																			
	ASELLIDAE	*Caecidotea brevicauda* (Forbes)	TP/TX	S4/G5	L	L		L	L	L	L		L		L	L			F
AMPHIPODA	CRANGONYCTIDAE	*Crangonyx forbesi* Hubricht & Mackin	TP	S4/G5	L	L		L		L	L		L			L			F
	GAMMARIDAE	*Gammarus pseudolimnaeus* Bousfield	TX	S5/G5										L					
		Gammarus troglophilus Hubricht & Mackin	TP	S4/G4	L			L		L	L		L			L			F
ARACHNIDA																			
PSEUDOSCORPIONES	NEOBISIIDAE	*Microbisium parvulum* (Banks)	TX	S5/G5															L
ACARINA	IXODIDAE	*Dermacentor variabilis* (Say)	PS	S5/G5															L
ARANEAE	AGELENIDAE	*Tegenaria domestica* (Clerck)	TX	S5/G5															
	LINYPHIIDAE	*Bathyphantes pallida* (Banks)	TX/TP	S4/G5				L											
		Centromerus latidens (Emerton)	TX/TP	S5/G5															
		Centromerus cornupalpis (O.P.-Cambridge)	TX	S5/G5				L											
		Eperigone maculata (Banks)	TX/TP	S5/G5															L
		Eperigone tridentata (Emerton)	TX	S5/G5															
		Linyphia (Niriene) radiata (Walckenaer)	TX	S5/G5															
	LYCOSIDAE	*Pirata sedentarius* Montgomery	TX	S5/G5			L	L									L		L
		Schizocosa ocreata (Hentz)	TX	S4/G4															V
	NESTICIDAE	*Eidmanella pallida* Emerton	TP	S5/G5						L									
	PHOLCIDAE	*Pholcus phalangioides* Fuesslin	TX	SE/G5															
	PISAURIDAE	*Dolomedes scriptus* Hentz	TX	S4/G5															
	TETRAGNATHIDAE	*Meta ovalis* (Gertsch)	TP/TX	S5/G5						L									L
		Tetragnatha shoshone Levi	TX	S4/G4															
	THERIDIIDAE	*Achaearanea tepidariorum* (Koch)	TX	S5/G5															

																																								St. Clair County																	
	Engelmann Cave	Frog Cave	Fruths Spider Cave	Haney Spring	Hidden Hand Cave	Horsethief Cave	Icebox Cave	Illinois Caverns	Jacobs Cave	Juelfs Cave	Kelly Spring Cave	Krueger-Dry Run Cave	Little Cave	Madonnaville Cave	Maya Spring	Metter Cave	Myrons Misery Cave	Pautler Cave	Rose Hole	Saltpeter Cave	seep near Valmeyer	Spider Cave	spring 2 miles north Fountain G	Talus Cave	Terry Spring Cave	Trout Hollow Spring	Two Row Cave	unnamed near Wartburg Cave	unnamed cave 2 miles north Fou	Veolker Well	Walsh Cave	Walsh Seep	Walsh Spring	Walsh Spring Cave	Wandas Waterfall Cave	Wannabe Karst Window	Wannabe Karst Window Cave	Wednesday Cave	Wildes Cave	Amphipod Hall Cave	Browns II Cave	Cement Hollow Spring	Dashed Hopes Pit Cave	drain tile 1.2 km E Stolle	Dupo Quarry Spring	Falling Spring Cave	Falling Spring	Imbs Station Road Spring	Pipe (Cement Hollow) Spring	Sparrow Spring	spring near Falling Spring	Spring Valley Spring Cave	Stemler Cave	Stemler Well	swale 1 mile south of Falling Sp	W. H. Karst Window	W. H. Spring
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Table 3 (cont.) Localities for species of lesser conservation interest.

Order	Family	Taxon	Ecological Classification	Rank	Monroe County														
					Andys Run Cave	Antler Cave	Bat Love Cave	Bat Sump Cave	Belle Fontaine Spring	Bicklein Cave	Camp Vandeventer Karst Window	Camp Vandeventer Spring	Cedar Ridge Cave	Collier Spring	Couchs Cave	Danes Cave	Danes Annex Cave	Dirks Cave	[illegible]
PHYLUM PLATYHELMINTHES																			
CLASS TURBELLARIA																			
TRICLADIDA	PLANARIIDAE	*Phagocata gracilis* (Haldeman)	TX/TP	S4/G5							L								
PHYLUM MOLLUSCA																			
CLASS GASTROPODA																			
PULMONATA	PHYSIDAE	*Physella sp.* (near *halei?*)	TP/TB	?							L					L			F
MESOGASTROPODA	POMATIOPSIDAE	*Pomatiopsis lapidaria* (Say)	TX	S5/G5															
BASOMMATOPHORA	CARYCHIIDAE	*Carychium exile* Lea	TX	S5/G5													L	L	
STYLOMMATOPHORA	PUPILLIDAE	*Pupoides albilabris* (Adams)	TX	S5/G5															
		Gastrocopta armifera (Say)	TX	S5/G5															
		Gastrocopta contracta (Say)	TX	S5/G5															
		Gastrocopta pentodon (Say)	TX	S5/G5															
	HELICODISCIDAE	*Helicodiscus singleyanus* (Pilsbry)	TX	S4/G4														L	
	LIMACIDAE	*Deroceras laeve* (Muller)	TX	S5/G5									L						L
	ZONITIDAE	*Hawaiia minuscula* (Binney)	TX	S5/G5															
		Zonitoides arboreus (Say)	TX	S5/G5									L						
	POLYGYRIDAE	*Inflectarius inflectus* (Say)	TP	S5/G5			L			L					L				
		Mesodon clausus (Say)	TX	S5/G5															
		Xolotrema fosteri (Baker)	TX	S5/G5									L				L		
PHYLUM ARTHROPODA																			
CLASS CRUSTACEA																			
EUCOPEPODA																			
SUBORDER CYCLOPOIDA																			
	CYCLOPIDAE	*Acanthocyclops brevispinosus* (Herrick)	TX	S5/G5								L							
		Acanthocyclops robustus (Sars)	TX	S5/G5				L											
		Acanthocyclops vernalis (Fischer)	TX	S5/G5				L											
		Acanthocyclops littoralis Petkovski	TX	S5/G5				L											
		Eucyclops agilis (Koch)	TX	S5/G5															
		Macrocyclops albidus (Jurine)	TX	S5/G5				L											
		Mesocyclops edax (Forbes)	TX	S5/G5								L							
		Microcyclops rubellus (Lilljeborg)	TX	S5/G5															
		Orthocyclops modestus (Herrick)	TX	S5/G5				L											
		Tropocyclops prasinus mexicanus Kiefer	TX	S5/G5								L							
SUBORDER HARPACTICOIDA																			
	CANTHOCAMPTIDAE	*Attheyella nordenskioldi* (Lilljeborg)	TX	S5/G5															
ISOPODA																			
SUBORDER ONISCOIDEA																			
	ARMADILLIIDIDAE	*Armadillidium nasatum* Budde-Lund	TX	SE/G5															L
	CYLISTICIDAE	*Cylisticus convexus* (DeGeer)	TX/TP	SE/G5															
	TRICHONISCIDAE	*Haplothalmus danicus* Budde-Lunde	TX/TP	SE/G5															
SUBORDER ASELLOTA																			
	ASELLIDAE	*Caecidotea brevicauda* (Forbes)	TP/TX	S4/G5	L	L		L	L	L	L		L		L	L			F
AMPHIPODA	CRANGONYCTIDAE	*Crangonyx forbesi* Hubricht & Mackin	TP	S4/G5	L	L		L		L	L		L			L			F
	GAMMARIDAE	*Gammarus pseudolimnaeus* Bousfield	TX	S5/G5										L					
		Gammarus troglophilus Hubricht & Mackin	TP	S4/G4	L			L		L	L		L			L			F
ARACHNIDA																			
PSEUDOSCORPIONES	NEOBISIIDAE	*Microbisium parvulum* (Banks)	TX	S5/G5															L
ACARINA	IXODIDAE	*Dermacentor variabilis* (Say)	PS	S5/G5															L
ARANEAE	AGELENIDAE	*Tegenaria domestica* (Clerck)	TX	S5/G5															
	LINYPHIIDAE	*Bathyphantes pallida* (Banks)	TX/TP	S4/G5				L											
		Centromerus latidens (Emerton)	TX/TP	S5/G5															
		Centromerus cornupalpis (O.P.-Cambridge)	TX	S5/G5				L											
		Eperigone maculata (Banks)	TX/TP	S5/G5															L
		Eperigone tridentata (Emerton)	TX	S5/G5															
		Linyphia (Niriene) radiata (Walckenaer)	TX	S5/G5															
	LYCOSIDAE	*Pirata sedentarius* Montgomery	TX	S5/G5			L	L									L		L
		Schizocosa ocreata (Hentz)	TX	S4/G4															W
	NESTICIDAE	*Eidmanella pallida* Emerton	TP	S5/G5						L									
	PHOLCIDAE	*Pholcus phalangioides* Fuesslin	TX	SE/G5															
	PISAURIDAE	*Dolomedes scriptus* Hentz	TX	S4/G5															
	TETRAGNATHIDAE	*Meta ovalis* (Gertsch)	TP/TX	S5/G5						L									L
		Tetragnatha shoshone Levi	TX	S4/G4															
	THERIDIIDAE	*Achaearanea tepidariorum* (Koch)	TX	S5/G5															

																																							St. Clair County																	
Fogelpole Cave	Frog Cave	Fruths Spider Cave	Haney Spring	Hidden Hand Cave	Horsethief Cave	Icebox Cave	Illinois Caverns	Jacobs Cave	Juelfs Cave	Kelly Spring Cave	Krueger-Dry Run Cave	Little Cave	Madonnaville Cave	Maya Spring	Metter Cave	Myrons Misery Cave	Pautler Cave	Rose Hole	Saltpeter Cave	seep near Valmeyer	Spider Cave	spring 2 miles north Fountain G	Talus Cave	Terry Spring Cave	Trout Hollow Spring	Two Row Cave	unnamed near Wartburg Cave	unnamed cave 2 miles north Fou	Veolker Well	Walsh Cave	Walsh Seep	Walsh Spring	Walsh Spring Cave	Wandas Waterfall Cave	Wannabe Karst Window	Wannabe Karst Window Cave	Wednesday Cave	Wildes Cave	Amphipod Hall Cave	Browns II Cave	Cement Hollow Spring	Dashed Hopes Pit Cave	drain tile 1.2 km E Stolle	Dupo Quarry Spring	Falling Spring Cave	Falling Spring	Imbs Station Road Spring	Pipe (Cement Hollow) Spring	Sparrow Spring	spring near Falling Spring	Spring Valley Spring Cave	Stemler Cave	Stemler Well	swale 1 mile south of Falling Sp	W. H. Karst Window	W. H. Spring
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Carychium nannodes Clapp TX File thorn snail

Monroe Co.: Metter Cave.

S/G-rank: S1/G4; Only Illinois record; otherwise of Appalachian distribution (Hubricht 1985).

Carychium riparium Hubricht TX Floodplain thorn snail

Monroe Co.: Danes Annex, Dirks, Fogelpole, Frog, Metter and Pautler caves; **St. Clair Co**.: Dashed Hopes Pit.

S/G-rank: S2/G3; Only Illinois records. Moist leaf litter of sinkhole floors, pits, and the twilight zone of these caves.

ORDER STYLOMMATOPHORA

FAMILY PUPILLIDAE

Gastrocopta abbreviata (Sterki) TX Plains snaggletooth snail

Monroe Co.: Fogelpole Cave; **St. Clair Co**.: Stemler Cave.

S/G-rank: S2/G3; Calciphile from over a dozen states in the central U.S. from the gulf coastal area to Wisconsin and North Dakota, including three sites in Illinois (Hubricht 1985).

Gastrocopta similis (Sterki) TX

Monroe Co.: Rose Hole; **St. Clair Co**.: Stemler Cave.

S/G-rank: S3/G4; Calciphile, from New York to the Dakotas (Hubricht 1985).

FAMILY STROBILOPSIDAE

Strobilops affinis Pilsbry TX Eightfold pinecone snail

St. Clair Co.: Stemler Cave.

S/G-rank: S2/G3; Leaf litter, Massachusetts west to Illinois and eastern Missouri, but known from relatively few localities (Hubricht 1985).

FAMILY PHILOMYCIDAE

Philomycus togatus (Gould) TX Toga mantleslug

Monroe Co.: Cedar Ridge Cave.

S/G-rank: S1/G4; Only known Illinois population and a large range extension of this Appalachian species, unknown from the intervening area of Indiana and western Ohio (Hubricht 1985).

FAMILY HELICODISCIDAE

Helicodiscus notius notius Hubricht TX Tight coil snail

Monroe Co.: Fogelpole Cave.

S/G-rank: S2/G4; Leaf litter on hillsides and ravines, common trogloxene, many sites in the southeastern U.S., including southwestern Illinois (Hubricht 1985); reported by Gardner (1986) from six Missouri caves.

Helicodiscus undescribed species TP/TX Undescribed terrestrial snail

Monroe Co.: Bat Love and Pautler cave, Rose Hole; **St. Clair Co**.: Stemler Cave.

S/G-rank: S1/G1; Resembles a hypertrophied *Helicodiscus parallelus* (Say), related to *H. eidenmanni*, a facultative cavernicole in Texas (Hubricht 1985, Grimm in litt. 1999).

FAMILY ZONITIDAE

Glyphalinia latebricola Hubricht TX Stone glyph snail

St. Clair Co.: Stemler Cave.

S/G-rank: S1/G2; Only Illinois record, the only published record is from northeastern Alabama (Hubricht 1985); Lewis (1998) found the snail in a cave in Orange County, Indiana.

Glyphalinia luticola Hubricht TX Furrowed glyph snail

Monroe Co.: Metter, Pautler and Wednesday caves; **St. Clair Co**.: Dashed Hopes Pit, Stemler Cave.

S/G-rank: S1/G4; Only Illinois records, typically found in moist floodplain forests in the southeastern U.S. (Hubricht 1985).

Paravitrea undescribed species TX Undescribed terrestrial snail

St. Clair Co.: Stemler Cave.

S/G-rank: S1/G1; Only known locality for this undescribed species.

Paravitrea undescribed species TX Undescribed terrestrial snail

Monroe Co.: Wednesday Cave.

S/G-rank: S1/G1; Only known locality for this undescribed species, which is distinct from the above species from Stemler Cave.

Ventridens intertextus (Binney) TX Pyramid dome snail

Monroe Co.: Danes Annex Cave.

S/G-rank: S1/G4; Only known Illinois record, a significant range extension to the west, mostly occurs in a band paralleling the Appalachians and extending south to Louisiana, frequently found in acidic habitats (Hubricht 1985).

Zonitoides nitidus (Muller) TX

Monroe Co.: Dirks, Pautler and Wednesday caves.

S/G-rank: S2/G5; Holarctic, reported from the northern tier of counties in Illinois (Hubricht 1985).

FAMILY POLYGYRIDAE

Xolotrema denotata (Ferussac) TX Velvet wedge snail

Monroe Co.: Danes Cave.

S/G-rank: S1/G4; Appalachians, west to three reported sites in southeastern Illinois (counties along the Wabash River), west to eastern Arkansas; previously unknown from other parts of Illinois (Hubricht 1985).

PHYLUM ARTHROPODA

CLASS CRUSTACEA

ORDER ISOPODA

FAMILY ASELLIDAE

Caecidotea packardi Mackin & Hubricht TB Packard's cave isopod

Monroe Co.: Fogelpole, Fruths Spider, Juelfs, Horsethief, Pautler, Terry Spring caves, Illinois Caverns (Peck & Lewis 1978), Antler, Danes, Frog, Icebox, Jacobs, Icebox, Kelly Spring, Krueger-Dry Run, Madonnaville, Spider, Walsh Spring, Wandas Waterfall and Wannabe Karst Window caves, Rose Hole, Haney Spring; **St. Clair Co**.: Falling Spring and Stemler caves (Peck & Lewis 1978), Dashed Hopes Pit Cave.

S/G-rank: S3/G3; Reported from 10 caves, springs and a pumpwell in Illinois, one record from a cave in Lincoln Co., Missouri (Lewis & Bowman 1981); found to be rare or absent despite seemingly suitable habitat in some caves in Monroe County.

Caecidotea spatulata Mackin & Hubricht PB Flat-tailed groundwater isopod

St. Clair Co.: swale 1 mile south of Falling Spring (type-locality).

S/G-rank: S1/G2; Reported by Mackin and Hubricht (1940) from temporary pools in St. Clair Co., Illinois, St. Louis and Boone counties in eastern Missouri; Lewis and Bowman (1981) regarded as a groundwater inhabitant. The type-locality has been heavily modified with quarry spoil and we were unable to find this species despite an exhaustive search (Lewis 2000a).

ORDER AMPHIPODA

FAMILY CRANGONYCTIDAE

Bactrurus brachycaudus Hubricht & Mackin TB Eastern Ozark cave amphipod

Monroe Co.: Fogelpole, Icebox, Juelfs, Pautler ,Terry Spring and unnamed near Wartburg caves, Illinois Caverns (Peck & Lewis 1978), Andys Run, Antler, Danes, Frog and Jacobs caves, Rose Hole, seep near Valmeyer, Walsh Seep; **St. Clair Co**.: Stemler Cave and spring near Falling Spring (Peck & Lewis 1978), Dashed Hopes Pit Cave, Cement Hollow, Imbs Station Road and pipe spring (Cement Hollow) springs, Schipps Well.

S/G-rank: S3/G3-4; Cave streams or seep springs; east central Missouri into southwestern Illinois. Reported from 19 Illinois caves, springs and seeps, 4 sites in Missouri (Peck & Lewis 1978). Gardner (1986) from caves in 13 Missouri counties.

Stygobromus subtilis (Hubricht) TB/PB Western Illinois groundwater amphipod

Monroe Co. Saltpeter Cave (Peck & Lewis 1978).

S/G-rank: S2/G2; Found in drip pools in Saltpeter Cave, otherwise reported from eight caves and seeps in Illinois, one cave in Missouri (Peck & Lewis 1978).

FAMILY GAMMARIDAE

Gammarus acherondytes Hubricht & Mackin TB Illinois cave amphipod

Monroe Co.: Fogelpole, Krueger-Dry Run and Pautler caves, Illinois Caverns (Peck and Lewis 1978), Madonnaville (Oliver & Graham 1988),Cedar Ridge, Danes, Frog, Spider and Wednesday caves, Rose Hole. **St. Clair Co**.: Stemler Cave (Peck & Lewis 1978).

S/G-rank: S1/G1; Endemic to the karst of Monroe and St. Clair counties, previously known populations were summarized by Webb et al. (1998), now known extant in six drainage conduits: (1) Fogelpole, (2) Illinois Caverns, (3) Krueger-Dry Run (including Spider Cave), (4) Pautler/Danes/Rose Hole, (5) Frog Cave, (6) Annbriar (Wednesday Cave and possibly Cedar Ridge Cave). In addition to the 10 cave populations in these six drainages, a single specimen was taken in Madonnaville Cave (in 1986), but a collection from the cave in 1995 failed to demonstrate its presence (Webb 1995). A collection in Stemler Cave likewise failed to demonstrate its presence (Webb 1995). The amphipod was not found in Stemler Cave during sampling for this project nor in community censusing in the main stream passage.

Gammarus minus Say TX

Monroe Co.: Andys Run, Juelfs and Madonnaville caves (Webb 1995);

Collier, Haney and Trout Hollow springs. **St. Clair Co**.: Falling Spring (Peck & Lewis 1978), Stemler Cave (Webb *et al*. 1994).

S/G-rank: S5/G5; Springs and cave streams, eastern U.S. (Holsinger 1972).

CLASS ARACHNIDA

ORDER PSEUDOSCORPIONES

FAMILY CHTHONIIDAE

Chthonius virginicus vs. *tetrachelatus* TX

Monroe Co.: Hidden Hand, Icebox caves.

S/G-rank: S1/G3; If this is *Chthonius virginicus*, these are the only known Illinois records (elsewhere from two caves and two epigean sites in Ohio, also Virginia, Maryland, North Carolina and the District of Columbia (Muchmore 1994), plus three Indiana caves (Lewis 1998). This group needs revision and it is impossible to separate *virginicus* from *tetrachelatus* at present (Muchmore in litt. 2001).

Mundochthonius cavernicolus Muchmore TB Illinois cave pseudoscorpion

Monroe Co.: Saltpeter Cave (Peck & Lewis 1978), Fogelpole Cave (Gardner 1986).

S/G-rank: S1/G1; Described from a single specimen taken in Saltpeter Cave (Muchmore 1968), endemic to the Renault karst area of Monroe Co., Illinois. A visit to the cave by JJL for the Illinois Natural Area Inventory in 1976 failed to find the pseudoscorpion. Two additional trips to the cave made during this survey including placing 10 pitfalls also failed to demonstrate its presence. Gardner (1986) reported *M. cavernicolus* from Fogelpole Cave, as well as a cave in Lincoln County, Missouri. Muchmore (in litt. 2001) now believes that the Missouri specimens represent an undescribed species.

ORDER PHALANGIDA

FAMILY ISCHYROPSALIDAE

Sabacon cavicolens (Packard) TP Cavernicolous harvestman

Monroe Co.: Fogelpole Cave.

S/G-rank: S1/G3; Southeastern U.S.; reported as *Sabacon* sp. from a cave in Johnson Co., Illinois (Peck & Lewis 1978) and one surface population in Illinois (Shear 1975). Lewis (1998) in two Indiana caves.

ORDER ARANEAE

FAMILY AGELENIDAE

Cicurina arcuata Keyserling TX

Monroe Co.: Illinois Caverns (Webb *et al*. 1994).

Webb *et al*. 1994 reported *Cicurina arcata* (sic) from Illinois Caverns. This species was reported by Chamberlin and Ivie (1940) only from the type-locality in Arcata, California, suggesting a transcription error by Webb *et al*. (1994) of *Cicurina arcuata*, an occasional trogloxene widespread in the eastern U.S. and Canada.

Cicurina brevis (Emerton) TX

Monroe Co.: Cedar Ridge Cave.

S/G-rank: S3 /G4; Chamberlin and Ivie (1940) from about 20 localities across the eastern U.S. and Canada, where it is presumed common in suitable habitats. Gardner (1986) from one Missouri cave.

Cicurina cavealis Crosby and Bishop TP Cavernicolous funnel web spider

Monroe Co.: Saltpeter Cave (Peck & Lewis 1978).

S/G-rank: S1/G3; Chamberlin and Ivie (1940) from two caves in Missouri and one in Arkansas. Gardner (1986) from several other Missouri caves.

FAMILY LINYPHIIDAE

Eperigone indicabilis Crosby and Bishop TX Minuscule sheet web spider

Monroe Co.: Illinois Caverns (Webb *et al*. 1994).

S/G-rank: S1/G1; Smallest of the linyphiid spiders (about one millimeter long), the S/G-ranks are probably inflated since the range is wide. Reported by Lewis (1994) from litter in William Cleveland Cave, Indiana; only other known collection is from the type-locality in New York (Millidge 1987).

Phanetta subterranea (Emerton) TB

Monroe Co.: Horsethief, Icebox, Juelfs and Terry Spring caves, Illinois Caverns (Peck & Lewis 1978), Antler, Bat Love, Bat Sump, Bicklein, Danes, Dirks, Fogelpole, Frog, Hidden Hand, Jacobs, Madonnaville, Pautler, Spider, Wandas Waterfall, Wannabe Karst Window and Wednesday caves, Rose Hole; **St. Clair County**: Browns II, Dashed Hopes Pit and Stemler caves.

S/G-rank: S3/G4; Eastern U.S., reported from over a dozen states, but only from caves (Millidge 1984).

Porrhomma cavernicola (Keys) TB Cavernicolous sheet web spider

Monroe Co.: Krueger-Dry Run Cave (Peck & Lewis 1978).

S/G-rank: S1/G3; *Porrhomma* sp. (Peck & Lewis 1978) presumably refers to *P. cavernicola*, the only cavernicolous species of the genus that occurs in the eastern U.S., where it is widespread, but sporadic in its occurrence.

FAMILY MYSMENIDAE

Maymena ambita (Barrows) TP Minute cave spider

Monroe Co.: Saltpeter Cave (Peck & Lewis 1978).

S/G-rank: S1/G2; Reported by Gertsch (1960) from 11 sites, including caves in Kentucky, Tennessee and Alabama. Sutton (1993) found it in 2 caves in Missouri.

CLASS DIPLOPODA

ORDER POLYDESMIDA

FAMILY NEARCTODESMIDAE

Ergodesmus remingtoni (Hoffman) TB Illinois cave milliped

Monroe Co.: Pautler Cave (Peck & Lewis 1978), Danes Cave, Rose Hole.

S/G-rank: S2/G2; The only U.S. nearctodesmid outside the Pacific Northwest, restricted to western Illinois counties of Adams, Jersey, Pike and Monroe (Hoffman 1962, Peck & Lewis 1978) and disjunctly in Cave Spring Cave, Hardin County (Shelley 1994). Known from eight caves, although Pautler and Danes caves as well as Rose Hole are parts of the same system.

FAMILY MACROSTERNODESMIDAE

Chaetaspis sp. TB Undescribed cave milliped

Monroe County: Pautler Cave (Peck & Lewis 1978), Danes, Icebox Cave.

S/G-rank: S1/G1; Peck and Lewis (1978) reported juveniles of an undescribed species of *Antriadesmus*, a synonym of *Chaetaspis* (Hoffman 1999), from Pautler Cave. Additional females were taken in the above caves during this project. The original collection was identified by Dr. N. Causey from females, but the cave lies within the range of *Chaetaspis albus* (Hoffman 1999) and a male specimen will be necessary to determine the identity of the species. *Chaetaspis* contains three troglobitic (or perhaps edaphic) species from Tennessee and Kentucky, with a fourth being described from Tumbling Creek Cave, Missouri (Lewis in progress 2002a).

ORDER CHORDEUMATIDA

FAMILY CONOTYLIDAE

Austrotyla specus (Loomis) TP Eastern Ozark cave milliped

Monroe Co.: Horsethief, Icebox and Krueger-Dry Run caves, Illinois Caverns (Peck & Lewis 1978), Bat Love, Bat Sump, Bicklein, Danes, Danes Annex, Dirks, Fogelpole, Frog, Hidden Hand, Jacobs, Juelfs, Kelly Spring, Madonnaville, Metter, Pautler, Spider, Two Row, Wandas Waterfall, Wannabe Karst Window and Wednesday caves, Rose Hole; **St. Clair Co**.: Stemler Cave (Peck & Lewis 1978), Brown II Cave.

S/G-rank: S3/G3-4; Illinois, eastern Missouri, southern Wisconsin, eastern Iowa and southern Minnesota (Shear 1971). Surface populations were reported in the northern part of the range, in the southern part of its range limited almost, or entirely, to caves. At Metter and Danes Annex caves the millipeds were taken from sinkhole floors (i.e., sheltered epigean habitat).

CLASS INSECTA

ORDER COLLEMBOLA

FAMILY ENTOMOBRYIDAE

Pseudosinella undescribed species near *argentea* TB Undescribed cave springtail

Monroe Co.: Saltpeter (Peck & Lewis 1978), Fogelpole, Spider and Wandas Waterfall caves.

S/G-rank: S2/G2; Peck and Lewis (1978) from 3 caves in Illinois and one in Missouri (Lewis 1974), to which Gardner (1986) added 6 more caves. Pseudosinella unidentifiable to species were also taken from Bat Love and Cedar Ridge caves.

FAMILY HYPOGASTRURIDAE

Sensillanura illina Christiansen & Bellinger TX Illinois springtail

Monroe Co.: Bat Sump Cave.

S/G-rank: S1/G1; Known only from Karber's Ridge, Illinois; a site in Johnson Co., Illinois, and the above record (Christiansen & Bellinger 1998a).

FAMILY ONCOPODURIDAE

Oncopodura iowae Christiansen TB Iowa cave springtail

Monroe Co.: Fogelpole Cave, Illinois Caverns.

S/G-rank: S1/G2; Christiansen *et al*. (1961), Christiansen and Bellinger (1998c) from caves in Iowa and Missouri, and a reference therein to an Illinois locality is based on an unpublished 1959 collection in Illinois Caverns (Christiansen, in litt. 2000). Christiansen and Bellinger (1996) reported that all

Oncopodura are either troglobitic or edaphic, are very uncommon, fragile, and usually represented in collections by very few specimens.

FAMILY ONYCHIURIDAE

Onychiurus reluctus Christiansen TP   Glistening springtail

Monroe Co.: Bat Sump, Fogelpole, Hidden Hand and Saltpeter caves; **St. Clair Co**.: Stemler Cave.

S/G-rank: S3/G3; Widespread in caves, few reports of surface populations (Christiansen 1982), reported from about two dozen caves in Missouri (Gardner 1986) and several in Indiana (Lewis 1998).

Onychiurus undescribed species TB   Undescribed cave springtail

Monroe Co.: Bat Love, Fogelpole, Frog and Icebox caves.

S/G-rank: S1/G1; Known only from these caves. This genus contains numerous undescribed species (Christiansen, in litt. 2000).

FAMILY SMINTHURIDAE

Arrhopalites carolynae Christiansen & Bellinger TB   Carolyn's cave springtail

Monroe Co.: Hidden Hand and Saltpeter caves.

S/G-rank: S1/G2; Only Illinois records, known from seven caves in Virginia (Christiansen & Bellinger 1996b, 1998d) and one in Indiana (Lewis 2002b in progress).

Arrhopalites undescribed species TB   Undescribed cave springtail

Monroe Co.: Frog, Hidden Hand, Jacobs, Madonnaville and Pautler caves, Rose Hole.

S/G-rank: S2/G2; Riparian habitats, known only from the above caves.

Arrhopalites ater Christiansen & Bellinger TB   Black Medusa cave springtail

Monroe Co.: Bicklein, Danes and Fogelpole caves.

S/G rank: S1/G2; Known from 5 caves in southern Indiana (Lewis 1998, Christiansen & Bellinger 1998d). The morphology of the specimens from Illinois is slightly different, tentatively regarded as geographic variation (Christiansen, pers. comm. 2000).

Arrhopalites hirtus Christiansen TB/ED   Hairy cave springtail

Monroe Co.: Fogelpole and Little caves.

S/G-rank: S1/G2; Christiansen (1966) from a drain tile in Union Co., Illinois, as well as caves in Iowa, Wisconsin and Ohio.

Arrhopalites lewisi Christiansen & Bellinger TB   Lewis' cave springtail

Monroe Co.: Icebox Cave.

S/G rank: S1/G2; Only Illinois record, known from caves in southern Indiana (Lewis 1998, Christiansen & Bellinger 1998d).

Arrhopalites whitesidei Jacot TP   Whiteside's springtail

Monroe Co.: Saltpeter Cave (Peck & Lewis 1978).

S/G-rank: S1/G2; Caves in the eastern U.S., including 5 Missouri counties (Gardner 1986, Christiansen 1966).

FAMILY TOMOCERIDAE

Tomocerus (*Lethemurus*) *missus* Mills TB   Relict cave springtail

Monroe Co.: Illinois Caverns (Peck & Lewis 1978), Bat Love and Pautler caves, Rose Hole; **St. Clair Co**.: Stemler Cave.

S/G-rank: S2/G2; Christiansen (1964) speculated that this species may be the last remnant of a group that was otherwise known only from Japan. Previously known from Illinois Caverns and Brainard Cave (type-locality) in Illinois, three caves in Indiana (Lewis 1998, single caves in Virginia and Tennessee, plus caves in Colorado. Even in areas collected rather thoroughly, like Missouri (Gardner 1986) or Indiana (Lewis 1998, 2002b) the species occurs sporadically. Christiansen (in litt. 1999) believes it is quite likely that two or more species are involved.

ORDER DIPLURA

FAMILY CAMPODEIDAE

Eumesocampa sp. TB   Undescribed cave dipluran

Monroe Co.: Horsethief, Icebox Madonnaville caves (Peck & Lewis 1978), Bat Sump, Bicklein, Danes, Fogelpole, Frog, Jacobs and Pautler caves, Rose Hole; **St. Clair County**: Browns II and Stemler caves.

S/G-rank: S2/G3; Known only from the above localities and six populations in caves of Jefferson, St. Genevieve and Perry counties in Missouri.

Eumesocampa sp. TB   Undescribed cave dipluran

Monroe Co.: Bat Love Cave.

S/G-rank: S1/G1; This species appears related to, but morphologically distinct, from the *Eumesocampa* listed above (Ferguson, in litt. 1999).

Haplocampa sp. TB   Undescribed cave dipluran

Monroe Co.: Illinois Caverns (Peck & Lewis 1978), Bicklein, Fogelpole, Jacobs, Pautler and Spider caves, **St. Clair Co**.: Stemler Cave.

S/G-rank: S2/G2; Reported previously in Illinois only from Illinois Caverns (Peck & Lewis 1978), is conspecific with populations in Crawford and Washington counties, Missouri (Ferguson, in litt 1999).

ORDER ORTHOPTERA

FAMILY GRYLLACRIDIDAE

Ceuthophilus elegans Hubbell TX

Monroe Co.: Fogelpole Cave, Illinois Caverns (Peck & Lewis 1978), Bicklein, Cedar Ridge, Couchs, Danes, Jacobs, Juelfs, Kelly Spring, Madonnaville, Pautler, Spider, Two Row, Wandas Waterfall and Wednesday caves, Rose Hole; **St. Clair Co**.: Stemler Cave.

S/G-rank: S3/G4; Common in the caves of this area and of the Ceuthophilus found in Monroe/St. Clair county caves, this is the species that occurs the deepest in the caves; a prairie species reported by Hubbell (1936) from about 20 sites, six in Illinois.

Ceuthophilus seclusus Scudder TX   Secluded camel cricket

Monroe Co.: Krueger-Dry Run Cave (Peck & Lewis 1978).

S/G-rank: S1/G3; Reported from about 25 sites by Hubbell (1936), first reported from Illinois by Peck and Lewis (1978). Not found in additional caves, but occurred on oat meal trails at Camp Vandeventer adjacent to Hidden Hand and Little caves. Gardner (1986) reported it from 36 Missouri caves.

Ceuthophilus williamsoni Hubbell TX   Williamson's camel cricket

Monroe Co.: Little Cave.

S/G rank: S2/G3; Hubbell (1936) from 11 sites, two in Illinois, with the rest in Missouri and Iowa. Six of Hubbell's sites were caves. Several of these crickets were also present in a collection made on an oatmeal trail at Camp Vandeventer along the creek bank adjacent to Little Cave. Gardner (1986) reported it from 35 Missouri caves.

ORDER COLEOPTERA

FAMLY CARABIDAE

Rhadine larvalis LeConte TP   Masked ground beetle

St. Clair Co.: Falling Spring Cave (Peck & Lewis 1978).

S/G-rank: S1/G2; One of two eastern *Rhadine*, also known from caves in Alabama and Florida (Barr, in litt 2000).

FAMILY LEIODIDAE

Ptomophagus cavernicola Schwarz TP

Monroe Co.: Bat Love, Cedar Ridge, Fogelpole, Icebox, Jacobs, Little, Pautler, Two Row and Wandas Waterfall caves; **St. Clair County**: Stemler Cave.

S/G-rank: S2/G4; Only Illinois records of this widespread troglophilic species, previously unknown from the state. Known almost entirely from caves, two surface collections exist; known from Mexico north to the Ozarks, then east to Florida (Peck 1973). Gardner (1986) reported from over 50 Missouri caves.

FAMILY STAPHYLINIDAE

Tychobythinus bythinioides (Brendel) TP   Cave-loving ant beetle

Monroe Co.: Pautler Cave.

S/G-rank: S1/G3-G4; Illinois to New England, but sporadic; three of the five known species of *Tychobythinus* are troglobites (Chandler 1997).

Thesiastes fossulatus (Brendel) TX   Grooved ant beetle

St. Clair Co.: Dashed Hopes Pit.

S/G-rank: S3/G3; Leaf litter on the pit floor.

Aleochara lucifuga (Casey) TP   Cavernicolous rove beetle

Monroe Co.: Frog Cave; **St. Clair Co**.: Stemler Cave.

S/G-rank: S1/G3-G4; Previously known in Illinois from Burton Cave, Adams Co. (Peck & Lewis 1978). Recorded only from caves and animals burrows; largely Appalachian from southern Pennsylvania to northern Alabama (Klimaszewski & Peck 1986). Lewis (1998) found it in several southern Indiana caves.

ORDER DIPTERA

FAMILY SPHAEROCERIDAE

Spelobia tenebrarum (Aldrich) TB

Monroe Co.: Antler, Bat Love, Bat Sump, Bicklein, Cedar Ridge, Couchs, Danes, Danes Annex, Dirks, Fogelpole, Frog, Hidden Hand, Jacobs, Juelfs, Icebox, Kelly Spring, Little, Madonnaville, Myrons Misery, Pautler, Saltpeter, Spider, Two Row, Wandas Waterfall, Wannabe Karst Window and Wednesday caves, Illinois Caverns, Rose Hole. **St. Clair County**: Browns II, Dashed Hopes Pit and Stemler caves.

S/G-rank: S4/G5; One cave in Illinois by Peck and Lewis (1978), but the unidentified *Leptocera* sp. reported from 20+ caves therein was probably this species. Marshall and Peck (1985) found that of over a hundred populations in the eastern U.S., all were from caves. They also described troglomorphisms that, when combined with its apparent restriction to cave habitats, indicated that this species was troglobitic. This species and *Megaselia cavernicola* probably occur in most Illinois caves.

DISCUSSION

RESULTS

Forty one species of global rarity are reported from the SHPK, of which 12 were G1, 14 G2 and 15 G3. Of these, 20 were reported by Peck and Lewis (1978), and Webb *et al*. (1998) added *Eperigone indicabilis*. Of the 71 sites visited, 39 produced at least one species of significance. For conservation purposes, all sites were rank-ordered by the number of global and state rare species present, as well as the number of troglobites. This produced a prioritized list for conservation purposes, e.g., acquirement of property (Table 4). Fogelpole and Stemler caves had the highest number of globally rare species with 18 and 16, respectively. The Pautler Cave System (combined Danes, Pautler, Camp Vandeventer caves and Rose Hole) had 20 globally and state rare species.

Twenty-four taxa thought to be obligate subterranean species were found. The highest number of troglobites found in a single cave was 14 at Fogelpole, although the Pautler Cave System was found to be inhabited by 16 troglobites. The zoogeographic and evolutionary scenario proposed by Peck and Lewis (1978) remains unchanged by the data presented here. With the discovery of *Caecidotea packardi* in southeastern Missouri (Lewis & Bowman 1981), all aquatic troglobites known from the SHPK except *Gammarus acherondytes* are known from southeastern Missouri. The isolation of the karst subunits of the SHPK is illustrated by the endemism of *Mundocthonius cavernicolus* to the Renault karst, and by *Chaetaspis* undescribed species and *Eumesocampa* undescribed species to the Waterloo karst. Although found outside of the SHPK, within the project area *Fontigens antroecetes* is known only from the Columbia karst, *Ergodesmus remingtoni* and *Arrhopalites lewisi* from the Waterloo karst, and *Stygobromus subtilis* and *Oncopodura iowae* from the Renault karst.

Table 4. Sites in the SHPK rank-ordered by the number of globally rare species and number of troglobites present

Site	Globally Rare Species	Troglobites
Fogelpole Cave	17	14
Stemler Cave	14	10
Pautler Cave	12	10
Rose Hole	10	10
Frog Cave	10	8
Illinois Caverns	9	9
Danes Cave	8	9
Jacobs Cave	7	8
Saltpeter Cave	7	5
Spider Cave	6	7
Madonnaville Cave	6	7
Camp Vandeventer Cave	6	6
Bat Love Cave	5	5
Hidden Hand Cave	5	4
Bicklein Cave	4	5
Wednesday Cave	4	4
Bat Sump Cave	3	5
Juelfs Cave	3	4
Wandas Waterfall Cave	3	4

PROBLEMATIC SPECIES

The presence of a milliped of the genus *Scoterpes* in Illinois was reported by Shear (1969) from an unspecified site in western Illinois, speculated by Peck and Lewis (1978) to be Illinois Caverns. Neither Peck and Lewis (1978), Webb et al (1994), nor this survey demonstrated the presence of *Scoterpes* in Illinois. Shear (in litt. 1999) was unable to provide further information on a locality and has seen no specimens of *Scoterpes* from Illinois. We have not included *Scoterpes* in the species list as we have been unable to verify its presence.

The troglobitic leiodid *Ptomophagus nicholasi* was described from Fogelpole Cave (Barr 1963), however Peck (1984) found this species to be identical to *P. hirtus* from the Mammoth Cave area of central Kentucky. The collector had been collecting in Mammoth Cave prior to visiting Fogelpole cave and the possibility of a mislabeled specimen from Kentucky was suggested (Peck & Lewis 1978). Due to the inability to rediscover *Ptomophagus nicholasi* in any Illinois cave, the unlikely dispersal event needed to explain the presence of a *P. hirtus*-like population in Illinois, and the possibility of labeling error, Peck (1984) suggested that the species in fact never existed and *P. nicholasi* was synonymized with *P. hirtus*.

STATUS OF *GAMMARUS ACHERONDYTES*

This species was previously recorded from six caves, to which we add six new sites (see species account), including those in the Annbriar and Frog Spring groundwater systems where the amphipod was not formerly known to occur. At present, the largest known population of *G. acherondytes* is known from Frog Cave (Lewis 2002c in progress). Pautler Cave had been reported as physically closed and the status of the amphipod was unknown (Webb 1995). In 1999 we found the cave to be open and *G. acherondytes* present. Preliminary findings (Lewis 2002c in progress) indicate that the second largest known population of *G. acherondytes* occurs in Pautler Cave. Identical to the finding of Webb (1995), we were unable to demonstrate the presence of *Gammarus acherondytes* in Stemler Cave, where the species was previously known to occur (Peck & Lewis 1978). We were furthermore unable to find *G. acherondytes* in any other site in the Columbia karst subunit. In Illinois Caverns *G. acherondytes* is present in the main entrance passage but disappears downstream (Lewis 2000b). The disappearance of the amphipod correlates with a decrease in the diversity of the invertebrate community and the appearance of filamentous biofilms on rocks in the stream (Lewis 2000b).

Gammarus acherondytes was found to have a wider habitat preference than found by Webb *et al*. (1998), that is, gravel riffle habitat of large streams such as in Illinois Caverns and Fogelpole Cave. We found the amphipod in similar habitat in

Spider and Frog caves, as well as in narrow headwater streamlets (less than 30 cm across) in Rose Hole and Wednesday Cave. In the latter, *G. acherondytes* was taken from a scoured rimstone pool with a bare limestone substrate containing only a couple of cobbles. The amphipod also accepts pool habitats (Lewis 2000b, 2002c in progress).

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ADDENDUM

As this paper was being sent to press new collections of *Gammarus acherondytes* were made in the following Monroe County localities: Snow White Cave (Dual Spring groundwater basin), Rick's Pit (Luhr Spring groundwater basin), Reverse Stream, Jason's Surprise and Triple Delight caves (Annbriar Spring groundwater basin). The first two sites represent the presence of the amphipod in previously unknown drainage basins.

The milliped *Ergodesmus remingtoni* was also found in Jason's Surprise Cave.

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MYCOLOGICAL SURVEY OF RÍO CAMUY CAVES PARK, PUERTO RICO

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The Río Camuy Caves Park is part of the Río Camuy Cave System in the northern karst belt of Puerto Rico. Thirty-nine fungal species and 11 cellular and plasmodial slime molds are new records for caves and sinkholes of the Río Camuy Cave Park. Two of the cellular slime molds Dictyostelium citrinum *and* D. macrocephalum *are new records for Puerto Rico.*

El Parque de las Cavernas del Río Camuy pertenece al Sistema de Cavernas del Río Camuy en el cinturón del carso norteño de Puerto Rico. Se informan 39 especies de hongos y 11 hongos mucilaginosos celulares y plasmodiales como nuevos registros para cuevas y sumideros del Parque de las Cavernas del Río Camuy. Dos de los hongos mucilaginosos celulares Dictyostelium citrinum *y* D. macrocephalum *son nuevos registros para Puerto Rico.*

Fungi play roles in cave communities as saprotrophs or pathogens. Fungi affect the population dynamics of cave biota and contribute in the decomposition of organic matter, making it available to other members of the cave community. Diets of many insect, including cavernicoles, include fungal spores and mycelia (Culver 1982), and spores from at least 15 fungal genera probably constitute an important element in the diet of springtails (Collembola: Insecta) (Cubbon 1976; Culver 1982; Roselló *et al.*, 1986). Insects are considered an effective dispersion vector of fungal spores and other microorganisms because of nonspecific factors in attachment to host insect cuticles (Boucias *et al.* 1988). Chiropterans, insects, and rodents transport many fungal species to this bat-guano enriched soil environments (Hoff & Bigler 1981).

