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NATIONAL SPELEOLOGICAL SOCIETY

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The Society serves as a central agency for the collection, preservation, and dissemination of information in fields related to speleology. It also seeks the preservation of the unique faunas, geological and mineralogical features, and natural beauty of caverns through an active conservation program.

The affairs of the Society are controlled by an elected Board of Governors, which appoints national Officers. Technical affairs of the Society are administered by specialists in fields related to speleology through the Society's Biology Section, Section on Cave Geology and Geography, Social Science Section, and Research Advisory Committee.

Publications of the Society include the quarterly *Bulletin*, the monthly *News*, an annual *Speleo Digest*, *Special Publications*, and the *Caving Information Series*. Members in all categories except Family receive the *Bulletin* and *News*.

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The Relationship Between Prehistoric Man and Karst

John S. Kopper* and Christopher Young†

ABSTRACT

Approximately 95% of African, American, Asian, and European hominid fossils to about 30,000 years ago have been collected from karst and other soluble-bedrock terrains. This constitutes a considerable anomaly, since it is calculated that such terrains compose only about 13% of these land masses. The tentative conclusion is that *Australopithecus africanus, A. robustus, A. habilis, Homo erectus, H. sapiens neanderthalis,* and *H. sapiens sapiens* preferred this specialized environment. Alternative explanations for this anomaly—better fossil preservation or sampling bias— are investigated on the basis of the European data and rejected in a causal relationship. Speculation on why our forebears chose this terrain is offered. . . without arriving at a definite conclusion.

Introduction

Little is known of the range and environmental determinants of early hominids. It is part of the central dogma of anthropology that hominids increasingly inserted a growing culture between themselves and their environment and, thus, assured their survival. But, what were the tangible realities of this hypothesized environment?

A significant anomaly in the occurrence of hominid fossils suggests that our ancestors were restricted to karst/soluble-bedrock terrains§. Probably, this natural setting itself was not deliberately selected as a habitat. Rather, the writers believe these lands supplied as yet unknown, unique conditions and resources that were important to hominid survival.

In support of this hypothesis, it was found that karst/soluble-bedrock constitutes a maximum of 12%-13% of any given large terrestrial surface (Sweeting, 1973, pp 6-7). About 95% of African, American, Asian and European hominid fossils to 30,000 B.P. have been collected from such terrains. Correspondingly, 92% of the sites at which these fossils were discovered are similarly located. Thus, a minimum 6:1 statistical anomaly is present.

Several possible reasons for the anomaly—preferential preservation, sampling bias, and coincidence with climatically desirable regimes—are investigated and rejected as explanations. Thereafter, common denominators of this restricted range are reviewed.

Distribution of Fossil Hominids

Only fully descriptive sources of hominid fossil occurrence were relied upon for the data which are summarized in Tables II, III, and IV (Oakley and Campbell, 1967, Oakley *et al.*, 1972 and 1975). In a further effort to make the data quantifiable, rigorous calculations of karst/soluble-bedrock distributions were utilized in correlating fossil occurrences in Europe, America and Africa (Herek and Stringfield 1972). The Asiatic bedrock data is less rigorous and had to be gleaned from a number of sources (*e.g.* Soetarjo, 1962; Richtoffen, 1912). No fossils are known from Australia before 26,000 B.P., so this continent is not included.

Time did not permit the correlation of non-fossiliferous Lower, Middle and Upper Paleolithic sites in the Old World with bedrock (no American sites containing cultural materials are known to date, unequivocally, before about 25,000 B.P.). Thus, the arguable assumption is that osseous remains—rather than the occurrence of artifacts—most nearly delineate the true range of the hominids.

A near cutoff point of 30,000 B.P. was selected, because this just predates the climatic deterioration that ushered in the final Würm-Wisconsin glacial stage. Including the whole Upper Paleolithic would have biased the European and Asiatic results even further in the direction of concentration of humans in karst/soluble-rock areas, because of increased population densities (cave) shelter against the extreme cold, and the consequent larger number of fossils in caves.

Radiometric determinations were relied upon in applying the cutoff date or, if these were not present or were equivocal, geological data were utilized. Where neither of these were present, artifact typologies were accepted as evidence of the date of the fossil. Very early Upper Paleolithic industries, such as Aterian, Lower Perigordian, Aurignacian O & 1, and Gravettian, qualified for inclusion in the sample. Later industries, such as Ibero-Maurusian, Dabban, later Aurignacian, and Perigordian, as well as Solutrean and Magdalenian, were considered too young for inclusion. All Lower and Middle Paleolithic industries were accepted, *i.e.:*

Acheulean
Abbevillian
Clactonian
Tayacian
Sangoan

etc. and all varieties of Mousterian.

To determine the provenance of the fossils from the catalog data (Oakley and Campbell, 1967; Oakley *et al.*, 1972 and 1975), the following places mentioned in the reference as being the site of discovery were accepted as evidence for a karst association (the terms are themselves used to define karst, *e.g.* Howard, 1963:

Cave
Sinkhole
Karst fissure, cutter, open joint in limestone
Ponor, aven, doline, polje, vauclusian spring

As evidence of soluble bedrock, but not (necessarily) of a karst association, the following descriptive terms were accepted:

Rock shelter in limestone
Limestone quarry
Travertine quarry
Calcareous, soluble, limestone, carbonate, calcareous sandstone, marble, marl, gypsum, anhydrite deposit or bed or. . .

In cases where the geological description was equivocal ("well sorted river gravels", "caliches surrounding eye of fossil spring", etc.), the fossil was equated with the highest