The Río Camuy Cave System [RCCS] is a 15-km long, subtropical karst feature carved by the Camuy River in the subtropical moist forest (Ewel & Whitmore 1973) of northern Puerto Rico. This system, one of the largest caves in Puerto Rico, is part of the National Parks Company of the Commonwealth of Puerto Rico natural protected area. In the 1960s, Russell and Jeanne Gurnee described the limestone features, caves, conservation, and future development, of what is now Río Camuy Caves Park [RCCP] (Gurnee 1967; Gurnee & Gurnee 1974, 1987; Martínez-Oquendo 1983) (Fig. 1). The geology and hydrology of the RCCS were treated by Thrailkill (1967), Monroe (1976, 1980), Torres-González (1983), Troester and White (1986), and Troester (1988, 1994). A recent study (Lugo *et al.* 2001) summarized what is known about the karst of Puerto Rico (including RCCS), including its importance and anthropogenic impact. Bat-guano enriched soil was formerly mined from Puerto Rican caves (Cadilla 1962; Beck *et al.* 1976; Campbell 1994; Frank 1998), but the guano in Río Camuy caves apparently was not heavily exploited (Cardona-Bonet, pers. comm. 2001).

In general, the rainy season in Puerto Rico peaks in May-June and August-September. Air temperatures in RCCS range from 18-25° C (Mercado, pers. comm. 2000), relative humidity from 88-100% (Troester 1988), and the average annual rainfall for Lares, 7 km SW of RCCP, is 2435 mm.

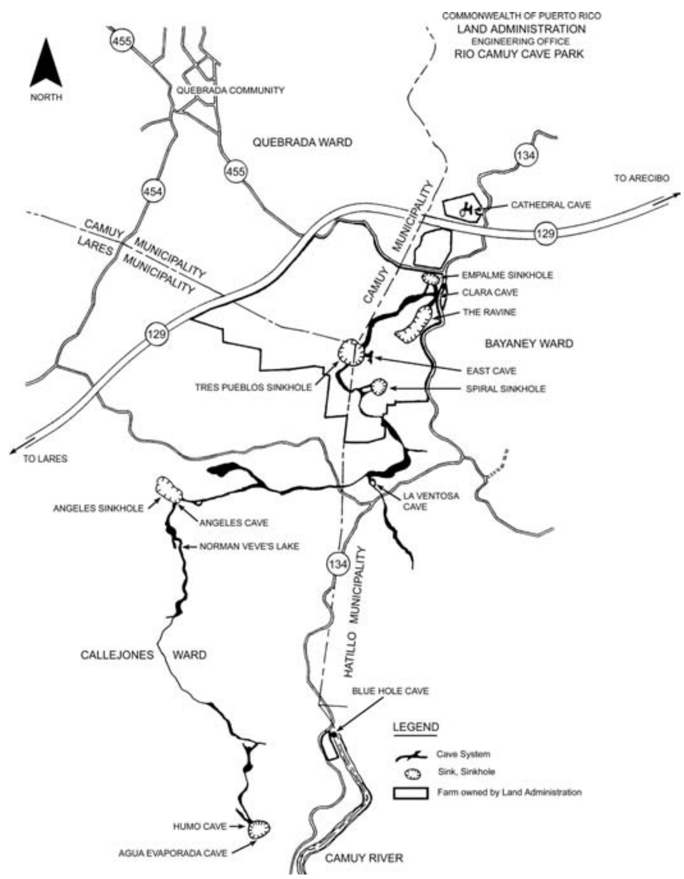


Figure 1. Map of Río Camuy Caves Park. Redrawn after Luis Ayala (November 1988) by permission (National Parks Company of the Commonwealth of Puerto Rico), based on Gurnee & Gurnee (1974) original map.

The vascular flora of the sinkholes and mogotes of RCCP was surveyed by Del Llano (1982) and Vives *et al.* (1985), recording 136 and 73 plant species, respectively. Reyes-Colón (1999) and Reyes-Colón and Sastre-DJ (2000) recorded 50 species: 31 mosses (11% of the moss flora of Puerto Rico) and 19 liverworts (8% of the liverwort flora of Puerto Rico) from 2 sinkholes (Espiral and Empalme Sinks) in RCCP.

The caves and sinkholes of RCCP are inhabited by a variety of invertebrates and vertebrates (Sullivan 1966, 1967; Peck 1974, 1981, 1994; Díaz-Díaz 1982, 1983; Santos-Flores 2001; Lugo *et al.* 2001). Multispecies assemblages of bats are reported from RCCP, as is common in many Puerto Rican caves (Rodríguez-Durán & Lewis 1987; Conde Costas & González 1990; Rodríguez-Durán 1998). With the exception of the endemic amphipod *Alloweckelia gurneei* Holsinger & Peck (Holsinger & Peck 1967) and the cave cockroach *Nelipophygus* sp. (Peck 1981), no other troglobites have been reported from RCCS.

Betancourt *et al.* (1988) recorded 8 genera of mitosporic fungi (*Aspergillus* sp., *Cladosporium* sp., *Curvularia* sp., *Fusarium* sp., *Geotrichum* sp., *Scopulariopsis* sp., *Sepedonium* sp., and *Rhizopus* sp.) from Ensueño Cave (3 km south of RCCP). Eight species of aquatic hyphomycetes (*Brachyosphaera jamaiciensis* [Crane & Dumont] Descals, *Clavariopsis azlanii* Nawawi, *Dendrosporium lobatum* Plakidas & Edgerton: Crane, *Isthmolongispora quadricellularia* Matsushima, *Tricladiospora brunnea* [Nawawi] Nawawi & Kuth., *Tripospermum* sp., *Varicosporeum giganteum* Crane, *Xenosporium berkeleyi* [Curtis] Pirozynski) were also isolated in river foam from Tres Pueblos Sinkhole (Santos-Flores & Betancourt-López 1997) in RCCP.

This report summarizes a mycological survey of the bat-guano enriched soil, leaf litter, wood, top soil, streams, and intermittent pools in RCCP.

METHODS

I conducted a basic inventory of the fungi, and the cellular/plasmodial slime molds at Cathedral Cave, Clara Cave, Empalme Sinkhole, and Tres Pueblos Sinkhole (RCCP, Bayaney topographic quadrangle) (Figure 1). These sites are described below.

•Cathedral Cave ("Cueva La Catedral") (18°21’04.2” N, 66°48’99.3” W), a hydrological inactive cave, is located adjacent to the hydrographic basin of the Río Camuy, at the north end of RCCP (Fig. 1). This cave is 122 m long, with 2 main parallel galleries (or chambers), which run north-south and are connected by a short passage, with 2 natural skylights, about 24 and 38 m above the floor of the cave. The west hall contains rock art of presumed aboriginal origin (42 pictographs in total; Nieves-Rivera, unpubl. data).

•Clara Cave ["Cueva Clara de Empalme", "Empalme Cave" of Peck (1974)] (18°20’85.4” N, 66°49’16.0” W) is located south of Cathedral Cave (Fig. 1). This cave is part of the ancient course of the Río Camuy and is higher than the present river level. The main passage is a diagonal tunnel 115 m long and 52 m high. A secondary passage extends 30 m to the west. The primary entrance is shown in Figure 2A; there is also a vertical shaft entrance at Empalme Sinkhole. Previous hydrological studies of 2 sites (streamlet/pool R-1 [Fig. 2B] and pool R-2, both intermittent) of Cueva Clara reported concentrations of 7.9-8.6 mg/L of dissolved oxygen at 22°C, and 0.131 to 0.040 mg/L of total phosphorous, respectively (Díaz-Díaz 1982). Pool water pH has been measured between 9.1 and 9.2 with conductivity rendering 200 µ (Nieves-Rivera, unpubl. data). Fecal coliform counts have been reported as 1160 cells/mL for R-1 and 1810 cells/mL for R-2, respectively, indicating a runoff water with high organic input (fecal matter and detritus) (Díaz-Díaz 1982).

•Empalme Sinkhole ("Sumidero de Empalme") (18°20’79.9” N, 66°49’11.2” W) is a 99-m wide doline with a 125-m deep vertical shaft, connecting directly to Clara Cave (Fig. 1) and to the conical-shaped "Cueva Alta del Norte" (Fig. 2C). At the bottom, and along the upper reaches of the Río Camuy, numerous collapsed blocks are present, along with top soil composed of clay or dirt, leaf litter, mosses, and rocks with lichens. Further description of this doline was given by Gurnee (1967), Gurnee & Gurnee (1974), Reyes-Colón (1999), and Reyes-Colón & Sastre-DJ (2000).

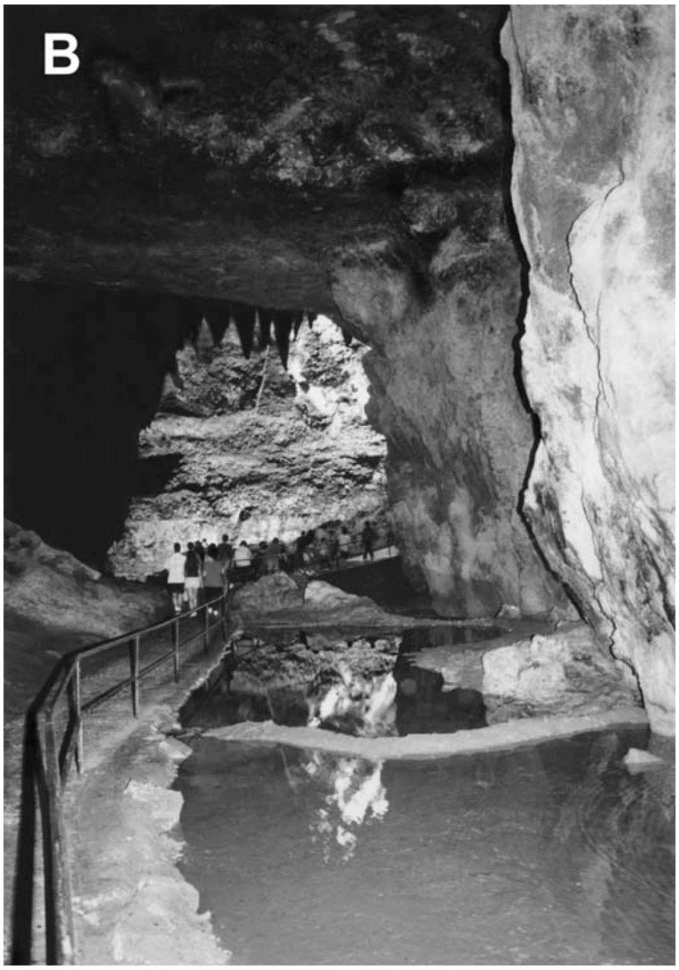
•Tres Pueblos Sinkhole ("Sumidero Tres Pueblos") (18°20’30.5” N, 66°49’26.3” W) is a doline in RCCP, and was described by Gurnee (1967) and Gurnee & Gurnee (1974).

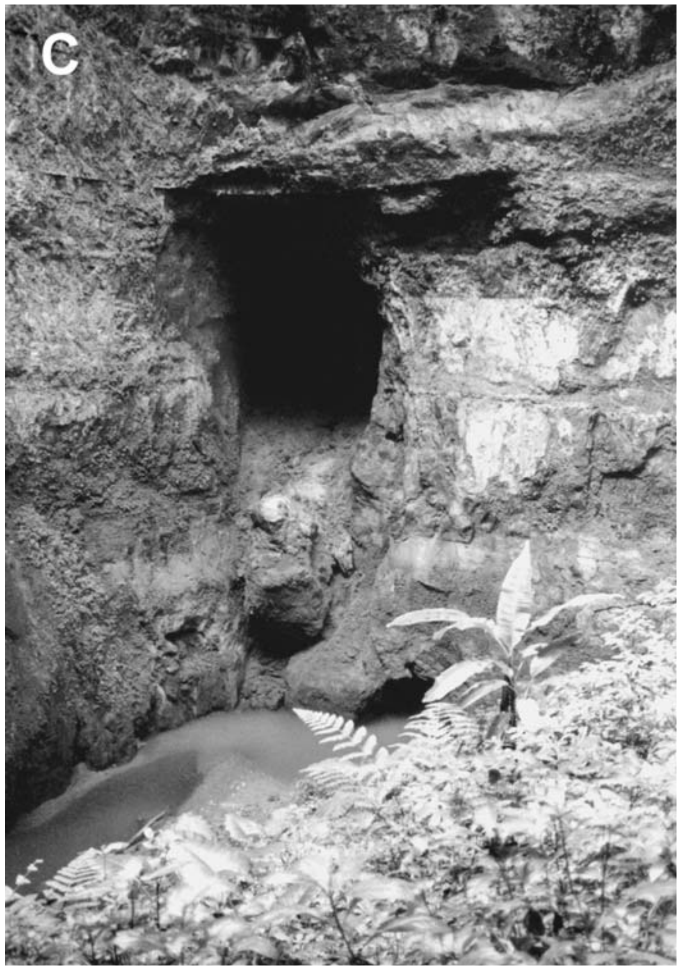
FIELD WORK

Field work at Cathedral Cave, Clara Cave, and Empalme Sinkhole was carried out on 8 August 1999, supplemented by river water and mud samples collected from Tres Pueblos Sinkhole in May 1993. Undergraduate and graduate students, and professors from the University of Puerto Rico at Mayagüez Campus (Departments of Crop Protection and Marine Sciences) participated in the survey.

LABORATORY WORK

Fungi were isolated from field-collected samples. Samples of bat-guano enriched soil, leaf litter, wood, water, and soil were collected using sterile plastic bags (Whirl Pak). Higher fungi (ascomycetes and basidiomycetes) were collected and processed following Nieves-Rivera *et al.* (1999). Bat-guano enriched soil samples were processed according to Orpurt (1964), Gaur and Lichtwardt (1980), and Rutherford and Huang (1994). Freshwater fungi sampling followed Sparrow (1960), Nieves-Rivera and Betancourt-López (1994) and Santos-Flores and Betancourt-López (1997). Potato dextrose agar acidified with 10% lactic acid, Rose Bengal agar, and Sabouraud’s dextrose agar were used as fungal growth media. Wet mount observations were made with a Nikon Labophoto-2 microscope. All voucher specimens were taken to the Center for Forest Mycology (U.S. Department of Agriculture, Forest Products Laboratory, Sabana Station, Puerto Rico) where they are being prepared for deposition in the herbarium of the Department of Natural Sciences, University of Puerto Rico





Figures 2A-C. Río Camuy Caves Park study sites. A. Main entrance of Clara Cave. B. Intermittent streamlet R-1 seen from inside Clara Cave. C. Inside Empalme Sinkhole (with a view of Cueva Alta del Norte), mesophytic forest, Río Camuy is at the bottom.

Piedras, Puerto Rico.

RESULTS AND DISCUSSION

A total of 45 true-fungi (39 new records) and 16 fungal-like organisms (11 Dictyosteliomycota/Myxomycota and 5 Oomycota; all new records) are reported from RCCS. Of these, a total of 36 taxa (34 micromycetes and 2 macromycetes) from 17 genera were isolated from cave bat-guano enriched soil or topsoil (Table 1). *Aspergillus*, *Penicillium*, *Fusarium*, *Cladosporium*, *Trichoderma*, *Paecilomyces*, *Curvularia*, *Gliocladium*, *Hirsutella*, and *Sepedonium* were the most common hyphomycete genera in cave soil (Table 1). All these genera are dematiaceous hyphomycetes. *Mycelia Sterilia sensu* Rutherford & Huang (1994) was also present in cave soil. Mitosporic fungi isolated in this study were present as spores, actively growing mycelium or as resting mycelial cysts. Other frequently isolated fungi were members of the Zygomycota, *Mucor*, *Rhizopus*, and an undetermined entomophylic species. The pathogen *Histoplasma capsulatum* Darling, the causative agent of histoplasmosis, was not isolated from cave samples, but was found in 1979 in Humo Cave, part of RCCS (Carvajal-Zamora, pers. comm. 1998; Table 1).

The habitat below the skylights and at other openings of RCCS differs little from the surface (Gillieson 1996). Outside of the study area, *Xylaria* (Ascomycota) and *Lepiota* (Basidiomycota) have been found in caves below skylights in Espinar Cave (Mona Island), De los Santos/Braceros Cave

Table 1. Summary of the mycobiota of the Río Camuy Cave System, Puerto Rico. Nomenclature is based on Hawksworth *et al.* (1995), Alexopoulos *et al.* (1996), and Lodge (1996).

TAXON	**FAMILY**	**SUBSTRATE** [1]	**REFERENCES** [2]
FUNGI [= MYCOTA]			
HYPHOMYCETES [= MITOSPORIC FUNGI]			
Aspergillus flavus Link	Anamorphic (A.) Trichocomaceae	S	2, 5, 7
Aspergillus fumigatus Fresenius	A. Trichocomaceae	S	2, 5, 7
Aspergillus nidulans (Eidam) G. Winter	A. Trichocomaceae	S	2, 5
Aspergillus niger var. *niger* van Tieghem	A. Trichocomaceae	S	1, 2, 4, 5, 7
Brachiosphaera jamaiciensis (Crane & Dumont) Descals	—————————-	S	6
Cladosporium cladosporoides (Fresenius) deVries	A. Mycosphaerellaceae	D, S, W	2, 5, 7
Cladosporium herbarum (Pers.) Link	A. Mycosphaerellaceae	S, D	1, 2, 5, 7
Clavariopsis azlanii Nawawi	—————————-	L, R	6
Curvularia sp.	A. Pleosporaceae	S	1, 5
Dendrosporium lobatum Plakidas & Edgerton: Crane	—————————-	L, R	6
Fusarium cf. *oxysporum* Schl.	A. Hypocreaceae	S	1, 2, 5, 7
Fusarium solani (Martius) Sacc.	A. Hypocreaceae	S	5, 7
Geotrichum sp.	A. Dipodascaceae	S	1, 5
Gliocladium cf. *roseum* Bain.	—————————-	S	2, 5
Hirsutella sp.	—————————-	I	2, 5
Histoplasma capsulatum Darling [3]	A. Onygenaceae	S	3, 7
Isthmolongispora quadricellularia Matsushima	—————————-	L, R	6
Neurospora crassa Shear & Dodge	Sordariaceae	S	2, 5, 7
Paecilomyces sp.	A. Trichocomaceae	S	2, 5
Penicillium cf. *crysogenum* Thom	—————————-	S	2, 5, 7
Penicillium lilacinum Thom	—————————-	S	2, 5, 7
Penicillium roqueforti Thom	—————————-	S	2, 5
Penicillium variable Westling	—————————-	S	2, 5
Scopulariopsis sp.	A. Microascaceae	S	1
Sepedonium sp.	A. Hypocreaceae	S	1, 5
Tricladisopora brunnea (Nawawi) Nawawi & Kuth.	—————————-	L, R	6
Trichoderma koeningii Oudermans	A. Hypocreaceae	S	2, 5
Trichoderma viridae Pers.: Fr.	A. Hypocreaceae	S	2, 5, 7
Tripospermum sp.	A. Capnodiaceae	L, R	6
Varicosporium giganteum Crane	—————————-	L, R	6
Xenosporium berkeleyi (Curtis) Pirozynski	—————————-	L, R	6
Mycelia Sterilia	Agonomycetaceae	S, W, I	2, 5
ASCOMYCOTA			
Xylaria polymorpha (Pers.: Mérat) Grev.	Xylariaceae	W	2, 5, 7
Xylaria sp.	Xylariaceae	W	2, 5
BASIDIOMYCOTA			
Cotylidia aurantica (Pers.) A. L. Welden	Podoscyophaceae	W	8
Geastrum cf. *saccatum* (Fr.) Ed. Fischer [4]	Geastraceae	S	5
Lepiota sp.	Agaricaeace	S	2, 5
Marasmius cf. *atrorubens* (Berk.) Berk.	Tricholomataceae	L	5
Polyporus tenuiculus (Beauv.) Fr. [5]	Polyporaceae/Coriolaceae	W	5
Ramaria sp.	Ramariaceae	L	8
Rigidoporus microporus (Fr.) Overeem.	Polyporaceae/Coriolaceae	W	8
ZYGOMYCOTA			
Mucor sp.	Mucoraceae	D, S, W	2, 5
Rhizopus stolonifer (Ehr.: Fr.) Vuill.	Mucoraceae	D, S	1, 2, 5, 7
Undetermined species	Mucoraceae	I	5
CHYTRIDIOMYCOTA			
Rhizophydium sp.	Chytridiaceae	P	5
CHROMISTA [= STRAMINIPILA]			
OOMYCOTA			
Achlya americana Humphrey	Saprolegniaceae	R	4, 5, 7
Achlya parasitica Coker	Saprolegniaceae	R	4, 5
Apodachlya sp.	Leptomitaceae	R	4, 5
Brevilegnia sp.	Saprolegniaceae	R	4, 5
Saprolegnia sp.	Saprolegniaceae	R	4, 5

PROTOZOA			
DICTYOSTELIOMYCOTA			
Dictyostelium aureostipes Cavender, Raper & Norberg [6]	Dictyosteliaceae	L, S	4, 5
Dictyostelium citrinum Vadell, Holmes & Cavender [6]	Dictyosteliaceae	L, S	4, 5
Dictyostelium giganteum Singh [6]	Dictyosteliaceae	L, S	4, 5
Dictyostelium macrocephalum Hagiwara, Yeh & Chien [6]	Dictyosteliaceae	L, S	4, 5
Dictyostelium mucoroides Brefeld [6]	Dictyosteliaceae	L, S	4, 5
Dictyostelium purpureum Olive [6]	Dictyosteliaceae	L, S	4, 5
Polysphondylium pallidum Olive [6]	Dictyosteliaceae	L, S	4, 5
Polysphondylium violaceum Brefeld [6]	Dictyosteliaceae	L, S	4, 5
MYXOMYCOTA			
Arcyria cf.	Arcyriaceae	B, W	4, 5
Comatricha cf.	Stemonitidaceae	L	5
Stemonitis cf. *herbatica* Peck	Stemonitidaceae	W	4, 5, 7

[1] Substrates: B = Bat bones; D = Dung; I = Dead insects; L = Leaf litter; P = Pollen; R = River water or foam; S = Bat-guano enriched soil or top soil; W = dead wood. The substrates were the location where the fungus was found growing or just the site from which a spore was isolated.

[2] References: 1 = Betancourt *et al.* (1988); 2 = Carvajal-Zamora & Nieves-Rivera (1998); 3 = Lewis (1989); 4 = Nieves-Rivera & Carvajal-Zamora (2000); 5 = Nieves-Rivera (present work); 6 = Santos-Flores & Betancourt-López (1997); 7 = Stevenson (1975); 8 = D. J. Lodge (pers. comm. 2001).

[3] Carvajal-Zamora (pers. comm. to Norman Veve Carreras [SEPRI] in 1979 and to me in 1998) isolated this pathogen from bat-guano of Humo Cave (= Cueva Humo) in 1979.

[4] *Geastrum* cf. *saccatum* was collected directly from top soil (not in bat-guano enriched soil), next to the edge of Tres Pueblos Sinkhole.

[5] *Polyporus tenuiculus* (= *Favolus brasiliensis* [Fr.] Fr.) basidiomata was consumed by *Caracolus caracola* (Pulmonata: Gastropoda) in a similar way as reported by Lodge (1996).

[6] Species cultured and identified by John C. Landolt, Shepherd College, Shepherdstown, WV.

(Cabo Rojo), and Cathedral Cave (Nieves-Rivera, unpubl. data). These openings admit plant debris from which fungi sporulate and fruiting bodies may develop.

Food is, in general, relatively scarce in deeper portions of caves (Culver 1982; Gillieson 1996). Most of the fungi isolated in this study are edaphic microfungi. These fungi feed and sporulate on different substrates (e.g., a carcasses, hair, seeds, or bat-guano). Use of similar substrata by both lower and higher fungi has been reported for Diablo Cave (Mexico) (Hoffman *et al.* 1986), Hendrie River Water Cave (Michigan) (Volz & Yao 1991), West Virginia Caves (Rutherford & Huang 1994), and Kozlov Rob Cave (Slovenian) (Gunde-Cimerman *et al.* 1998).

Other fungal species recorded in RCCP, particularly in wet soil and ponds formed when the river rises, included various species of Oomycota (e.g., *Achlya americana* Humphrey, *A. parasitica* Coker, *Brevilegnia* sp., and *Saprolegnia* sp.) Nieves-Rivera & Betancourt-López (1994) isolated *Saprolegnia ferax* (Gruith.) Thuret and *Achlya americana* Humphrey from a stream pond in El Convento Cave Spring System (Guayanilla, southwestern Puerto Rico), an ancient course of Río Camuy (Troester 1988). A chytrid (*Rhizophydium* sp.) was isolated from Tres Pueblos Sinkhole in 1993 and also has been isolated from a stream (Quebrada de Oro) at Mayagüez (Nieves-Rivera, unpubl. data).

In the entrances of RCCS, several higher fungal species, *Cotylidia aurantica* (Pers.) A. L. Welden, *Rigidoporus microporus* (Fr.) Overeem., *Ramaria* sp., *Geastrum* cf. *saccatum* Fr. (Fig. 3J), *Marasmius* cf. *atrorubens* (Berk.) Berk., and *Polyporus tenuiculus* (Beauv.) Fr. [= *Favolus brasiliensis* (Fr.) Fr.] were collected. *Polyporus tenuiculus* was observed being consumed by the land snail *Caracolus caracola* L. (Pulmonata: Gastropoda). Lodge (1996) reported *C. caracola* devouring basidiocarps of *P. tenuiculus* from El Verde Long Term Ecological Research site in the Luquillo Mountains, northeastern Puerto Rico. Undetermined microfungi are dominant on bat-guano deeper in RCCS (e.g., Cathedral Cave). These mycelial mats are found in caves with bat colonies in the northern and southern karst areas of Puerto Rico (Nieves-Rivera, unpubl. data).

Myxomycetes (plasmodial slime molds) *Arcyria* cf., *Comatricha* cf., and *Stemonitis* cf. *herbatica* Peck were collected from all entrances sites, except Empalme Sinkhole. Eight species of dictyostelids (cellular slime molds) were isolated from bat-guano enriched soil, or leaf litter, including *Dictyostelium aureostipes* Cavender, Raper & Norberg, *D. citrinum* Vadell, Holmes & Cavender, *D. giganteum* Singh, *D. macrocephalum* Hagiwara, Yeh & Chien, *D. mucoroides* Brefeld, *D. purpureum* Olive, *Polysphondylium pallidum* Olive, and *P. violaceum* Brefeld (Table 1). *Polysphondylium violaceum* and an undetermined myxomycete plasmodium were previously isolated from bat-guano enriched soil from El Caballo/Pájaros Cave (Playa de Pájaros) and a bat cave (Uvero), both in Mona Island (Landolt, pers. comm. 1998; Nieves-Rivera & McFarlane 2001: map). *Polysphondylium violaceum* is fairly widespread in many tropical, subtropical, and temperate habitats (Landolt *et al.* 1992; Reeves *et al.* 2000); *P. violaceum* has been isolated from Appalachian Mountains and eastern Russia, and is widely distributed at lowlands and high altitudes – one isolate came from ~2000 m msl (Landolt, pers. comm. 2002). *Dictyostelium* and *Polysphondylium* species are inhabitants of moist forest soils and litter (Stephenson & Landolt 1996; Stephenson *et al.* 1999).

Forty-four of the 50 fungi and slime molds are new records for Cathedral Cave, Clara Cave, and Empalme and Tres Pueblos Sinkholes of RCCP (part of the RCCS). The cellular slime molds *Dictyostelium citrinum* and *D. macrocephalum* are new records for Puerto Rico.

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MORPHOMETRIC AND SPATIAL DISTRIBUTION PARAMETERS OF KARSTIC DEPRESSIONS, LOWER SUWANNEE RIVER BASIN, FLORIDA

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This study describes an application of Geographic Information Systems (GIS) to examine the morphometric and spatial distribution of karstic depressions in the lower Suwannee River basin. Morphometris analysis of some 25,000 karstic depressions in an area covered by twenty-four 1:24,000 scale standard USGS topographic quadrangles were made possible by the analytical capabilities of the GIS. The parameters calculated for the study area include length, width, orientation, area, depth, circularity index, depression density, pitting index, and nearest neighbor index. Analysis of ~25,000 depressions in the lower Suwannee River basin reveals that the Florida karst is represented by broad, shallow depressions with an average density of 6.07 depressions/km² and an average pitting index of 14.5. Morphometric and spatial distribution parameters of karstic depressions within the lower Suwannee River basin show significant variations.

The robust GIS methodology used in this study provides not only a rapid analysis of spatial data on a large population of karstic depressions, but also an objective approach with consistent measurement and calculation processes in which human errors and bias were eliminated. In accordance with the increasing use of GIS in analyzing spatial data on diverse applications, this study shows that the GIS environment can also be efficiently used for karst landform studies.

Surrounded by submarine escarpments from both east and west, the Florida Platform consists of a thick sequence of limestone and dolomite deposited during the Tertiary Period. The generally unconfined or semiconfined hydrogeologic conditions of the Floridan aquifer system in the lower Suwannee River Basin have produced a fascinating collection of karst depressions illustrating a complex evolutionary history controlled by the lower sea-level stands of the Pleistocene and the formation of the Suwannee River (Denizman & Randazzo 2000).

Morphometry can be defined as the measurement and mathematical analysis of the configuration of the Earth's surface and of the shape and dimensions of its landforms (Bates & Jackson 1987: 235). Application of morphometric techniques to karst landforms provides an objective and quantitative system of karst landform description and analysis. Morphometric techniques have been applied to a variety of karst regions and proven to be very effective in placing many karst landforms, especially depressions, in perspective (Williams 1972a, 1979; Day 1983; Troester *et al*. 1984; Magdalena & Alexander 1995).

There have been few quantitative investigations of Florida's complex karst features. Certainly, little attention has been given to the morphometric and spatial distribution parameters of enclosed depressions. The work of Troester *et al.* (1984), Beck and Jenkins (1985), and Bahtijarevic (1996) on depression morphometry and spatial distribution were of local scale with small depression populations. In this study, morphometric analysis of a relatively large part of the lower Suwannee River karst area (4063 km²) was made possible by the powerful and rapid analytical capabilities of Geographic Information Systems (GIS). Application of GIS to spatial data has proven to be instrumental in the analysis of complex problems in earth and environmental sciences (ESRI 2000). GIS provide rapid access, integration, and analysis of spatially referenced data stored in large numerical databases. It also display the results graphically in maps and charts.

METHODOLOGY

Morphometric and spatial distribution parameters of karstic depressions in the lower Suwannee River basin were evaluated in the GIS environment, using ArcInfo 7.0 and ArcView 3.0. In this study, morphometric analysis of ~25,000 karstic depressions in an area covered by twenty-four 1:24,000 scale standard USGS topographic quadrangles (4063 km²) was made possible by the powerful and rapid analytical capabilities of the GIS. The topographic quadrangles analyzed in this study are shown in Figure 1. The procedure followed in this study consists of extensive manual and computer work.

The first stage of the study involved detailed topographic map analysis. All the natural depressions depicted by hachured closed contours on topographic maps along the Suwannee River were delineated on transparent papers. Depressions delineated on topographic quadrangles were then transferred to ArcInfo (GIS) environment. Digital layers (coverages) of depressions were produced. In order to utilize GRID functions of ArcInfo, vector coverages of depressions were converted to raster files. GRID is a cell-based module of ArcInfo. It manipulates raster files in which a regular "mesh" is draped over the

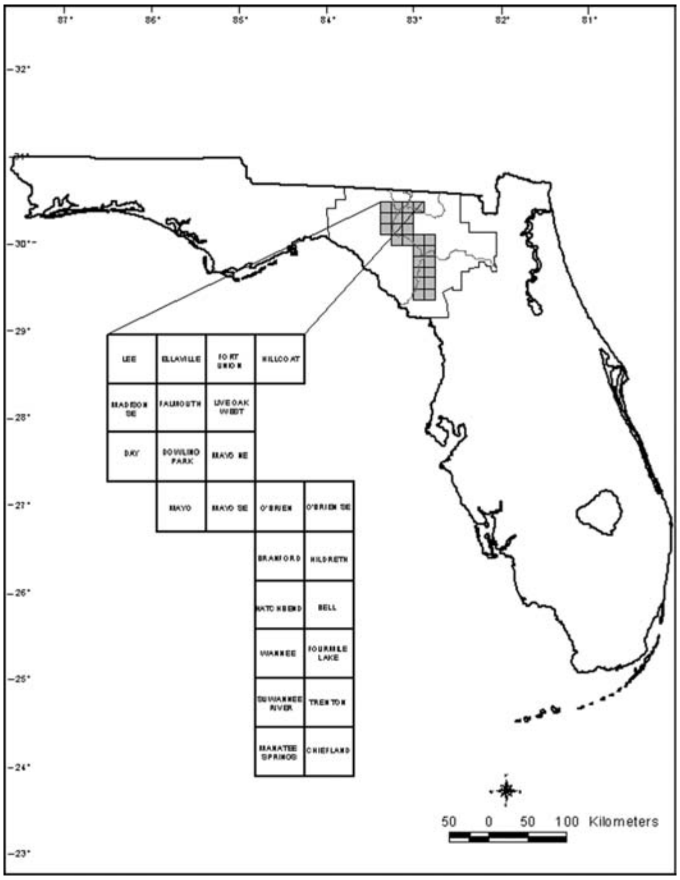


Figure 1. General location of the Suwannee River basin and the study area.

landscape. Morphometric measurements (length, width, area, perimeter, major axis orientation) were performed on each depression using zonal functions (zonalgeometry and zonalcentroid) of GRID. Depressions were represented by their highest contour for measurements of length, width, depth, area, perimeter, and major axis orientation.

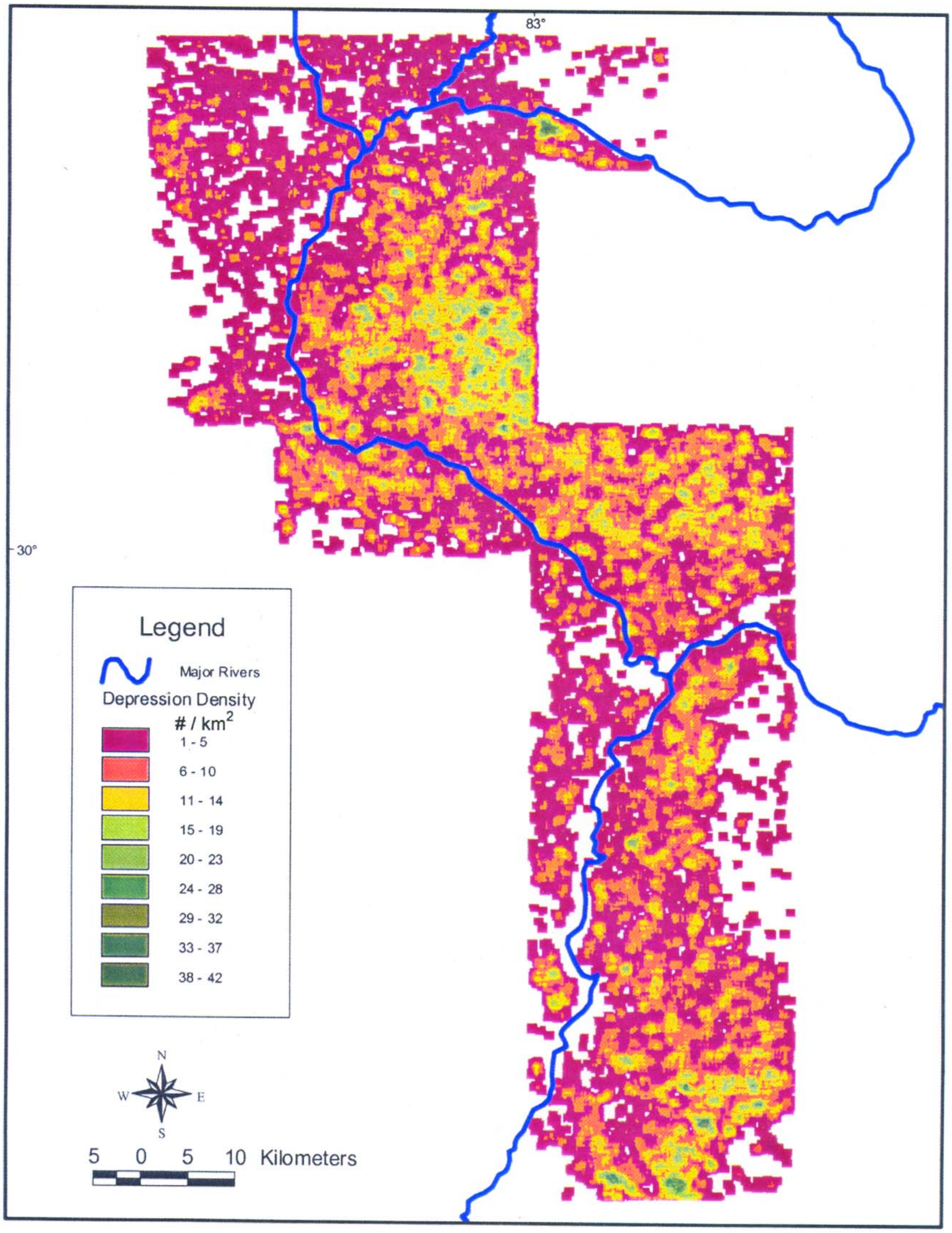
Nearest neighbor analysis was performed for each quadrangle as well as the whole study area. Compound depressions were divided into their components and each depression was taken into account individually. Nearest neighbor distances for each quadrangle were calculated by using Fragstats, a powerful spatial analysis software originally created for landscape pattern analysis of digital data. Calculations for the whole study area were made using the Euclidian functions of GRID. In these analyses, depressions were represented by their centroids, determined by the “zonalcentroid” function of GRID. Ideally, karstic depressions are represented by their deepest points, i.e., swallets as in Williams (1972a) for an accurate spatial description that is of paramount importance in spatial analysis. Williams (1972a, 1972b) was able to detect the swallets and drainage patterns in the polygonal karst of New Guinea. However, they are not detectable in the low-relief karst of Florida, which is covered by at least several meters of soil and thick vegetation. Therefore, in order to maintain consistency and avoid subjectivity in assessing point locations for depressions, they were represented by their centroids that were readily and precisely determined by GRID functions in GIS.

As explained above, two GIS databases for karstic depressions were created in ArcView: The morphometric database includes morphometric parameters such as depression area, perimeter, length, width, mean diameter, length/width ratio, circularity index, major axis orientation, and approximate depth. The spatial distribution parameters database includes

Table 1. Spatial distribution parameters of depressions per topographic map quandrangle.

Quadrangle Name	Number of Depressions	Density (#/km^2)	Total Depression Area (km^2)	Mean Depression Area (km^2)	Mean Nearest Neighbor Distance (m)	Nearest Neighbor Index (R)	Distribution Pattern	Pitting Index	Length/ Width
WANNEE	904	5.3	10.7	0.012	186.2	0.9	Tending to cluster	15.83	1.70
FOURMILE LAKE	588	3.4	8.5	0.014	212.6	0.8	Tending to cluster	20.15	1.81
SUWANNEE RIVER	953	5.6	9.8	0.010	164.4	0.8	Tending to cluster	17.35	1.72
TRENTON	1283	7.5	20.5	0.016	174.8	1.0	Near random	8.35	1.74
MANATEE SPRINGS	953	5.6	12.4	0.013	170.8	0.8	Clustered	13.72	1.82
CHIEFLAND	1742	10.2	8.5	0.005	129.7	0.8	Tending to cluster	20.23	1.62
LEE	593	3.5	18.0	0.030	235.4	0.9	Tending to cluster	9.41	1.70
MADISON SE	405	2.4	13.0	0.032	245.4	0.8	Tending to cluster	12.84	1.99
ELLAVILLE	622	3.6	14.1	0.023	214.7	0.8	Tending to cluster	12.18	1.89
FORT UNION	482	2.9	16.6	0.034	255.5	0.9	Tending to cluster	10.20	1.80
FALLMOUTH	1002	5.8	11.4	0.011	174.9	0.8	Tending to cluster	15.06	1.80
LIVE OAK WEST	1389	8.1	19.1	0.014	161.3	0.9	Near random	8.97	1.69
HILLCOAT	444	2.6	4.2	0.009	178.8	0.6	Clustered	40.91	1.90
DAY	388	2.7	7.3	0.019	241.4	0.8	Tending to cluster	19.49	1.84
DOWLING PARK	1514	8.9	21.7	0.014	159.6	1.0	Near random	7.89	1.76
MAYO NE	2721	15.8	23.5	0.009	128.9	1.0	Near random	7.32	1.61
MAYO	1273	7.5	13.2	0.010	160.9	0.9	Tending to cluster	12.86	1.77
MAYO SE	1187	6.9	11.6	0.010	179.7	0.9	Near random	14.81	1.72
O'BRIEN	1724	10.1	16.6	0.010	160.3	1.0	Near random	10.27	1.72
O'BRIEN SE	1663	9.8	25.4	0.015	158.5	1.0	Near random	6.70	1.74
BRANFORD	766	4.5	8.4	0.011	191.0	0.8	Tending to cluster	20.15	1.81
HILDRETH	971	5.7	11.7	0.012	189.1	0.9	Near random	14.47	1.80
HATCHBEND	753	4.4	8.8	0.012	205.3	0.9	Tending to cluster	19.60	1.82
BELL	837	4.9	16.4	0.020	187.0	0.8	Tending to cluster	10.37	1.89
TOTAL	25157								

Figure 2. Depression density distribution within the study area.



centroid locations of depressions, nearest neighbor distances, and azimuth values for nearest neighbor vectors for individual depressions.

Among a great number of morphometric parameters proposed by various karst geomorphologists, only those that are possible to be measured or calculated by GIS based on the available data were included in this study:

Length: length of the major axis of an ellipsoid representing the depression.

Width: length of the minor axis of an ellipsoid representing the depression.

Orientation: orientation of the major axis. Originally expressed by GRID as the angle from the east, counterclockwise, it was converted to regular azimuth values.

Area: area of each depression measured in m².

Pitting index: (Area of karst)/(Total depression area).

Circularity index: the measure of the circularity of a depression.

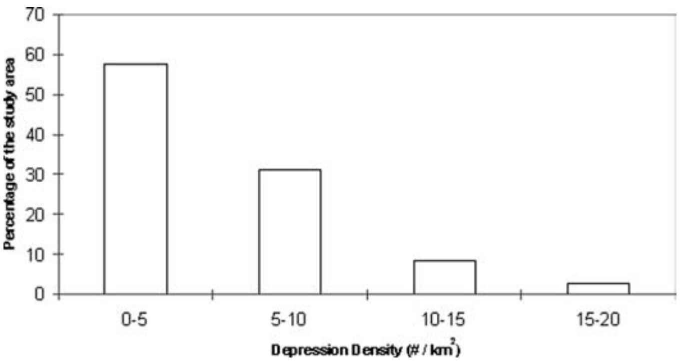


Figure 3. Distribution of depression density.

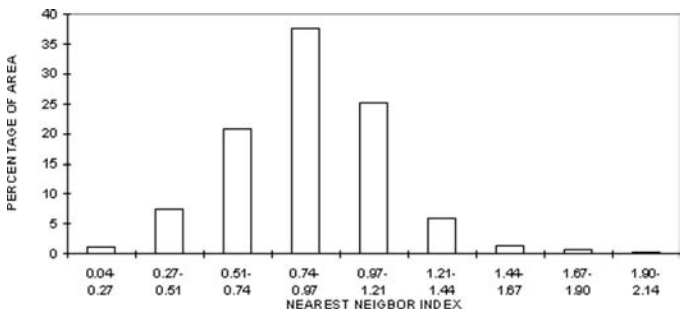


Figure 4. Distribution of nearest neighbor index.

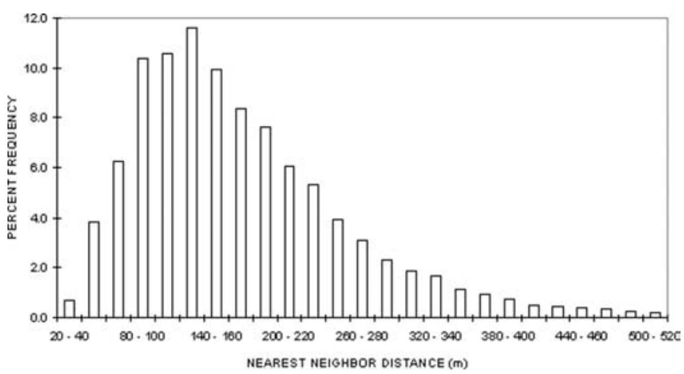


Figure 5. Frequency distribution of nearest neighbor distance.

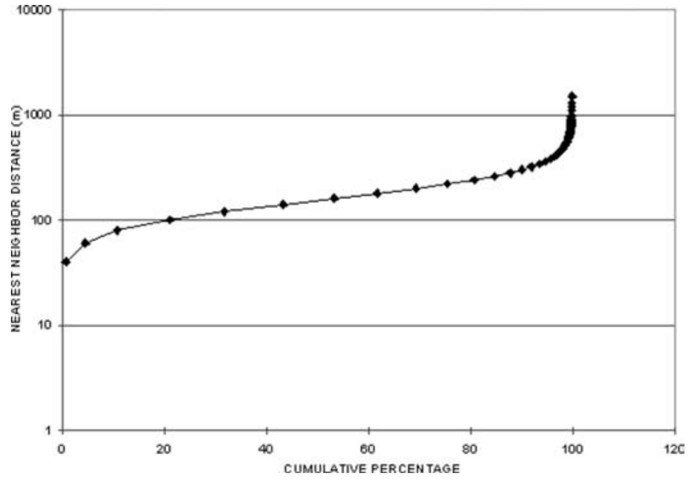


Figure 6. Cumulative percentage of nearest neighbor distance.

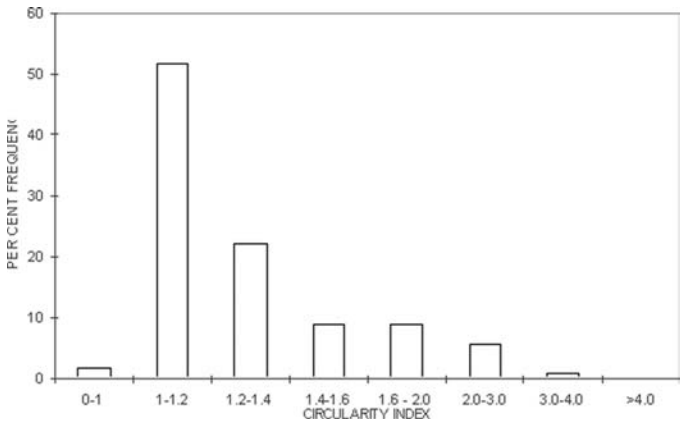


Figure 7. Frequency distribution of circularity index.

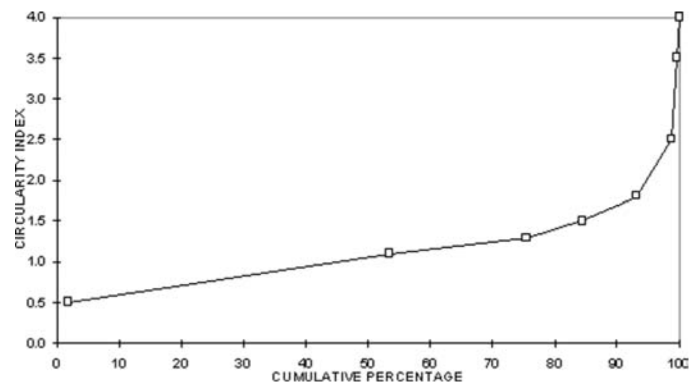


Figure 8. Cumulative percentage of circularity index.

Depth information was obtained by counting the number of closed contours for each depression.

RESULTS

DEPRESSION DENSITY

Depression densities were calculated for each topographic quadrangle by dividing the number of depressions by area (Table 1). Mean depression density for the 4063 km² area is 6.1/km². It ranges from 2.4 (Madison SE) to 15.8 (Mayo NE) with a standard deviation of 3.2.

Distribution of depression density is also presented as a GIS layer with a spatial resolution of 10 m (Fig. 2). It was created by calculating the number of depression centroid points in a 1 km² window moving 10 m at each step. Nearly half of the study area (~1900 km²) is represented by a depression density between 1 and 5 /km² (Fig. 3).

The area of each depression for each quadrangle was cal-

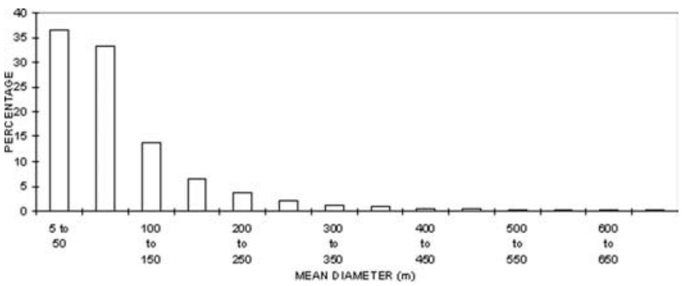


Figure 9. Distribution of mean diameter.

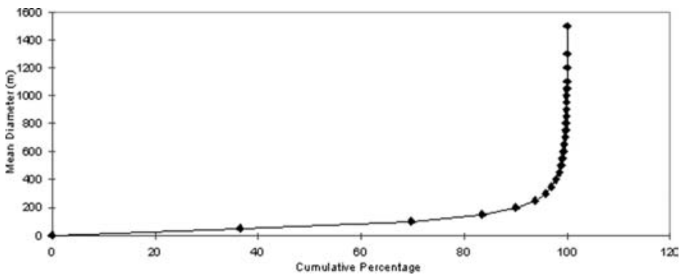


Figure 10. Cumulative percentage of mean diameter.

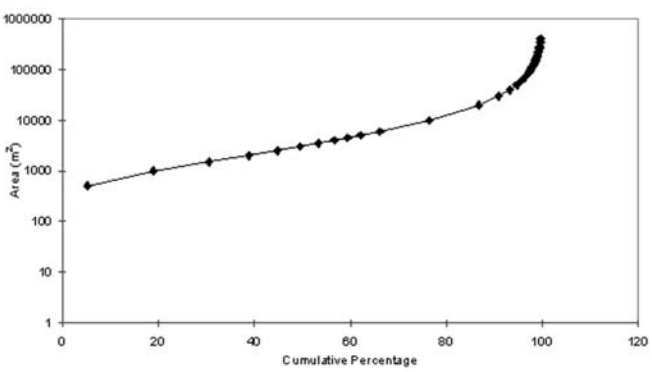


Figure 11. Cumulative percentage of depression area.

culated by GIS functions (Table 1). Total depression area varies from 4.2 km² (Hillcoat) to 25.4 km² (O'Brien SE) with a mean of 13.8 km² and a standard deviation of 5.4 km². Grand total of the depression area is 331.4 km², corresponding to 8.2% of the study area (4063 km²).

As a measure of surficial karst development, the pitting index (total area of karst/total depression area) provides information about the extent of karstification. For the polygonal karst landscapes covered by tightly spaced depressions, the pitting index approaches unity. The pitting index varies from 6.7 (O'Brien SE) to 40.91 (Day) with a mean of 14.5 and a standard deviation of 7.0 (Table 1).

Spatial distribution of depression centroids was analyzed using the simple nearest neighbor technique (Williams 1972a, 1972b). The mean nearest neighbor distance (La) for karstic depressions within each quadrangle was calculated using Fragstats (Table 1). It ranges from 129.0 m (Mayo NE) to

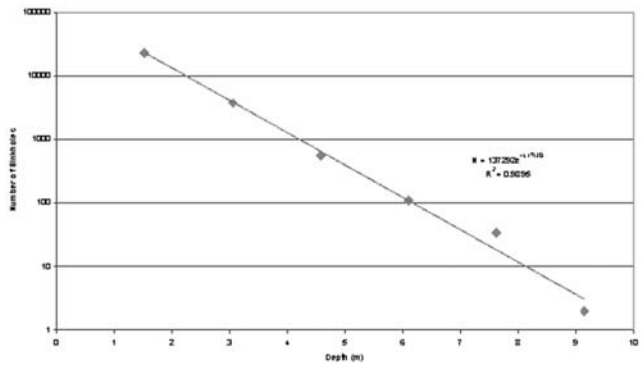


Figure 12. Depression depth frequency.

255.5 m (Fort Union) with an overall mean and standard deviation of 186.1 m and 33.3 m respectively. The expected mean nearest neighbor distance (L_e) in an infinitely large, randomly located population with same depression density, D, is given by $L_e = 1/(2\sqrt{D})$ and ranges from 125.8 m (Mayo NE) to 321.0 m (Madison SE).

The nearest neighbor index R, described as the ratio of L_a/L_e, was derived for corresponding quadrangles (Table 1). It ranges from 0.6 (Hillcoat) with a clustered distribution to 1.0 (Mayo NE and O'Brien), which represents randomly distributed depressions. Mean nearest neighbor index for the whole area is 0.9. Most of the topographic quadrangles reveal a depression distribution significantly different from random expectation (R=1) at the 0.05 level. All the depressions except those in Trenton, Live Oak West, Dowling Park, Mayo NE, Mayo SE, O'Brien, O'Brien SE, and Hildreth indicate a tendency towards clustering.

Nearest neighbor analysis was also performed for the whole area by using map algebraic functions of the GIS. Based on the centroid locations of depressions, layers of measured nearest neighbor distance, L_a, and expected nearest neighbor distance, L_e, were created. The distribution of nearest neighbor index (R) was obtained by the ratio of two GIS layers (L_a/L_e). A greater part of the study area is represented by a nearest neighbor index less than 1, indicating a trend towards clustering (Fig. 4).

A histogram of nearest neighbor distance data set for depression centroids is shown in Figure 5. The mean distance to nearest neighbor is 188.1 m. The values range from 20-2956.0 m with a standard deviation of 116.5 m. A cumulative percentage graph of depression nearest neighbor distance values shows that 90% of depressions are located closer than 500 m to their nearest neighbor (Fig. 6).

PLANIMETRIC SHAPE

As an indicator of planimetric shape, circularity index was utilized. The circularity index is a measure of the circularity of a depression. It is the ratio between the measured depression area and the area of a circle with the same perimeter. Using GIS-measured area and perimeter values for each depression,

Table 2. Statistical summary of morphometric parameters.

	Area (m^2)	Mean Diameter (m)	L/W	Circularity Index
Mean	14571.4	98.6	1.74	1.33
Maximum	5,804,750.0	2785.9	14.1	8.86
Minimum	75.0	10.1	1.0	0.006
Standard Deviation	71355.2	106.6	0.68	0.455

the circularity index was calculated in ArcView 3.0 by Table operations. It approaches unity as depressions become circular. For a perfectly circular depression, the index of circularity would be unity. The greater it departs from one, the less circular is the depression. Elongated features have values smaller than one whereas convoluted shapes present values greater than one.

Most depressions are nearly circular in plan with the major modal ratio class between 1-1.2 (Fig. 7). Mean circularity index value is 1.33 with a standard deviation of 0.45. Approximately 85% of the total population have a circularity index smaller than 1.5 (Fig. 8).

MEAN DIAMETER

Mean depression diameters were estimated in ArcView tables by obtaining the mean of length and width also measured in the GIS environment for each depression. In karst morphometry, the use of mean diameter is more helpful than major and minor axes, because these measures represent maximum rather than average dimensions.

Mean diameter distribution for the total population is shown in Figure 9. The values range from 5.6 - 2785.9 m with a standard deviation of 106.6 and a mean of 98.6 m. The major modal class is 5-50 m. Cumulative frequency distribution of mean diameter (Fig. 10) indicates that some 95% of the total population have a mean diameter of less than 300 m.

PLANIMETRIC AREA

The cumulative frequency distribution of depression areas for the total measured population is given in Figure 11. The mean value is 14,570 m^2, the standard deviation 71,349 m^2, and the range of values from 25 - 5,804,750 m^2. Within the total measured population, 50% of depressions are smaller than ~5000 m^2.

DEPTH OF KARSTIC DEPRESSIONS

In their comparative study of various karst regions, Troester *et al.* (1984) concluded that depression depth distributions in temperate and tropical karst regions could be explained by an exponential equation as follows:

$$N \text{ (number of sinkholes)} = N_o e^{-Kd}$$

where N_o and K are constants, and d is depth. The N_o coefficient is affected by the number of depressions, whereas the K coefficient varies within ranges corresponding to temperate and tropical karst areas. Comparing the internal relief within various karst regions, Troester *et al.* (1984) found that the Florida karst is very flat, represented by broad, shallow depressions with a K value of 1.18 m^{-1} (0.362 ft^{-1}).

The depth-frequency distribution for 23,031 depressions in the study area is shown in Figure 12. Depth values were estimated by manually counting the number of contours, representing the maximum depth values for depressions. The depth-frequency distribution was found to be changing exponentially with depth, expressed as:

Table 3. Spatial distribution parameters of karstic depressions in various karst regions of the world (Modified after Ford & Williams 1989).

AREA	NUMBER OF DEPRESSIONS	DENSITY	NEAREST NEIGHBOR INDEX	PATTERN
Papua New Guinea	1128	10 - 22.1	1.091 - 1.404	Near random to approaching uniform
Waitomo, New Zealand	1930	55.3	1.1236	Near random
Yucatan (Carrillo Puerto Formation)	100	3.52	1.362	Approaching uniform
Yucatan (Chicken Itza Formation)	25	3.15	0.987	Near random
Barbados	360	3.5 - 13.9	0.874	Tending to cluster
Antigua	45	0.39	0.533	Clustered
Guatemala	524	13.1	1.217	Approaching uniform
Belize	203	9.7	1.193	Approaching uniform
Guadeloupe	123	11.2	1.154	Near random
Jamaica (Browns Town-Walderston Formation)	301	12.5	1.246	Approaching uniform
Jamaica (Swanswick Fm)	273	12.4	1.275	Approaching uniform
Puerto Rico (Lares Fm)	459	15.3	1.141	Near random
Puerto Rico (Aguada Fm)	122	8.7	1.124	Near random
Guangxi, China	566	1.96 - 6.51	1.60 - 1.67	Approaching uniform
Spain, Sierra de Segura	817	18 - 80	1.66 - 2.14	Near uniform
Florida, Suwannee	25,157	6.06	0.854	Tending to cluster

N (number of depressions) = $137{,}292e^{-1.1713\,d}$.

It should be noted that the analysis of a much larger population of depressions in this study gives a K value of 1.1713 that is significantly close to 1.18 calculated by Troester *et al*. (1984) for Florida karst.

DISCUSSION

The landforms of the subtropical Suwannee River karst area can be compared to karst areas of different morphoclimatic settings. The application of GIS allows the capture, storage, analysis, and presentation of morphometric and spatial distribution parameters of karstic depressions. Despite the accurate, rapid, and objective data processing of GIS, it should be kept in mind that all the analyses performed here on karstic depressions are based on the resolution and precision of standard 7.5-minute USGS topographic quadrangles with a contour interval of 5 feet. Karstic depressions may have been underrepresented because of the constraints of map resolution, as well as the thick vegetation and sediment cover. Nevertheless, this study provides a quantitative expression of the morphometry and spatial distribution of karst depressions on a regional scale.

Spatial distribution parameters of the Suwannee River basin karst area are summarized as follows:

Total area: 4063 km².
Total depression area: 331 km².
Number of depressions: 25,157
Mean depression density: 6.1 depressions/ km².
Mean nearest neighbor distance: 186 m
Mean nearest neighbor distance index: 0.9
Mean pitting index: 14.5

A statistical summary of the morphometric parameters of karstic depressions is given in Table 2.

Table 3 compares the mean spatial distribution parameters obtained in this study with those of various karst regions from diverse morphoclimatic settings. It demonstrates the extraordinarily large database for the subtropical Florida karst, providing a comprehensive representation of karst landforms in a scale of 1:24,000. It should be noted that the values for depression density and the nearest neighbor index calculated for the study area show great variations. Depression densities calculated for individual quadrangles range from 2.4 (Madison SE) to 15.8 (Mayo SE), overlapping with values representing both temperate and tropical karst areas. Similarly, the nearest neighbor index, varying from 0.6 (Hillcoat) to 1.0 (Mayo NE), indicates a wide range of spatial distribution patterns of depressions in the study area ranging from clustered to uniform. These significant variations in morphometric and spatial distribution parameters along with the morphometry of depressions in a single morphoclimatic zone implicate other local factors (e.g., overburden thickness, potentiometric level fluctuation, fracture systems, soil types, recharge-discharge zones) in controlling the development of karstic depressions.

SUMMARY AND CONCLUSION

This study represents an application of GIS to examine the morphometric and spatial distribution of karstic depressions in the lower Suwannee River basin. The robust GIS methodology used in this study provides not only a rapid analysis of spatial data on a large population of karstic depressions, but also an objective approach with consistent measurement and calculation processes in which human errors and bias were eliminated. In accordance with the increasing use of GIS in analyzing spatial data on diverse applications, this study shows that the GIS environment can also be efficiently used for karst landform studies.

Analysis of the morphometric and spatial distribution parameters of karstic depressions reveals that the Florida karst is represented by broad, shallow depressions with an average density of 6.07 depressions/ km² and an average pitting index of 14.5. Morphometric and spatial distribution parameters of karstic depressions within the lower Suwannee River basin show great variations.

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ARRHOPALITES (COLLEMBOLA: ARRHOPALITIDAE) IN U.S. CAVES WITH THE DESCRIPTION OF SEVEN NEW SPECIES

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Seven new species of Arrhopalites *(Collembola: Arrhopalitidae) are described and illustrated. Two species are from Illinois:* A. sapo *and* A. madonnensis*, two from Virginia:* A. sextus *and* A. obtusus*, two from Colorado:* A. incertus *and* A. hubbardi*, and one from Idaho*: A. arca*. The known distribution of cave species of* Arrhopalites *in North America is discussed and both collection efficiency and regional differences are shown to play a role in the number of species known.*

This is a second paper dealing with the genus *Arrhopalites* in U.S. caves (see Christiansen & Bellinger 1996). The genus *Arrhopalites*, Börner 1906, is cosmopolitan, with ~100 described species. Although 28 of these species are known from North America the cave fauna of *Arrhopalites* in this region remains poorly known. In this work we describe 7 new cave species: 4 from the speciose areas of Indiana, Illinois, and Virginia and 3 from the little collected region of the eastern Rocky Mountains.

Species	**State**
arca	Idaho (ID)
incertus	Colorado (CO)
hubbardi	Colorado
madonnensis	Illinois (IL)
obtusus	Virginia (VA)
sapo	Illinois
sextus	Virginia

We use the system of Nayrolles (1991) for the apical sensory organ of the third antennal segment and that of Lawrence (1979) for the anal valve chaetotaxy. We describe the chaetotaxy of head, dens, and furcula following Christiansen (1966) and Christiansen and Bellinger (1998). In all cases, we found these systems to be the easiest to use and with the most general application. For details concerning the abbreviations used herein, see Christiansen & Bellinger (1996 or 1998).

Arrhopalites incertus new species (Fig. 1 A-J)

Description: Body sparsely clothed, posterior setae (Fig. 1C-b) 1.5 times longer than anterior setae (Fig. 1C-a). Antennal ratios as shown in Table 2. Antennal segment 4 (Ant. IV) divided into 4 distinctly ringed subsegments (Fig. 1A); longest setae ~1.8X the width of segment; apex with a capitate sense rod. Antennal segment 3 (Ant. III) slightly swollen basally; apical sense organ (Fig. 1B) with 2 parallel sense rods in a single shallow pit; seta Aai rod-like & blunt; seta Api slender with filamentous apex, Ape cylindrical & acuminate; Ae, Ap, & Ai normal (Ap with a slightly swollen base). Eyes 1+1. Cephalic A3, M4, & L & IL series spine-like, M5 absent (Fig. 1I). Metatrochanteral

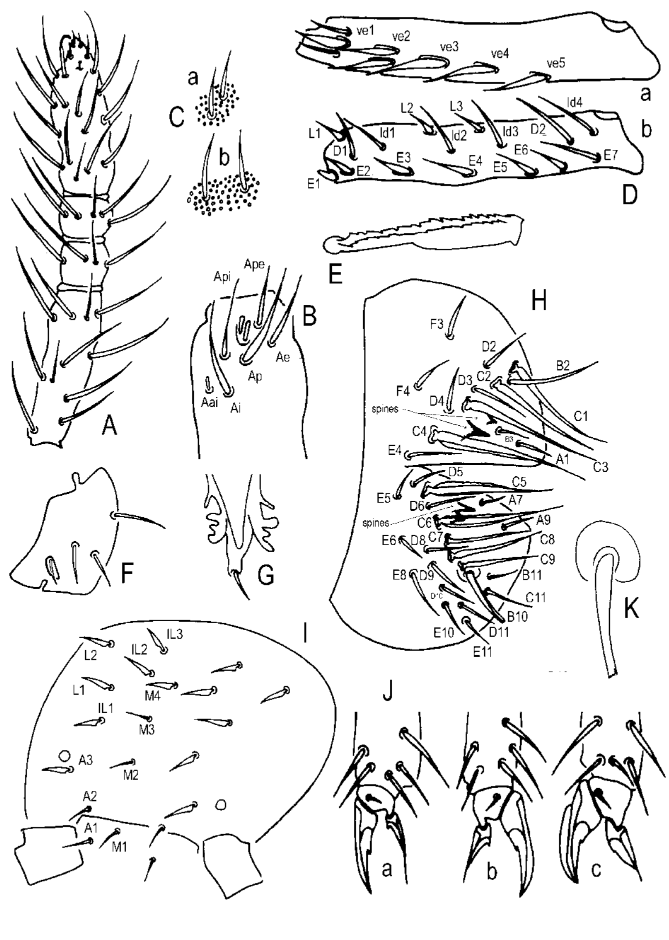


Figure 1. *Arrhopalites incertus* n. sp. A, 4th antennal segment; B, apical sense organ of 3rd antennal segment; C, body setae, a. anterior, b. posterior; D, chaetotaxy of dens, a. ventral surface, b. dorsal surface; E, mucro; F, metatrochanteral organ; G, tenaculum; H, anal valve chaetotaxy; I, posterior cephalic chaetotaxy; J, foot complex, a. 1st leg, b. 2nd leg, c. 3rd leg; K, female subanal appendage.

organ (seta D2) elongate (Fig. 1F). All ungues with inner tooth, 3rd unguis with a slight tunica (figs. 1 J-a-c). All unguiculi with corner tooth & short apical filament, not exceeding apex of unguis (Fig. J a-c). Tenaculum with one seta on anterior unpaired lobe (Fig. 1G). Dens with 7 dorsal E setae, E1 strongly spine like, E2 & E3 spine like; L1, L2 & L3 spine like, L4 absent; D1, D2, Id1, Id2, id3, & Id4 present (Fig. 1D-b); 5 ventral rows of heavy setae (3,2,1,1,1) present (Fig. 1 D-a), median ve1 strongly spinelike. Mucro narrow, gutter-like, both edges serrate (Fig. 1E). 2+2 cuticular spines on each side of the anal valve with setae C4-C6 lamellate, C1, C2, C3, & C8 swollen basally, C7 slender, as shown in figure 1H. Female subanal appendage rod like, somewhat flattened on apical half with truncate apex (Fig. 1K). Body length of the adult female Holotype 0.44 mm, head 0.24 mm.

Holotype: female, USA, CO, El Paso Co. Manitou Cave. 3- VIII -1996. on old wood, D. Hubbard Coll., locality 7990. Paratypes: 3 females on the same slide with Holotype. Biogeographic zone 7b.

Derivatio nominis: *Arrhopalites incertus* n. sp. was named after the difficulties in determining its precise position in the phylogeny (Zeppelini 2001) of the *A. coecus* group.

Remarks: *Arrhopalites incertus* is a typical *A. coecus* group species, with a E7 seta present & spine like medial Ve1 seta on the dens. It is easily separated from other members of the group by the subdivision of Ant IV into 4 ringed subsegments. It is also characterized by the single seta on the Tenaculum & the shape of the female subanal appendage.

The species most similar to *A. incertus* are specimens from AK, Poland, & Russia identified as *A. coecus*. These specimens differ from *A. incertus* by possessing anal valve seta D7 (absent in *incertus*), having valve setae C8-9 lamellate & the absence of the E7 on the dorsal surface of dens in *A. coecus* (present in *incertus*). In addition, incertus has ANT IV subsegments & a slight swelling at the base of the ANT III while *caecus* has 5 subsegments & no basal swelling.

Table 1. Arrhopalites in Nearctic caves (our records).

States	# of cave samples	# with Arrhopalites	%	# of species	# of troglobite species
Alabama	113	9	8	2	0
Arizona	18	1	6	1	0
Arkansas	74	34	46	2	1
California	154	0	0	0	0
Colorado	45	4	9	3	2
Georgia	32	0	0	0	0
Idaho	8	2	25	2	2
Iowa	62	12	19	5	2
Indiana	228	61	27	9	4
Illinois	85	19	22	8	5
Kentucky	176	21	12	4	2
Maryland	27	8	3	2	0
Missouri	407	82	20	4	1
N. Carolina	36	3	8	1	0
Ohio	32	0	0	0	0
Oregon & Washington	18	2	20	1	0
Tennessee	110	10	9	2	0
Texas	557	15	3	2	1
W. Virginia	101	7	7	3	1
Virginia	249	84	34	18	12

Arrhopalites hubbardi new species (Fig. 2 A-L)

Description: Body sparsely clothed, posterior setae (Fig. 2D-b) 1.5 times longer than anterior setae (Fig. 2D-a). Antennal ratios as shown in Table 2. Ant. IV, divided into 7 subsegments (Fig. 2A); longest setae 3X the width of segment; Ant. IV apex with a capitate sense rod (arrow in Fig. 2B). Ant. III with a clear, prominent basal papilla (Fig. 2C) ; sense organ (Fig. 2C) with 2 parallel sense rods in a single shallow pit; seta Aai rod-like; seta Api & Ape slender, the latter with a filamentous apex; Ae, Ap, & Ai normal. 1+1 clear & 1+1 vestigial eyes. No cephalic spines, M5 present (Fig. 2J). Metatrochanteral organ elongate (Fig. 2G). All ungues with inner tooth, without tunica (Figs. 2K a-c). All unguiculi with corner tooth, 1st unguiculus with a long apical filament, exceeding the unguis tip, 2nd & 3rd unguiculi with short apical filament,

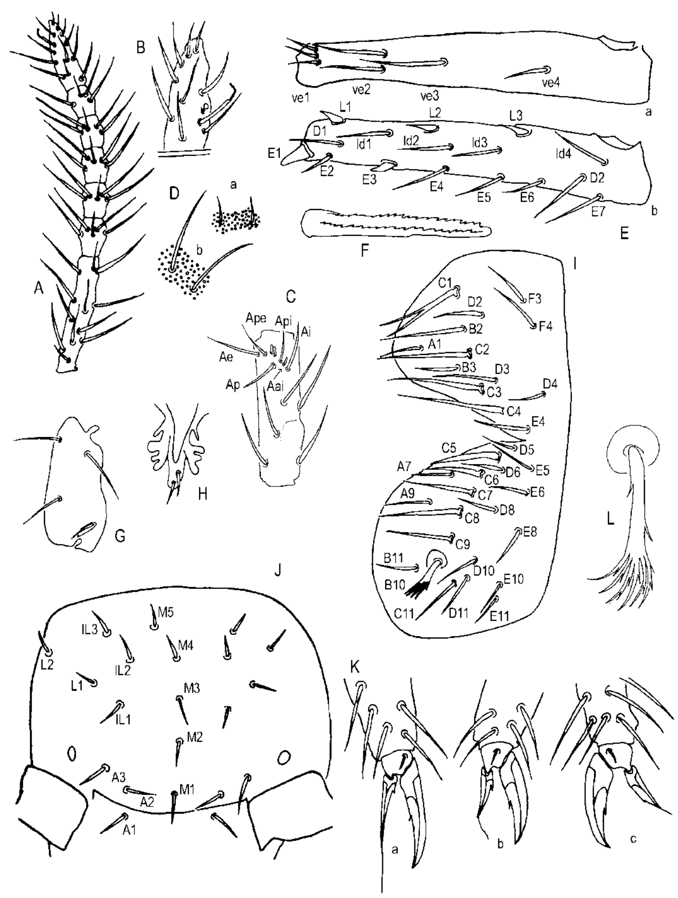


Figure 2. *Arrhopalites hubbardi* n. sp. A, 4th antennal segment; B, apex of 4th antennal segment; C, 3rd antennal segment; D, body setae, a. anterior, b. posterior; E, chaetotaxy of dens, a. ventral surface, b. dorsal surface; F, mucro; G, metatrochanteral organ; H, tenaculum; I, anal valve chaetotaxy; J, posterior cephalic chaetotaxy; K, foot complex, a. 1st leg, b. 2nd leg, c. 3rd leg; L, female subanal appendage.

not exceeding apex of unguis (Fig.2K b-c). Tenaculum with 2 setae on anterior unpaired lobe (Fig. 2H). Dens with 7 dorsal E setae, E1 & E3 strongly spine-like, other E setae normal; L1, L2, & L3 spine like, L4 absent; D1, D2, Id1, Id2, Id3, & Id4 present (Fig. 2E-b); 4 ventral rows of setae (3,2,1,1) present (Fig. 2E-a). Mucro narrow, gutter-like, both edges serrate (Fig. 2F). No cuticular spines on anal valve; C1 bifurcate, chaetotaxy as in Figure 2I. Female subanal appendage palmate (Fig. 2L). Body length of the adult female Holotype 0.44mm, head 0.28mm.

Holotype: female, USA, CO, Garfield Co. Glenwood Caverns. 9– VI I - 1999. D. Hubbard coll, locality 9452. 2 paratypes CO, Garfield Co. Glenwood Caverns, Fairy cave 15 IV 2000, Steinmann coll 9655. Biogeographic zone 7b

Derivatio nominis: This species is named after David Hubbard, whose collecting has been instrumental for this work.

Remarks: One specimen appears to have only 1 + 1 eye but the others have a clear vestige of a 2nd eye present. This species is closely related to *A. clarus*, *A. hirtus*, & *A. habei* &, all of which, circumanal seta C1 forked. It can be distinguished from all these by the anal valve chaetotaxy, the strong basal papilla on the 3rd antennal segment & 4th antennal segment subsegmentation. The features separating the species of this group are shown in Table 3

Table 2. Antennal and Cephalic diagonal measurements in mm

A. incertus

A1	0.0255	0.01785	0.01785	0.0204
A2	0.06375	0.04845	0.04845	0.051
A3	0.08925	0.06375	0.0765	0.0765
A4	0.1785	0.1224	0.1275	0.14025
CD	0.19125	0.153	0.153	0.17085

A. hubbardi

A1	0.03825	0.051	0.04335
A2	0.0765	0.102	0.08925
A3	0.1326	0.1632	0.1479
A4	0.32385	0.408	0.3366
CD	0.255	0.36975	0.306

A. arca

A1	0.0255	0.0459	0.0255	--------	0.04335
A2	0.0816	0.102	0.0765	--------	0.102
A3	0.14025	0.16575	0.11475	--------	0.16575
A4	0.408	0.4743	0.357	0.408	0.47685
CD	0.24225	0.255	0.204	0.21675	0.255

A. sapo

A1	0.03825	0.0459	0.0306	0.03825	0.03825	0.04335	0.04335	0.0255
A2	0.0714	0.0765	0.06375	0.0765	0.0765	0.0867	0.06885	0.06375
A3	0.13005	0.14025	0.11475	0.1224	0.1224	0.14535	0.11475	0.102
A4	0.31365	0.357	0.255	0.3315	0.31875	0.3927	0.3009	0.26265
CD	0.255	0.2805	0.24225	0.2805	0.255	0.34425	0.255	0.2244

A. sapo

A1	0.04335	0.03825	0.0306
A2	0.0663	0.102	0.06885
A3	0.14025	0.1428	0.1071
A4	0.3825	0.36975	0.2805
CD	0.29325	0.3315	0.2295

A. sextus

A1	0.0765	0.0561	0.0765	0.0765	0.08925	0.07905	0.06375	0.03825
A2	0.1428	0.1428	0.1683	0.1428	0.1785	0.16575	0.14025	0.08925
A3	0.255	0.255	0.34425	0.2856	0.306	0.31365	0.255	0.14025
A4	0.49725	0.612	0.82875	0.663	0.77775	0.72675	0.62475	0.41565
CD	0.36975	0.39525	0.4335	0.459	0.4845	0.459	0.42075	0.255

A. sextus

A1	0.0765	0.0561	0.0561
A2	0.1785	0.14025	0.11475
A3	0.3468	0.255	0.24225
A4	0.7905	0.6375	0.5355
CD	0.47175	0.408	0.357

A. obtusus

A1	0.051	0.04845	0.05355	0.051	0.03825	0.0459	0.051
A2	0.0969	0.09435	0.09435	0.0969	0.0765	0.1173	0.10965
A3	0.1938	0.19125	0.19635	0.21675	0.153	0.22695	0.2142
A4	0.4335	0.44625	0.4386	0.51765	0.3825	0.49725	0.47685
CD	0.306	0.31875	0.31875	0.3315	0.255	0.34425	0.3825

A. madonnensis

A1	0.02805	0.03315	0.0306
A2	0.07395	0.0765	0.0765
A3	0.11475	0.1173	0.10455
A4	0.306	0.255	0.2856
CD	0.255	0.255	0.24225

Arrhopalites arca new species (Fig. 3 A-K)

Description: Body sparsely clothed, posterior setae (Fig. 3C-b) 1.5 times longer than anterior setae (Fig. 3C-a). Antennal ratios as shown in Table 2. Ant. IV divided into 7 subsegments (Fig. 3A); longest setae 3X the width of segment; Ant. IV apex with a capitate sense rod. Ant. III without basal swelling; sense organ (Fig. 3B) with 2 parallel sense rods in a single shallow pit; seta Aai club-shaped & blunt; setae Api & Ape slender with filamentous apex; Ae, Ap, & Ai normal. 1+1 eyes & a circular smooth area behind each eye. No cephalic spines, M5 absent (Fig. 3I). Metatrochanteral organ (seta D2) elongate (Fig. 3F). 1st unguis slender, without inner tooth, 2nd & 3rd ungues with inner tooth & tunica absent (Figs. 3J a-c). All unguiculi with corner tooth, 1st & 2nd unguiculi with a long apical filament, exceeding the unguis tip, 3rd unguiculus with short apical filament, not exceeding apex of unguis (Fig. 3J a-c). Tenaculum with 2 setae on anterior unpaired lobe (Fig. 3G). Dens with 7 dorsal E setae, E1 & E3 strongly spine like, other E setae normal; L1, L2, & L3 spine like, L4 absent; D1, D2, Id1, Id2, Id3, & Id4 present (Fig. 3D-a); 4 ventral rows of setae (3,2,1,1) present (Fig. 3D-b). Mucro narrow, gutter-like, both edges serrate (Fig. 3E). No cuticular spines on anal valve; seta C1 bifurcate, chaetotaxy as in Figure 3H. Female subanal appendage palmate (Fig. 3K). Body length of the adult female Holotype 0.88 mm, head 0.38 mm.

Derivatio nominis: Latin arcus = arch, after the type locality cave.

Holotype: female, USA, ID, Lincoln Co. Little Arch Cave, 16- VII- 1999. D. Hubbard coll. locality 9453,. Paratypes: 5 female & 2 males, same data as Holotype.

Other localities: ID, Lincoln Co. Tee Cave, 16 – VII-1999 D. Hubbard Coll. Locality 9451. Biogeographic zones 8 & 7B

Remarks: This species is very similar to *A. hubbardi* n. sp.; however it lacks the strong 3rd antennal segment basal papilla seen on *A. hubbardi*. This species can also be differentiated from *A. hubbardi* by lacking the M5 seta on the posterior part of head, by the presence of D9 seta on the anal valve & the shape of the female subanal appendages not branched at its shaft.

Arrhopalites sapo new species (Fig. 4 A-K)

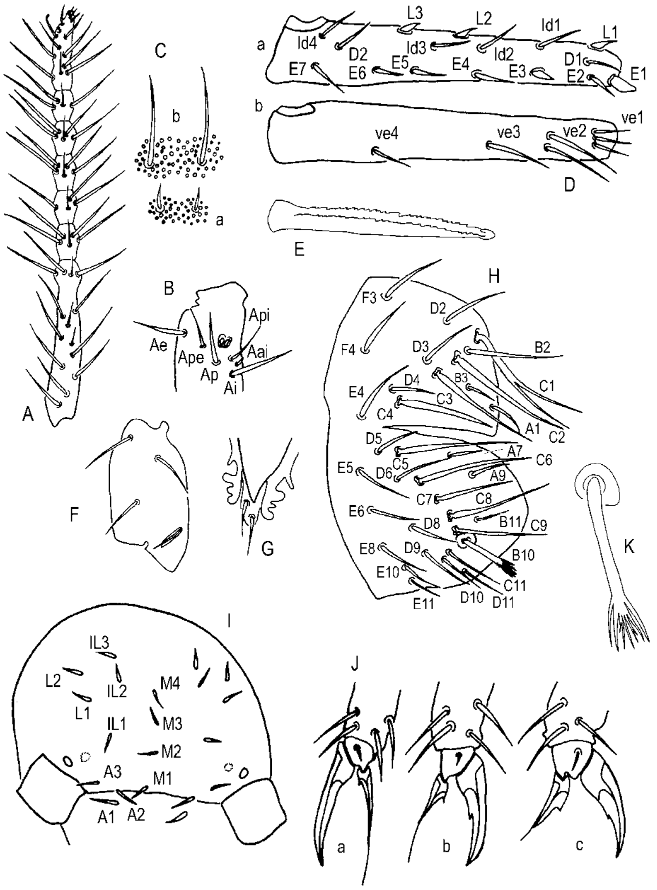
Description: Body sparsely clothed, posterior setae (Fig. 4D-b) 1.5 times longer than anterior setae (Fig. 4D-a). Antennal ratios as shown in Table 2. Ant. IV, divided into 5 subsegments (Fig. 4A); longest setae 2X the width of segment; Ant. IV apex with a very small capitate sense rod. Ant. III without basal swelling; sense organ with 2 parallel sense rods in a single shallow pit; seta Aai rod-like & acuminate; seta Api & Ape slender & filamentous ; Ae, Ap, & Ai normal. 1+1 eyes. No cephalic spines, M5 absent (Fig. 4J). Metatrochanteral organ elongate (Fig. 4G). All ungues elongate, with inner tooth near base, no tunica (figs.4Ka-c). 1st & 2nd unguiculi with small corner tooth (Fig. 4K-a&K-b) , 3rd smooth (Fig.4K-c), long apical filament on 1st unguiculus, exceeding the unguis tip, 2nd & 3rd unguiculi with short apical filament, not exceeding apex of unguis. Tenaculum with 2 setae on anterior unpaired lobe (Fig. 4H). Dens with 7 dorsal E setae, E1 strongly spine-like, other E setae long & acuminate; L1, L2, & L3 not spine like but L1 is slightly swollen basally, L4 absent; D1, D2, Id1, Id2, Id3, & Id4 present (Fig. 4E-b); 4 ventral rows of setae (3,2,1,1) present (Fig. 4E-a). Mucro narrow, gutter-like, both edges serrate (Fig. 3F). No cuticular spines on anal valve; C1-C6 spiny or finely denticulate, chaetotaxy as in Figure 4I. Female subanal appendage spatulate with edges of distal 3rd serrate . Body length of the adult female Holotype 0.72 mm, head 0.4 mm.

Holotype: female, USA, Illinois, Monroe Co. Frog cave, locality 9462. paratypes 1 male, 2 females & one juvenile on the same slide as the Holotype. 4 VII 1999. J. Lewis coll.

Other localities: IL, Monroe Co. Rose hole cave, 5 – VII-1999 locality 9464. Pautler cave, 6-VI-1999 locality 9465. Jacobs Cave, 8-XI I -1998 locality 9466. All J. Lewis coll. Biogeographic zone 7a

Derivatio nominis: From Portuguese sapo = frog, after type locality cave.

Remarks: Arrhopalites sapo n. sp. is easy to recognize



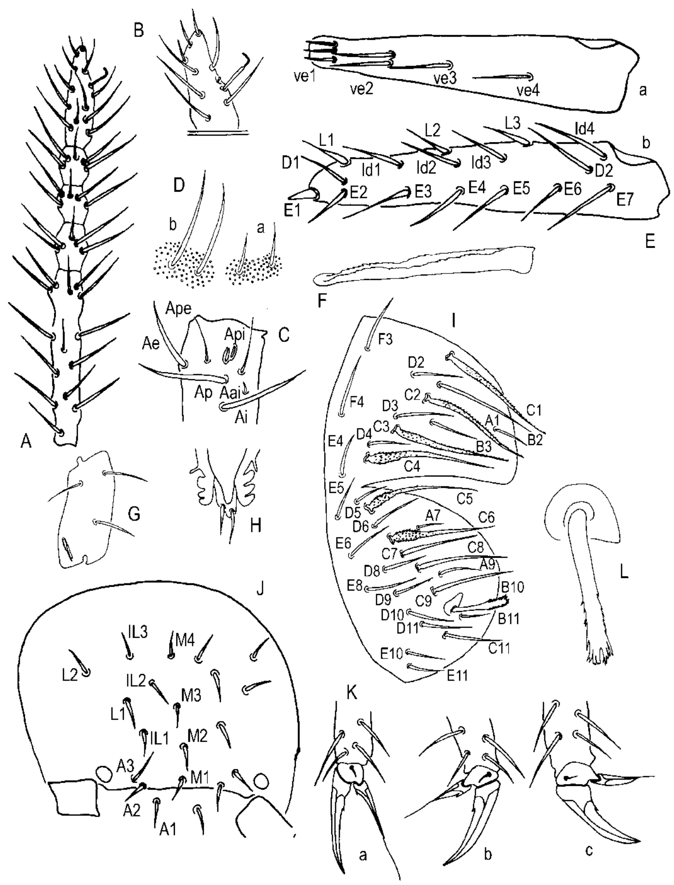


Figure 3. ***Arrhopalites arca*** **n. sp. A, 4th antennal segment; B, apical sense organ of 3rd antennal segment; C, body setae, a. anterior, b. posterior; D, chaetotaxy of dens, a. dorsal surface, b. ventral surface; E, mucro; F, metatrochanteral organ; G, tenaculum; H, anal valve chaetotaxy; I, posterior cephalic chaetotaxy; J, foot complex, a. 1st leg, b. 2nd leg, c. 3rd leg; K, female subanal appendage.**

Figure 4. ***Arrhopalites sapo*** **n. sp. A, 4th antennal segment; B, apex of 4th antennal segment; C, apical sense organ of 3rd antennal segment; D, body setae, a. anterior, b. posterior; E, chaetotaxy of dens, a. ventral surface, b. dorsal surface; F, mucro; G, metatrochanteral organ; H, tenaculum; I, anal valve chaetotaxy; J, posterior cephalic chaetotaxy; K, foot complex, a. 1st leg, b. 2nd leg, c. 3rd leg.**

Table 3. Characteristrics of the clarus group of Arrhopalites.

	Species			
CHARACTER	*hubbardi*	*clarus*	*hirtus*	*habei*
Anal valve seta D7	absent	present	present	present
Anal valve seta D9	absent	present	present	present
Seta E7 of dens	present	present	absent	present
Subegments ANT IV	7divided	7divided	6divided	7divided
Apical ANT III seta Api	normal	normal	normal	rod like
Apical ANT III seta Ape	normal	normal	normal	Rod like
Ant III basal swelling	present	absent	absent	absent
cephalic seta M5	present	present	present	absent
Female subanal appendage	Palmate, short branches in its shaft	Rod like	Palmate, smooth shaft	flattened and fringed

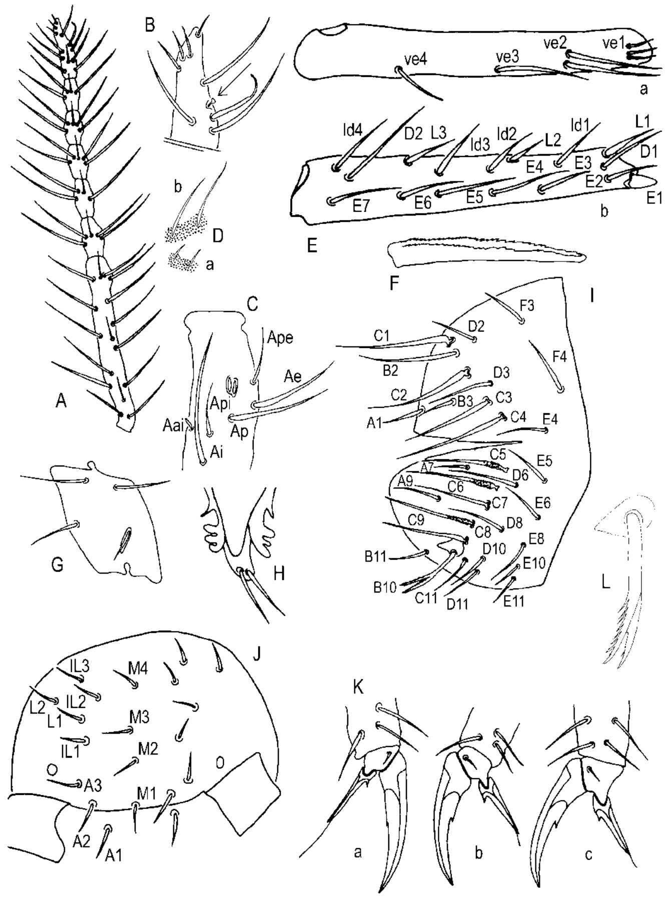


Figure 5. *Arrhopalites sextus* n. sp. A, 4th antennal segment; B, apex of 4th antennal segment; C, apical sense organ of 3rd antennal segment; D, body setae, a. anterior, b. posterior; E, chaetotaxy of dens, a. ventral surface, b. dorsal surface; F, mucro; G, metatrochanteral organ; H, tenaculum; I, anal valve chaetotaxy; J, posterior cephalic chaetotaxy; K, foot complex, a. 1st leg, b. 2nd leg, c. 3rd leg; L, female subanal appendage.

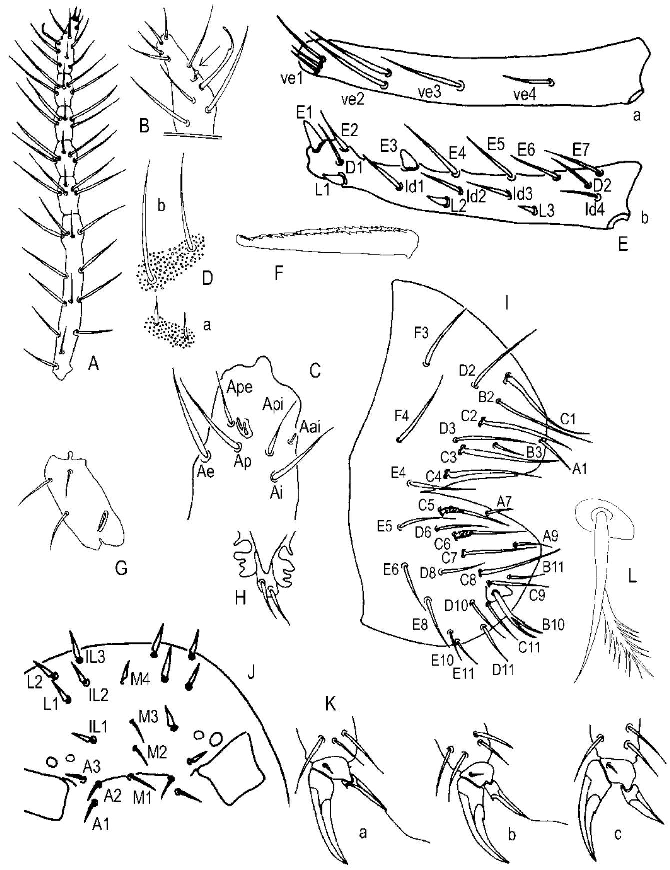


Figure 6. *Arrhopalites obtusus* n. sp. A, 4th antennal segment; B, apex of 4th antennal segment; C, apical sense organ of 3rd antennal segment; D, body setae, a. anterior, b. posterior; E, chaetotaxy of dens, a. ventral surface, b. dorsal surface; F, mucro; G, metatrochanteral organ; H, tenaculum; I, anal valve chaetotaxy; J, posterior cephalic chaetotaxy; K, foot complex, a. fmrst leg, b. 2nd leg, c. 3rd leg; L, female subanal appendage.

based on its subanal appendage the spiny setae on C series of anal valve & the basal inner ungual teeth. It is closely related to *A. commorus* but differs from it by lacking the basal papilla on antennal segment III & in the 4th antennal segment subsegmentation as well as the denticulate anal valve setae.

Arrhopalites sextus new species (Fig. 5 A-L)

Description: Body sparsely clothed, posterior setae (Fig. 5D-b) 1.5 times longer than anterior setae (Fig. 5D-a). Antennal ratios as shown in Table 2. Ant. IV, divided into 7 subsegments (Fig. 5A); longest setae 3.6X the width of segment; Ant. IV apex with a capitate sense rod. Ant. III without basal swelling; sense organ with 2 parallel sense rods in a single shallow pit; setae Aai rod like & pointed; setae Api & Ape slender with filamentous apex; Ae, Ap, & Ai normal (Fig. 5C). 1+1 eyes. No cephalic spines, M5 absent (Fig. 5J). Metatrochanteral organ (seta D2) elongate (Fig. 5G). All ungues elongate, with inner tooth, no tunica (Figs. K a-c). All unguiculi with corner tooth, long apical filament on 1st unguiculus, as long as the unguis tip, 2nd & 3rd unguiculi with shorter apical filament, not exceeding apex of unguis. Tenaculum with 2 setae on anterior unpaired lobe (Fig. 5H). Dens with 7 dorsal E setae, E1 strongly spine like, other E setae normal; L1, L2, & L3 not spine like but L1 is swollen basally, L4 absent; D1, D2, Id1, Id2, Id3, & Id4 present (Fig. 5 E-b); 4 ventral rows of setae (3,2,1,1) present (Fig. 5E-a). Mucro narrow, gutter-like, both edges serrate (Fig. 5F). No cuticular spines on anal valve; C5, C6, & C8 fine denticulate, chaetotaxy as in Figure 5I. Female subanal appendage forked & serrate along the distal half (Fig. 5L). Body length of the adult female Holotype 1.2 mm, head 0.52 mm.

Holotype: female, USA, VA, Wythe Co. Sam Six Cave. 25-XI-1998. On water surface, D. Hubbard coll. Locality 9951. Paratypes: same data as Holotype, 3 females. Biogeographic zone 7a

Derivatio nominis: Latin sextus = sixth, after the type locality – Sam Six cave.

Remarks: Arrhopalites sextus n. sp. shares the peculiar denticulate C series setae on the anal valves with *A. commorus* & *A. sapo* n. sp. It differs from them in the forked female subanal appendages, the 7-4th antennal segment subsegments, anal valve chaetotaxy & structure of the unguiculi.

Arrhopalites obtusus new species (Fig. 6)

Description: Body sparsely clothed, posterior setae (Fig. 6D-b) 1.5 times longer than anterior setae (Fig. 6D-a). Antennal ratios as shown in Table 2. Ant. IV, divided into 6 subsegments (Fig. 6A); longest setae 2.9X the width of segment; Ant. IV apex with a capitate sense rod. Ant. III without basal swelling; sense organ with 2 parallel sense rods in a single shallow pit; seta Aai club-shaped & blunt; seta Api & Ape slender with filamentous apex; Ae, Ap,

& Ai normal (Fig. 6C). 2+2 eyes but the 2nd eye is reduced to a circular smooth area & is much smaller than each lens-bearing eye. A3, M4, & L & IL series spine-like, M5 absent (Fig. 6J). Metatrochanteral organ elongate (Fig. 6J). 1st unguis without inner tooth, 2nd & 3rd with very weak teeth; No tunica (figs. a-c). 3rd unguiculus without corner tooth, 1st & 2nd with long apical filament, exceeding the unguis tip, 3rd unguiculus without apical filament. Tenaculum with 2 setae on anterior unpaired lobe (Fig. 6H). Dens with 7 dorsal E setae, E1 & E3 strongly spine like, other E setae normal; L1, L2, & L3 spine like, L4 absent; D1, D2, Id1, Id2, Id3, & Id4 present (Fig. 6E-b); 4 ventral rows of setae (3,2,1,1) with the external Ve2 2X the length of the others (Fig. 6E-a). Mucro narrow, gutter-like, both edges serrate (Fig. 6F). No cuticular spines on anal valve; Seta C1 simple, not forked, C5 & C6 finely denticulate (Holotype) or smooth (Paratypes), chaetotaxy as in Figure 6I. Female subanal appendage forked & serrate along one margin in the distal half (Fig. 6L) in Holotype but smooth in paratypes. Body length of the adult female Holotype 0.9 mm, head 0.4 mm.

Holotype: female, USA, VA, Rockingham Co. Bakers cave. 6-XII -1994. D. Hubbard coll. Locality 7801, Paratypes: same data as Holotype, 1 juvenile & 4 specimens from nearby Orebaugh Cave, 2- I- 2002, Hubbard Coll. Locality 9679. Biogeographic zone 7a

Derivatio nominis: Latin obtusus = blunt after the blunt E1 & E3 setae.

Remarks: This species is closely related to *A. jay* (Zeppelini 2001) but can easily distinguished by the unforked C1 seta & heavy spine-like cephalic setae on *A. obtusus*. Despite the denticulate C series setae on some specimens, this species is not related to *A. sextus* n. sp. It lacks setaceous L setae & has thick spine-like E3 seta on the dens. This species was collected both times along with specimens of the *A. pygmaeus* (Zeppelini 2001) group.

Arrhopalites madonnensis new species (Fig. 7 A-L)

Description: Body sparsely clothed, posterior setae (Fig. 7D-b) 1.5 times longer than anterior setae (Fig. 7D-a). Antennal ratios as shown in Table 2. Ant. IV subdivided into 5 subsegments (Fig. 7A); longest setae 2X the width of segment; Ant. IV apex with a capitate sense rod. Ant. III without basal swelling; sense organ (Fig. 7C) with 2 parallel sense rods in a single shallow pit; seta Aai club-shaped & blunt; seta Api short with filamentous apex, Ape short & acuminate; Ae, Ap, & Ai normal. 1+1 eyes. No cephalic spines, M5 absent (Fig. 7J). Metatrochanteral organ elongate (Fig. 7G). All ungues with inner tooth, tunica lacking (Figs. 7K a-c). 3rd unguiculus without corner tooth, 1st & 2nd with long apical filament, exceeding the unguis tip, 3rd unguiculus with a short apical filament. Tenaculum with 2 setae on anterior unpaired lobe (Fig. 7H). Dens with 6 dorsal E setae, E1 & E3 short heavy & strongly spine like as in *A. obtusus*, other E setae normal; L1 & L2 spine like but L3 is not. L4 absent; D1, D2, Id1, Id2, Id3, & Id4 present (Fig. 7E-b); 4 ventral rows of setae (3,2,1,1) present (Fig. 7E-a). Mucro narrow, gutter-like, both edges serrate (Fig. 7F). No cuticular spines on anal valve; setae C1(not bifurcate), C4, C5, & C6 lamellate, chaetotaxy as in Figure 7I. Female subanal appendage palmate (Fig. 7L). Body length of the adult female Holotype 0.54 mm, head 0.33 mm.

Holotype: female, USA, IL, Monroe Co. Madonnaville Cave. 11-XII -1998. J. Lewis. Paratypes: same data as Holotype, 1 female + 1 specimen in alcohol, locality 9961. Biogeographic zone 7a

Derivatio nominis: This species was named after type locality Madonna Ville Cave.

Remarks: This species is related to A. whitesidei & A. sericus (Zeppelini 2001). The two can be separated by their female subanal appendages, acuminate in *A. whitesidei & A. sericus* and palmate in *madonnensis*. It is also similar to *A. pavo* in many respects but differs sharply in the structure of the apical organ of the 3rd antennal segment. In *pavo* Ai is equal to or longer than Ap & Ae & below Aai. In *madonnensis,* Ai is much smaller than Ap & Ae & located on a level with Aai. One specimen has an unusual abnormality on one dens. Dorsal seta L2 is positioned between Id1 & Id2 rather than m outside these & in line with L1 & L3 as is normal.

DISCUSSION

The 28 previously described North American species of *Arrhopalites* are listed, keyed, described and figured in Christiansen and Bellinger (1998). The present work brings

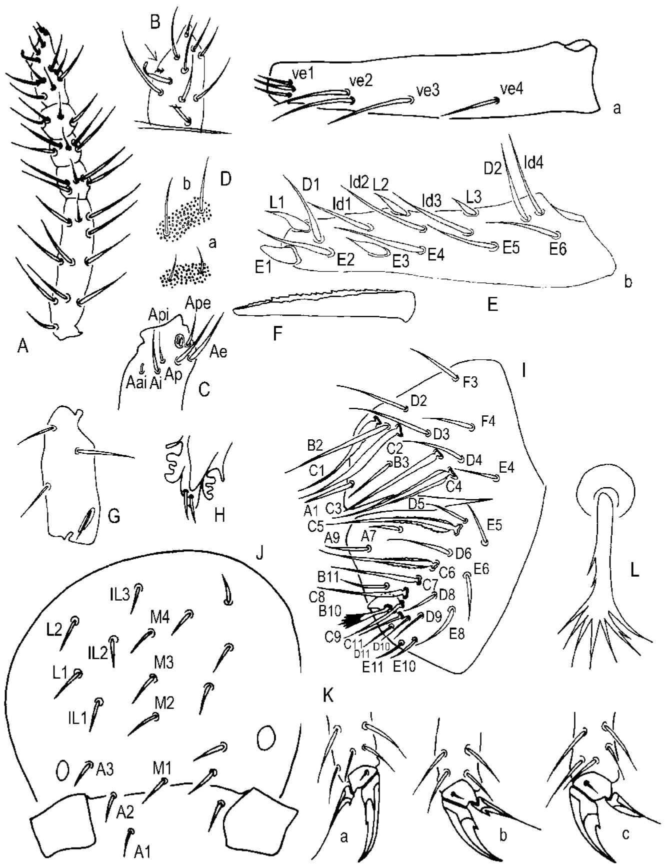


Figure 7. *Arrhopalites madonnensis* n. sp. A, 4th antennal segment; B, apex of 4th antennal segment; C, apical sense organ of 3rd antennal segment; D, body setae, a. anterior, b. posterior; E, chaetotaxy of dens, a. ventral surface, b. dorsal surface; F, mucro; G, metatrochanteral organ; H, tenaculum; I, anal valve chaetotaxy; J, posterior cephalic chaetotaxy; K, foot complex, a. 1st leg, b. 2nd leg, c. 3rd leg; L, female subanal appendage.

this number up to 35 but the fauna is still poorly known. This lack of knowledge almost certainly is partly because of problems collecting specimens of this genus. *Arrhopalites* species frequently are found on the surface film of water and are difficult to collect. It also appears likely that troglobitic species are more difficult to collect than the troglophile forms. The difficulty of collecting this genus is evidenced by the nature of *Arrhopalites* collections from VA. In our records, there are 153 Virginia cave collections made by David Hubbard and 96 made earlier by others. In collections made by those other than Hubbard, 14 (15%) yielded specimens of *Arrhopalites*. These specimens fell into 4 species only one of which was troglobitic. In contrast, 46% of Hubbard's collections yielded *Arrhopalites* with >10 troglobitic species. These data make any judgments about the richness of *Arrhopalites* fauna of any region questionable.

However, it does appear that there are regional differences (Table 1). Thus, in Missouri where we know of 407 collections of cave Collembola, 82 (20%) of these contain *Arrhopalites* belonging to 4 species only 1 of which is troglobitic. Similarly, in Iowa, where 62 cave collections of Collembola have been made, 12 (19%) contained specimens of *Arrhopalites*. This indicates a very limited *Arrhopalites* fauna. This difference is not primarily collector determined because the Iowa caves were sampled by the junior author who has had great success in collecting this genus, yet in 62 caves with Collembola only 19% yielded specimens of *Arrhopalites*. Further evidence of geographic variation in species diversity is shown by the samples taken by Hubbard from 30 caves in Colorado and Idaho. Only 3 (10%) of these were found to contain *Arrhopalites*. Twenty-two percent of 85 collections of Collembola from Illinois caves yielded 8 species of Arrhopalites. Five of these are troglobites. Indiana has similar ratios of caves yielding Arrhopalites and troglobite species. Table 1 shows a mixture of genuine geographic differences and collector bias with the large percentage of caves with known *Arrhopalites* for Indiana and Illinois probably partly a genuine geographic variation but also influenced by the extensive collections made by Jerry Lewis in these regions. Similarly, while the large difference between Virginia and West Virginia or North Carolina in percentage of caves yielding *Arrhopalites* may to some degree reflect biogeographic features, the primary cause is almost certainly collector bias. On the other hand, the paucity of species in Texas and the West coast is probably mainly the result of biogeographic differences rather than collector bias. The junior author made many of the Texas collections and these did not yield more *Arrhopalites* that those made by other collectors. A better understanding of the geographic distribution of this group must await more extensive and effective collections; however, it is clear that the genus is poorly represented in caves both west of the Mississippi and in the extreme south of the continent. This trend seen in the U.S. is carried on in Mexico where, although 12 species have been recorded, only 3 are found in caves and 2 of these are troglobites.

ACKNOWLEDGMENTS

This study was made possible by the collections of a number of speleologists. In addition to David Hubbard and Jerry Lewis, whom we have already mentioned, we would like to thank David Steinmann for his collections. Summer Ventis assisted with the preparation of the manuscript. The research was made possible by a grant to the senior author from the Brazilian CNPq and grants from Grinnell College.

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GYPSUM WEDGING AND CAVERN BREAKDOWN: STUDIES IN THE MAMMOTH CAVE SYSTEM, KENTUCKY

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Many segments of dry passages in the Mammoth Cave System contain an unusual breakdown lying unconformably over underlying stream sediments. The association of many of these breakdown areas with sulfate minerals (primarily gypsum) suggests that crystal wedging and replacement of limestone by gypsum are important factors in this type of cavern collapse. The following features are characteristic of mineral-activated breakdown: 1) Walls and ceilings fractured in irregular patterns often with visible veins of gypsum following the fractures; 2) Breakdown consisting of characteristic thin, irregular splinters and shards of bedrock; 3) Curved plates of bedrock ranging in size from a few centimeters to more than a meter hanging from the ceiling at steep angles and cemented only by a thin layer of gypsum; 4) Collapses that take the form of symmetrical mounds with coarse irregular blocks at the base grading upward into a rock flour at the top. Thin sections of the curved plates clearly show gypsum replacing limestone. Possible sources for the sulfate-bearing solutions are from the weathering of pyrite either at the top of the overlying Big Clifty Sandstone or in the limestone wall rock surrounding the cave passage. Reactions of the percolating solutions produce sulfate minerals in the wallrock adjacent to cave passages. Gypsum and other sulfate minerals created in the wall rock are less dense than calcite and exert sufficient pressure to spall off bits of the rock, some of which remain cemented in place by the gypsum.

Breakdown occurs widely in caves. For the most part, breakdown results from simple mechanical processes of bed failure under gravitational load. Proposed failure mechanisms include brittle fracture of incompetent beams (White & White 1969, 2000) and failure by inelastic creep (Tharp 1994, 1995). Breakdown in dry caves generally requires some sort of initiation process such as the invasion of surface waters to widen fractures in otherwise stable rock layers. Existing breakdown piles can be removed by dissolution thus removing support from walls and ceilings and triggering new breakdown. Dissolution by vadose water moving along fractures can convert fixed beams into cantilever beams. These and related processes are well recognized and discussed in textbooks (e.g., Bögli 1980; White 1988; Ford & Williams 1989). The size and shape of breakdown fragments depends in a complicated way on preexisting conditions of bed thickness, the existence of partings along bedding planes, and density of fracturing that cuts across bedding as well as the shape of dissolution surfaces that exist prior to bedrock failure. The complexity of accurately classifying breakdown is discussed in some detail by Jameson (1991). The present paper concerns a special category of breakdown in which the initiating process is chemical reaction and wedging due to crystal growth rather than purely mechanical fracturing under gravitational load.

Piles of angular rock fragments near cave entrances formed by water freezing in fractures are observed in many caves. A layer of angular rock fragments in the sedimentary deposits in alpine caves has been ascribed to frost action deep in the bedrock during Pleistocene ice advances (Schmid 1958). In some caves, typically in very dry passages, there occurs breakdown composed of irregular fragments, shards and splinters ranging in size from millimeters to a meter in width and fractions of a millimeter to a few centimeters in thickness. This breakdown is associated with gypsum deposition and was ascribed to crystal wedging effects (White & White 1969). Gypsum crystal wedging breakdown also has been described in the Friars Hole Cave System in West Virginia (Jameson 1991). Crystal wedging and spallation by the crystallization of halite has been described in the Nullarbor Caves in Australia (Lowry & Jennings 1974).

Crystal wedging breakdown and associated features are particularly well displayed in Turner Avenue in the Flint Ridge section of the Mammoth Cave System. Although the unusual breakdown in Turner Avenue has been recognized since the early exploration of the Flint Ridge Cave System (Smith 1964), no formal description of these deposits has been published. The objectives of the present paper are to describe in some detail the characteristic features of the gypsum wedging breakdown in Turner Avenue and to examine the geochemical mechanisms responsible for this particular breakdown process.

GEOLOGIC SETTING

Mammoth Cave is developed in the Mississippian St. Louis, Ste. Genevieve, and Girkin Limestones. Below the St. Louis is the relatively non-karstic Salem/Warsaw Formation, which acts as an aquiclude at the base of the section. Above the Girkin is the Big Clifty Sandstone which forms a protective caprock for the Mammoth Cave Plateau. The monoclinal structure dips to the northwest and is accompanied by minor folds and small-displacement faults. Details of the geology may be found in White et al. (1970), Palmer (1981), and White and

White (1989).

The great length of Mammoth Cave, ~570 km at the time of this writing, is possible because of interconnected groundwater basins with large surface catchment areas combined with survival of older passages protected by the overlying caprock. The time sequence represented by Mammoth Cave extends from the late Tertiary to the present (Palmer 2000; Granger *et al*. 2001). Upper level passages protected by the caprock tend to be dry. Passages that extend beneath the valley walls or that lie below valley floors tend to be wet. Growth of sulfate minerals and the process of crystal wedging take place in the very dry passages.

CHARACTERISTIC FEATURES OF CRYSTAL WEDGING BREAKDOWN

BREAKDOWN MORPHOLOGY

Evidence for crystal wedging can be found in many of the dry passages of Mammoth Cave, for example in Cleaveland Avenue, one of the main tourist routes. Similar evidence has been noted in other dry, gypsum-containing caves. The most extensive and best developed displays of crystal wedging breakdown occur in Turner Avenue, and for this reason, this area is described in some detail as the prototype to establish the diagnostic features of crystal wedging breakdown.

Turner Avenue extends from Argo Junction, a collapse on the wall of Houchins Valley, 2.9 km northward beneath Flint Ridge to another blockage at Brucker Breakdown (Brucker & Burns 1964). The north end is quite wet from vadose seepage and from vertical shafts, but the central portion of the passage, deep beneath the caprock on Flint Ridge, is extremely dry. Turner Avenue is an elliptical tube where not modified by breakdown. There is a shallow floor channel visible in many places. Scalloping near the floor of the conduit suggests final flow velocities of 10s cm/s. There is a thin layer of sand and silt sediment on the floor of the passage. Also in the sediment are some quartz pebbles from the basal conglomerate of the Pennsylvanian Caseyville Formation, which is exposed on Flint Ridge as a Pennsylvanian infilling of a late Mississippian paleochannel. The passage is at an elevation of 167 m and falls within Palmer's (1981) C level of Mammoth Cave. According to Granger et al. (2001), the quartz pebbles were deposited 1.46 Ma ago.

Breakdown deposits in Turner and Upper Turner Avenues often consist of masses of irregular slabs and other fragments that lie unconformably above the clastic sediments (Fig. 1). The breakdown is admixed with substantial amounts of gypsum. Gypsum forms along bedding planes and spreads over the passage walls as crusts (Fig. 2). Rubble piles of the sort shown in Figure 1 are suggestive but not diagnostic. More diagnostic of crystal wedging breakdown are the thin slabs that have apparently been split from the limestone beds. These grade downward into thin shards and splinters only millimeters thick (Figs. 3, 4). Crystal wedging breakdown is a subset of what Davies (1949) called "chip breakdown". Chip breakdown consists of rock fragments that are smaller than individual bedding plane slabs and can result from many processes including purely mechanical ones.

Figure 1. Rubble wall caused by gypsum deposition along bedding planes. Note hardhat for scale.

Figure 2. Wall of Turner Avenue showing extrusion of gypsum along bedding planes.

Figure 3. Thin plates and other fragments, some held to the ceiling by gypsum, in Upper Turner Avenue (Type II breakdown). Hardhat provides scale.

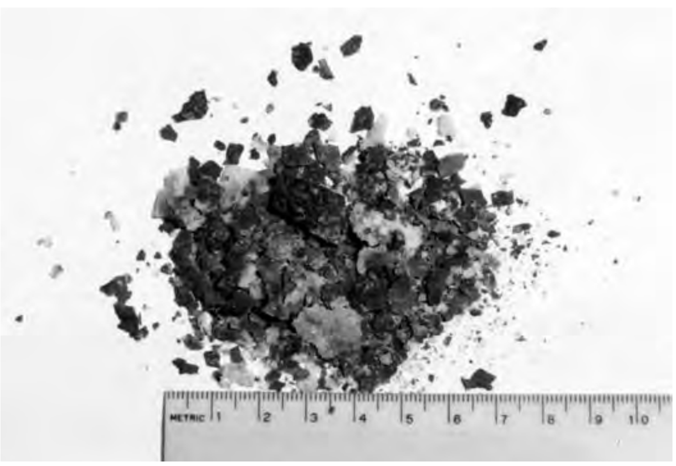

Figure 4. Breakdown splinters. Smallest rock fragments produced by gypsum-induced spalling.

Crystal wedging breakdown itself appears to be of two types. Type I consists of angular rock fragments broken on sharp planes that cut the bedding planes (Fig. 5). In the example shown, the fractures are filled with gypsum. Type I breakdown results from mechanical wedging due to crystallization of the gypsum. Similar rock fragments are found near cave entrances where they result from frost action. Type I crystal wedging breakdown results from purely mechanical pressures generated by crystal growing in small cracks and fractures. As an end member type, no chemistry is involved. Type II breakdown is more complex. The fragments and plates are angular,

Figure 5. Massive bedrock shattered by growth of gypsum in fractures producing Type I breakdown. Brunton compass provides scale.

sharp and are fractured across the usual zones of weakness – bedding planes and joints–as shown in Figures 3 and 4. Within this mass of fragments are small shards and splinters, only a few centimeters on a side and often less than a millimeter thick, which crush like broken glass when walked upon. These irregular plates, shards, and splinters are the signature of the crystal wedging process. The limestone bedrock is shattered and intermixed with gypsum so that entire passage walls become piles of rubble.

The thin shards of breakdown are also found in the ceilings completely surrounded by gypsum. It appears that they have been plucked from the bedrock ceiling and have remained embedded in the gypsum growth. At the northern end of Turner Avenue, where the passage becomes wet because of recent erosion of the caprock, some rock shards are found but the gypsum has been dissolved away.

CURVED BREAKDOWN PLATES

A less common but more diagnostic feature of gypsum wedged breakdown is shown in Figure 6. These are curved plates of limestone that appear to have been peeled from the ceiling and bent under their own weight. Some of these sagging beds take on a blister shape that appears to have been punched out of the ceiling (Fig. 6A). Close examination shows that these are indeed beds of limestone ~5 cm thick that are curved as though they had become plastic. Microscope examination of thin sections of the bent beds shows that the sagging and bending are due to the direct replacement of limestone by gypsum (Fig. 7A, B). Thin veinlets of gypsum occur throughout the solid slab of limestone. A total of 21 thin sections were prepared from breakdown slabs of various lithologies including some with no obvious curvature. Gypsum veinlets appear in most of them including the ones without obvious curvature.

The thin section data provide clear evidence that gypsum is not only crystallizing in joints and bedding plane partings, thus fracturing the rock, it is also crystallizing by direct chemical replacement of the limestone. Intrusion of gypsum causes the

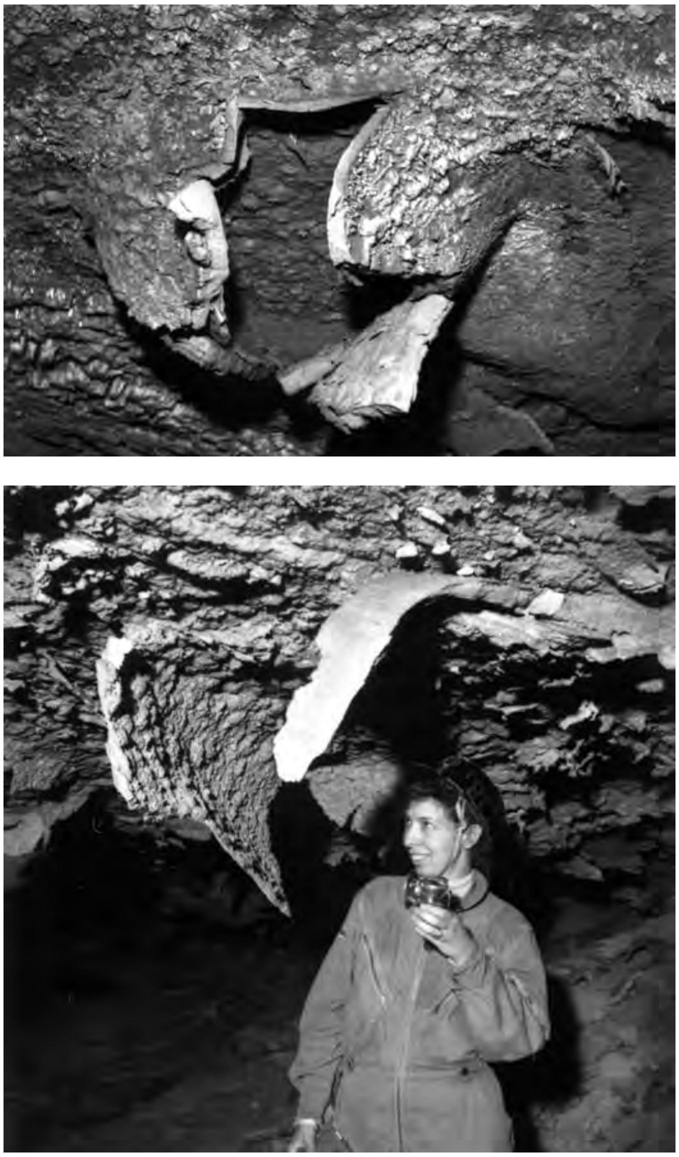

Figure 6. Curved breakdown slabs in Turner Avenue. (A-top) "Punch-out" of sagging bedrock slab. (B-bottom) Large curved plates.

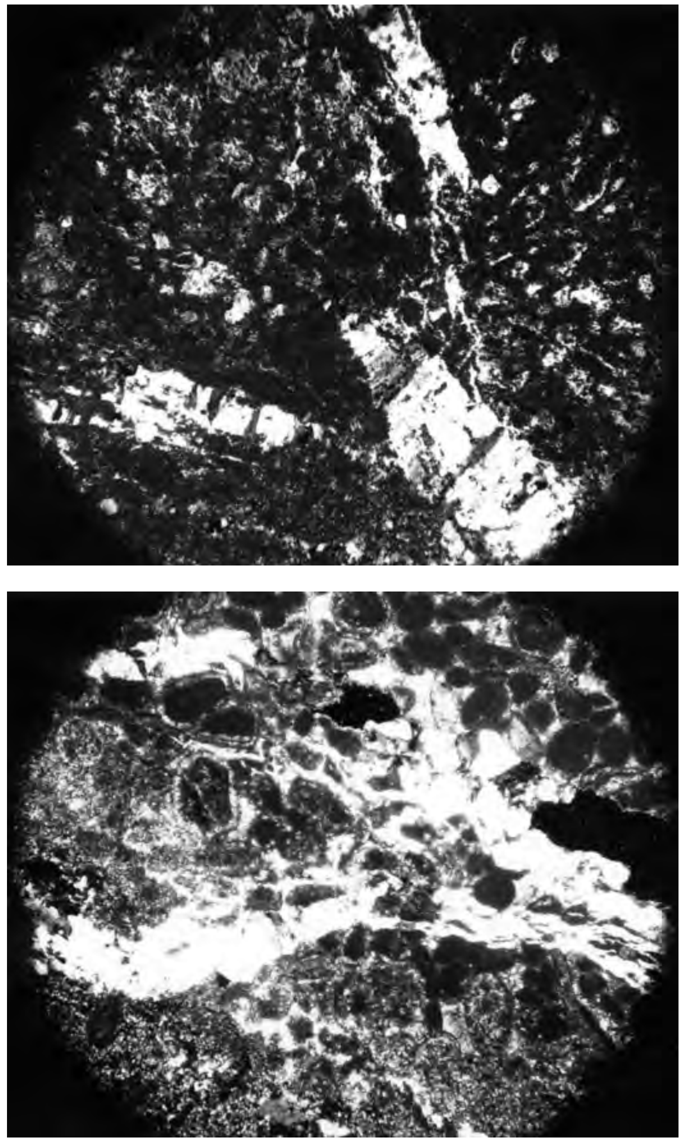

Figure 7. (A-top) Thin section of curved breakdown plate. Fine-grained material is limestone; large clear crystals are gypsum. (B-bottom) Thin section of curved breakdown plate showing limestone almost completely replaced by gypsum.

limestone beds to swell and curve with the harder and more brittle limestone sliding along the softer gypsum. There are thus two processes, one mechanical and one chemical, acting together to produce Type II gypsum wedged breakdown.

MASSIVE COLLAPSE AND ROCK FLOUR

Additional evidence for the chemical intrusion of gypsum is provided by ruptured ceiling beds. Along Upper Turner Avenue, a sequence of rubble piles occur directly below collapse features in the ceiling (Fig. 8). The ceiling at the location shown in Figure 8 is a massive limestone bed 20–30 cm thick. Above the massive bed is a layer of thin-bedded limestone that has been extensively infused with gypsum. The gypsum formed in the thin-bedded limestone apparently built up sufficient pressure to force the collapse of the underlying massive bed thus creating a collapse dome in the ceiling of the passage (Fig. 9). The debris pile is a chaotic mixture of rock fragments, gypsum crystals, and rock flour. The fragments of limestone appear to be etched and have very corroded surfaces.

Rock flour is characteristic of many of the gypsum wedged breakdown areas. Samples were collected from 5 locations and examined by x-ray diffraction, optical microscopy, scanning electron microscopy (SEM), and energy dispersive x-ray spectroscopy (EDX). The rock flour by microscope and x-ray evidence is found to be calcite dust mixed with ooids and fossil fragments. A minor amount of gypsum occurs in the rock flour. Scanning electron microscope images of rock flour sample 402 (Fig. 10A) reveals a uniform powder of strongly etched calcite

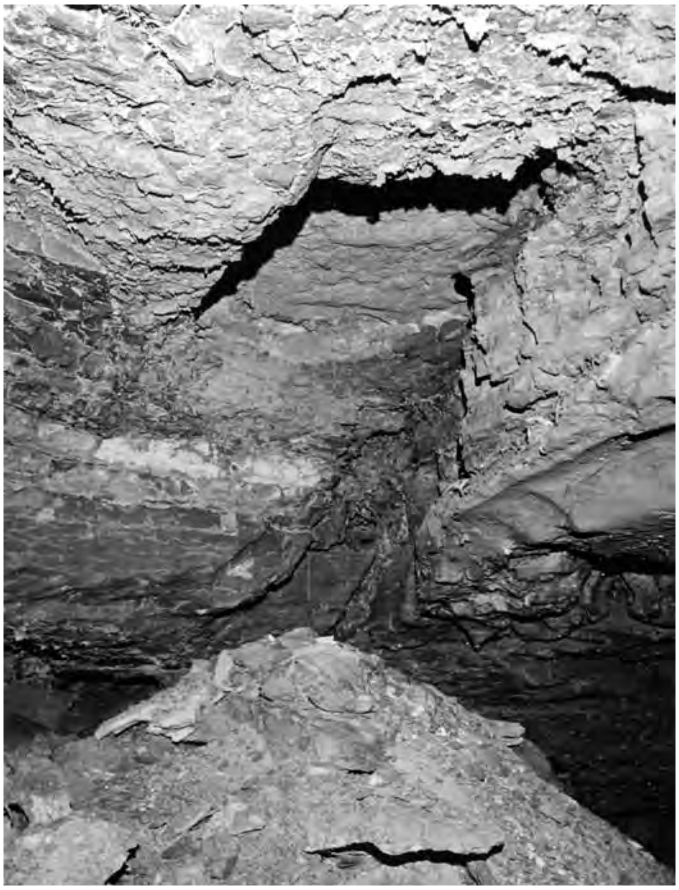

Figure 8. A ceiling breakout forming a rubble pile of rock fragments and rock flour.

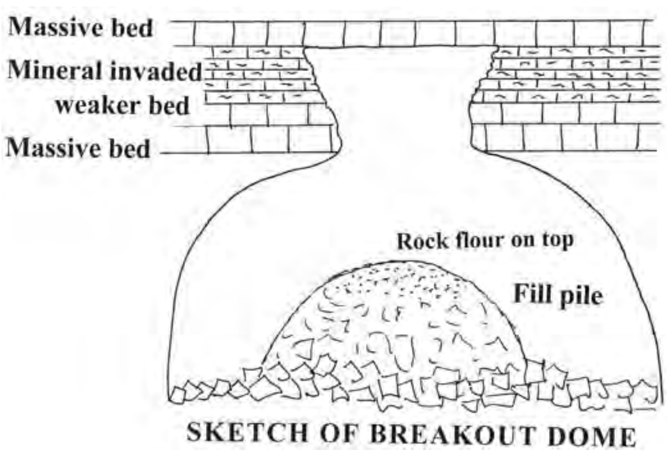

Figure 9. Sketch showing stratigraphic relations of ceiling breakout.

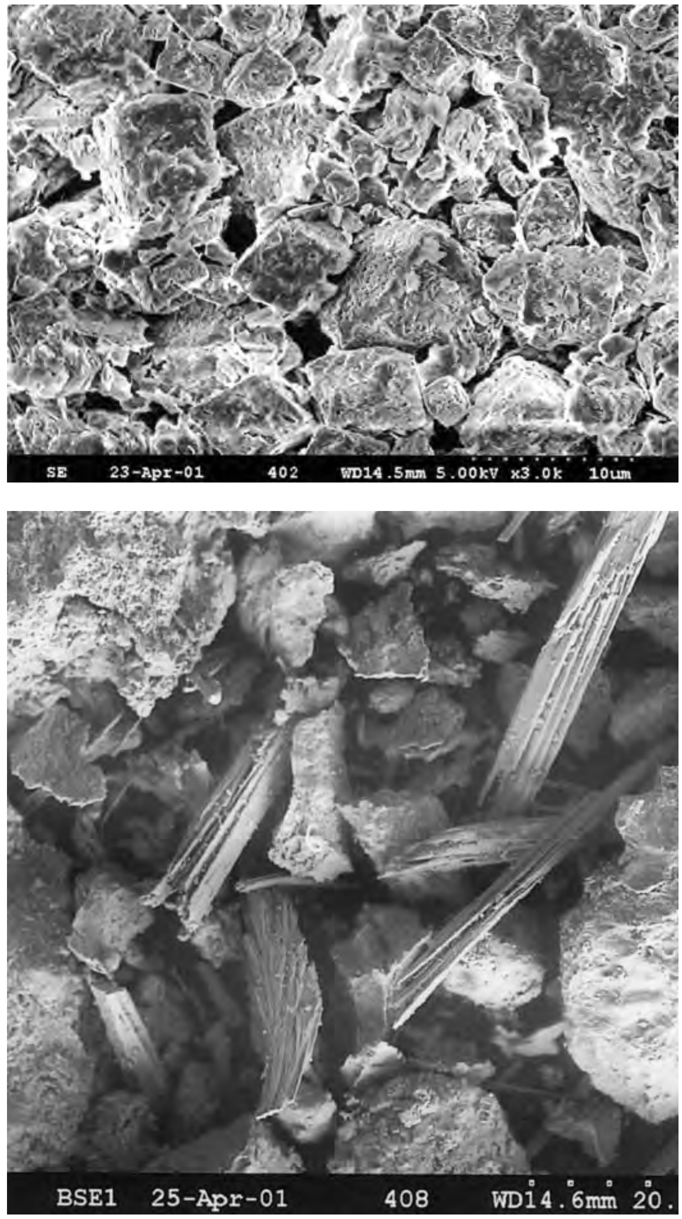

Figure 10. Scanning electron microscope images of rock flour. (A-top) Sample 402 from Turner Avenue consists mainly of etched calcite rhombs. (B-bottom) Sample 408 from Turner Avenue at intersection of Dead Bat Trail is a mix of limestone rock fragments (large lump), acicular gypsum crystals, and some minor quartz sand grains.

rhombs. Particle sizes are in the range of 10-50 µm. EDX analysis shows that some of the irregular small particles consist mainly of silica, presumably quartz. The SEM image of sample 408 (Fig. 10B) shows a more complex mixture. There are irregular rock fragments, some as large as one mm, mixed with irregular smaller particles and acicular crystals. EDX analysis shows the larger particles to contain mainly calcium with no other elements. This identifies them as calcite because carbon and oxygen do not appear in the EDX spectra. The absence of a magnesium peak suggests that the parent rock is limestone, not dolomite. Some of the smaller particles contain mainly silica, which is probably quartz. The acicular crystals contain both calcium and sulfur, thus identifying them as gypsum. A total of 30 images were obtained from various samples

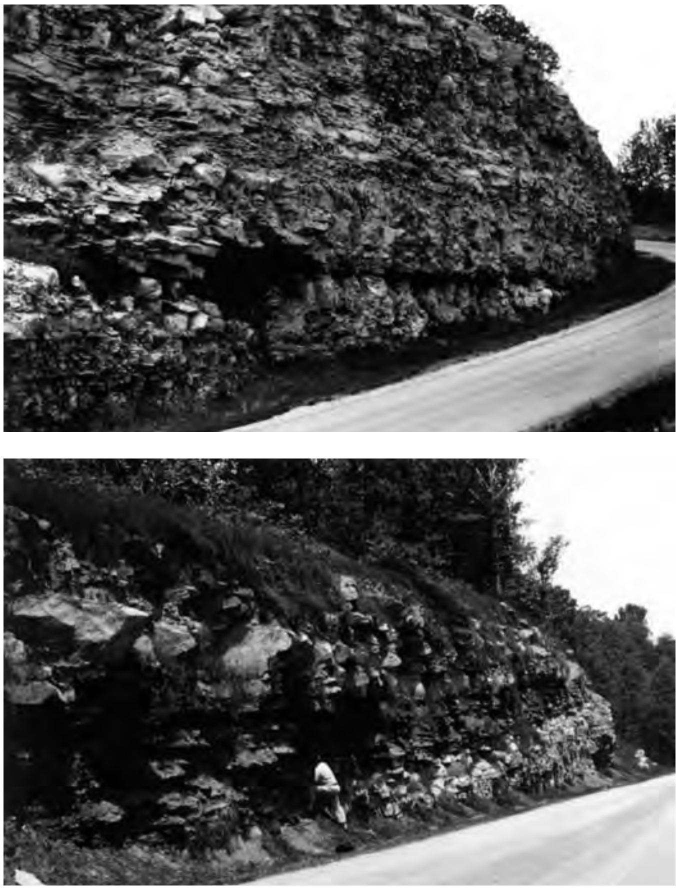

Figure 11. The contact between the Girkin Limestone and the Big Clifty Sandstone. (A-top) The road cut along Highway 70 on Joppa Ridge just west of the trail leading to Sandhouse Cave and Turnhole Spring. The contact is unconformable with the sandstone resting directly on the limestone. (B-bottom) Roadcut on Highway 422 near the Cedar Sink parking area. About 2 m of black impermeable shale separate the sandstone and the limestone. The separation of roadcuts (A) and (B) is 1.5 km.

taken at the 5 rock flour locations. The images were all variants on the two images reproduced in Figure 10. The rock flour appears to be residual debris from the chemical breakdown of the limestone bedrock.

BREAKDOWN MECHANISMS

GYPSUM SOURCES

Three hypotheses have been proposed to account for the gypsum in the caves of the Mammoth Cave region:

(1) Sedimentary anhydrite occurs in thin beds scattered through the Mississippian limestones, particularly the St. Louis Limestone. This anhydrite can be dissolved in circulating groundwater, transported to the caves, and redeposited as gypsum through evaporation (George 1977);

(2) Oxidation of pyrite that occurs disseminated, particularly in the Girkin Limestone, provides sulfuric acid that reacts with the limestone to produce gypsum. Palmer (1986) and Palmer and Palmer (1995) proposed this source as part of their mechanism of gypsum deposition. Pyrite oxidation from a local source becomes part of what will be called the "Palmer Hypothesis";

(3) E.R. Pohl long ago argued that the primary source of gypsum was oxidation of pyrite from a pyrite-rich layer at the top of the Big Clifty Sandstone (Pohl & Born 1935; Pohl & White 1965). This source will be incorporated in what will be called the "Pohl Hypothesis".

The few measurements on sulfur isotope ratios that have been made seem to rule against sedimentary anhydrite as a primary source (Furman et al. 1999). Three samples of Mammoth Cave gypsum were analyzed giving $\delta^{34}S$ values of -5.06, -8.12, and -7.82, all in reasonable agreement with the values of -9 to -4.2 found for Mississippian pyrites but not in agreement with the values of -19 to -14 found for St.Louis anhydrites. This bit of evidence supports the hypothesis that the gypsum is derived from the oxidation of pyrite, not from the anhydrite that occurs interbedded in the limestones.

Pyrite does occur disseminated in the Girkin Limestone. Pyrite in the form of faceted crystals up to several millimeters in size has been observed by the authors. Palmer and Palmer (1995) have claimed, based on thin section evidence, that 0.1% of the rock mass is comprised of pyrite. They further claim that areas of extensive gypsum deposition coincide with areas of high pyrite concentration. According to the Palmer Hypothesis, the oxidation of pyrite, the reaction of sulfuric acid with the limestone to form gypsum, and the replacement of calcite by gypsum all take place in a relatively thin reaction zone surrounding the cave passage. No long distance transport mechanism is necessary.

Likewise, pyrite does indeed exist at the top of the Big Clifty Sandstone. Good exposures of this pyrite were directly visible in fresh roadcuts on Cane Run just north of the National Park that were made during the construction of the Nolin River Reservoir in 1963. The pyrite was associated with a coal-like organic layer and occurred in large quantities as nodules on the order of 10 cm thick. The organic bed was ~0.6 m thick and was estimated to contain 5-10% pyrite. X-ray diffraction of pyrite collected at this time confirmed the identification of the mineral. This deposit of pyrite was extremely reactive and oxidized very rapidly. Samples collected in the field were found to decompose in a few months even in sealed containers in the laboratory. Sulfuric acid was liberated and unidentified white fibrous crystals grew from the surface of the nodules. The pyrite disappeared very rapidly from exposed outcrops.

If the extensive pyrite at the top of the Big Clifty Sandstone is the source of the sulfate, rather than the sparse pyrite that occurs disseminated through the Girkin Limestone, there must be pathways for the migration of solutions through the sandstone and into the limestone. These pathways could also account for the spotty occurrence of sulfate minerals in the cave. Some dry areas contain a great deal of gypsum. Other dry

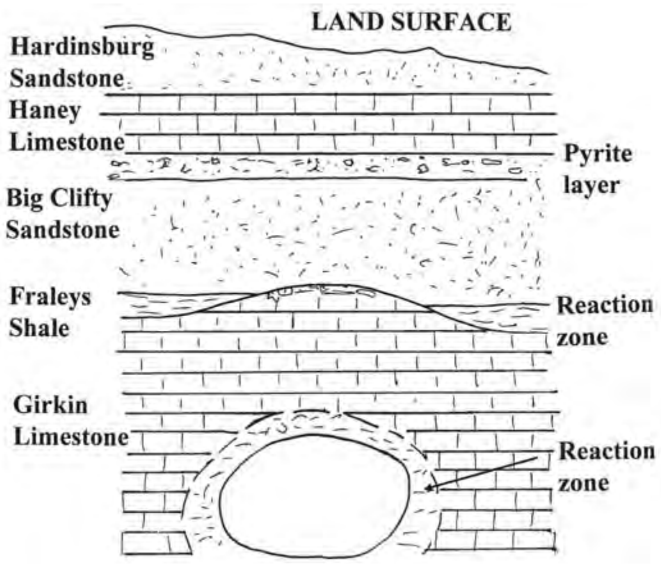

Figure 12. Sketch showing the physical model for transport of sulfate minerals from overlying Big Clifty Sandstone into cave passages in the limestones below.

areas are almost barren. The responsible geologic feature may be the Fraileys Shale. The Fraileys Shale is an intermittent black shale at the contact between the Big Clifty Sandstone and the Girkin Limestone. Where the shale is absent, the solutions can percolate down into the limestone. Where present, the shale presents a barrier and in these regions the underlying caves would be barren of gypsum. Figure 11 shows the Big Clifty/Girkin contact at 2 locations on Joppa Ridge, immediately south of Mammoth Cave Ridge. These photographs were taken in 1963 when the re-routing of Kentucky Route 70 produced fresh roadcuts. In one contact, the Big Clifty rests unconformably on the Girkin Limestone with no barrier to vertical percolation. In the other contact, less than a kilometer from the first, 2 m of black shale separate the 2 formations. At the time of this writing, the outcrop with the unconformable contact remains well exposed but weathering of the shale and growth of vegetation has largely concealed the other contact.

The oxidation of pyrite provides a source of sulfate ions and hydrogen ions. The iron released from the pyrite is not mobile and remains at the original location. Gypsum in the cave is generally free of iron-containing minerals. The sulfuric acid bearing solutions percolate very slowly through the Big Clifty and into the Girkin Limestone. Evidence from the breakdown, the breakout domes, and the rock flour suggests that the gypsum is formed *in situ* by chemical replacement of calcite in the wallrock immediately adjacent to the cave passages. Gypsum forms in a reaction zone in the cave passage walls regardless of the location of the pyrite.

The physical model is sketched in Figure 12. The transport medium is the vertical percolation of groundwater in the vadose zone. There is a source area for sulfate ions and acidity at the top of the Big Clifty Sandstone. There are 2 reaction zones, one at the contact between the sandstone and the Girkin Limestone and one in the wallrock immediately surrounding the cave passage.

CHEMISTRY OF PYRITE OXIDATION

Establishment of the chemical mechanism for gypsum deposition must be largely deductive because the slowly seeping solutions cannot be sampled. There is no liquid water in evidence in the gypsum areas. New growth over scratch marks and over areas where early Americans mined the sulfate minerals shows that the reactions must be proceeding under present-day conditions. The continued growth of gypsum and other sulfate minerals requires that slowly percolating solutions must exist in the pores and along fractures and bedding plane partings in the wallrock, although their chemistry remains unknown.

The chemistry of pyrite weathering has been extensively investigated because of its importance in understanding acid mine drainage (Langmuir 1997; Drever 1997). Pyrite is oxidized by the reaction

$$FeS_2 + 7/2\ O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$$

which produces for each mole of pyrite a mole of ferrous iron and two moles of hydrogen ion. The ferrous iron can oxidize slowly by a purely inorganic process to ferric iron which then precipitates as highly insoluble $Fe(OH)_3$

$$Fe^{2+} + \tfrac{1}{4}\ O_2 + 5/2\ H_2O \rightarrow Fe(OH)_3 + 2H^+$$

thus releasing more acidity. Superimposed on these inorganic processes in mine spoil piles is an autocatalytic set of reactions mediated in large part by microorganisms.

$$4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O$$

The ferric iron then reacts with more pyrite to produce additional acidity.

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$$

Although the detailed reaction mechanisms of pyrite oxidation either within the limestone bedrock or in the Big Clifty Sandstone are not known, the end products are the release of hydrogen ions and sulfate ions, which can ultimately react with calcite from the limestone to form gypsum.

GYPSUM DEPOSITION: THE POHL HYPOTHESIS

The physical model (Fig. 12) shows 2 possible reaction zones. One is at the contact of the Big Clifty Sandstone and the Girkin Limestone and the other is in the wallrock immediately surrounding the cave passage. Given a flux of sulfuric acid migrating downward from the Big Clifty, the task is to explain why the acidity is not completely neutralized at the limestone contact. It also is necessary to account for the evidence that gypsum is formed in-situ by replacement of calcite in the cave walls.

In an open system with continuously migrating solutions across the sandstone/limestone interface, the reaction would be

$$CaCO_3 + H^+ + SO_4^{2-} \rightarrow Ca^{2+} + HCO_3^- + SO_4^{2-}$$

The reaction is written with sulfate ion on both sides of the equation to indicate that in this system, the sulfate ion is simply carried along in solution. All product ions would migrate downward into the limestone dissolved in the vadose seepage. Because gypsum is ~10x more soluble than calcite, the ions remain in solution until the concentration builds up to gypsum saturation. This would take place on the cave walls because of evaporation of the solution. The bicarbonate ion would also be lost as CO_2 discharged into the cave atmosphere. In this system there might be breakdown due to crystal wedging because of crystallization of gypsum in fractures and bedding plane partings, but it is not clear whether or not there would be actual replacement of calcite by gypsum in the cave walls. One might see Type I breakdown but not Type II breakdown.

The reaction by which calcite is replaced by gypsum can be written in a number of ways. Two possible reactions, both noted by Palmer (1986), maintain all species in solution

(a) $CaCO_3 + SO_4^{2-} + H^+ + 2H_2O \rightarrow CaSO_4 \bullet 2H_2O + HCO_3^-$

$$\frac{a_{HCO_3^-}}{a_{H^+}\, a_{SO_4^{2-}}} = K_a = 2.812 \times 10^6 = 10^{6.449}$$

(b) $CaCO_3 + 2H_2O + SO_4^{2-} \rightarrow CaSO_4 \bullet 2H_2O + CO_3^{2-}$

$$\frac{a_{CO_3^{2-}}}{a_{SO_4^{2-}}} = K_b = 1.349 \times 10^{-4} = 10^{-3.870}$$

A third way is to assume that the reaction releases CO_2 gas. This should be appropriate for reactions in the walls of dry cave passages where all solutions eventually evaporate. There is transport of material into the cave by slow percolation of solutions in the vadose zone but there is no transport of material out of the cave. The replacement reaction can be written

(c) $CaCO_3 + SO_4^{2-} + 2H^+ + 2\ H_2O \rightarrow CaSO_4 \bullet 2H_2O + CO_2$

$$\frac{P_{CO_2}}{a_{H^+}^2\, a_{SO_4^{2-}}} = K_c = 1.914 \times 10^{14} = 10^{14.282}$$

where the a's are the activities of the designated ions. Numerical values for the equilibrium constants were calculated using Gibbs free energies of formation at 25° C from Drever (1997).

These reactions are not independent. All three are connected by the equilibria among the carbonate species. As a result

$K_b/K_a = K_2$ and $K_a/K_c = K1\ K_{CO2}$

Where K_1 and K_2 are the first and second ionization constants of carbonic acid and K_{CO2} is the Henry's law constant for dissolution of gaseous CO_2 in water. Numerical values are given in Langmuir (1997) and Drever (1997).

The sulfate ion activity in the percolating solutions in the source area is unknown. It depends on the flux of slowly percolating solutions balanced against the weathering rate of pyrite deep within the bedrock. However, evaporation of the solutions in the vicinity of the cave passage must eventually bring the solutions to saturation with gypsum if gypsum is to be deposited. At saturation,

$$a_{Ca^{2+}}\, a_{SO_4^{2-}} = K_{gyp} = 2.488 \times 10^{-5}$$

The solubility product constant for gypsum, K_{gyp}, at 25° C was calculated from Drever's (1997) thermodynamic data. Gypsum has a retrograde solubility but recalculating to 12° C only changes the solubility product constant to 2.510×10^{-5}. The sulfate ion activity will be 4.958×10^{-3} for a solution saturated with gypsum. Inserting this into replacement equation (c) reduces it to

$\text{Log}\ P_{CO2} = 11.980 - 2pH$

for limestone and gypsum coexisting in equilibrium.

Reaction of sulfuric acid with calcite at the Big Clifty/Girkin contact will release carbon dioxide into the pore spaces within the rock. When the CO_2 pressure exceeds atmospheric pressure, the CO_2 will be forced out of the reaction zone. According to the equation above, this will occur until the pH reaches 5.99. Thus much of the neutralization of acidity from the pyrite takes place in the reaction zone at the sandstone/limestone contact, generating Ca^{2+} ions and sulfate ions which are carried downward by vadose seepage. However, some residual acidity remains and can be carried downward into the limestone and the underlying cave passages. According to measurements by Miotke (1974), the CO_2 pressure in Mammoth Cave is exceptionally low, $10^{-3.3}$, only a little above the outside atmospheric pressure, $10^{-3.47}$. Continued replacement of calcite by gypsum in the wallrock with release of CO_2 into the cave atmosphere would proceed until the pH reaches 7.64 at which point the pressure of released CO_2 becomes equal to the CO_2 pressure of the cave atmosphere.

GYPSUM DEPOSITION: THE PALMER HYPOTHESIS

The Palmer hypothesis also depends on a flux of vadose seepage water originating at the land surface but with a different geochemical interpretation. Most limestone soils have CO_2 pressures in the range of 10^{-2} to 10^{-1} atm (1-10% CO_2 by volume). The soil water migrates downward to the limestone bedrock contact where it reacts, dissolving calcite to concentrations close to equilibrium at the P_{CO2} of the soil. The water, with its dissolved load of Ca^{2+} and HCO_3^- ions, continues downward through pores and fractures in the bedrock until it reaches a cave passage where the CO_2 pressure is much lower, typically $10^{-2.5}$. Excess CO_2 is degassed into the cave passage with concurrent precipitation of $CaCO_3$. This is the standard and long accepted mechanism for the deposition of calcite speleothems. Palmer (1986) notes that this mechanism assumes that the system is open so that the CO_2 consumed by dissolution of limestone at the soil/bedrock interface is replaced by fresh CO_2 from the overlying soil. The CO_2 pressure remains constant. He argues that vadose seepage waters in the sandstone-capped ridges of the Mammoth Cave area will behave as a closed system. The porous, sandy soils of the Mammoth Cave Plateau have typical CO_2 pressures of 10^{-3} to

$10^{-2.3}$ atm, only ~10x the CO_2 pressures in the cave atmosphere. When vadose water seeps through the sandstone to the underlying limestone, the dissolution reaction will proceed with CO_2 being consumed until the system comes to equilibrium.

Using a typical soil CO_2 concentration of 0.3% by volume ($P_{CO2} = 10^{-2.5}$ atm), Palmer (1986) calculates a closed system P_{CO2} of 4.5 x 10^{-5} atm ($10^{-4.35}$) and a pH of 8.85 for the seepage water when it reaches equilibrium. The calculated P_{CO2} is not only lower than that of the cave atmosphere, it is lower than that of the surface atmosphere. A rough calculation using Langmuir's (1971) closed system model gives values of $P_{CO2} = 10^{-4.12}$ and pH = 8.76 for an initial CO_2 concentration of 0.3 volume percent, which would be considered good agreement with Palmer's results.

The low CO_2 pressure in the seepage water emerging from the cave wall means that this water will absorb CO_2 from the atmosphere, become undersaturated, and can attack the limestone in the cave wall. Palmer uses this mechanism to account for the zones of active attack observed on cave walls including a location near Brucker Breakdown at the north end of Turner Avenue. Palmer's proposed mechanism accounts very nicely for the patches of "wet rot" observed at various places in the cave system. An additional question is whether or not the exceptionally low CO_2 pressure is sufficient to drive a direct replacement reaction of carbonate by sulfate.

Palmer uses reaction (b) to describe the carbonate replacement reaction. In order for this reaction to proceed to the right, it is necessary that the activity ratio

$$\frac{a_{SO_4^{2-}}}{a_{CO_3^{2-}}} \geq \frac{1}{K_b}$$

It may be assumed that the pore fluids are saturated with gypsum and thus the sulfate ion activity is determined by the solubility constant for gypsum. The carbonate ion is a minor species in the pH range of 8-9. The carbonate ion activity can be calculated from the estimated CO_2 pressure of the pore fluids in terms the various carbonate equilibrium constants and the pH.

$$a_{CO_3^{2-}} = \frac{K_1 K_2 K_{CO_2}}{a^2_{H^+}} P_{CO_2}$$

If we take the sulfate ion activity = 4.958 x 10^{-3} and choose CO_2 pressures of 4 x 10^{-4} atm, the cave atmosphere and 4.5 x 10^{-5} according to Palmer's (1986) calculation for the closed system pore fluid, the sulfate/carbonate activity ratio is 48 and 352 respectively. The calculations outlined in the previous section give 1/Kb = 7400. Palmer (1986) gives 5400 and Palmer and Palmer (1995) give 4900. For the estimated pore fluid chemistry, the sulfate/carbonate activity ratio is about an order of magnitude short of what is needed to drive the direct replacement reaction. In order to drive the direct replacement reaction, the closed system needs to pull down the CO_2 pressure of the vadose seepage solutions by at least another order of magnitude. Whether or not this may actually happen is difficult to determine in the absence of any chemical data on the pore fluids.

Comparison of hypotheses

It is emphasized that the oxidation of pyrite will produce acidity which can react directly with limestone to produce Ca^{2+} and SO_4^{2-}. These ions will combine to form gypsum where ever the solutions are allowed to evaporate. Gypsum can be formed from the oxidation of pyrite in the limestone and it can form from vadose seepage carrying ions from the pyrite zone at the top of the Big Clifty. Either hypothesis can provide the gypsum but both hypotheses have difficulty explaining the direct observational evidence that calcite replacement by gypsum takes place in the cave walls.

The Palmer hypothesis is the most direct in that all reactions take place immediately in the site of gypsum deposition and formation of the gypsum crystal breakdown. It requires that the highly irregular distribution of gypsum in the cave be dictated by the distribution of pyrite in the limestone. There is a question of whether the volume of pyrite is sufficient to account for the large volumes of gypsum observed in the cave. If this gypsum is indeed derived from pyrite in the adjacent wall rock, it is curious that there is so little iron hydroxide in evidence.

The Pohl hypothesis has the advantage that very large masses of pyrite are available at the top of the Big Clifty Sandstone. Iron compounds resulting from the oxidation of the pyrite would remain in the upper Big Clifty, conveniently out of sight. The distribution of gypsum would be controlled by the distribution of the Fraileys Shale, also an unknown quantity. The difficulty is in maintaining a chemical driving force for the replacement of calcite by gypsum in the cave walls.

It should also be noted that these hypotheses are not mutually exclusive. Both sources may be functional, including the possibility that one may dominate in some locations in the cave while the other source may dominate in other locations.

Crystal wedging

The chemical reaction that describes the replacement of calcite by gypsum shows that the replacement takes place on a mole-for-mole basis. Decomposition of one mole of calcite produces one mole of gypsum. The replacement, however, results in a volume expansion of about a factor of two. Using the calcite unit cell parameters of Reeder (1983) with 2 formula units of $CaCO_3$ per unit cell gives a molar volume of 61.305 $Å^3$ whereas the unit cell parameters for gypsum (Cole & Lancucki 1974) with 4 formula units per unit cell give a molar volume of 123.59 $Å^3$. It is this large volume expansion that is responsible for the mechanical wedging that produces the fracturing of the shards and splinters as well as the curved breakdown plates.

Palmer and Palmer (2000) have calculated a somewhat different mechanism for replacement of calcite by gypsum in the sulfuric acid caves such as Carlsbad and Lechuguilla. Their mechanism involves a reaction in which 2 moles of calcite are replaced by one mole of gypsum with the other half of the calcium being carried off in solution. With this mechanism, there would be an almost negligible volume expansion because of the fortuitous approximately 1:2 ratio in the molar volumes of calcite and gypsum. The replacement reactions in sulfuric acid caves differ from those in the dry passages of Mammoth Cave in that the reactions were assumed to take place when the caves were water-filled. In Mammoth Cave, all water is lost by evaporation and the mechanism would not apply.

CONCLUSIONS

Examination of the breakdown in many sections of Mammoth Cave but particularly in Turner and Upper Turner Avenues in the Flint Ridge Section of the cave reveals evidence for crystal wedging and chemical replacement by gypsum and other sulfate minerals as the primary mechanism for the breakdown. Field evidence includes bedrock fractured into slabs, shards, and splinters of many sizes; breakdown consisting of curved rock slabs; breakout domes with a rubble of rock fragments; gypsum crystals; and rock flour. Laboratory evidence includes microscopic examination of thin sections that show calcite replacement by gypsum. X-ray powder diffraction, optical microscopy, scanning electron microscopy, and energy dispersive x-ray spectroscopy of the rock flour show it to be a reaction product of calcite replacement. The geochemistry of gypsum deposition is examined in some detail. Possible sources of gypsum include a pyrite-rich horizon at the top of the Big Clifty Sandstone and pyrite dispersed in the Girkin Limestone.

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THE KUKA‘IAU CAVE, MAUNA KEA, HAWAII, CREATED BY WATER EROSION, A NEW HAWAIIAN CAVE TYPE

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In 2000 and 2001, two large (each ca. 1000 m long) cave systems have been surveyed on the eastern, heavily eroded, flank of Mauna Kea: The Pa’auhau Civil Defense Cave and the Kuka‘iau Cave (at first called ThatCave/ThisCave System). Both caves occur in the Hamakua Volcanics, 200-250 to 65-70 ka old. They are the first substantial caves documented for lavas of Mauna Kea and the first caves on Hawai’i showing extensive morphological signs of water erosion.

The Pa’auhau Civil Defense Cave is a lava tube, as attested by the presence of the typical morphological elements of lava tubes, including secondary ceilings, linings, base sheets, stalactites and lava falls. Subsequently, the cave was modified erosionally by a stream which entered upslope and traversed much, but not all, of the cave, leaving waterfalls, waterfall ponds, scallops, gravel, rounded blocks and mud (Kempe et al*. 2003). In contrast the Kuka‘iau Cave – a still active stream cave with a vadose and phreatic section - is essentially erosional in origin. This is concluded from the geology of the strata exposed in the cave and from its morphology: At the upper entrance the cave is situated in a thick series of aa and the lower section was created by removing aa and diamict layers, therefore excluding the possibility that the cave developed from a precursor lava tube. Also, in its phreatic section, the cave makes several right angle turns and moves upward through a series of pahoehoe sheets, unlike any lava tube. Furthermore, a base layer can be followed along which the major section of the upper cave has developed. Allophane and halloysite – minerals produced by weathering - helped in sealing the primary porosity of this base layer causing a locally perched water table. Water moving along this base layer on a steep hydraulic gradient through the interstices of aa and through small pahoehoe tubes exerted a high pressure on the porous diamict of the lower cave, causing its erosional removal. Our observations of water erosional caves in lavas of Hawaii offer a new perspective on deep-seated water courses in volcanic edifices.*

On Hawaii, hundreds of small and large lava tubes have been explored in the last 20 years, largely by members of the Hawai‘i Speleological Survey and the Hawaiian NSS Grotto. These tube systems are located on Kilauea, Mauna Loa and Hualalai. Mauna Kea, however, remained somewhat of a blank spot speleologically. Old reports of caves being intercepted by water wells have not been documented sufficiently so far. Along the old Mamalahoa Highway and along the road to the Waipio Valley Outlook west of Honoka‘a there are a few artificial caves, but they are former quarries where road building material such as cinders and aa was mined.

Hawaiian microclimates vary widely from extremely humid to extremely dry conditions on the same island. On the windward side of the Big Island of Hawai‘i Mauna Kea’s NE flank receives up to 90 inches of rain per annum (1961-1990 average annual precipitation Data, U.S. National Oceanic and Atmospheric Administration). This has led, despite the highly porous nature of volcanic rocks, to the formation of perennial and episodic streams, which in turn have significantly dissected the eastern flank of Mauna Kea. Its morphology is characterized by several deep gulches and countless V-shaped gullies and streamways, which funnel the water straight to the ocean without forming large tributary river systems. The last eruption on Mauna Kea occurred at the summit under the ice, i.e., during the Last Glacial. Any lava tubes that have formed on the lower flanks are therefore older and may have formed several tens of thousands of years ago. Thus, such tubes, if any, should be either invaded and plugged by younger lavas, filled by ashes, or should have collapsed under the weight of overlying strata. Therefore, no systematic search was made for caves on Mauna Kea. When the first caves on Mauna Kea came to the notice of the Hawaiian Speleological Survey in 1995, this came as quite a surprise. These were two caves in Honoka‘a and the Civil Defense Cave at Pa‘auhau. First rough maps were published by Werner, 1997. Further findings, three small caves in Kalopa State Park and a larger system in the Hamakua Forest Reserve were reported by Halliday (2000 a, b). Pa‘auhau Civil Defense Cave was studied in detail in 2001 (Kempe *et al*. 2003) and turned out to be a lava tube heavily impacted by water erosion.

In March 2000 Robert van Ells told M.S. Werner about another cave on Mauna Kea (Werner *et al*., 2000; Kempe *et al*., 2001). He reported having entered through a pit and then having exited makai[1] from a resurgence by swimming through a small pond. We relocated these two entrances on March 15th 2002. The cave was initially called ThisCave because we suspected that the cave already had a local name. Because it serves as the source of a stream at flood, we concluded that

[1] makai = Polynesian for “towards the sea” i.e., downslope

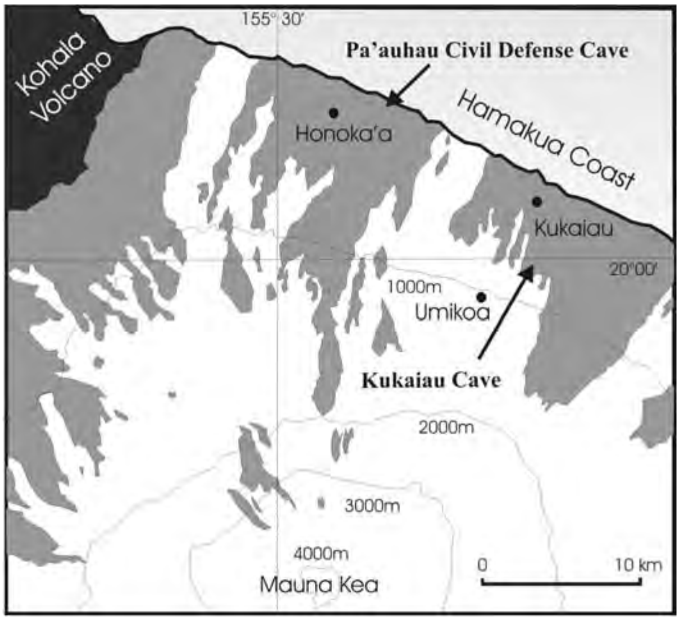


Fig. 1: Location of Kuka'iau Cave and Pa'auhau Civil Defense Cave and geological map of the Northern section of Mauna Kea. The dark gray area represents the outcrops of the Hamakua Volcanics and the white area represents the distribution of the overlying Laupahoehoe Volcanics (redrawn according to Wolfe *et al*. 1997).

there must be a stream sink mauka[2] as well. M.S. Werner then scouted the area and found the sink in a creek bed leading to a large vadose underground stream passage. It was provisionally called ThatCave. None of the ranchers interviewed knew about this entrance even though it is quite obvious and fences run nearby. In 2000 ThisCave and ThatCave were explored and surveyed by teams led by S. Kempe and M.S. Werner. In addition geological investigations were carried out in ThatCave by S. Kempe, I. Bauer and H.-V. Henschel in 2001 and 2002. In 2002, the sump, so far separating the two caves, was explored physically by H.-V. Henschel, S. Kempe, and M.S. Werner, linking the survey of the two caves. The story of the discovery of these caves is related in Werner *et al*. (2002). Initial reports were given in Kempe, 2000; and Kempe *et al*., 2001. In June 2002 we also learned that Dr. Fred Stone of the University of Hawai'i, Hilo, had investigated ThatCave biologically in 1992 (Stone 1992). He had named the cave Kuka'iau Piping Cave. Since older names take precedence, we changed the name of the cave to Kuka'iau Cave, dropping "piping", because the cave name should not give an interpretation of the mechanism of its formation. We also learned that Stearns and Macdonald (1946) mention the cave (p. 244): "A large lava tube 2.3 miles S. 10°W (longitude obviously in error, note of S.K.) of Kuka'iau Post Office constitutes an unusual source of water. Half a mile south of this point a stream disappears underground, apparently flowing into the tube. During heavy rains a large stream of water emerges from the lower end of the tube, but it does not flow in dry weather. A large body of water remains in the tube, however, and is used to supply cattle tanks. About 50,000 gallons is siphoned from the tube every two months, but the tube never has been emptied." This citation explains the presence of bent and rusted pipes in ThisCave and of a well head above the sump in ThisCave.

Table 1. GPS locations of Kuka'iau Cave entrances (map datum: Hawaiian):

Date: 04.03.01	North	West	Altitude a.s.l.
ThisCave Entrance	20°00,033'N	155°21,316'W	740 m
ThisCave Pit	19°59,972'N	155°21,317'W	746 m
ThatCave St. 1 (post)	19°59,617'N	155°21,387'W	869 m
ThatCave St. 4	19°59,637'N	155°21,398'W	843 m
ThisCave to Pit	Distance: 111 m	Bearing: 180°N	Vertical: 6 m
ThatCave 1 to ThisCave E.	Distance: 780 m	Bearing: 9°N	Vertical: 103 m
ThatCave 4 to ThisCave E.	Distance: 748 m	Bearing: 10°N	Vertical: 97 m

LOCATION AND GEOLOGICAL SETTING

The Kuka'iau Cave is located on the north-eastern flank of Mauna Kea (Hamakua Coast), south of Kuka'iau (Fig. 1). We obtained valid GPS locations for the three entrances (Silva Multinavigator) (Table 1).

The location indicates (pers. com. Dr. Frank Truesdale, Hawaiian Volcano Observatory, USGS) that the cave is situated in the Hamakua Volcanics. These are the oldest volcanic rocks exposed on the Mauna Kea (Wolfe *et al*. 1997). They are dated to between 200-250 to 65-70 ka BP and consist mostly of alkalic and transitional basalts. In the upper part of the volcano glacial deposits are found as well.

The cave offers an excellent opportunity to study the structure of the upper Hamakua Series. It contains aa rubble and aa core layers as well as thick series of tubiferous (tube-bearing) pahoehoe, surface pahoehoe (with ropy surface structures), diamict layers (a layer of mixed rock sizes in a finer matrix of unclear genesis) and soil layers. The rocks are generally very weathered and have lost much of there original brittleness. All in all one can differentiate five units exposed in the cave. These are (from mauka to makai):

1. The Entrance Pit Series (pahoehoe, soils, aa rubble and core layer);
2. the Entrance Hall Series (a thick series of aa ruble and core layers);
3. the Vadose Stream Series (several aa ruble and core layers, paleosoil / red Marker Layer, tubiferous pahoehoe and surface pahoehoe);
4. the Sump Series (pahoehoe sealed by halloysite); and
5. the ThisCave Series (overlaying the Sump Series, consisting of a soil, an aa, and a diamict layer, and a thick aa core, which serves as the roof of ThisCave).

[2] mauka = Polynesian for "towards the mountain" i.e., upslope

Table 2. Survey statistics for the Kuka'iau Cave, separate for the ThisCave and ThatCave Sections, as of June 2002 (St. = survey station, see Fig. 2).

	Measurement	ThisCave	ThatCave
1	Total added survey lines	272.1 m	1064.7 m
2	Total cave length (survey lines)	198.6 m	942.5 m
3	Total main passage survey	186.9 m	719.0 m (St. 12-23A*)
4	Total side passages (see below)	14 m	153.0 m
5	Total cave length (3+4)	200.9	872.0m
6	Total main passage length horizontal	184.5 m	704.7 m
7	Total main passage length horizontal (measured along center of passage)	160 m	679 m (dripline to St. 23A*)
8	End-to-end distance	132.5 m	572 m (dripline to St. 23A*)
8a	End-to-end distance total (not the sum of line 8)		716 m (dripline to dripline)
9	End-to-end direction (magnetic)	354°N	2.7° N (St. 1-23A*)
9a	Total		1.4° N (dripline to dripline)
10	Sinuosity of total cave (horizontal)	-	1.17 ((160+679)/716)
11	Total altitude difference in caves	+1.3 m (St.6-23)	-87.3m (St.12.-75)
11a	Total altitude difference entrance to exit		-85.4 m
12	Total altitude difference		-104.8 m (St. 5-75)
13	Entrance canyon vertical difference		-17.42 m (St. 5-12)
14	Maximal pressure above sump		65 m = 6.5 bar
15	Average slope of main passage (St.12-60)		9.4° ($\tan^{-1}$(77/464))
16	Average slope of main passage (St.12-75)		6.9° ($\tan^{-1}$(87/719))

*23A = Station 23A in ThisCave

The total of all surveyed and unsurveyed but explored side passages in ThatCave is:

A) At Station 23, Sand Tube:	31.8 m
B) At Station 24:	5 m
C) Stations 31-35: (- 4 m St. 31-32)	42 m
D) At Station 41:	5 m
E) Station 47 to 47C	26.8 m
F) Side passage between St. 53 and 56	40 m (not surveyed, horiz. estimate)
G) Station 77-78 (*0.5)	2.40 m
Total side passages	153.0 m (line 4 in Table)

MORPHOLOGY OF KUKA'IAU CAVE

GENERAL DESCRIPTION AND SURVEY DATA

Kuka'iau Cave consists in essence of one continuous underground stream passage (Fig. 2), directed mostly S-N. It has an upper entrance (a series of waterfalls in the gully of an intermittent stream) and a lower exit (a portal at the head of another gully, pirating the water from its neighbor). Only one other entrance is present, a 5 m deep pit at the upper end of ThisCave, possibly dug by the local ranchers to gain access to the water supply of the head sump for cattle (Stearns & Macdonald 1946).

This sump separates the two cave sections. We had to wait for two years before the water fell low enough to wade through the sump section and to tie the two surveys together (07.06.02). Compared to the GPS locations the survey was in error for 3.8 m in the N-S direction (mostly the tape and inclination error) and for 15.5 m in the E-W direction (mostly the compass error). Total main passage length of ThatCave is 719 m and of ThisCave is 187 m. The total cave length adds up to 1073 m (inclusive of some unmapped side passages see Table 1, Lines 3 and 4). Not many side passages exist (14 m in ThisCave and 153 m in ThatCave). The ratio between the main passage and the side passages is 5.2. The total vertical extent, according to our survey, is 105 m (for details see Table 2). For comparison, the vertical GPS difference between St. 4 (in the creek of the upper entrance) and the exit of ThisCave is 97 m (see Table 1), to which one has to add the drop from the roof of the cave (where the GPS measurement was obtained) to the floor of the stream bed which is ca. 6 m, yielding a very good correspondence between the GPS altitude difference and our underground survey. The slope of ThatCave is 6.9°. It is, however, steeper in the upper part of the cave. The sinuosity of the cave is 1.17.

GENERAL MORPHOLOGY

The importance of the cave system rests on the fact that the morphology of the cave is almost entirely determined by erosional features. The cave has morphologically four sections (compare Fig. 2):

- the unroofed entrances waterfall series, comprised of three up to 6 m tall water falls, water fall pools, steep and partly overhanging walls and a prominent meander;

- the steep, vadose underground stream course, mostly of a rectangular cross-section, dominated by water falls, water fall ponds, polished and scalloped rock bed chutes, rounded boulders and gravel chutes, undercut water fall lips, undercut walls and polished and scalloped walls;

- the level and even upward sloping phreatic sump section, mostly of an oval cross-section, showing several right angle bends and dominated by polished and scalloped floors, walls and ceilings, gravel banks and steep upward gravel and rock chutes;

- the gently inclined vadose underground stream passage of ThisCave, of a wide rectangular cross-section, with only a few cascades, polished and scalloped rock chutes and a bed of large, rounded boulders and gravel.

Regarding side passages, two types have to be discerned: a very tight distributary side passage in ThisCave, which has been carved out at the interface between the underlying pahoehoe and the diamict, and those being most probably small lava tubes in origin (all the side passages in ThatCave).

These latter side passages partly form oxbows and cut-arounds, feeding back into the main cave and either serving as high water bypasses or forming blind appendices blocked by lava fills or collapses either mauka or makai. In these side passages, some of the features of small lava tubes are preserved, such as accretionary linings, glazing, and rarely stumps of lava stalactites and stalagmites. For example, the cave crosses a filled lava tube with recognizable linings between St. 51 and 52. At the beginning of the high water bypass at St. 32 there is glazing preserved at both sides of the entrance. In the cupola at St. 28 there may by an open tube crossing high up in the wall, out of which water seeps into the

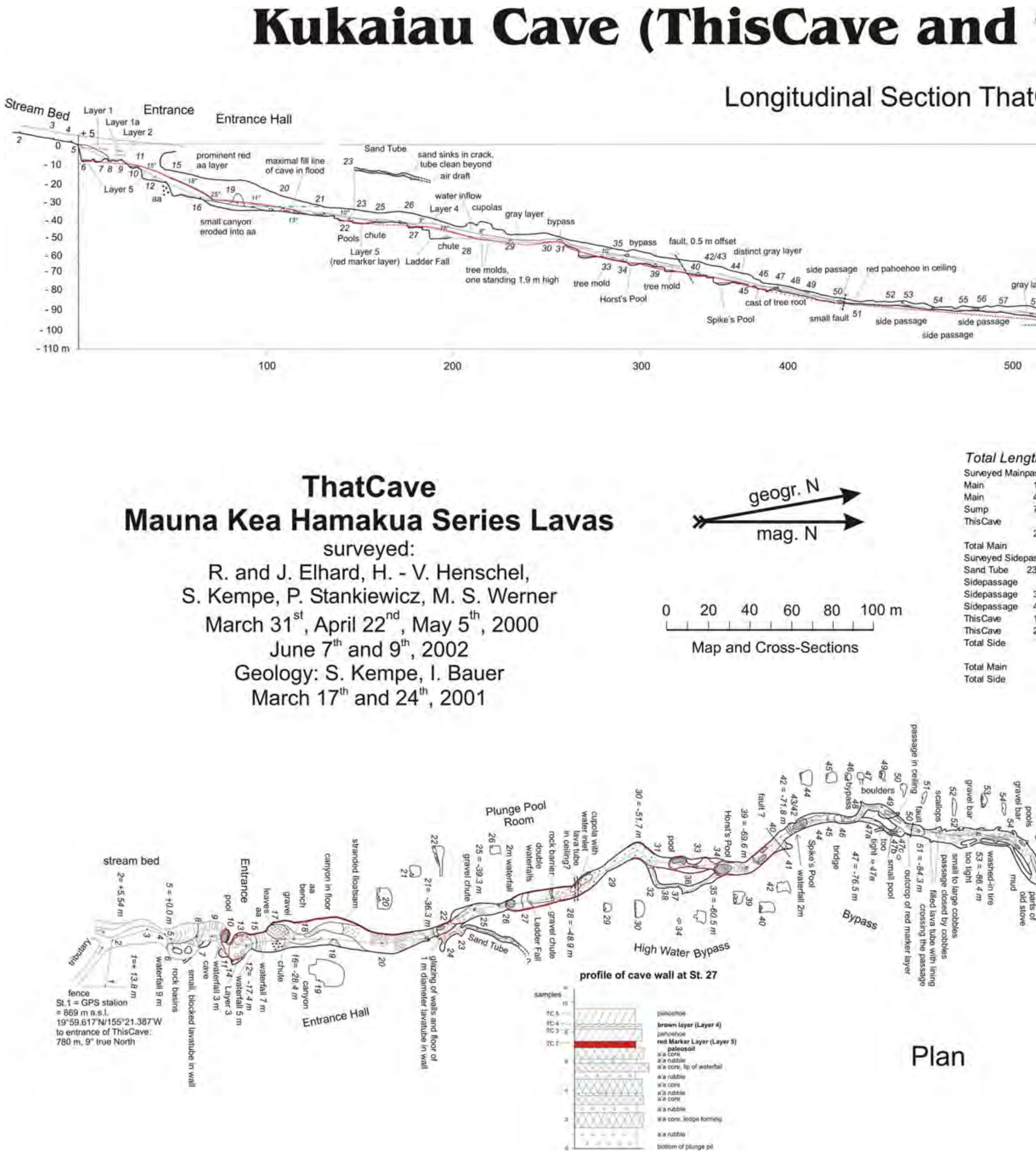
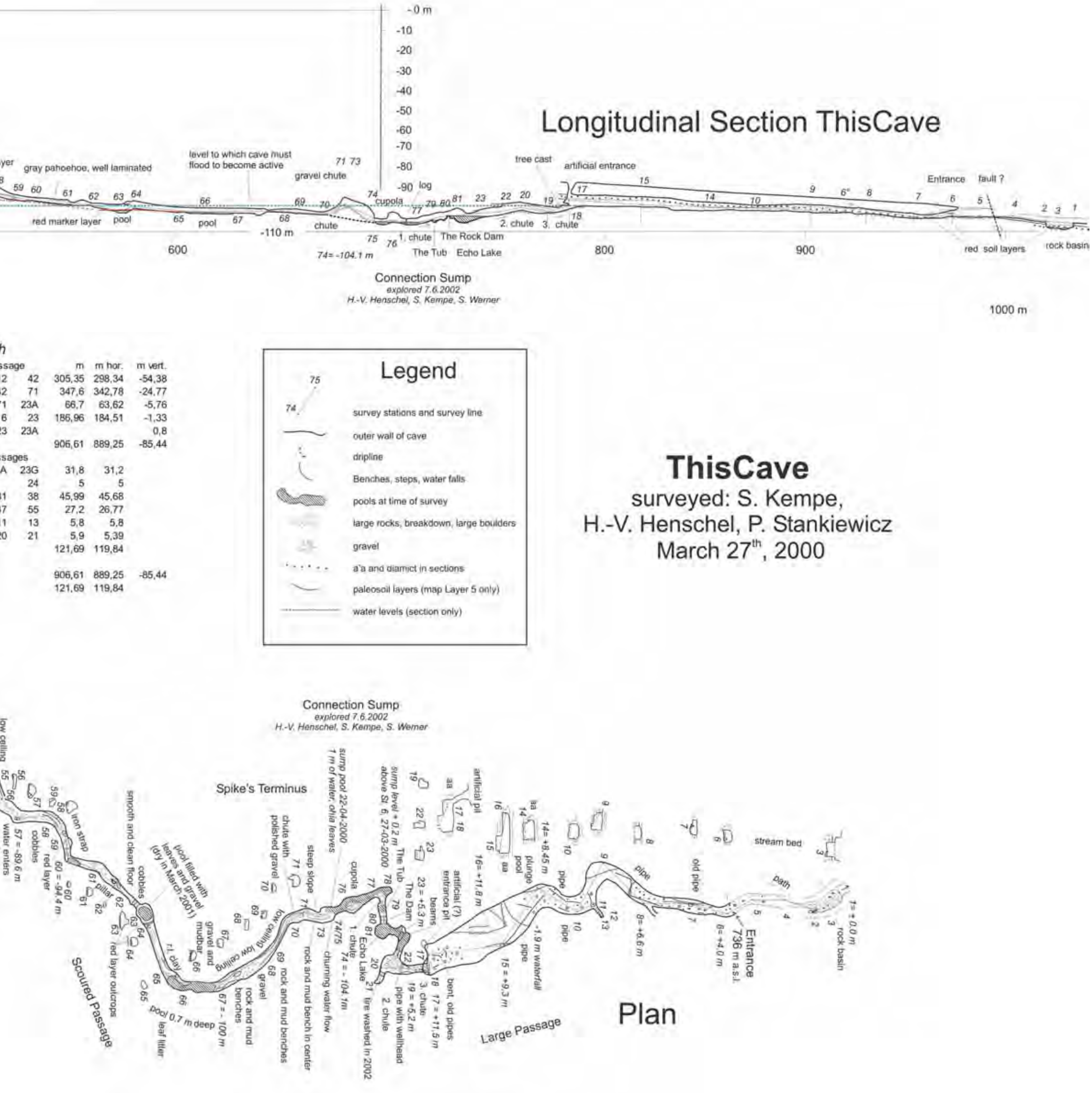


Figure 2. Map of ThatCave/ThisCave System. Note that the longitudinal Section has a slightly smaller scale than map and profiles. I

ThatCave), Mauna Kea, Hawai'i

Cave



Drawn by S. Kempe.

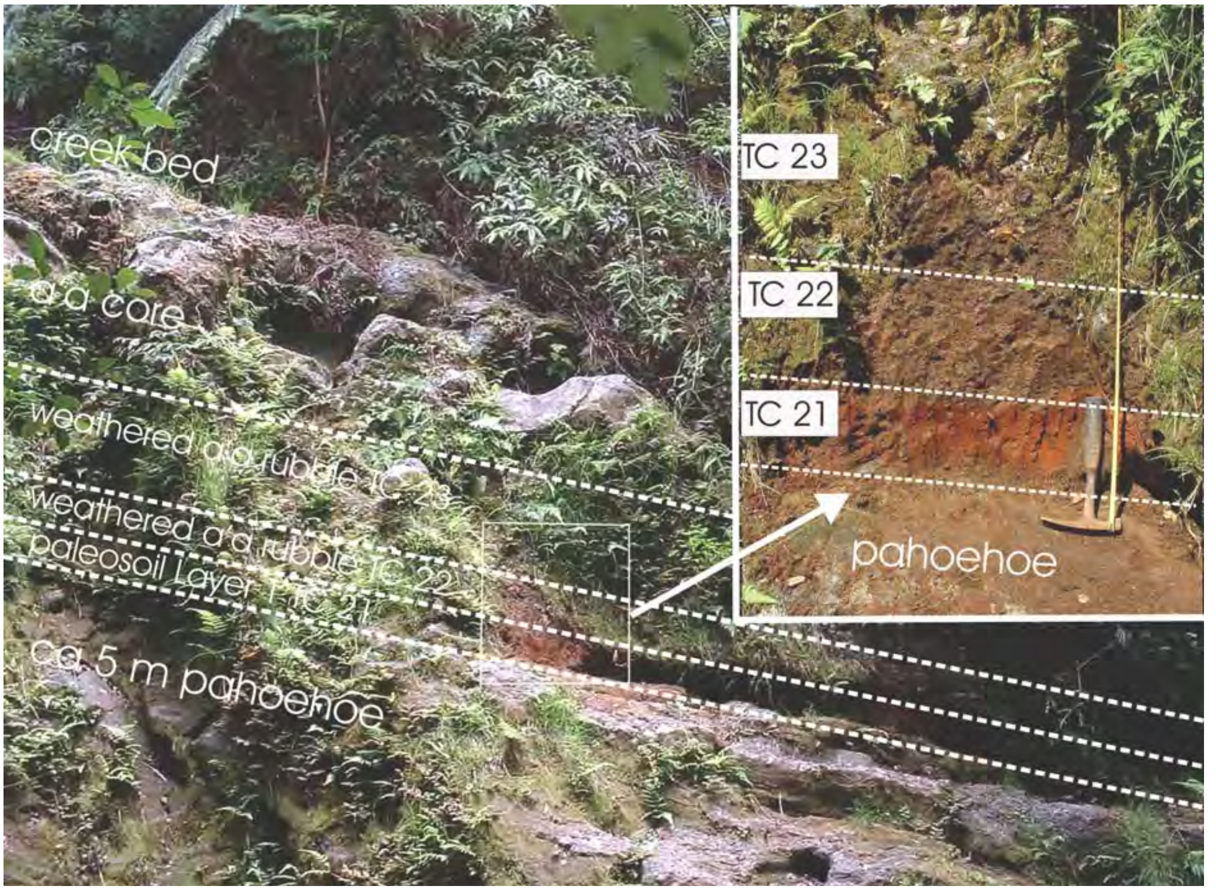


Figure 3. Geological situation at the lip of the first water fall at the mauka entrance to Kuka'iau cave. The underlying pahoehoe is superceded by the quartz-bearing soil Layer 1 and covered by an aa flow. Its rubble is highly weathered and the core forms the present creek bed (lettering refers to XRD analyses given in Table 3).

cave. Also Dr. W.R. Halliday noted during a visit in February 2002 a piece of upward facing glazing on the eastern wall near St. 22. He collected a sample which he kindly forwarded to the authors together with on-site photographs. The sample plus the pictures and a site inspection in June 2002 shows that a filled lava tube has been eroded into sideward. The piece of glazing is part of a former lava tube representing the upper surface of a bench or ledge, from the left-hand side of a tube (left-hand looking makai). This is concluded from the fact that the specimen submitted has a wedge-like rim, which could be a flow line. This wedge-like rim is directed towards the present day wall, showing - as explained above - that the present cave has cut with its right-hand (eastern) wall through the left-hand (western) wall of a former, completely filled lava tube. The former floor of this ca. 1 m high lava tube is directed into the main cave and appears to form a prominent ledge. Where this small tube leaves the main cave could not be verified. Above this site, another small lava tube, albeit obliterated by breakdown, causes a widening of the main cave. This tube (Sandy Tube) departs from the same wall a few meters makai and was followed for ca. 30 m before becoming too tight. All these examples show that part of the vadose section of the cave was eroded into a stack of tubiferous pahoehoe, featuring several smaller tubes on top of each other.

Other features, which could be mistaken for lava tube formations such as structures similar to lava falls or flow lines are present throughout the cave. Upon closer inspection, none

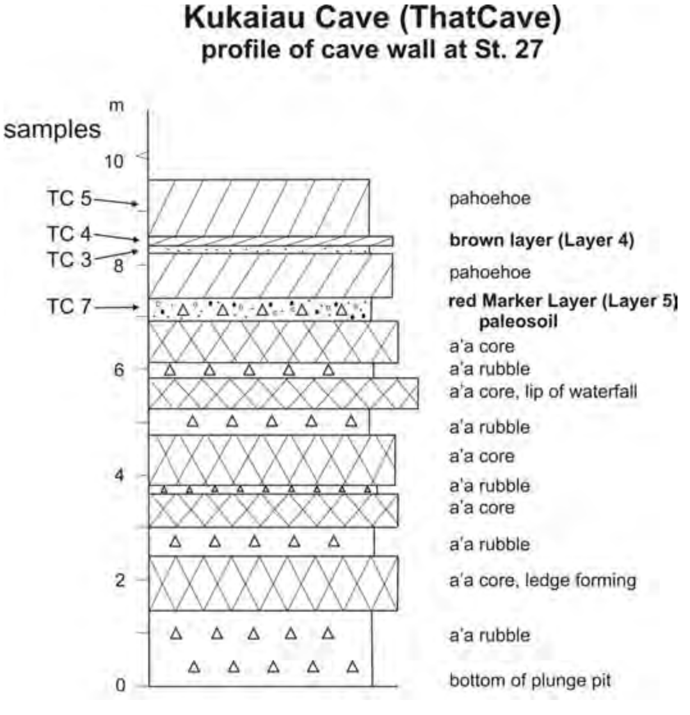
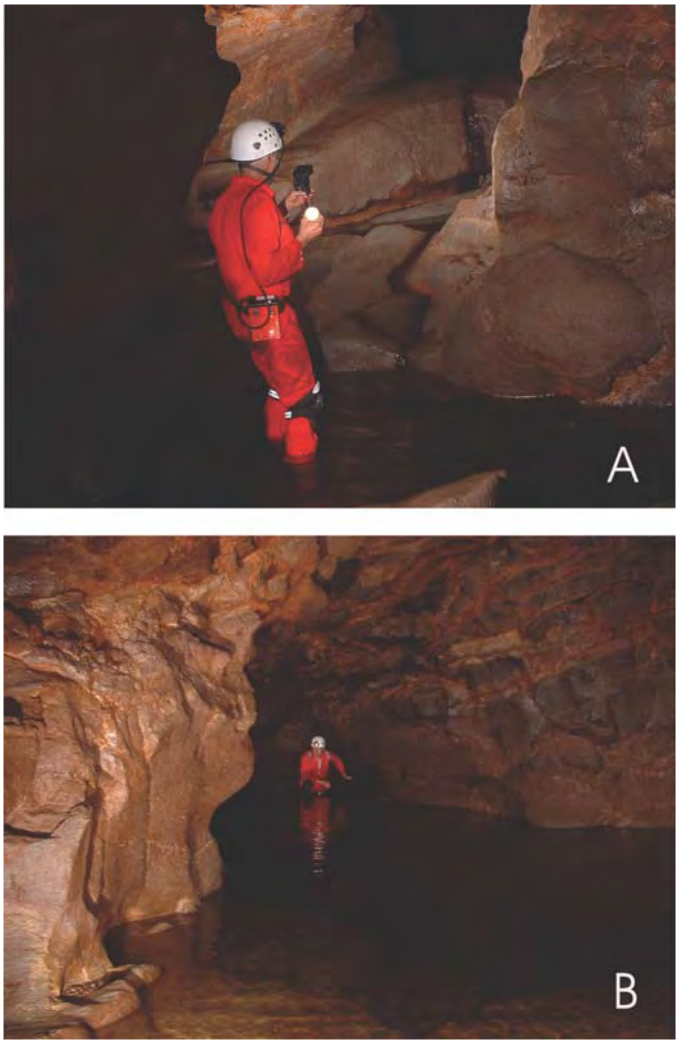


Figure 4. Stratigraphic section exposed in Kuka'iau Cave at the plunge-pool series near Station 27 (sample numbers refer to XRD analyses given in Table 3).



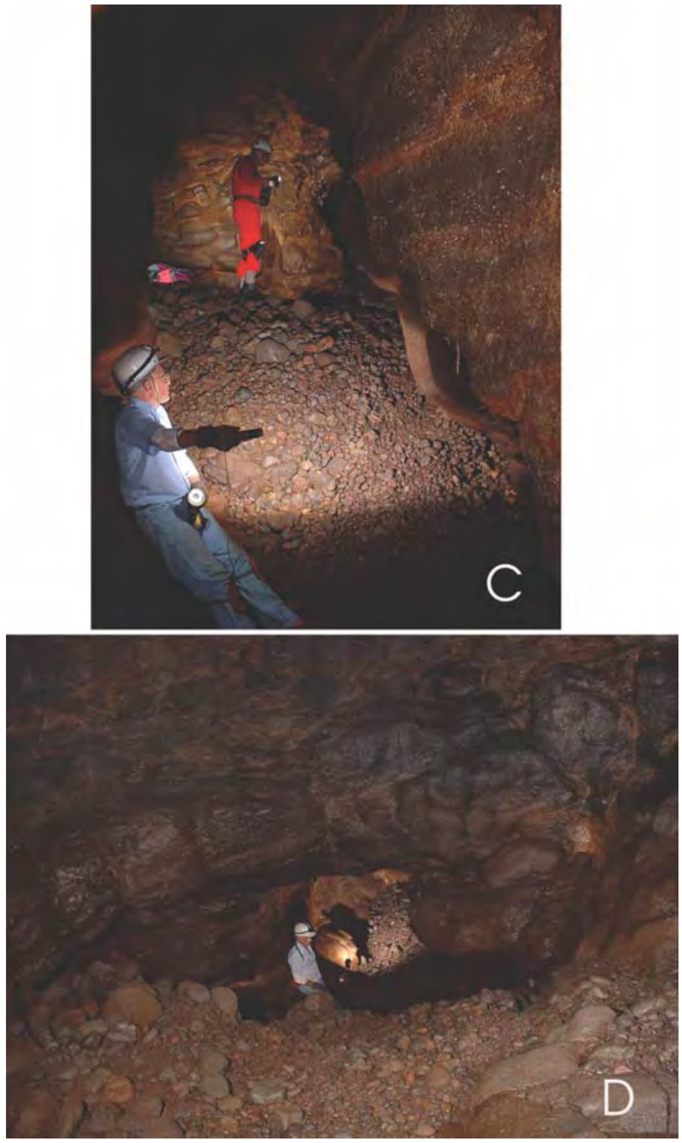


Figure 5. The connection sump: (A) view makai at the Rock Dam holding back Echo Lake. Note the notch cut by water overflowing the Rock Dam back into the deeper part of the sump (where person is standing). (B) View from the crest of the Rock Dam, across Echo Lake into the lower part of ThisCave (person at St. 23A). Even when the sump is dry, Echo Lake is kept flooded because of the halloysite filling all the interstices of the rock in this section of the cave. (C) As the water rises out of Echo Lake it has to move up this gravel chute into the Wellhead Room. Note size of gravel (up to 10 cm in diameter) being moved uphill makai by water when the cave floods. (D) View mauka, down the last gravel chute. Person stands at the makai end of the Wellhead Room. Here the water rises from the sump to overflow into the vadose stream passage in ThisCave. Note the size of the gravel and stones being moved up this steep gravel chute. Pictures by S. Kempe.

of these features are, however, lava tube-related, rather they represent exposed aa blocks or differentially eroded sheeted lava flows.

The typical morphological elements of larger lava-tube systems (reviewed, for example, in Kempe 2002; compare also Allred 1997; Greeley *et al*. 1997; Kempe 1997) are however missing. These include large tributary branches, primary tubes near the ceiling of the tube, wide halls being eroded underneath deep lava falls, secondary ceilings which separate deeply eroded canyons into two or more passages, remains of welded breakdown and others. Furthermore, the large change in the gradient of the cave is atypical for lava tubes, and upward gradients have never been documented.

On the mesoscale the absence of accretionary linings, lava falls (which would have been eroded anyway) and lava-tube floor formations such as tube-in-tube structures and others should be noted. On a smaller scale, flow features along floor, ceiling and walls (e.g., levees, accretionary ledges, lava balls, glazed surfaces, stalactites and stalagmites, runners and drip piles) or any other features caused by molten lava and associated with lava tube formation are not seen.

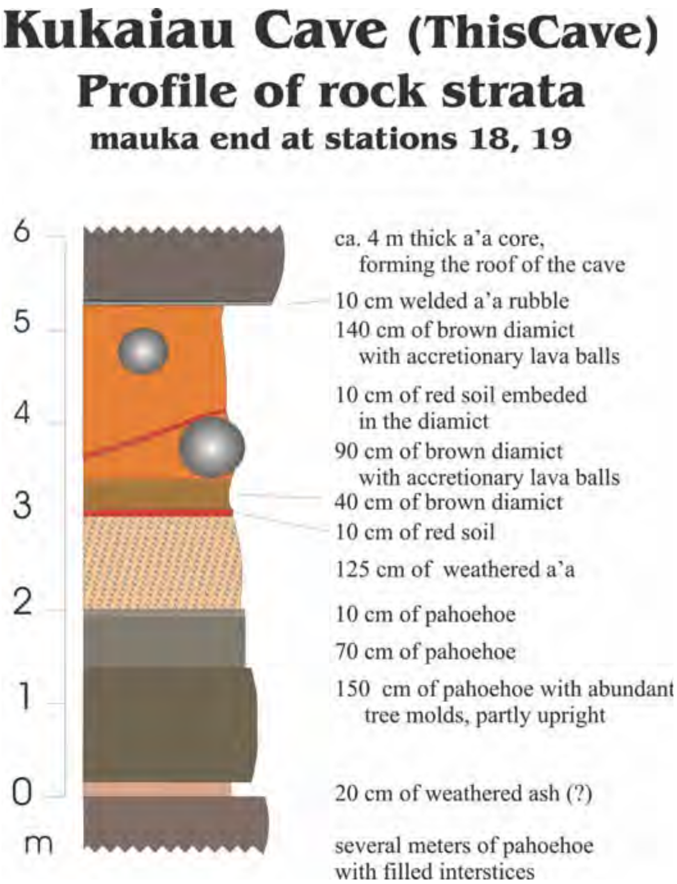


Figure 6. Geological profile of the ThisCave Series at the head of the Large Passage in ThisCave.

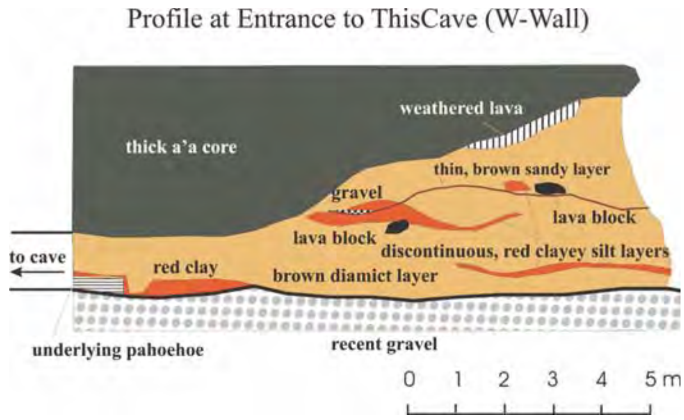
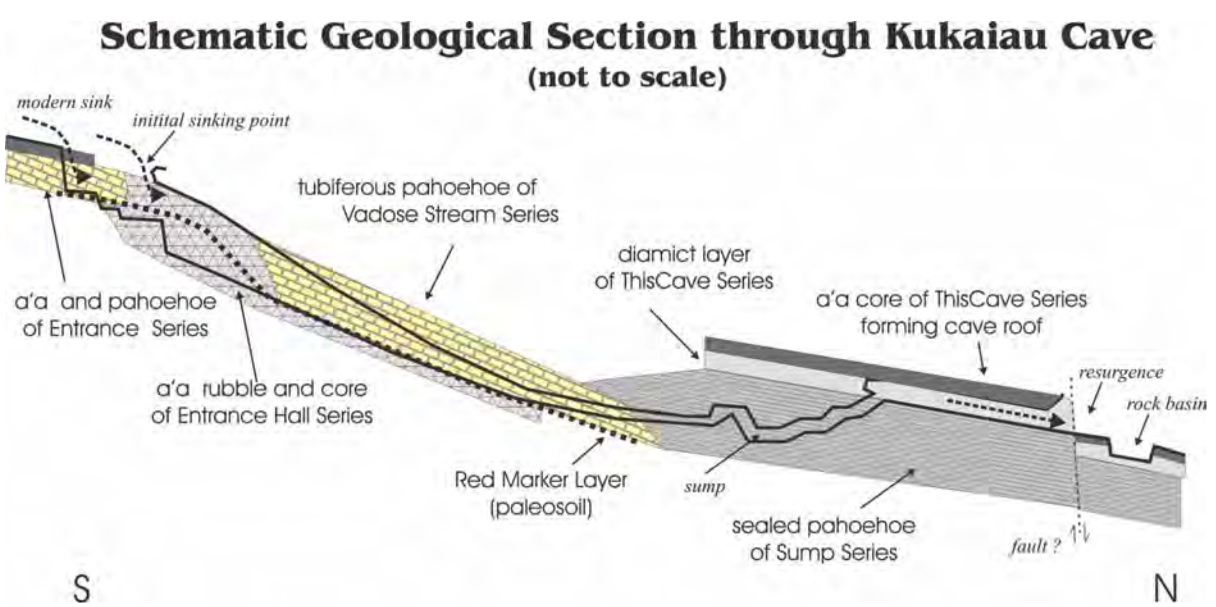


Figure 7. Geological profile of the ThisCave Series at eastern wall of the resurgence.

The morphological elements of an erosional origin are, on the other hand, ubiquitous. The cave floor is either composed of solid rock sculptured by stream pots, chutes or scallops, or it consists of beds of rounded boulders, cobbles, or gravel. Garbage, plant residue, and parts of trees are found throughout the cave, testifying to its function as a recent water course as well. Farther down, where the passage narrows, one finds Styrofoam debris wedged into cracks in the ceiling by high water. The solid-rock sections include waterfalls with water fall lips, undercut waterfall walls and large plunge pools. The gravel sections include gravel chutes, leading upward and out of plunge pools, boulder jams, behind which gravel is impounded, and older gravel banks are consolidated by mud (in the lower part of the cave).

The walls of the cave are either stream worn (in their lower reaches) or show bare, joint-controlled faces making visible the bedrock through which the cave has cut. The ceiling is shaped either by breakdown, exposing horizontal and planar

Figure 8. Schematic longitudinal section through Kuka'iau Cave with the most important geological units.



lava partings such as aa core – aa rubble interfaces, pahoehoe surface roping or pahoehoe sheet separations. In a few constrictions of the lower reaches of the cave and in the sump section, the ceiling also shows marks of erosive action.

The cross-sections of the cave vary from wide canyons, to narrow canyons, from rectangular habitus to a more oval shape. In the main passage, they appear more to be determined by breakdown enlargement rather than by down-cutting.

A WALK THROUGH THE CAVE

The episodic surface stream, which feeds the cave, runs on top of an aa core (in Hawaii called "blue rock") that shows vertical, wide-spaced, irregular columnar contraction joints. At Station 5 (St. 5) of our survey this layer is breached and the stream plunges down into a pit 6 m deep with two plunge pools at the bottom. This and the two successive water falls, which lead down to the cave entrance, constitute the impressive entrance series. All water falls could be bypassed or free climbed. On the walls various steeply sloping layers of loose brownish or reddish paleosoils are exposed (Layers 1, 1a, 2 and 5 marked in the Longitudinal Section, Fig. 2) (Fig. 3). Vegetation and moss make it difficult to follow these layers entirely. Layer 5 can be traced from the bottom of the two plunge pools of the first water fall to the foot of the second water fall and along both sides of the widening below the last of the three water falls, where it dips makai with 15°. Then one stands in the gaping, 6.5 m high and 3 m wide, mouth of the cave. Inside is another waterfall to be climbed down. It exposes a thick layer of aa rubble, only partly consolidated by fine-grained matrix and interspersed core layers making climbing down the 6 m step easy and dangerous at the same time since the abundant hand- and footholds can readily break off. To the right, solid rock occurs and here the water normally plunges down, having carved chutes. To the left, aa rubble and thin, ledge-forming and steeply inclined (at first sloping at 18° then at 25°) aa core layers compose the wall. The aa rubble must belong to at least two different flows since the redbrown paleosoil Layer 5 (termed Marker Layer) can be followed from the entrance high up in the wall. The lower aa rubble could represent a lateral levee of a large aa flow, the core of which now forms the right-hand wall. The core layer is vertically jointed (either tectonically or through contraction) and can easily be mistaken as the remains of a thick lining.

The Entrance Hall is the largest room in the cave, 10 to 12 m high and 8 to 11 m wide. The plunge pit is filled with leaves and tree trunks. Some large blocks from the aa bench litter the floor. A chute with large, rounded blocks leads to a steeply dipping solid platform (one of the blue rock layers) into which a small canyon is cut. It is partly covered by large breakdown blocks. The passage declines less steeply than the layering of the rocks and the prominent red Marker Layer exposed on the left wall meets the floor at about 70 m below the entrance (Layer 5) for the first time.

This layer apparently played an important role for the genesis of the cave, because it will be seen again and again up to St. 65 either along the walls of the cave or at the base of plunge pools. The solid lava sheet above it very often forms the floor of the cave, sculptured by the running water. Above this solid-lava layer is found another important layer, Layer 4. It is composed of bedded but very weathered brown or gray material. It can also be traced down to at least St. 59 and appears to be the parting from which this section of the cave originated. Consequently, from St. 21 onward, the cave follows the local inclination of the strata which is actually highly variable as indicated in the Longitudinal Section in Fig. 2.

Between St. 19 and 20, below the left wall, flotsam, composed of plastic bottles, plastic parts, sandals, wood, and the like is concentrated. Water apparently ponds up to this level when the cave floods. This conclusion is substantiated by the observation that the walls below this point appear clean-washed while the walls of the upper Entrance Hall are encrusted with dust.

Below St. 21, the cave widens as several small lava tubes are intersected as described above. The upper one leads mauka to a collapsed room, but can be penetrated for more than 30 m makai. At first it is floored by muddy sand, which shows that at high water the tube is also inundated. There are no signs of erosion though. Towards the end, the sand disappears, presumably washed into a crack in the floor and the tube continues as a pristine small lava conduit. There is an air draft, indicating that the tube does not end blindly, it is however too small to be easily followed further.

At St. 26, the Plunge Pool Room opens up, offering the most detailed view into the strata below the red Marker Layer and an almost ten meter-high section of lava sheets and intermittent aa layers can be studied (Fig. 4 and inset in Map of Fig. 2). Further makai, the floor levels off as the red Marker Layer descends down to the floor. Above, breakdown cupolas open up to a height of 8 m. From one of them water seeps down, possibly from an open lava tube intercepted at the ceiling by breakdown.

Behind a prominent bend in the cave at St. 31, the first high-water bypass opens up, a small lava tube developed at the level of Layer 4. Its floor also forms the floor of the main tube i.e. the lava sheet above the red Marker Layer. It is the base of the stack of tubiferous pahoehoe. This sheet is relatively dense and hard, showing that it was quickly cooled. Above it several other sheets occur, on first inspection more vesicular and possibly less quickly cooled. The next one up is the one in which the small lava tube is situated. This layer could therefore have been inserted between the base sheet and the next one up, thereby forming a hot core in the inflating lava flow (for the concept of how primary lava conduits form at the tip of tube-fed pahoehoe flows compare Kauahikaua *et al*. 1998). The hot core is the site where the proto-tubes form, often in parallel to each other. The branching-off of the side passage suggests that there may have been a small tube also within the main passage mauka. There are remains of glazing on the right wall of the main passage immediately below the branching, therefore a small tube may also have continued down the main passage.

A little further makai, the base sheet of the tubiferous flow has been cut through by the erosion of the stream, exposing the red Marker Layer, lining the sides of the plunge pool below. A small canyon, formed by the protruding ledges of the base sheet of the pahoehoe flow, forms the lower part of the main passage. Here molds of trees, encased by the base sheet are exposed. They illustrate that the Marker Layer is in fact a paleosoil, which carried a forest.

At the lower intersection with the bypass, a large pool is situated (Horst's Pool, named in honor of Horst-Volker Henschel who took a plunge in it when one of the handholds of the lateral traverse came loose).

Mauka of St. 40, a fault is crossed, down-faulted makai. Then Spike's Pool is encountered, below a 2 m high waterfall. It is the best example of a deep, wall-to-wall pool. Seemingly not climbable, Spike Werner found a way around it, needing to follow one of the lower aa layers beneath the lip of the water fall along the right wall. Below St. 47 (at a depth of 76.5 m below the first waterfall in the entrance), several more lava tube-bypasses occur on the right-hand side and the cave becomes somewhat smaller and less steep. At St. 50, before a small fault at which the mauka side is down-faulted, the red layer reappears once more. Below St. 51, a filled lava tube is cut through, as already mentioned. In this section the exposed pahoehoe is rather thin-sheeted and bears rope marks typical of pahoehoe solidified at the surface. Makai more small tubes enter and leave the main passage at various levels. The cave now is considerably lower than before and has more the appearance of a phreatic tube than that of a canyon. The floor consists of gravel.

The clean-washed floor reappears before St. 62, where the cave narrows once more. This is the section which best resembles the appearance of a lava tube. Since we have been this low in the cave only twice (due to the high risk of being caught by a sudden storm discharge) there is not enough information to assure that this section of the cave is also structurally a lava tube. Below this constriction (2*1.5 m) the cave opens up once more into a larger plunge pool room. Again the red Marker Layer is seen along the perimeter of the pool below the waterfall lip. In spite of the otherwise wetter conditions (compared to the spring of 2000), this pool was empty in March 2001 (except for a thick deposit of decaying leaves), suggesting that the water can escape into a deeper groundwater body by means of the various aa layers underlying the tubiferous pahoehoe. One has to climb upward and out of the pool at the makai end, unlike the end of the previous pools which terminate mostly in gravel chutes. This raises the question where the material eroded from the pool was transported. The passage beyond is horizontal and floored with sandy mud. In April 2000, it was dry, but in March 2001 it was filled with water from a previous flood in the cave and sumped at around St. 68, so that the terminal sump could not be reached.

From here on, no remains of small tubes have been noticed, the cave moves through a tightly sealed stack of pahoehoe sheets. The "terminal sump" was reached first by M.S. Werner and R. Elhard in May 2000. On June 7th 2002 we entered the makai entrance when exploring the sump section and investigated it geologically on a trip through the entire cave on June 23rd. The passage leading toward it has the most unusual form: First it rises up by 5 m and then becomes very low because of gravel being transported up a chute; it then plunges down by 7 m to a terminal pond filled with murky brown water (in May 2000). Solid mud banks with cobbles line the passage, and these have more recently been cut and partially removed. Overall, the hall above the sump gives an impression of how the water churns when at full flow.

In summer 2002 the water level fell about a meter below its stand in May 2000, making the sump accessible. Still one has to wade and in Echo Lake one is up to the belly in the water. From the terminal sump the passage is level, much deeper on the left than on the right side. It ends blindly at St. 78. A gravel bank leads into the continuing passage which makes a sharp right turn. Here the upward rising rock floor is encountered again. A large stream pot, "The Tub", interrupts the floor. Beyond, a solid Rock Dam bars the passage, damming "Echo Lake" from flowing back mauka into the sump. This is the most unusual feature in the cave, difficult to envisage even when described. There is even a small channel incised into the dam, through which the water of Echo Lake trickles backward into the lower-lying but dry sump. The crest of the Rock Dam is horizontal, in level with Echo Lake. The lake is about 8 m across and over 2 m deep at the far side and a sizeable cupola helps to reflect the sound giving the lake its name. The Rock Dam prevents the water level from falling lower, the level is therefore no indicator if the sump mauka of the lake is passable or not. We only understood that the sump opened up because of a pulsating air flow.

The passage makes another sharp turn to the left and one emerges from the lake into the lower part of ThisCave where the passage turns right again (Fig. 5). A few logs rest on the lake floor. At S. 23A the two surveys were tied together. The floor of the passage rises out of the water and meets a steep gravel chute leading upward into the Well Head Room. On the far side there is a blind appendix again, carved out by the water jet churning around. Here we found in June 2002 a truck tire resting on our survey St. 21. It must have passed the cave during a flood in the winter 2001/2002. The passage makes one last left-hand turn and another gravel chute leads steeply upward into the vadose passage of ThisCave, breaking through the top of the pahoehoe Sump Unit. This unit is characterized by the absence of any open space in the rock package: All bedding planes, all contraction cracks and the vesicles of the rock are filled with a white, waxy material, thereby effectively sealing the rock. Due to this compact wall surface, scalloped on ceiling, walls and floors, the passages reverberate with sound, similar to the acoustic perception of limestone caves. None of the wall sections inspected revealed any lava tube

Table 3. A) Semi-quantitative results of X-ray-diffraction analyses of rock samples (analyses courtesy of R. Apfelbach, Darmstadt). Percent concentrations were estimated according to the reflex intensity as compared to known standards. Percentages refer to X-ray active minerals only where there is a large amorphous fraction. In the samples with small amorphous fractions the amorphous fraction was estimated as well. As an example the results of samples TC-21 to TC 23 are given in both notations, simple numbers denote overall composition, numbers in brackets denote composition of the crystalline fraction only. Sample ThatCave 3 was analyzed for various grain size fractions.

Sample	Color of ground sample	Plagioclase	Augite	Olivine	Hematite	Others	Rest
Samples collected Aug. 2000 between St. 25 and 27 by M.S. Werner and W.R. Halliday							
ThatCave 1, Gray, vesicular (2-3 mm) lava, white pore fillings	Light gray	25%	24%	42%			9% amorphous
ThatCave 2a. Brown, vesicular (ca. 1mm) lava	Dark brown	7%	58%	-	4%	5% meta-halloysite	26% amorphous
ThatCave 2b brown mud on surface of 2a	Brown	-	43%		5 %		50% amorphous
ThatCave 3a (3=red Marker Layer) coarse component	Reddish brown	-	48%		14%		28% amorphous
ThatCave 3b Green shards of augite clasts	Light greenish gray	-	96%				
That Cave 3c fine-grained components	Reddish brown lighter than 3a)	14%	52%	-	12%	5% meta-halloysite	17% amorphous
That Cave 3c fine-grained components (< 2µ)	Reddish brown	13% (forsterite)	53%	6%	17%	11% meta-halloysite	Some amorphous
March 2001							
TC 1 surface between This- and ThatCave, yellowish weathered rock	Light gray	64%	23%	10%	-	3% Magnetite	
TC3, Profile St. 26-27 Layer 4! (10cm crumbly rock)	Light brown	14 %	36%	47%	3%		
TC4, ProfileSt.26-27 above Layer 4 (13 cm harder layer)	Light gray, brownish	21%	36%	40%	3%		
TC5, Profile St. 26-27 above Layer 4(1 m crumbly rock)	Light gray	26%	45%	27%	2%		Large X-ray amorphous component
TC 6, Layer 4 St. 31 begin of bypass	Light gray-brownish	22%	53%	14%	5%	Halloysite: 6%	Large X-ray amorphous component
TC 7, Red Layer, Layer 5, makai St. 31	Light gray brownish	16%	28%	19%	29%	8% undeterminable	Large X-ray amorphous component
TC 9, Lava from wall, above St. 42, large white spec in pores	Brownish	23%	48%	13%	11%	5% undeterminable	Large X-ray amorphous component
TC 10, layer 1 at St. 7	Light brown red	12%	48%	13%	45%		Large X-ray amorphous component
TC 11, layer 1a at St. 9	Brown red	-	-	-	37 %	Quartz! 19% Donathite* 44%	Very large X-ray amorphous component
TC 12. Layer 2, at St. 9	Dark gray brown	-	15%	41%	22%	Illite 18% 4% undterminable	Very large X-ray amorphous component
TC 14, Layer 5 between St. 20 and 21	Brown-red	15%	45%	13%	22%	5% undeterminable	Very large X-ray amorphous component
TC 15, Layer 5, red Marker Layer at St. 23	Intensive brown-red	0%	39%	16%	39%	6% undeterminable	Large X-ray amorphous component
TC 16, solid lava above red Marker Layer at St. 22	Light gray	32%	39%	22%	0%	7% undeterminable	Medium X-ray amorphous component
June 2002							
TC 20 ThisCave, white waxy material sealing voids in Sump Pahoehoe Unit	Light grey	-	-	-	-	100% Halloysite	Large amorphous component
TC 21, Layer 1a at entrance to ThatCave, St. 5	Reddish brown	5% (15%)	-	-	5% (15%)	Quartz 11 % (33%) Halloysite 5% (15%) Donathite 7% (21%)	67% amorphous
TC 22, weathered aa rubble above TC 21	Light brown	4%	-	-		Halloysite 18% (72%)	75% amorphous
TC 23, weathered aa rubble above TC 22	Dark brown	7%	-	-	-	Halloysite18%(67%) Magnetite 2% (7%)	73% amorphous

Note that samples from 2000 were dried at < 50°C transforming the halloysite into meta-halloysite.

*Donathite (Fe,Mg)(Cr,Fe)$_2$O$_4$)

Table 3. B) Results of carbon, nitrogen, sulfur (C, N, S) total elemental analyses of rock samples from ThatCave, results are given as weight percent.

Sample	C(total) %	C(inorg.) %	C(org.) %	Total org. matter %	N %	C/N	S %
ThatCave 2b brown mud on surface of 2a	3.67	0.33	3.34	8.35	0.43	7.8	1.19
That Cave 3c fine-grained components	0.04	0.00	0.04	0.1	0.11	0.36	0.76

Table 3. C) Results of porosity analysis of rock sample from ThatCave.

ThatCave 2a. Brown,	weight	Envelope volume	Sample volume	Density	porosity
vesicular (ca. 1 mm) lava	43.804 g	27.54 cm^3	13.78 cm^3	3.178 g/cm^3	49.9%

structure. The upward course of the passage, the fact that the ceiling of the passage jumps upward from sheet parting to sheet parting and the seemingly joint-controlled sharp turns of the passage exclude any possibility that a precursor lava tube has been enlarged by erosion in this section of the cave

Beyond the third and last chute the water boils upward into the rectangular vadose passage of ThisCave, which is up to 14 m wide. Light filters down through the pit in the corner to the left. From here on, the passage drops at about 6° to the stream resurgence less than 200 m away. On its way it winds through an S-shaped bend. The floor of the cave is formed by the sealed pahoehoe of the Sump Unit (Fig. 6). The last sheet carries many tree molds (best exposed at some of the cataracts), suggesting that there was a longer hiatus between the deposition of the bulk of the Sump Unit and the last flow covering it. Below the layer with the tree trunk a thin bed of soft material is found, possibly also a paleosoil. At places the water has eroded several meters into the top of the Sump Unit, forming cascades and showing scalloping and stream pots. The wide and flat roof is formed by the lower interface of a thick aa core layer. Only in a few places have blocks fallen out of the ceiling. They are the source of the large rounded blocks in the streambed. The walls are composed of a series of unconsolidated rocks (Fig. 6). There are two red paleosoil layers, one immediately on top of the pahoehoe Sump Series, an aa rubble layer and a thicker diamict layer on top. The diamict layer continues to the mouth of the cave. There it increases in thickness causing the blue rock ceiling to rise on the last few meters of the passage. On the left wall the diamict shows an interesting internal structure with discontinuous red soil layers incorporated in it (Fig. 7). It is this diamict layer which has been removed to create the cave. Certainly no precursor lava tube could have existed in this rock series. This section of the cave is entirely erosional in origin.

Outside of the cave’s exit a cobble bank causes water to pond inside the entrance, forming a temporary lake. This temporary lake may have caused the ranchers to dig the artificial pit in order to gain access to the water in the sump at all times. From the mouth of the cave the stream flows first over gravel but then the blue rock of the cave roof is encountered again, possibly down-faulted by a small fault crossing the creek. A few meters makai the creek plunges into an impressive rock basin. There the diamict layer is exposed once more, featuring also a red soil layer.

PETROGRAPHIC DATA

In spite of the morphological clues speaking of an erosive origin for Kuka‘iau Cave, it nevertheless is challenging to explain the origin of an erosive cave of such dimensions in lava layers which at least in part lack the advantage of a precursor lava tube. In order to advance our understanding of the cave genesis we therefore took rock samples for mineralogical, petrographic and geochemical analysis in August 2000 (W.R. Halliday and M.S. Werner, designated “ThatCave 1 to 3”), March 2001 (S. Kempe and I. Bauer, labeled “TC 1 to 16”) and in June 2002 (labeled “TC 20-23”). A subset of these samples was ground and X-ray-diffraction (XRD) analyses were conducted (Philips PW 1949 powder diffractometer, data evaluation according to the International Centre for Powder Diffraction Data). Additionally some thin sections were made and elemental carbon, nitrogen, and sulfur concentrations (CNS Analyzer Vario El, Elementar) were determined. Porosity was measured on one sample as well. All results are listed in Table 3.

The analytical results show four general types of composition: (i) samples with a general basaltic composition, (ii) samples with a high hematite content, (iii) samples with a composition unusual for Hawai‘i, and (iv) samples with a high halloysite content.

The first group comprises the samples (ThatCave and TC1, 3, 4, 5, 6, 9, 16). They have high augite, olivine and plagioclase contents; hematite may be present in small quantities. These samples are gray or gray with a brownish hue in color and represent the solid lava samples composed of tholeiitic and alkalic basalt representing the Hamakua Volcanic Series of the Mauna Kea volcanic edifice. In thin section, the olivine is partly altered to iddingsite ($MgFe_2Si_3O_{10}*4H_2O$) or hematite (Fe_2O_3) which form along the cleavages of the olivine crystals.

The samples (ThatCave 3 and TC 7, 10, 14, 15) from the bright red brown, unconsolidated material of Layers 1 and 5 form the second group. They are also composed of augite, olivine, and plagioclase but have significantly higher hematite contents. These samples most probably represent paleosoils developed on weathered volcanics.

Samples TC 11, TC 12, and TC 21 belong to a third group. They represent unconsolidated, fine-grained material with a composition atypical of Hawaiian lava, i.e., with significant concentrations of quartz, donathite, and illite. Layer 1a, which contains quartz, donathite and hematite, is a soil layer containing continental (Asian) dust (the only known source of quartz for Hawaii). Under the ESEM (environmental scanning electron microscope) quartz particles were difficult to find since they are coated with hematite and amorphous Al-silicates. The few grains identified by EDX (energy dispersive analysis of X-rays) had a short, rounded, columnar form, 1-2 µ long. This habit would support the interpretation of continental dust as a source for the quartz. Layer 2 contains illite in addition to augite, olivine, and hematite. It again could be a paleosoil in which illite could be either a dust-born addition or a weathered equivalent of the plagioclase.

Sample TC 6 (Layer 4), 20, 22 and 23 – the fourth group of samples–have high contents of halloysite ($Al_2Si_2O_5(OH)_4*4H_2O$). In samples from March 2000 (Samples That Cave 2a, 3c) meta-halloysite ($Al_2Si_2O_5(OH)_4$) was detected. It most probably originated from halloysite because the samples taken in 2000 were dried at higher temperatures. Halloysite is the only X-ray detectable component in the white, waxy material filling the voids in the Sump Series pahoehoe (Sample TC 20). Halloysite was also detected in several of the samples from Pa‘auhau Civil Defense Cave (see Kempe *et al*. 2003). Halloysite is a clay mineral which forms during weathering and is common in Hawaiian soils and weathered basaltic rocks (so called saprolite) (e.g., Patterson 1971; Vitousek *et al*. 1997).

To check if all of the white, waxy material in the vesicles of the lava is halloysite, we scraped some of it from the pores of rock sample TC 9 and X-rayed it. It proved to be amorphous. We then looked at this waxy material under the ESEM and analyzed its composition by EDX. It contains a variable amount of Al and Si; thus it could either be the amorphous forerunner of halloysite or represent the amorphous Al/Si phase called allophane ($(Al_2O_3)(SiO_2)_{1.3}*2.5H_2O$).

ESEM examination of a subsample from Layer 1a (the one with the quartz, TC 11 and TC 21) and Layer 2 (with illite, TC 12) showed that layered, amorphous Al-Si phases are ubiquitous in the paleosoils. They, together with the very fine-grained hematite mantle all the surfaces of other minerals almost completely. It is difficult to identify the other phases in the sample by EDX, and only the larger grains of weathered augite seem to be relatively clean. This, however, could be due to the fact that they easily break in sample preparation, producing fresh cleavage faces.

C-N-S data (Table 3b) show that the mud on the wall of the cave (sample ThatCave 2b) is eroded recent soil with a high organic C content (3.3 %) and a high C/N ratio (7.8 by weight). In contrast, the red Marker Layer (sample TC 3c) has very low C and N contents. This is either due to its older age or to the fact that the soil was baked by the transgressing pahoehoe sheets which oxidized all of the former soil matter.

CONCLUSIONS FROM THE MORPHOLOGICAL AND GEOLOGICAL OBSERVATIONS

The XRD data illustrate that the weathering of feldspars, olivine, and augite has created amorphous or poorly crystallized clays, i.e., halloysite and allophane. These accumulate in the voids of the rock, causing the rock layers to become less permeable. This in turn gives rise to a local perched water table. The more the sinking water is retarded, the more weathering will occur facilitating the final closing of vesicles and other interstices.

The geological observations in the cave allow us to identify two major impermeable layers: The paleosoil Layer 5, i.e. the red Marker Layer inclusive of the pahoehoe sheets immediately above it and the Sump Series pahoehoe. The

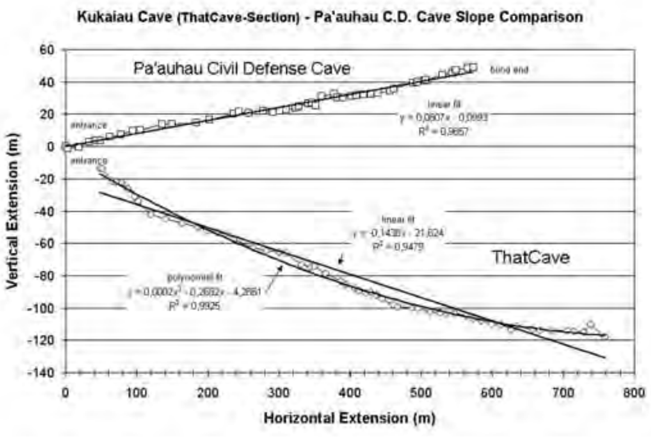


Figure 9. Comparison of the depth/length profile of ThatCave (erosional) and Pa‘auhau Civil Defense (lava tube).

paleosoil could have served as an initial water impediment to retard further vertical drainage and cause lateral groundwater flow in the small lava tubes above the base sheet and through the partings between these lava sheets. This alone however is not enough to form the cave.

A large hydrostatic pressure must be exerted as well. This was possible because Layer 5 runs through a highly porous aa rubble series near the entrance which was intercepted by a gully. This water could rapidly infiltrate through the aa, fill the voids in the stack of the tubiferous pahoehoe below and exert a pressure of almost 10 bar on the distal part of the groundwater body. This could have been enough pressure to force the water along orthogonal joints upward through the otherwise impermeable pahoehoe Sump Series into the overlying diamict. The diamict has a high porosity (no exact data yet available because the rock is very crumbly) and could conduct the water along its layer to a new exit, the present resurgence. In this way an erosive cave could have formed by a set of fortuitous geological circumstances at this site (Fig. 8). In this model it is not necessary to have a tubiferous pahoehoe as an initial water conductor. aa rubble or any other rock types of a high initial porosity would serve just as well. Therefore the cave is not just an eroded lava tube where a stream invaded at the mauka end and flowed out at the makai end (for an example of this type see the Pa‘auhau Civil Defense Cave, Kempe *et al*. 2003), but it is the product of a complex interaction between a perched water table and the structural components of the rock strata.

CONCLUSIONS DERIVED FROM CHANNEL MORPHOLOGY AND SOIL AGE FOR THE AGE OF THE SYSTEM

The morphology of bedrock channels is determined by substrate and hydraulics, (e.g., Wohl & Merritt 2001). According to Wohl (1998) the reach-scale morphology (i.e., the morphology of a section of the channel several times longer than its width) of Kuka‘iau Cave can be classified as a single flow path, variable bed gradient channel, with a dominant step-pool morphology (“downstream bed undulations in form of vertical steps with pools between them”). The step-pool morphology is aided by the heterogeneity of the bedrock itself: lava layers are separated by layers of loose material which can be ash layers, paleosoil layers, aa rubble, or simply contact zones between pahoehoe sheets. Also, vertical contraction cracks and possibly faults play a role in bedrock strength in Kuka‘iau Cave. Overall the bedrock is inhomogeneous, therefore aiding in the formation of a step-pool morphology.

Overall, the depth-length relation of the cave is best described by a polynomial fit (given in Fig. 9), consistent with a water-related origin. Groundwater tends to sink quickly toward the water table before flowing horizontally. In contrast, lava tubes follow the slope of the mountain and tend (on the hundred meter scale) to have a linear depth-length relation. This is best shown by the comparison between the profiles of the upper part of Kuka‘iau Cave (i.e. ThatCave) and Pa‘auhau Civil Defense Cave (Fig. 9). Also, the general decrease of the passage size with length is a feature more consistent with water flow than of lava flow.

Total stream power (in watts) is calculated from maximal flow, the specific density of water and bed gradient. The total-reach gradient is ca. 100 m/1000 m, i.e., 0.1, or ca. 0.18 if considering only the mauka vadose section of Kuka‘iau Cave. This is comparable with other gradients of step-pool streams, such as those given in Wohl and Merrit (2001, Table 2), who list eight rivers with gradients between 0.02 and 0.2 and maximal discharges of between ca. 4 and 700 m^3/sec. The overall gradient appears to be the most important factor determining step-pool channels as illustrated by the statistical analysis of Wohl and Merrit (2001) of over 40 river channels. The analysis suggests also that step-pool channels develop where there is a relatively low ratio between driving forces (i.e., stream power) and rock resistance. “The presence of steps and plunge pools, which may result from differential erosion associated with substrate heterogeneity localizes and maximizes erosional force in the plunge pools” (Wohl & Merrit 2001, p. 1211). Since maximal flow of the creek feeding Kuka‘iau Cave remains unknown at this stage of the investigation, maximal stream power cannot be determined as yet, but cobble size and inclination of pool-exit chutes should provide clues to estimate this important stream characteristic in further studies.

It is also interesting to consider the temporal aspect of the evolution of the cave. Apparently no model exists as yet which links down-cutting rates of bedrock channels with gradients, water flow and substrate characteristics. Even if such models would exist, it will be difficult to apply them to the ThatCave case, simply because we do not know how active the creek is. We do know - due to a rim of modern flotsam - that the creek periodically floods the cave in present time up to a height of 65 m above the level of the sump. The cave flooded in November of 2000 when the island of Hawai‘i experienced an exceptionally heavy rainy season and in the winter of 2001-2002, as indicated by the tire, which was washed through the cave. However, the cave’s formation may well be linked to past climatic conditions, for example, to the time when the ice cap of Mauna Kea melted at the end of the Last Glacial Maximum. Dethier (2001) published a recent overview of river incision rates for the Western United States, using the Lava Creek B Tephra, erupted from the Yellowstone caldera ca. 0.64 Ma ago, as a time Marker Layer. His results show that incision rates ranged from 30 (for very steep terrain in the Rockies) to < 5 cm/ka (along the plains west of the Mississippi/Missouri) since the deposition of the tephra. If such values also apply for ThatCave (average height assumed as 3 m) then the cave could have formed in a period of less than 10 ka to more than 60 ka.

The finding of quartz and illite (a fine-grained mica) in the paleosoil Layer 1 (TC 11 and TC 20) suggests that this soil was exposed to higher dust-fluxes, such as occurring during glacial times. Vitousek et al. (1997) describe sites on Mauna Kea with 20 ka old soils and on Kohala with a soil age of 150 ka. Both sites contain dust-derived quartz. Kurtz *et al*. (1999) found a total of 6 g dust per cm^2 at the 20 ka site and of 14-18 g/cm^2 in the older sites. We found (sample TC 20) a quartz content of ca. 11% of the total. If we assume a soil density of 1.5 g/cm^3 and a layer thickness of ca. 20 cm, one can estimate the quartz content to ca. 3 g/cm^2. Compared to the Mauna Kea site of Vitousek *et al*. (1997), Layer 1 could have an exposure time of around 10 ka. Total weathering time can be estimated by looking at the feldspar contents. Vitousek *et al*. (1997) show that feldspar is lost between the 20 ka and the 150 ka old sites. Since feldspar is missing in the samples containing quartz (TC 11) and illite (TC 12) (but not in sample TC 21) and in one of our samples from the red Marker Layer (sample TC 15) one must assume that these soils have a weathering age older than 20 ka. Since exposure time and weathering time do not agree, one can tentatively conclude that the weathering of the soils continues even after they have been covered by the next lava flow. This conclusion is also substantiated by the observation that the aa layer above Layer 1 is well weathered (TC 22 and TC 23, compare also Fig. 3), containing large fractions of amorphous matter and only a few percent of feldspar. Apparently the underlying soil served as a water retarder, facilitating the continuation of the weathering reactions. At the same time it is illustrated that water must have collected and flowed above the soil through the interstices of the aa rubble. The presence of magnetite in place of hematite and donathite could suggest that this weathering occurred under reducing conditions, again pointing at weathering within a perched groundwater body.

All these observations allow concluding that the lavas into which the cave system was eroded must be at least predating the last glaciation. They could be as old as 100 ka, but not much older than that, consistent with the published youngest ages of the Hamakua Volcanic Series (see Chapter 2). This limits the age of the cave to a few 10 ka fitting into the considerations derived from the discussion of the erosion rate.

We hope to get a further age constraint of the bedrock of the cave from a charcoal sample recently recovered by Dr. Jack Lockwood in ThisCave from the aa rubble below the diamict.

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RAW SEWAGE AND SOLID WASTE DUMPS IN LAVA TUBE CAVES OF HAWAII ISLAND

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Lava tubes on the island of Hawaii (and elsewhere) are possible subsurface point sources of contamination in addition to more readily identifiable sources on the surface. Human and animal waste, and hazardous and toxic substances dumped into lava tube caves are subject to rapid transport during flood events, which are the dominant type of groundwater flow through Hawaiian lava tubes. Although these waste materials may not be a major source of pollution when compared with some surface sources, this potential hazard should be evaluated much as in the case of karstic floodwater conduits.

This paper explores the interaction of water flow and solid waste dumps and sewage in lava tubes and lava tube caves of Hawaii Island, Hawaii - an island almost as large as the state of Connecticut (Fig. 1)-and resulting potential threats to groundwater quality. In recent years, Hawaiian cavers and speleologists have become increasingly concerned about these occurrences. Some of the solid waste dumps can be seen to contain partially empty containers of toxic and/or hazardous substances (Fig. 2), including automotive and agricultural waste. Stinking raw sewage speaks for itself (Fig. 3), and members of the Hawaii chapter of the National Speleological Society have been shown the top of a septic tank or cesspool near Keaau said to consist of an unlined segment of lava tube cave. The subject is especially controversial because no known case of human death or illness has been traced to any of these cave sites, and no toxic level of harmful chemical is known to have been identified in local drinking water sources. Further, no one has attributed current pollution of Hilo Bay and decimation of the island's marine fisheries to these sources. Consequently, these practices traditionally have been condoned regardless of federal, state, and local laws and regulations.

OVERVIEW OF LAVA TUBES AS GROUNDWATER CONDUITS

Perhaps thinking of the now infamous "natural sewers" beneath Bowling Green, Kentucky, and other classical American karsts, Palmer (1946) wrote that "lava tubes (on the island of Oahu - W.R.H.) would be as good as artificial pipes, but they are far from common". More recently an enthusiastic journalist wrote that "when rain falls on the Big Island (Hawaii Island - WRH), it apparently collects in lava tubes and is whooshed down to the sea..." (Hastings 1989). Neither assertion was correct, but both contained important insights. In some parts of the world, lava tube caves function full-time as conduits for stream flow. In Oregon, a vigorous headwater of the Rogue River flows through a lava tube cave more than 100 m long (Fig. 4). On the volcanic island of Terceira (Azores, Portugal), spelean waterworks capture year-round stream flow to serve a town (Fig. 5). The stream in Utah's Duck Creek Lava Tube has been dammed to supply a local ranch. Other

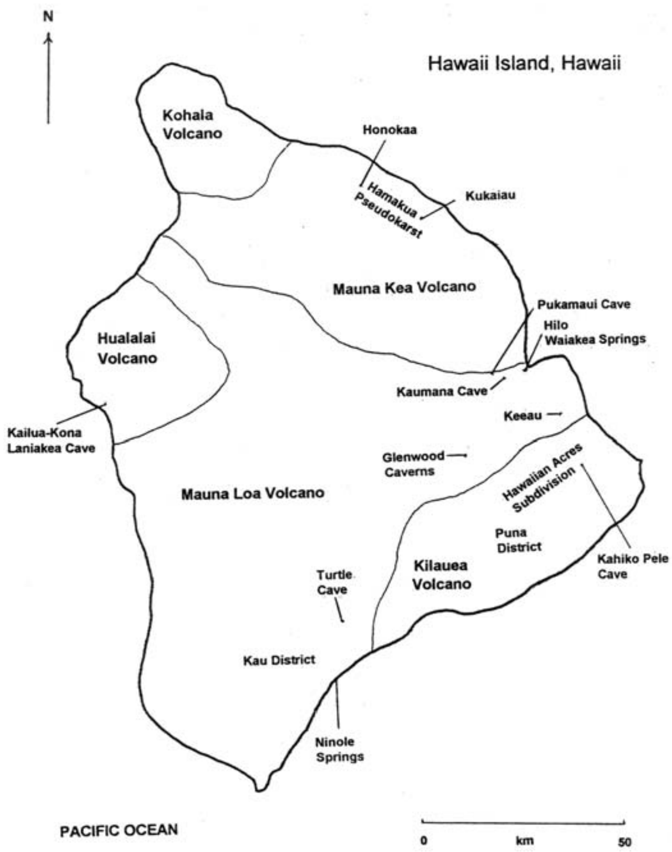


Figure 1. Map, Hawaii Island.

examples are reported in volcanic terrain from Madagascar and Tahiti to Iceland. Beneath a layer of kaolinized volcanic ash on Mauna Loa volcano on the island of Hawaii, a stream up to 0.6 m deep flows in Glenwood Caverns, but only about half the year (Halliday 2001). Even standing freshwater bodies are largely lacking in Hawaiian lava tube caves. Aside from a few at sea level where basal fresh water floats on sea water in highly permeable volcanic rocks that include the caves, only a single small perched pond is on record for the entire island - the pond in the lower cave near Kuka'iau (Stearns & Macdonald 1946).

Figure 2. Incompletely drained containers of pesticides, herbicides, and other agricultural and automotive chemicals dumped in Kaumana Cave.

Figure 3. Looking diagonally upward to a pipe connected directly to a toilet in north Puna District, near Keaau. A pile of moist feces was present beneath the pipe.

Figure 4. Spring runoff passing through a lava tube cave in the headwaters of the Rogue River, Oregon.

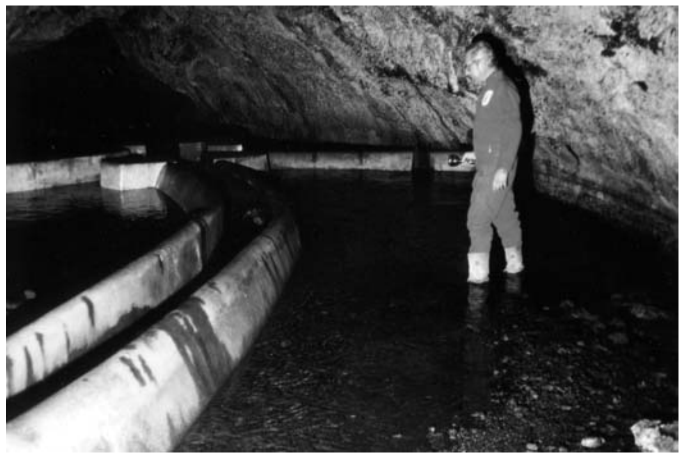
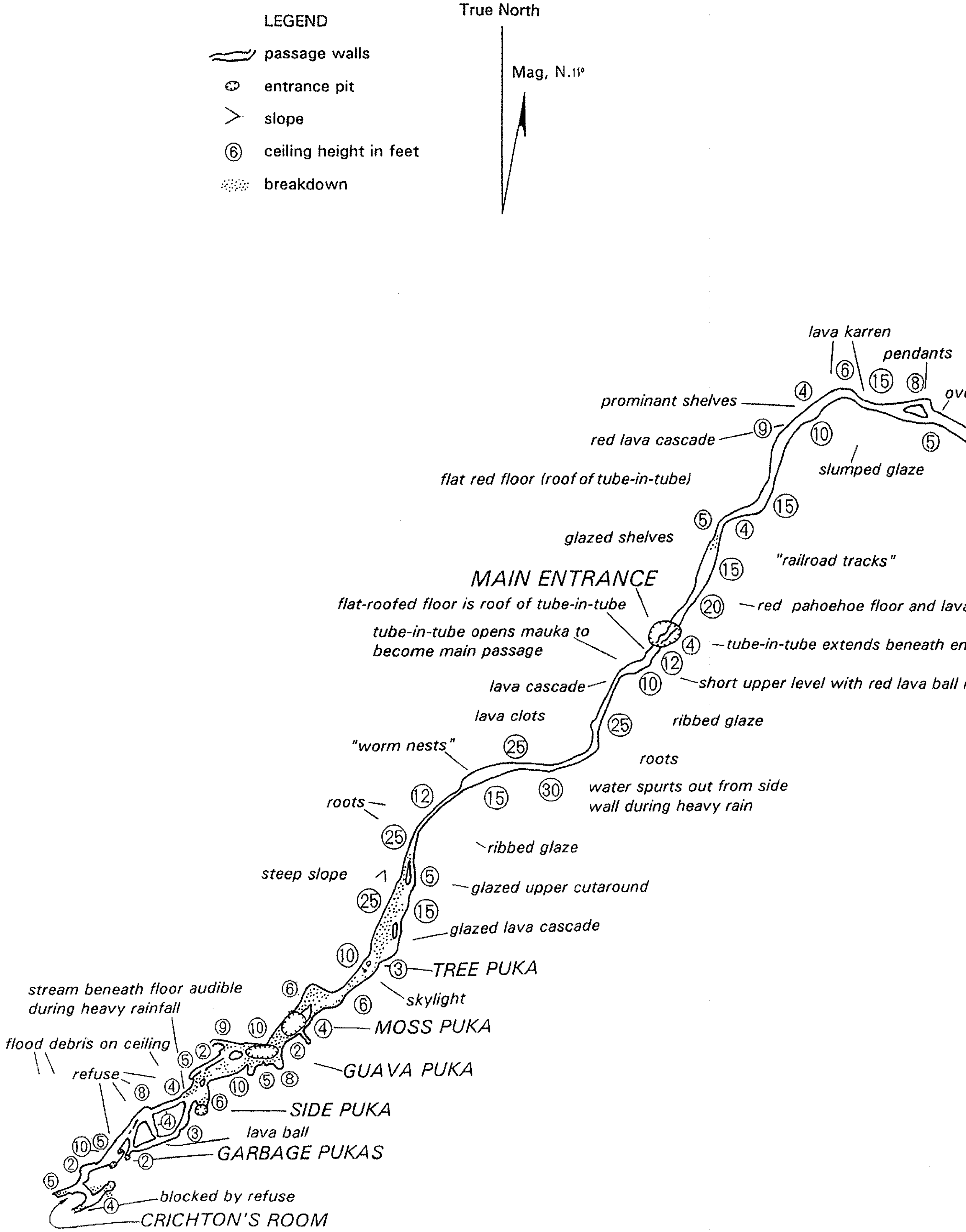


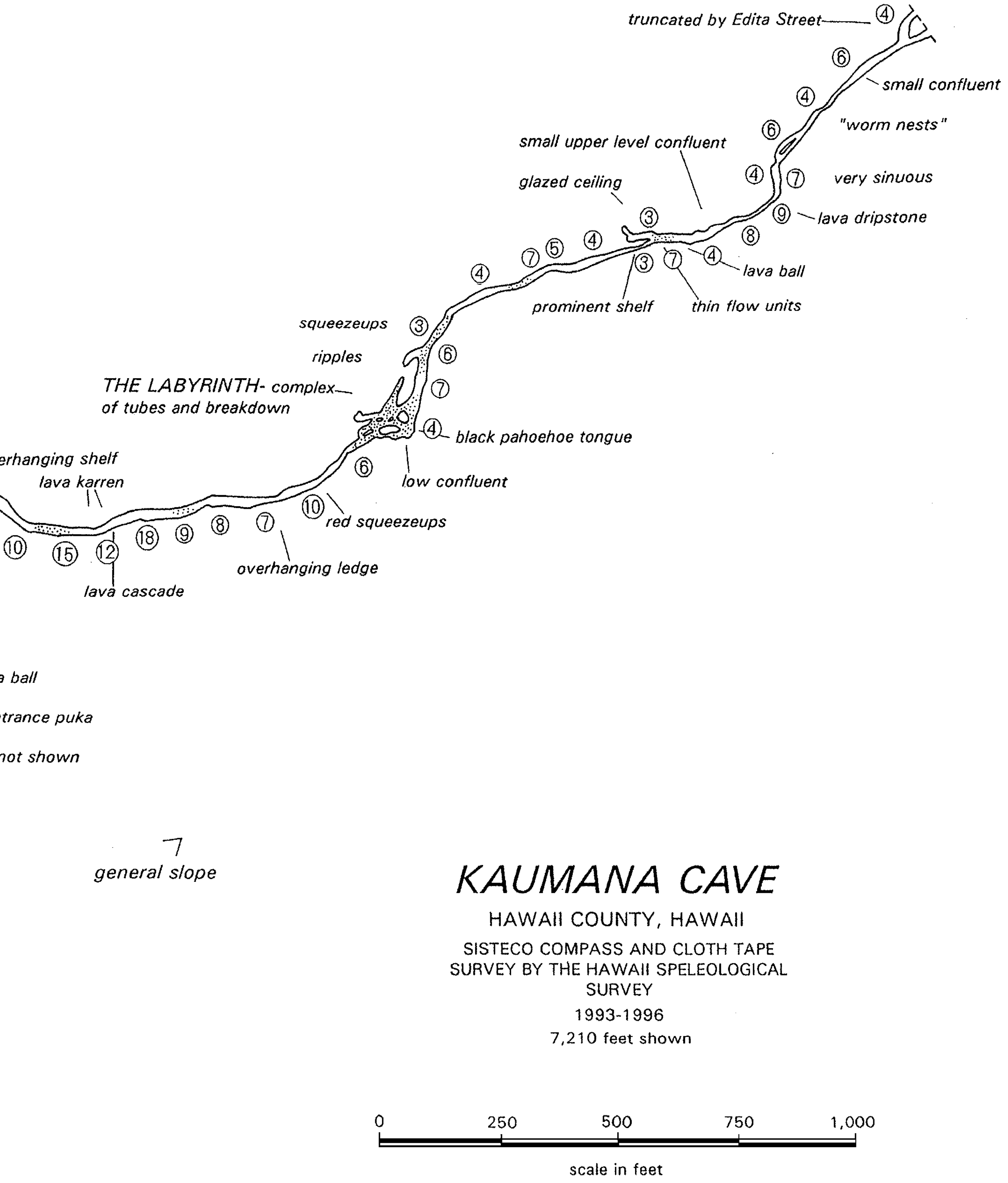
Figure 5. Artificial channeling of groundwater flow in a lava tube cave on the island of Terceira, Azores, Portugal, for domestic purposes.

PUBLISHED STATEMENTS ABOUT HAWAIIAN LAVA TUBES AS WATER CONDUITS

Stearns and Clark (1930) may have begun the discussion of Hawaiian lava tubes as water conduits: "Such systems of tubes, of which there are literally thousands in the Kau District, of course offer free passage to ground water". They reported observing fresh water emerging from lava tubes at the huge Ninole Springs complex, a statement later repeated by Stearns and Macdonald (1946). Unfortunately, this appears to have been conjecture. It is true that there are thousands of lava tubes in the Kau District (nearly all are only a few centimeters in diameter) but at Ninole Springs, no one else seems to have observed any lava tube resurgences and none are seen today. They also mentioned brackish water in once celebrated Laniakea Cave, near the shore in downtown Kailua-Kona. But they evidently considered these to be mere isolated curiosities rather than inherent parts of the groundwater transport system

Figure 6.
Map, Kaumana Cave.




truncated by Edita Street
small confluent
"worm nests"
small upper level confluent
glazed ceiling
very sinuous
lava dripstone
lava ball
prominent shelf
thin flow units
squeezeups
ripples
THE LABYRINTH- complex of tubes and breakdown
black pahoehoe tongue
lava karren
low confluent
red squeezeups
overhanging ledge
lava cascade
general slope
KAUMANA CAVE
HAWAII COUNTY, HAWAII
SISTECO COMPASS AND CLOTH TAPE SURVEY BY THE HAWAII SPELEOLOGICAL SURVEY
1993-1996
7,210 feet shown
0
250
500
750
1,000
scale in feet

of volcanic pseudokarsts. In discussing first-order Waiakea Springs in downtown Hilo, they did not consider any of the lava tube caves in that city, and evidently they knew nothing of the lengthy caves upslope from other large springs along the coast near Keaau.

Macdonald and Abbott (1970) briefly mentioned water flow in lava tube caves but omitted it from their conceptual diagrams. In the revised second edition (Macdonald *et al*. 1983, p. 283) a photograph shows water gushing from a small lava tube cave, but even the minimal 1970 text was omitted. The multivolume Geological Society of America overview of American geology (Hunt *et al*. 1980) mentioned lava tubes as mostly “less than a meter in diameter and of small lateral extent”, with a maximum length of “several km”. Kazumura Cave actually has 65.6 km mapped at present (K. & C. Allred, pers. comm. 2001). These writers were the first to include a lava tube in a conceptual diagram of water flow in Hawaii. However, they minimized the roles of lava tubes in groundwater flow by grouping them with joints, cracks, rubble, clinker beds, and waterflow voids together producing a “hydraulic conductivity of a few hundred to a few thousand meters per day”. Aley (1997) mentioned no water flow through lava tubes of any size: “through basaltic lava flows; dye transport has apparently occurred (only) through fractures and through paleosoil zones.”

Stearns and Macdonald (1946) recorded 2 important phenomena on Hawaii Island. One was a spectacular floodwater diversion of the Wailuku River through Pukamaui Cave; the cave had to be walled up to return Hilo’s principal water source to its normal intake. The other consisted of 2 lava tube caves near Kuka‘iau in the Hamakua pseudokarst on Mauna Kea Volcano. They perceived these as a swallet cave and a seasonal resurgence cave in a conduit system. The lower cave is the site of the perched pond mentioned above. The other is a swallet only seasonally but has extraordinary erosional and depositional features discussed below.

COMPARISON BETWEEN KARSTIC AND LAVA TUBE CONDUITS

Unless directly fed by surface streams, lava tube caves generally carry a smaller and less significant proportion of groundwater flow than do their karstic analogues. Under certain circumstances, however, their flow is disproportionately important. Basal groundwater may flow freely for dozens of meters in lava tubes near sea level. Tubes associated with significant aquacludes (e.g., kaolinized volcanic ash, paleosols, unfractured basalt, etc.) may carry perched streams for hundreds of meters and much more in times of flood. Beneath a suburb of Hilo, Kaumana Cave is an example of a lava tube cave that carries floodwater for more than 1 km.

Above the water table, lava tubes function as “leaky pipes”. Through large and small cracks, water leaks in and out of tubes, depending on saturation of extensive interconnected extratubal spaces that function as potential reservoirs. In addition to cracks, these include spaces within aa lava, volcanic breccia and rubble, and various other small cavities. They vary markedly in lateral extent and in depth to the water table or to aquacludes, and evidently also in their rate of percolation.

On much of the island of Hawaii, these reservoir spaces permit year round, near vertical percolation for dozens or hundreds of meters. Those adjoining a lava tube less than 0.5 m in diameter on Kohala volcano are typical. Here, seemingly unlimited quantities of surplus water from an irrigation ditch are absorbed by this small tube, whence it leaks rapidly into the reservoir space. In the latter, it evidently percolates nearly vertically to the basal water table without spillover or intermediate resurgence (S. Bowen, pers. comm. 2000). Such reservoir spaces provide a large but necessarily limited dilution factor for fecal bacteria and toxic chemicals, and also a very large surface area for adsorption of some of the latter. In Hawaii Island, groundwater conduit flow is almost exclusively a floodwater phenomenon. Effective conduit flow occurs only where water flow overwhelms crevices in the “leaky pipe” and/or saturates the immediate peritubal reservoir space. This occurs especially where lava tubes are located close to basal groundwater or to an underlying aquaclude. Natural and artificial channelization of surface runoff (e.g., pirated stream gullies, roadside drainage ditches, etc.) may be major contributing factors.

WATER FLOW IN AND BENEATH KAUMANA CAVE

Located beneath a suburb of the city of Hilo, Kaumana Cave is an especially well known example (Fig. 6). Its main entrance section is the principal feature of Kaumana Caves County Park and is much visited. The lower 2.2 km of this cave (from Kilua Road to Edita Street) lacks streamflow unless rainfall exceeds ~20 cm within a period of 2-3 days: a common occurrence in all seasons. Stone (1992) has graphically described local flooding and fecal contamination in various parts of the cave that extend several kilometers upslope from Kilua Road. All known parts of the cave vary so markedly in shape and size that numerical estimates of streamflow discharge are challenging. No instrumental measurements are on record. It is visited so frequently, however, that numerous observations document location and general magnitude of streamflow under varying meteorological conditions.

The lower end of Kaumana Cave opens into a drainage ditch several meters below the roadway of Edita Street. Both the ditch and the street are at right angles to the cave. This street is the up slope margin of a 1960s subdivision built atop a section of the cave ~0.8 km long, now segmented and obstructed by the roadway. At least once in the 1970s, floodwaters emerged from its lower entrance and overflowed Edita Street and part of the subdivision (Stone 1992).

This cave has been mapped several times, but only as far as Kilua Street where garbage becomes daunting (Fig. 7). In periods of normal rainfall, running water sometimes is audible beneath the floor of this section of the cave. Rainfalls of 20-30 cm produce waterfalls spouting from cracks high on the wall

Figure 7. Part of the largest solid waste dump in Kaumana Cave, located in a suburb of Hilo, Hawaii.

of one cave section (Fig. 8). They form a small stream that runs on or just beneath the floor for several hundred meters before finally sinking into cracks. Its flow is augmented by several small bubbling springs at or just above floor level and part of its flow also is lost into small floor-level cracks.

During a record-breaking flood in November 2000, this cave overflowed through a ceiling orifice located in the gutter of Uhaloa Street upslope from the mapped section (Fig. 9), perhaps forcing a new opening at the edge of a metal plate embedded in the roadway at the site of a previous breakout 3-4 m above floor level.

The cave's best-known garbage dump is located just downslope from Kilua Street, on State of Hawaii property. Partially emptied containers of hazardous and/or toxic waste are present (Fig. 2). Torrential rains of November 2000 compacted and partially distributed this dump down tube (Halliday 2001). Worn-out tires were washed more than 100 m to a point where they piled up against a rocky obstacle (Fig. 10). Smaller solid objects were washed up and over this obstacle and were jammed beneath rocks in the next chamber. Floatable waste

Figure 8. In addition to floodwaters which briefly fill much or all of Kaumana Cave, moderate rains cause episodic waterfalls two to three m high, spouting from the walls of the cave.

Figure 9. January 2001 photograph of overflow point of Kaumana Cave, in Kaumana community resulting from November 2000 flood. The location is the site of a former opening of the cave which was bridged to permit road construction.

hung on projections up to 3 m above the floor at points much farther down the cave.

The ultimate resurgence of Kaumana Cave floodwaters is unknown. Hilo's first-order Waiakea Springs are ~7 km downslope. No dye traces are on record. Hilo Bay is so polluted that swimming is prohibited, but shoreline fishing for family consumption is a popular hobby.

CONDUIT FLOW IN OTHER HAWAII ISLAND CAVES

Clear evidence of flooding is present in several other caves on this island. The Hamakua pseudokarst on the well-watered windward slope of Mauna Kea volcano contains several caves in Hamakua volcanic rocks: The oldest tube-forming lavas known on Hawaii Island (Wolfe *et al*. 1997). A lava tube cave in Honokaa opens at the lower end of a narrow lava trench containing large accumulations of solid waste which is swept into the cave by periodic floods. This cave also smells of raw sewage, at least intermittently (M.S. Werner, pers. comm., 1998). Another lava tube cave in this town long served as an open sewer for a hospital and several churches and business establishments (ParEn 1990); its present status is unknown. Farther upslope are several seasonal swallet caves and a few seasonal resurgence caves. Most of them demonstrate extensive erosion of accreted tube linings together with accumulated sediments ranging from rounded boulders >0.5 m in diameter to multilayered mud. The larger of the 2 caves near Kuka'iau is so heavily eroded that some well-reputed investigators have found no evidence that it originally was a lava tube, and consider it purely erosional (Kempe *et al*. 2001).

In North Kona District, upslope from Kailua-Kona, the name of Gomes Flashflood Cave is self-explanatory. Entry requires crawling through a large pile of stream-wedged branches and small trees, hung up at the low entrance. Inside, mud banks up to 1 m high have been eroded into long, tapered forms. In Kau District, the downslope end of well-known Turtle Cave has been eroded away by a surface stream that downcut a deep, narrow gully diagonally across the cave. About 100 m of this level was backflooded in November 2000, with several centimeters of mud and floatable debris deposited almost to the famous "turtle", a lavaball partially "submerged" in the smooth pahoehoe floor of the cave (Halliday 2001). This cave also has a lower level with a covert orifice somewhere in the streambed, capable of passing large stream cobbles as well as smaller clastic material. Before the 2000 flood, the lower end of this passage was notable for mud deposits up to 2 m above the floor, and the ceilings of its unmapped terminal branches sloped down to thick accumulations of watery mud on their floors. This appearance was unchanged after the 2000 flood. Elsewhere in this passage, newly-sorted stream sediments appeared to be located in the same positions as their counterparts before the flood. Back-filling was much less pronounced than in the upper passage.

In Puna District, Kahiko Pele Cave is the final swallet of an artificial channel for intermittent floodwaters; its floor sediments are almost entirely mud. This small cave is of particular concern because of the partially emptied pesticide containers found in it.

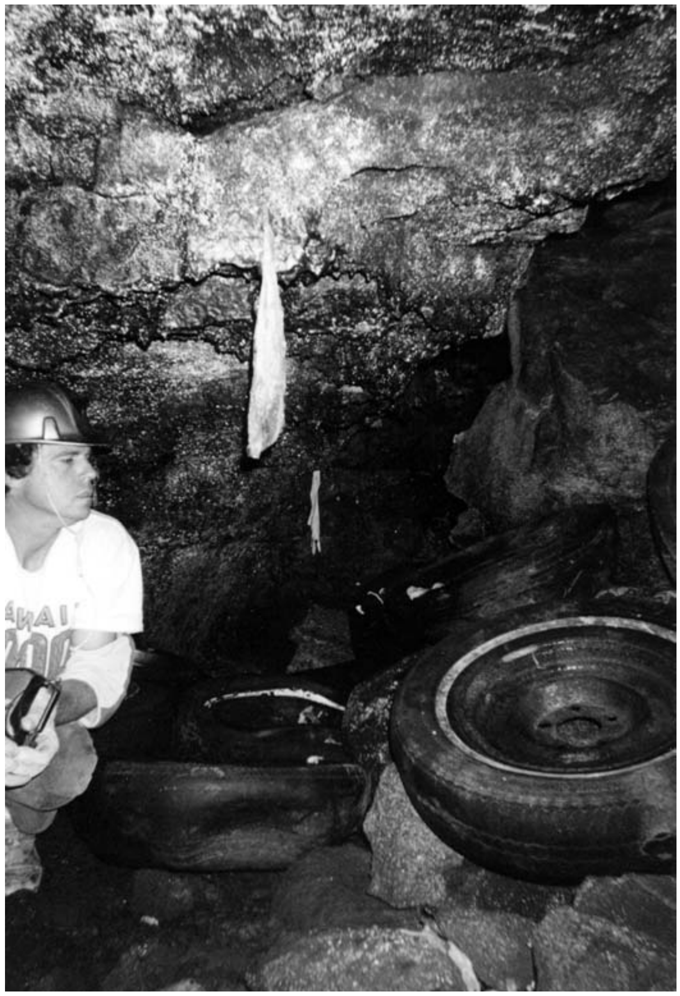


Figure 10. High velocity floodwaters washed these abandoned tires about 100 m down-cave from the main garbage dump in Kaumana Cave in November 2000. Here they were stopped by a pile of fallen rock. Lighter material from this dump was washed up and over this rockpile and was found at downslope points up to 3 m above the cave's floor.

SIGNIFICANCE

Present data indicate that, by today's standards, Hawaii Island drinking water sources are not at risk from floodwater dissemination of lava tube contaminants. Nationally, a trend is evident toward stricter standards for water quality, and each year, additional chemicals are added to the list that must be monitored.

Further, populations on large cavernous pahoehoe lava flows (rheogenic pseudokarsts) such as Hawaiian Acres Subdivision are increasing rapidly. In rainy Puna District, part of their need for domestic water can be met by rooftop catchment despite the risk of leptospirosis. But, additional subsurface water sources will be needed in the near future, and they will have to be located away from plumes of groundwater contamination.

Potentially alarming solid waste dumps on Hawaii Island are not limited to lava tube caves, and much of the island's sewage goes directly to groundwater through crevices rather than through lava tube caves. Some Hawaii Island floods are so overwhelming that lava tubes carry only a small portion of their total contaminant load. When pollution or contamination is identified in drinking water or in marine fisheries, or impairs beach recreation, remediation far beyond the island's lava tubes will be needed. Lava tubes containing unlawful sewage and solid waste, however, are prominent among the identifiable points to which relevant laws and regulations can be applied readily. Even now, they are obvious sites for cleanup efforts.

On August 2, 2000, the Hawaii Chapter of the National Speleological Society convened a Hawaiian Conference on Lava Tubes and Ground Water. In followup, the Safe Drinking Water Branch of the Hawaii State Department of Health has begun tabulating and documenting cave dumps on Hawaii Island, looking toward funding cleanup activities on state lands. All sewage and solid waste dumps in caves on this island, and elsewhere in Hawaii, should be reported to the Hawaii Chapter or the Hawaii Speleological Survey of the National Speleological Society for transmissal to the appropriate state authorities.

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The reviews of Jim Kauahikaua and an anonymous reviewer significantly improved the text of this paper. The observations reported here could not have been made without the invaluable field assistance of fellow members of the Hawaii Speleological Survey and the Hawaii and Salt Lake chapters of the National Speleological Society, and also Os Montanheiros, the speleological society of the island of Terceira, Azores, Portugal. My heartfelt thanks to all.

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Stephan Kempe, Ingo Bauer, and Horst-Volker Henschel - Pa'auhau Civil Defense Cave on Mauna Kea, Hawai'i - A lava tube modified by water erosion. *Journal of Cave and Karst Studies, v. 65*, n. 1, p. 76-85.

PA‘AUHAU CIVIL DEFENSE CAVE ON MAUNA KEA, HAWAII A LAVA TUBE MODIFIED BY WATER EROSION

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In 2000 and 2001, 2 large (1000 m long) cave systems were surveyed on the eastern, heavily eroded flank of Mauna Kea: The Pa‘auhau Civil Defense Cave and the Kuka‘iau Cave. Both caves occur in the Hamakua Volcanics, 200-250 to 65-70 ka old. They are the first substantial caves documented for lavas of this volcano and the first caves on the island of Hawaii showing extensive morphological signs of water erosion.

All observations lead to the conclusion that the Kuka‘iau Cave is erosional in origin (Kempe & Werner 2003). These observations include: missing lava tube features, a graded hydraulic profile, a base layer along which the major section of the cave seems to have developed, and allophane and halloysite that sealed the primary porosity causing a locally perched water table.

In contrast to this feature, the Pa‘auhau Civil Defense Cave originated as a lava tube. This is attested to by the presence of the typical morphologic elements of a lava tube, such as secondary ceilings, linings, base sheets, lava stalactites, and lava falls. Nevertheless, the cave was heavily modified by a stream that entered upslope and traversed much, but not all, of the cave. It left waterfall walls, large plunge pools, stream potholes, scallops, flutes, gravel, rounded blocks, and mud.

The finding of water-erosional caves in the lavas of Hawaii offers a new view on deep-seated water courses in volcanic edifices.

On Hawaii, hundreds of small and large lava tubes have been explored in the past 20 years, largely by members of the Hawaii Speleological Survey and the Hawaiian NSS Grotto. These tube systems are on the volcanoes of Kilauea, Mauna Loa, and Hualalai. Mauna Kea, however, remained somewhat of a blank spot speleologically. Old reports of caves being intercepted by water wells have not been sufficiently documented so far. Halliday (2000a, b) reported some small natural caves on Mauna Kea. Along the old Mamalahoa Highway west of Honoka‘a, along the road to Waipio Valley and near the power station at Honoka‘a there are a few artificial, cave-like excavations, where road building material such as cinders and aa were mined.

Hawaiian hydrology ranges from extremely humid to extremely dry on a single island. On the windward side of the Big Island, Mauna Kea’s NE flank receives up to 2.3 m of rain per annum (1961-1990 average annual precipitation data, U.S. National Oceanic and Atmospheric Administration). This led, in spite of the highly porous nature of volcanic rocks, to the formation of perennial and occasional streams, which in turn have significantly dissected the eastern flank of Mauna Kea. The flank’s morphology is characterized by several deep gulches and countless V-shaped gullies and stream ways that funnel the water straight to the ocean without forming large tributary river systems.

The last eruption on Mauna Kea occurred at the summit under the ice of the Last Glacial. The upper slopes of the volcano are composed of volcanics of the Laupahoehoe Series, <60 ka old, while the older Hamakua Series is exposed in the gulches of the Hamakua Coast (Wolfe *et al*. 1997). It is dated to between 200-250 to 65-70 ka BP and consists mostly of alkalic and transitional basalts. In the upper part of the volcano, glacial deposits are found as well. Any tubes on the lower flanks, therefore, predate the Last Glacial and formed at least several 10s of 1000s of years ago. Thus, they could have been invaded and plugged by younger lava, been filled by ash, or collapsed under the weight of overlying strata. Because of this anticipation, no systematic search has been made for caves on Mauna Kea as yet.

W.R. Halliday gained knowledge of the locally known Pa‘auhau Civil Defense Cave, and in 1998 a team of the Hawaii Speleological Survey visited it, exploring it to a mauka[1] end. The cave, as the name states, had been on the list of civil defense shelters during the cold war, and it was also visited extensively by ancient Hawaiians. They left stone piles, smaller and larger cairns, small platforms, upright stones, stone rings, and bits of charcoal from their torches. In 2001, Pa‘auhau Civil Defense Cave was fully explored and surveyed by a (Kempe *et al*. 2001).

In 2000, 2 more caves were found: ThisCave and ThatCave, also in the Hamakua Series. They were explored and surveyed by teams led by S. Kempe and M.S. Werner. In addition, geologic investigations were carried out in ThatCave by S. Kempe and I. Bauer in March 2001. In June 2002 the

[1] *mauka* = Hawaiian for “upslope”

sump between the caves was explored and both caves, now called Kuka‘iau Cave, were connected. Kuka‘iau Cave proved to be entirely of erosional origin, a novelty for lava caves (Kempe & Werner 2003). The story of the discovery of these caves and initial reports are given in Werner *et al*. (2000, 2003); Kempe (2000), and Kempe *et al*. (2001).

GENERAL LAVA TUBE MORPHOLOGY OF PA‘AUHAU CIVIL DEFENSE CAVE

The map of Pa‘auhau Civil Defense Cave shows a branched pattern (Figs. 1, 2). Total passage length is 1000.5 m (988 m horizontal). The ratio between the main passage length to those of the side passages is 1.37. Total vertical extent is 48.9 m, and the slope along the main survey line is 4.87° (5.56° if calculated for the distance as-the-crow-flies). The detailed statistics of Pa‘auhau Civil Defense Cave are given in Table 1.

The present entrance, situated at the makai[2] end of the cave, looks out into a modern canyon (Kahawaili‘ili‘i Gulch). In the gulch wall, left of the entrance, a small cut-around opens up leading back into the cave a few meters. Its opening is perched near the ceiling a ~2 m above the floor, thus illustrating where the lava sheet had initially formed conduits and how much the lava had cut down during its active flow period. The main passage is ~2 m high and 2-3 m wide near the entrance (Fig. 3) and gradually widens mauka. It then trends south for 348 m. There, mauka of Station 40 (abbreviated St. in the following), the cave branches: To the east, tributary passages join (Sidepasssage, Collector-Alpine Streamway, Sandpassage-Unhawaiian Crawls) and to the west a distributary passage (Mudcrawl) leads off. The main passage rises farther until it ends 580 m mauka and 49 m above the entrance. Interestingly, this passage ends at an apparently solid wall. A small hole that blows air, however, suggests further passage mauka. Possibly the main passage is genetically only a side passage that was blocked by lava intruding it from the main lava feeder beyond.

The main proof that this passage was not the main lava feeder is given by the situation above Plunge Pool 4: The floor of Sidepassage is lower than that of Stone Ring Hall in the main passage (compare Fig. 4). Apparently lava from Sidepassage back-flooded mauka into Stone Ring Hall, suggesting that actually Sidepassage is the primary and last active lava feeder. The mauka end of Sidepassage is collapsed, but it may have connected into Alpine Streamway (see dashed connection on Fig. 1). The mauka end of Alpine Streamway is blocked by breakdown composed of large blocks. Roots are visible, and kukui nut shells gnawed open by rats are abundant, suggesting that we are viewing the inner side of a collapse along the northern Kahawaili‘ili‘i gulch wall. Therefore, the main lava feeder cannot be explored any farther mauka. In June 2002, we searched the gully hoping to locate both the mauka exit of the cave and the main lava feeder. We found a

Table 1: Statistics of the survey of Pa‘auhau Civil Defense Cave, March 2001.

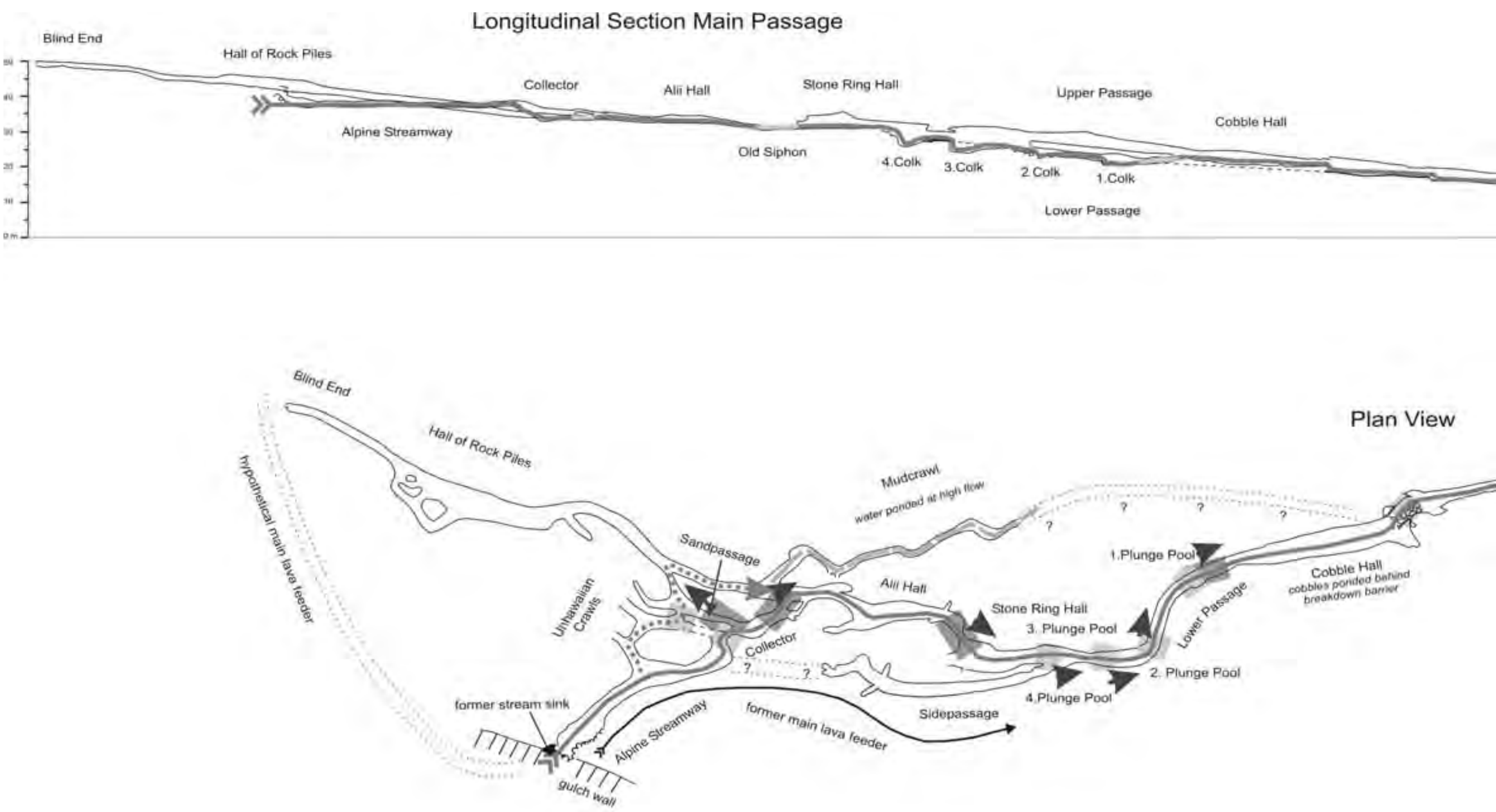
	Stations	Real (m)	horizontal (m)
Main survey line	1 to 74	579.62	573.37
Cut-around at entrance	3 to 5	5.33	5.33
1. secondary ceiling	3 to 8	16.62	16.56
Recess at Cobble Hall	23 to 24	5.94	5.94
2. secondary ceiling	26 to 36	45.25	44.39
Minus parts of St. 26 to 27		-7.50	-7.00
Sidepassage	44 to 55	57.69	56.90
Branch	59 to 99a	8.55	8.50
Alpine Streamway	75 to 93a	88.24	85.08
Treemold	76 to 78	3.00	3.00
Squeeze	79 to main passage	4.00	4.00
Sandpassage	80 to 65	26.70	26.29
Branch	83 to 85	6.84	6.83
Unhawaiian Crawls	82 to 90	37.78	37.68
Mudcrawl	63 to 110	77.28	77.07
Branch	67 to 111a	10.70	10.66
Cut-around at end	116 to 113	27.45	27.30
Cut-around at St. 71	Estimated	4.00	4.00
Connection	112 to 70	3.00	3.00
sum:		1000.49	988.90
Side passages sum:		420.87	415.53
As-the-crow-flies (horizontal)			502.62
Sinuosity main passage			1.14
Vertical	1 to 74	48.93	
Slope ($\tan^{-1}$ 48.93/573.3)			4.87°
Slope ($\tan^{-1}$ 58.93/502.62)			5.56°
Main passage/side passage ratio			1.37
Secondary ceiling ratio			0.11
Coordinates of begin of path to entrance			020°05.153’N 155°26.275’W

place blocked by rounded boulders ~5 m above the stream bed that could be the blocked exit of the cave. We also found, on the opposite wall, a ~30 m long small lava tube running mauka at the level of the cave. It could represent another tributary branch of the cave. We did not find, however, the main feeder. This is not surprising, considering the collapsed nature of the gully walls.

All-in-all the general pattern of the cave displays typical lava tube characteristics (recently summarized in Kempe 2002). This conclusion is also corroborated by the medium- to small-scale tube morphology. Most importantly, we find 2 sections of secondary ceilings. The first one occurs just mauka of the entrance and is 16.6 m long. The second starts above St. 26 and extends mauka for 49 m. There follows a section where the secondary ceiling collapsed, but its remains can be seen high up on the walls as ledges. Actually these ledges connect into the back-flooded lava sheets of Stone Ring Hall, illustrating that the lava of the secondary ceiling must have come from a surge of lava out of Sidepassage as explained above. Secondary ceilings form whenever the lava has cut down so much that an airspace develops above the flowing lava. If enough airflow can be established, then the lava can solidify in the cave, forming a secondary ceiling (Kempe 1997). Secondary ceilings are therefore very good indicators that a lava cave is, in fact, a lava tube created by flowing lava.

A score of other features typical of lava tubes occurs as well: Linings with vertical lamination along the wall, ledges of former lava stands along the sides of the passage, small lava

[2] *makai* = Hawaiian for “downslope”



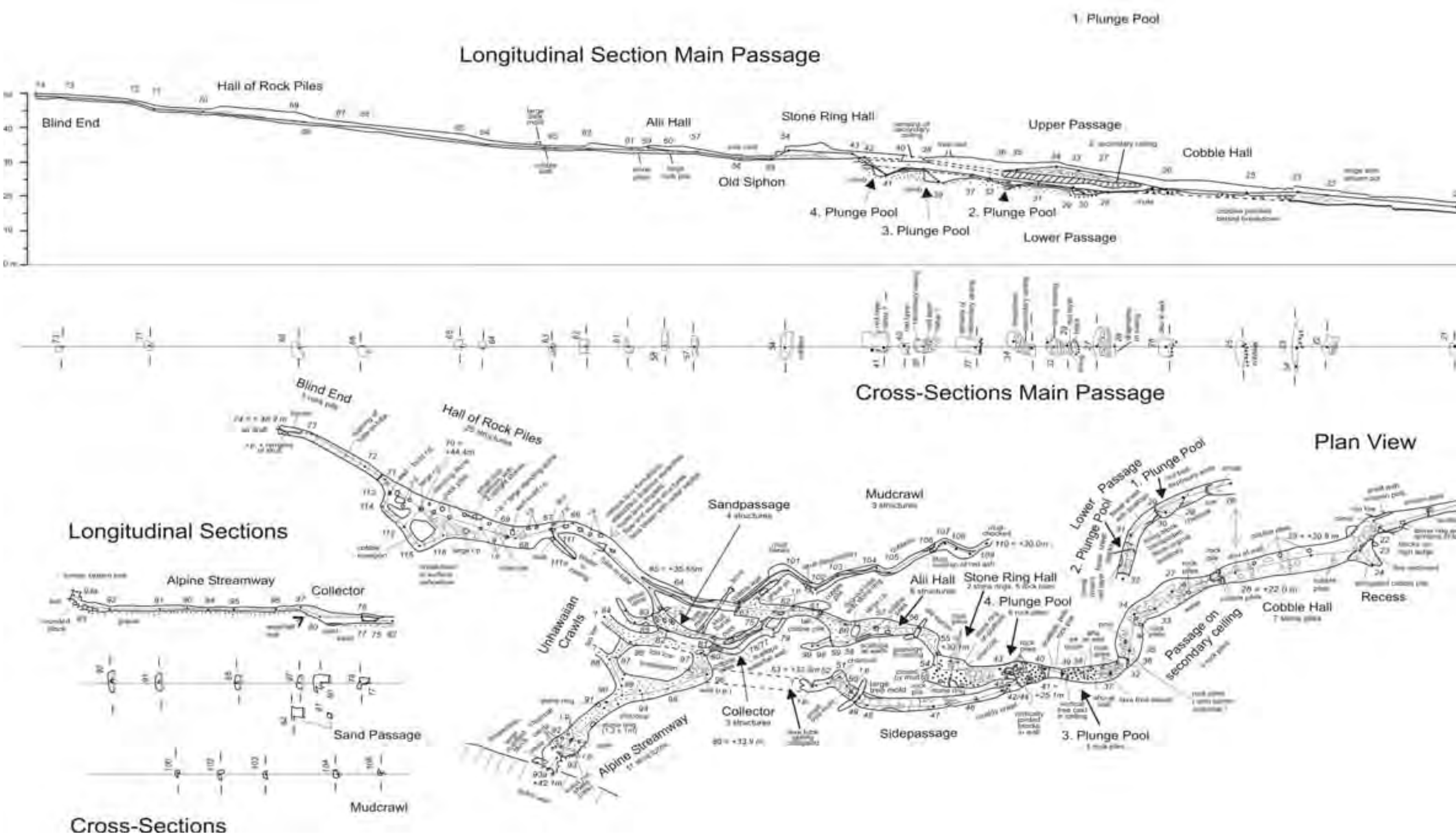


Figure 1 (bottom). Map and sections of Pa‘auhau Civil Defense Cave, Hawaii. **Figure 2 (top). Paleohydrologic Map of Pa‘auha**

Fig. 2: Reconstruction of Paleohydrography

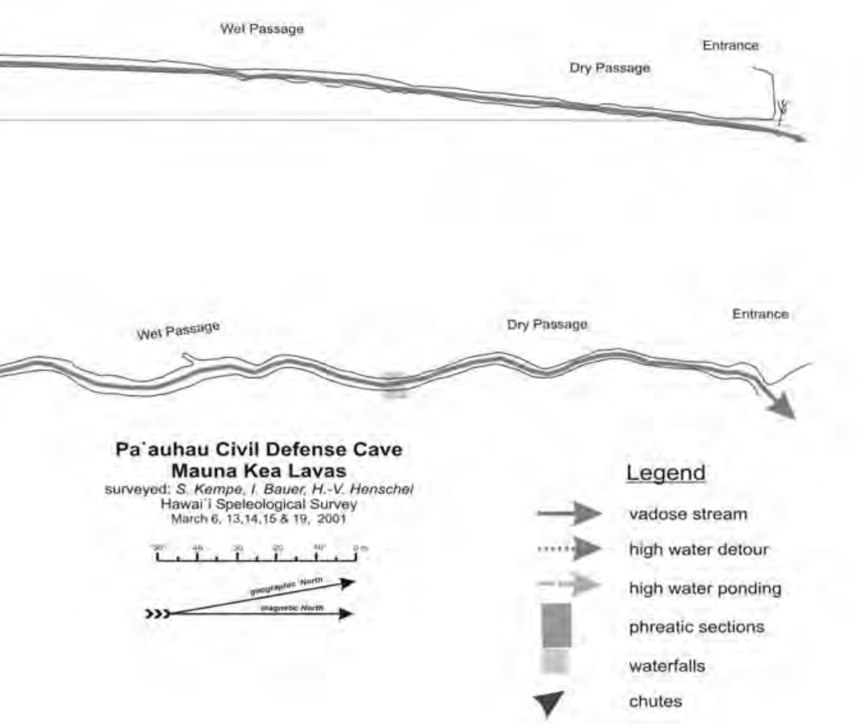
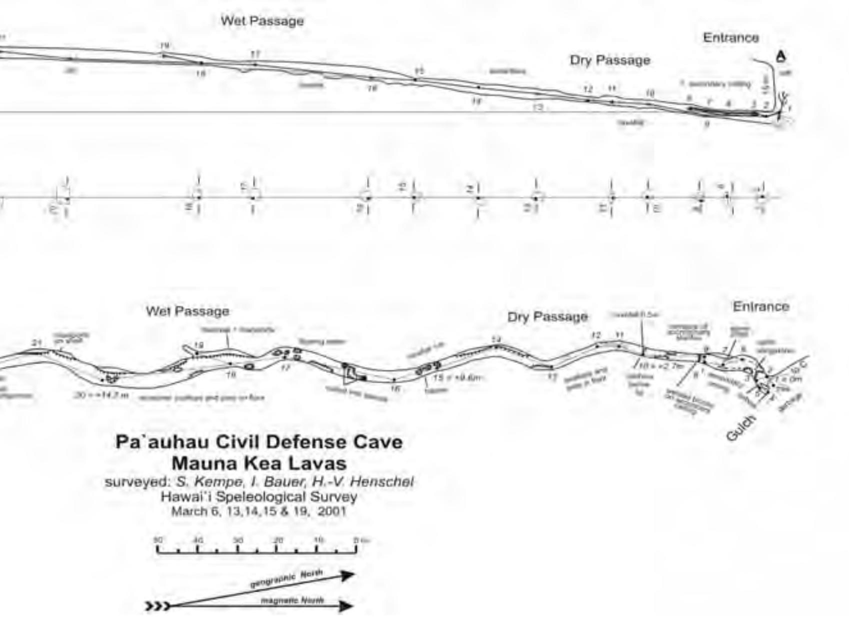


Fig. 1: Detailed Map and Sections



u Civil Defense Cave.

falls (in the entrance series), tube-in-tube features on the floor (at the upper end), pahoehoe flow lobes on the floor (also at the upper end), abundant lava stalactites, and loose lava droplets in places (near St. 95). All these features together establish beyond doubt that the cave is a lava tube by origin.

EROSIONAL MORPHOLOGY OF PAʻAUHAU CIVIL DEFENSE CAVE

A second set of features, however, is observed in the cave, indicating that it was secondarily sculptured by flowing water (Fig. 2). These features are noticed on the floor of the cave beginning just beyond the entrance. Scallops and stream potholes, partly filled with rounded stones, are the most obvious of these features. Closer inspection shows that the entire surface of the bottom sheet of the lava tube is smoothed and that it has lost its original pahoehoe morphology. Also, the lower stretches of walls are smoothed. These signs of erosion become more prominent as one proceeds into the cave. At several places, for example at the small lava fall at St. 10, erosion has cut through the bottom lava sheet exposing underlying sediment (Fig. 5). Shortly, the erosion potholes become larger, forming elongated stream potholes (Fig. 6) and 1-2 m long basins, often up to 1-m deep (Fig. 7). Initially the passage is dry, but beyond St. 16 water stands in the potholes and a little water even runs along the floor, spilling from pothole to pothole. None of this water ever makes it to the entrance, apparently because this flow seeps down and out of the cave via floor cracks. These basins, partly filled with water, apparently gave rise to the idea to use the cave as a civil defense shelter. At least 2 large iron barrels were brought into the cave in the 1950s to serve as emergency water containers; some boards and supplies in tin cans were placed in this part of the cave. Everything is now so rusted and decayed that only mulch and rust remains.

At St. 22, we encounter an old (i.e., predating the water-worn morphology) barrier caused by breakdown blocks. The water had to flow along the western wall and cascaded down the blocks and along a ledge, ~80 cm above the floor. On this ledge several potholes occur, one of them passes clear through the ledge (Fig. 8). Beyond the breakdown blocks, the floor of the cave is much higher and is composed of rounded blocks, gravel, sand, and mud (Cobble Hall). Apparently, the gravel transported along the cave was caught behind the breakdown blocks, forming a natural dam. This explains the lack of substantial gravel beds in the lower section of the cave. From St. 23 onward, gravel, sand, mud, and rounded blocks are common in the cave.

With the beginning of the second secondary ceiling, the picture of the cave floor changes once more: Up to the first branch of the cave at St. 40, we encounter 4 large

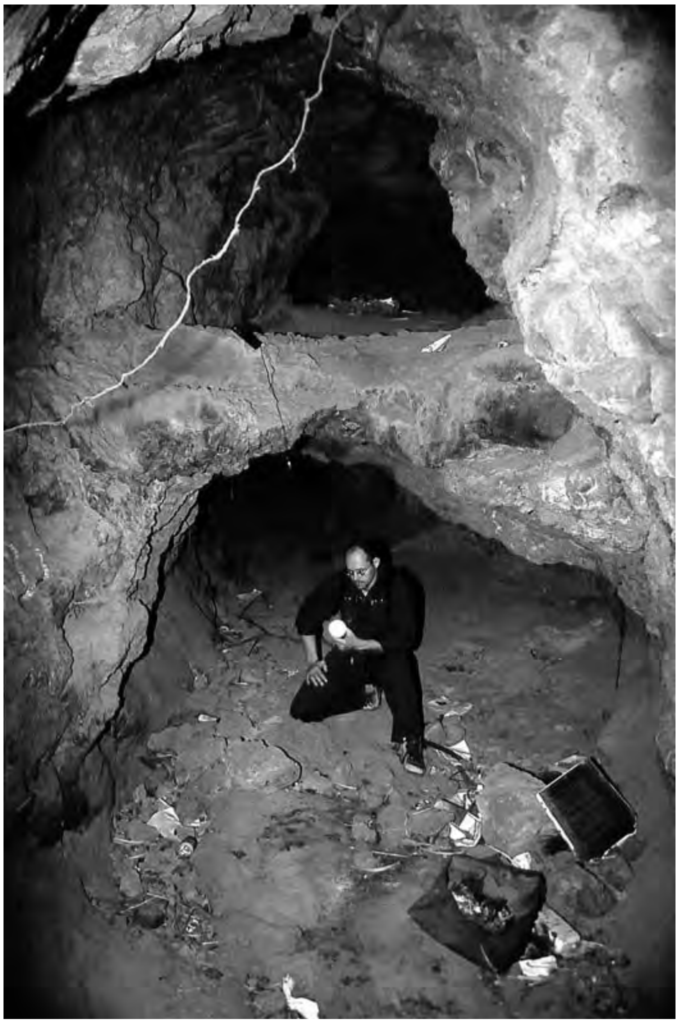


Figure 3. Entrance of Pa'auhau Civil Defense Cave; note the beginning of the first secondary ceiling above the head of Bauer.

plunge pools. In each of them, the bottom sheet of the cave, 20-40 cm thick, has been removed completely, and the water has excavated up to 3 m into the underlying sediment best described as a diamict (Figs. 4 & 9): It contains disintegrated aa blocks imbedded in fine-grained, non-consolidated material. Its origin remains unclear, it could be a mudflow, a lahar, the blocky layer of an aa flow filled with ash, or a tuff.

The mauka end of each pond is a steep wall, exposing the diamict nicely. It is reddish down to a depth of ~20 cm, whereas below the diamict is brown. This reddening may have been caused either by weathering and soil formation on the surface of the diamict or may signify oxidation caused by the overriding hot lava. The makai end of the plunge pools is formed as a chute along which the water dragged gravel and boulders. Any gravel originating upstream must have passed these plunge pools. Possibly the material excavated in the plunge pools alone provided enough material to account for the gravel pond behind the breakdown barrier and not much gravel needed to be imported from farther upstream.

Figure 4. View mauka into the Dry Passage: Station 10 is on the left side of the small lava fall in the foreground. Water erosion has cut a pothole into the lavafall and tugged stream-worn pebbles into the pocket below the lip (note Bauer for scale).

The wall of Plunge Pool 4 leads, on the eastern side, up into Sidepassage, which does not show any sign of erosion by flowing water. It also opens up into the Hall of Stone Rings on the western side, from where the water cascaded down 4 m into the plunge pool (Fig. 4). The floor of the Hall of Stone Rings is much thicker (4 lava sheets) due to the back-flooding of lava as explained above; therefore, the floor dips down at the mauka end of the hall where the intruded lava laminae apparently end. This caused an upward flow of the water, flooding the passage beyond up to the ceiling, creating a sump (Old Siphon). A similar sump, with signs of erosion on the ceiling, occurred also at the makai end of the second secondary ceiling (St. 26-28).

In the main passage, beyond Old Siphon, we enter Ali'i Hall, a clean-washed section of the cave covered by fine-grained sediment. After another constriction, a round tube, ~1 m in diameter, branches to the east at floor level (Fig. 10). All sides of the tube are polished, showing that it is a former sump as well. Sediment was transported upward on a chute in front of it. Beyond the tube, one can stand up again and enter a canyon-like room, the Collector (Fig. 11). Its walls show large scallops, and the floor is covered with coarse sediment. At this passage's end, again a former sump, a low crawl leads upward into Sandpassage. On the eastern side, one can climb up a former waterfall headwall, nicely scalloped and dotted with stream potholes. From there, one enters the Alpine Streamway. The Alpine Streamway's floor is blanketed with coarse-grained sediment and cobbles, some of them up to 50 cm in diameter. The sediment floor is nearly horizontal; possibly the sediment is impounded in a once deeper passage connecting into the collapsed Sidepassage. The present connection into the Collector follows an upper level of the lava tube, a level that is also seen at the makai end of the Collector, where 2 tubes led flood water into Ali'i Hall. The mauka end of the Alpine Streamway is now blocked by breakdown on top of the large

Figure 5. View mauka into the Wet Passage between St. 15 and 16. Large basin cut into the bottom sheet of the lava tube by water (Bauer for scale).

Figure 6. Potholes with cobbles in the Wet Passage (note hand for scale).

stream worn boulders. This area was a former sink along the Kahawaili‘ili‘i Gulch stream, feeding all or part of its waters into the lava tube.

Mauka of Alpine Streamway and Collector, we find the Unhawaiian Crawls (named because these are the only sections of the cave showing no evidence of Hawaiian visitation) and the Sandpassage. The Unhawaiian Crawls are very low, and to survey them we had to shift cobbles out of the way before squirming through. The Unhawaiian Crawls lead to another waterfall wall entering the Sandpassage. Both Unhawaiian Crawls and Sandpassage contain pebbles and cobbles, unlike the Collector. Apparently these passages were high water detours, moving water uphill when the collector and its drains could not transport all of the inflowing water. From the mauka end of the Sandpassage, water overflowed back into the main passage (Fig. 2).

During such flooding events, water also entered the Mudcrawl, where it partially ponded. Mudcrawl was a distributary lava tube that possibly connected further makai into Cobble Hall. If so, this passage’s lower end is masked by ponded gravel and fine-grained sediment fill in the lower reaches of Cobble Hall. Therefore, the water could not be discharged quickly once the Mudcrawl filled during flooding, and the suspended sediment settled, making Mudcrawl particularly muddy. In recent times, a seepage-water-fed small stream has removed some of the mud, so that the former rock floor is visible. At one place, even the bottom lava sheet has been eroded through, and the underlying red diamict is visible. The Mudcrawl ends in an impenetrable, muddy choke with no air draft present.

There is no evidence of extensive water flow in the area above the junction of Sandpassage with the main passage (i.e., mauka of St. 65). At the blind mauka end, a pit is encountered that contains some sediment, partly dug up by Hawaiians. It may have been washed in through a small hole with a strong air draft at the upper end of the pit.

ADDITIONAL GEOLOGIC OBSERVATIONS

Rock and sediment samples were taken in order to characterize the geology of the cave. Grain size analysis was conducted on 5 samples. Figure 13 shows 2 samples from the diamict profile of Plunge Pool 4 (compare Fig. 4) plus 3 samples from fluvial sediment.

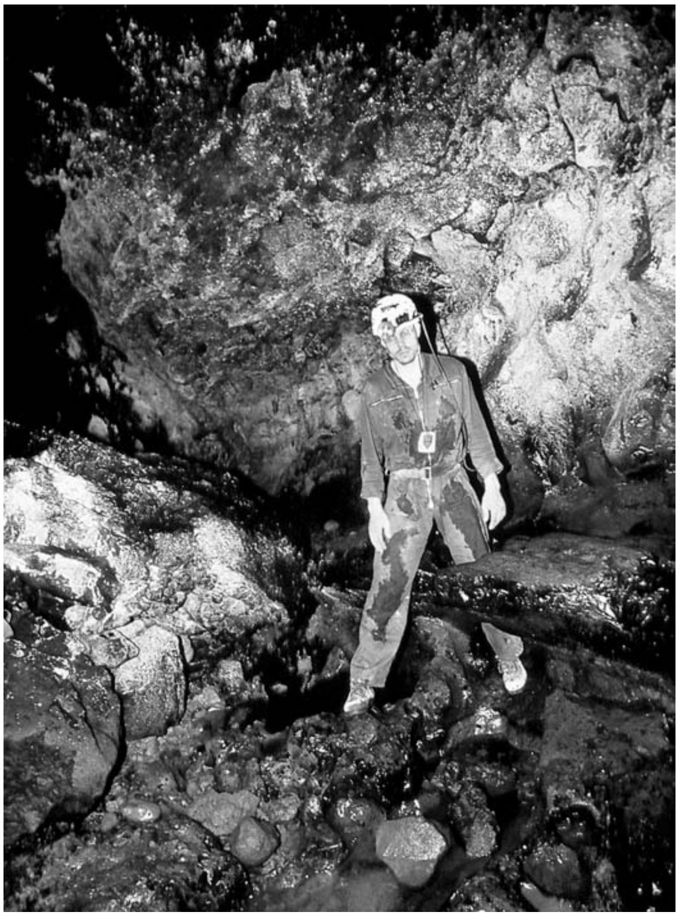


Figure 7. Ledge at St. 22 through which a stream pothole has drilled (Bauer standing with one leg in it).

Figure 8. View mauka out of Plunge Pool 1 onto the face of a former waterfall. Kempe sits on the eroded bottom sheet of the lava tube. The plunge pool eroded into reddish sediment below the lava flow, forming a circular outcrop from the left to the right side of the pool. Note the low ceiling; this is because Plunge Pool 1 is below the second secondary ceiling. Water flow has eroded a semicircular ceiling as in a phreatic tunnel.

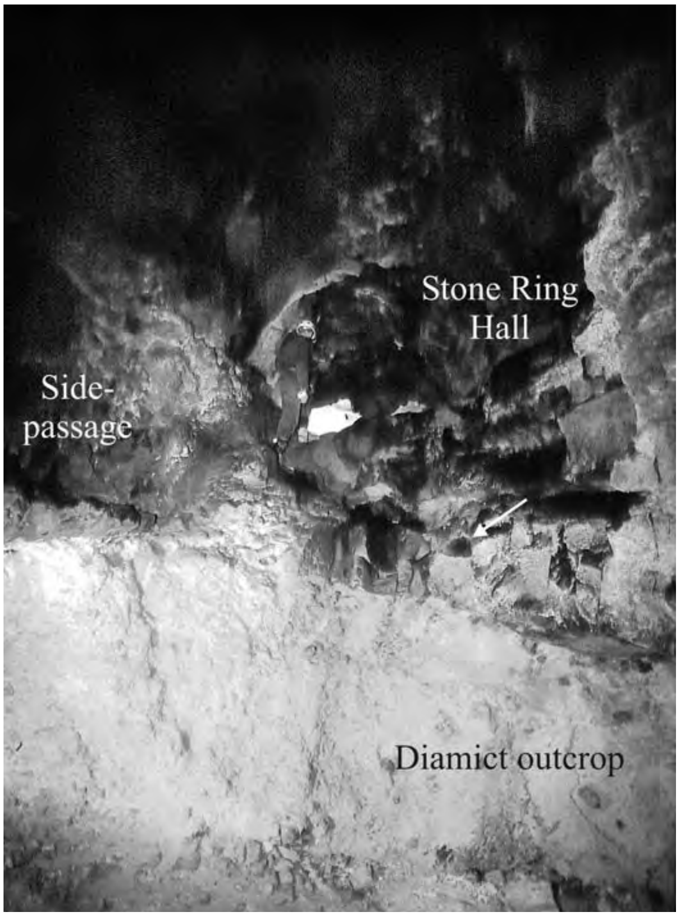


Figure 9. View mauka out of Plunge Pool 4 onto the 4 m high wall of a former waterfall. To the left, Sidepassage branches off; to the right, the Stone Ring Hall is entered. Bauer stands on several lava sheets (arrow) that have back-flooded the floor of the Stone Ring Hall, illustrating that Sidepassage was the main terminal lava feeder. The exposed, reddish diamict below the bottom sheet of the lava tube grades into brownish colors below. The sediment is composed of large blocks and fine weathered ash.

The two samples from Plunge Pool 4 are quite different; P1 (sample size 170 g) represents the red-brown matrix from the surface of the profile, while P2 (175 g) was recovered from the brown matrix at a depth of 2 m. The larger components (>1cm) enclosed in the matrix were not incorporated in the analysis. These components are rather weathered but they appear to be angular to sub-angular pieces of lava, not rounded by water transport. The <1 cm fraction of sample P1 is very fine-grained, and almost 75% of its mass is silt- or clay-sized. The <1 cm fraction of sample P2 is much more coarse-grained and shows a more linear appearance on the grain size plot. This difference within the same diamict could have come from sustained weathering in the top layer with enrichment of the paleosoil in fine-grained iron oxides and clay minerals through the disintegration of coarse-grained feldspar and augite. This would indicate that the diamict was an open system for a long

Figure 10. View from Station 62 into the phreatic outlet of the Collector (Kempe inside of Collector for scale). Note the smooth floor covered with water deposited sandy sediment.

Figure 11. View mauka into the Collector. Person stands on the waterfall wall from where the water plunged out of the Alpine Streamway into the Collector. Note pool at floor and stream worn wall with large scallops on left hand wall (Kempe at far end of Collector for scale).

Figure 12. View into the eastern end of the cast of a large tree (most probably a Koa tree) mauka of St. 63. Kempe crouches inside the rootstock, which branches into three principal roots. Note the casts of the bark on the right hand side. The tree was uprooted by the lava flow and came to rest across the flow path of the lava. The primary tube established itself just under the tree trunk.

time (i.e., it is a true paleosoil). From the many tree casts in the lava above the diamict (i.e., in the lava that formed the tube), we know that the diamict carried a fully grown forest (see large tree mold, Fig. 12), indicative of a longer time gap between the deposition of the diamict and the emplacement of the tube-bearing lava on top of it.

Three samples (P3, P4, P5; 742 143, 34.4 g, respectively) from the fluvial floor sediment of the cave were also analyzed for their grain-size distribution (Fig. 13). P3 from the Collector and P4 from the main passages near the entrance to Mudcrawl show high percentages of coarse material (more than 95 and 85% is sand and gravel, respectively), while the sample (P5) from the Mudcrawl has only 70% in the coarser fraction, mostly sand, hardly any gravel, illustrating that the water ponded in the Mudcrawl. On some of the sediment and rock samples, x-ray diffraction analyses and C-N-S analyses were made (Table 2a, b).

Sample P6 is the only one representing the lava that formed the cave. It was taken from the bottom sheet (makai of Plunge Pool 4), the layer of lava that solidified on the sediment. It is a rather hard, dark gray, fine-grained, and not very porous lava. The olivine does not form conspicuous phenocrysts, but feldspars are macroscopically visible. All other samples are devoid of olivine and have higher plagioclase and augite concentrations and contain appreciable amounts of hematite. The increased plagioclase content probably is caused by differential weathering with olivine being lost first, then augite, and then feldspar. This is nicely shown in sample P1, representing the former paleosoil, where both olivine and augite have disappeared. The increased hematite content has 2 causes. In samples P8 and P9, it is primary hematite, precipitating last on the surface of the solidifying lava, giving it its bluish hue, while in the other samples hematite is a

Table 2: A) Results of x-ray-diffraction analyses of rock samples from Pa‘auhau Civil Defense Cave. Results are estimated weight percents.

Sample March 2001	**Color** of ground sample	**Plagioclase**	**Augite**	**Olivine**	**Hematite**	**Clay**	**Residue**
P1, red-brown sediment, Plunge Pool 4, surface	Red-brown	29%	-	-	59%	12% Halloysite	High x-ray amorphous component
P2, gray-brown sediment Plunge Pool 4.2 m depth	Light gray, brownish	41%	13%	-	31%	10% Halloysite	5% undeter.
P3, fluvial sediment floor of Collector	Light brown	32%	31%	-	14%	9% Halloysite 8% Donathite*	6% undeter. Large x-ray amorphous component
P4, Fluvial floor sediment, main passage between St. 62 and 75	Light brown	46%	26%	-	15%	8% Halloysite	5% undeter. Large x-ray-amorphous component
P5, Fluvial floor sediment, Mudcrawl, St. 100	Light brown	32%	42%	-	19%		7% undeter. Large x-ray amorphous component
P6, Basal sheet of cave, St. 41, Plunge Pool 4, dark gray, low porosity, no larger phenocrysts	Gray-greenish	50%	11%	22%	5%	8% Halloysite	4% undeter. Very large x-ray amorphous component
P8 Wall of cave at St. 42, irregular lava, low porosity, light gray, rather weathered and soft	Light gray	27%	25%	-	24%	-	24% undeter. Large x-ray amorphous component
P 9 Stalactite and glazing, fragile, weathered, from inside of tree mold mauka St. 63.	Gray brownish	32%	29%	-	22%	-	7% undeter. Large x-ray amorphous component

* Donathite ((Fe,Mg)(Cr,Fe)$2O_4$)

Table 2: B) Results of carbon, nitrogen, sulfur elemental analyses of sediment samples from Pa‘auhau Civil Defense Cave (weight percent).

Sample	**C**	**N**	**S**	**C/N**
P1	0.031	0.052	0.38	0.60
P2	0.035	0.057	0.55	0.61
P3	0.15	0.072	0.11	2.05
P4	0.25	0.062	0.84	4.08
P5	0.40	0.11	0.009	3.64

weathering product causing a brownish or red-brown coloration.

Halloysite (a clay mineral) is present in appreciable quantities. Together with hematite, it is among the products of silicate mineral weathering and common in weathered basalt of Hawaii and elsewhere (e.g., Patterson 1971). In the sediment underlying the cave, it is highest in concentration, but it also occurs in the fluvial sediment that is composed of material washed into the cave from weathered rocks higher on the mountain. In addition, there is a large x-ray amorphous fraction, most probably allophane, as described in the paper by Kempe and Werner (2003).

The high halloysite content in the sediment exposed in the plunge pools is important for the speleogenesis of the cave. It could have closed the pore space of the sediment, therefore enabling the stream to flow in the cave without sinking.

Overall, the samples contain only very low concentrations of C, N, and S (Table 2B). The lowest C concentrations of 0.03% were found in the underlying diamict in the profile of Plunge Pool 4 (P1 & P2), illustrating that the diamict is not a cumulative body of fluvial sediments. Possibly it is sort of lahar, or mudflow originally incorporating unweathered ashes and lava blocks. Compared to these samples, the fluvial sediment (P3-P5) has a higher, but still very low C concentration. The highest C content was found in the sample from the Mudcrawl (P5), which has the finest sediment. The same distribution, but with a lower spread in values, is found for the total nitrogen content. The sulfur values vary greatly and are difficult to interpret. The C/N ratio is <1 for P1 and P2, indicative of inorganic nitrogen (nitrate). Even in the fluvial sediment, the ratio is rather low but more toward the composition found in soils (C/N ~6).

The composition of the diamict exposed in the plunge pool walls does not differ much from that of the solid rock; it, therefore, is most likely volcanic ash. Due to the presence of large, irregular lava pieces in the ash, it most probably did, however, not originated as an ash fall. Either the larger fractions represent aa rubble into which later ash was washed in, or the entire layer is a sort of lahar or mud flow of mixed coarse components and fine-grained material.

AGE OF THE SYSTEM

So far we can only be sure that the Pa‘auhau Civil Defense Cave is older than 60 ka, because its lava layer is a member of the Hamakua Volcanic Series (Wolfe *et al*. 1997). Eventually,

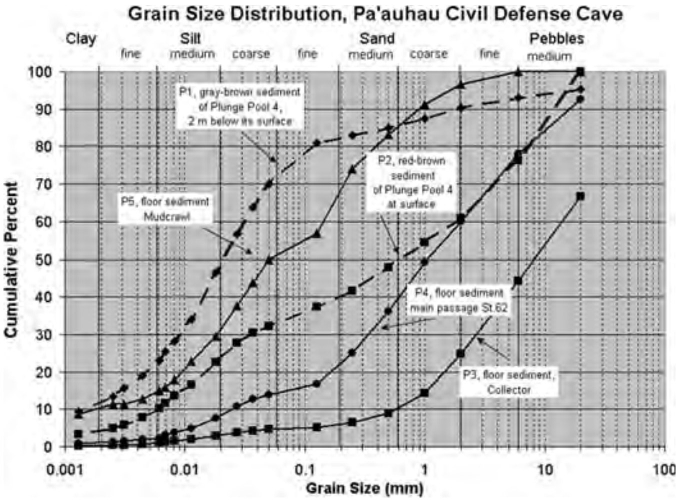


Figure 13. Plot of grain-size analyses for 5 samples from Pa‘auhua Civil Defense Cave. Broken lines indicate sediment underlying and predating the cave, solid lines denote fluvial sediment from within the cave.

better dates both for the formation of the lava conduit and of the erosional event may be obtained. This can be done by applying optically stimulated luminescence analysis to both the sediment underlying the lava tube (accessible in the plunge pools) and the fluvial sediment in the cave. We already have taken 4 samples in the dark, which can be used toward this purpose if dating can be funded.

As yet, one can only say that the erosional phase must be quite old, in spite of the fact that the erosional morphology looks very fresh, specifically in the inner part of the cave. Three clues suggest the antiquity of this erosion event: (i) the gulch is now about 20 m deeper (at the cave entrance) than at the time of the hydrologic activity in the cave; (ii) the erosion is older than the Hawaiian usage of the cave because none of their stone piles, even where placed in the middle of the vadose stream course, are disturbed; and (iii) there is a pile of soil in front of the entrance that was washed down from the plateau above. Apparently no significant amount of water has issued from the cave for some time because this pile of soil debris would have been washed away. Possibly the erosional phase dates as far back as the Last Glacial (i.e., to the time when the gulch had a higher downcutting rate than today due to snowmelt events or due to a much less extensive vegetation cover). At any rate, the Pa‘auhau Civil Defense Cave is certainly the oldest substantial lava conduit cave yet discovered on the island of Hawaii.

ACKNOWLEDGMENTS

We thank M.S. Werner, W.R. Halliday, and O. Fulks for continuous and profound help in the field, R. Apfelbach, for XRD analyses, G. Schubert for grain-size measurements, R. Brannolte for CNS analyses and E. Wettengl for help in drawing the maps, all in the Institute of Applied Geosciences, Darmstadt. We thank B. Rogers and G. Moore for their thorough reviews.

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CAVE SCIENCE NEWS

NSS CONVENTION - CALL FOR PAPERS

The NSS Section of Cave Geology and Geography is accepting abstracts of papers for presentation at the Geology and Geography Session of the 2003 NSS Convention, to be held in Porterville, California, from 4-8 August 2003. Abstracts should be no more than 250 words in length (this limit must be strictly met). In addition to the text, the abstracts should contain the title of the paper, and the name(s) and address(es) of the author(s). The abstracts should be informative summaries that include the conclusions, and not lists of topics that "...will be discussed." Bibliographies and references should not be given in the abstracts. Papers may be submitted for either oral presentation or as a poster.

Send any questions and your abstracts by mail, e-mail, disk, or fax to: George Veni 11304 Candle Park San Antonio, Texas 78249-4421 210-558-4403 413-383-2276 (fax) gveni@satx.rr.com

The deadline for abstracts is 15 May 2003. Early submissions are encouraged. Confirmation notes will be sent to everyone sending an abstract. Details on presentations times, dates, and other information will be sent to all confirmed participants after the deadline. For online details about the convention, visit: http://www.nss2003.com/

In addition to the regular sessions above, the convention will include a special GIS & Digital Mapping Symposium sponsored by the Geology and Geography Section. The symposium will include oral presentations (PowerPoint or slides) and will also offer additional slots for "how to" or software demonstrations. Presentations should be 20-30 minutes long, additional time for special presentations can be accommodated. Interested individuals are encouraged to submit papers or presentations on all topics related to GIS and digital mapping. If you have questions or are interested in presenting a paper or demonstration please contact the symposium organizer, Bernie Szukalski, at bszukalski@esri.com or call 909-793-2853 ext.1315 for more details. Abstracts for this session should be sent to Bernie. The deadlines and guidelines for abstracts given above also apply to this symposium and all NSSCON 2003 sessions.

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LETER TO THE EDITOR

An abstract published on page 187 of the December 2002 issue (v. 64, n. 3) perpetuates a charming but, unfortunately incorrect, bit of folklore: That Kenya's Kitum Cave was excavated by salt-seeking animals, primarily elephants. All participants in the 1998 excursion to that cave after the 8th International Symposium on Vulcanospeleology concluded that it primarily is solutional in origin. This also is the conclusion expressed in the scientific literature on the cave, e.g.:

Sutcliffe, A., 1967, A caving expedition to East Africa: William Pengelly Cave Studies Association Newsletter, n. 9, p. 17.
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William R. Halliday

THE NATIONAL CAVE AND KARST RESEARCH INSTITUTE: AMERICAN SPELEOLOGY'S REMARKABLE OPPORTUNITY

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Oceanography has Woods Hole and Scripps. Astronomy has Arecibo, JPL, the Hubble and Chandra orbital observatories, the VLA, and several other national research laboratories. The atmospheric sciences have NCAR. Physics and chemistry have the Stanford Linear Accelerator, Los Alamos, Savannah River, and numerous other major facilities. The development of federally funded, internationally recognized research centers available to researchers from a wide spectrum of institutions has been a rite of passage for scientific disciplines in the United States. Now it is speleology's turn to "come of age" scientifically as the National Cave and Karst Research Institute (NCKRI) enters its "gearing up" phase. Cave and karst scientists, and practitioners of its numerous sub-disciplines have an unparalleled opportunity to participate in the development of this important new entity within our community.

Currently, the National Cave and Karst Research Institute comprises a triad of primary partners. By congressional mandate, the National Park Service has the lead in establishing the Institute and the current Director is an NPS employee. The Park Service has provided 49% of this year's operating funds. The State of New Mexico has provided the remaining (51%) operating funds through another primary partner, the New Mexico Institute of Mining and Technology (NMT) in Socorro, New Mexico. NMT has two full-time employees affiliated with the Institute, a graduate student working on a cave-related thesis, and several additional graduate students who will begins cave related dissertation projects later this year.

This year, our third primary partner, the City of Carlsbad, NM, has promised $1.3 million towards the headquarters building to be located in that municipality. The State of New Mexico has encumbered $1 million towards the project. Next year's NM State budget promises another $350 thousand towards the building fund. Of the funds already committed for the Institute's building (total $4.65 million), 43% ($2 million) are federal funds. Unlike most of the federally funded research institutes mentioned above, NCKRI derives less than half its current funding from the federal coffers. In fact, its enabling act (see back cover) *requires* that Park Service funding NOT exceed 50%. This is a unique situation. Thus, it will be up to the caving community to help generate non-federal funds to ensure the growth of this resource.

As building design starts this month, the Institute looks to all of our colleagues to join in creating the long-term vision.

Many questions remain unanswered and will benefit from the pro-active involvement of experienced cave and karst researchers, educators, and land managers. Will the Institute be a site with facilities for scientists to work during sabbaticals and academic breaks? Will the Institute have working scientists on its own staff? Will the Institute initiate and run its own education programs? Or, will it only assist established programs? How might it interact with the variety of established professional groups in our discipline, including municipal governments, private consulting firms, regional water authorities, and other entities? As we develop our long-term vision of the Institute, we will have to mold the administrative structure to the tasks we envision. The legislation calls for the research institute to be "jointly administered" by the NPS and another entity. Who will be that entity and where will the balance of power lie? Will NCKRI follow the model of many DOE labs (e.g., Los Alamos, Sandia, Argonne, Ames, etc.) and be run by a single university with federal oversight? Or, will our community put together a coalition (e.g., UCAR/NCAR, NOAO/Association of Universities for Research in Astronomy, Inc.) to work with the Park Service? Each of these potential choices will have profound effects on the kind of institute NCKRI becomes.

The long-term vision, building design, and the administrative structure will mostly be decided this coming year. We will best serve our science, the caves, and our community by working together to create the strongest and best institute we can devise to serve all our varied needs.

[1]Former NSS Liaison to NCKRI

NATIONAL CAVE AND KARST RESEARCH ACT OF 1998
S.231

One Hundred Fifth Congress of the United States of America
at the second session
begun and held at the City of Washington on Tuesday, the twenty-seventh day of January, one thousand nine hundred and ninety-eight
An Act To establish the National Cave and Karst Research Institute in the State of New Mexico, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE.

This Act may be cited as the 'National Cave and Karst Research Institute Act of 1998'.

SECTION 2. PURPOSES.

The purposes of this Act are-

to further the science of speleology;

to centralize and standardize speleological information;

to foster interdisciplinary cooperation in cave and karst research programs;

to promote public education;

to promote national and international cooperation in protecting the environment for the benefit of cave and karst landforms; and

to promote and develop environmentally sound and sustainable resource management practices.

SECTION 3. ESTABLISHMENT OF THE INSTITUTE.

IN GENERAL- The Secretary of the Interior (referred to in this Act as the 'Secretary'), acting through the Director of the National Park Service, shall establish the National Cave and Karst Research Institute (referred to in this Act as the 'Institute').

PURPOSES- The Institute shall, to the extent practicable, further the purposes of this Act.

LOCATION- The Institute shall be located in the vicinity of Carlsbad Caverns National Park, in the State of New Mexico. The Institute shall not be located inside the boundaries of Carlsbad Caverns National Park.

SECTION 4. ADMINISTRATION OF THE INSTITUTE.

MANAGEMENT- The Institute shall be jointly administered by the National Park Service and a public or private agency, organization, or institution, as determined by the Secretary.

GUIDELINES- The Institute shall be operated and managed in accordance with the study prepared by the National Park Service pursuant to section 203 of the Act entitled 'An Act to conduct certain studies in the State of New Mexico', approved November 15, 1990 (Public Law 101-578; 16 U.S.C. 4310 note).

CONTRACTS AND COOPERATIVE AGREEMENTS- The Secretary may enter into a contract or cooperative agreement with a public or private agency, organization, or institution to carry out this Act.

FACILITY-

LEASING OR ACQUIRING A FACILITY- The Secretary may lease or acquire a facility for the Institute.

CONSTRUCTION OF A FACILITY- If the Secretary determines that a suitable facility is not available for a lease or acquisition under paragraph (1), the Secretary may construct a facility for the Institute.

ACCEPTANCE OF GRANTS AND TRANSFERS- To carry out this Act, the Secretary may accept—

a grant or donation from a private person; or

a transfer of funds from another Federal agency.

SECTION 5. FUNDING.

MATCHING FUNDS- The Secretary may spend only such amount of Federal funds to carry out this Act as is matched by an equal amount of funds from non-Federal sources.

AUTHORIZATION OF APPROPRIATIONS- There are authorized to be appropriated such sums as may be necessary to carry out this Act.

Speaker of the House of Representatives,
Vice President of the United States, and
President of the Senate.

National Speleological Society
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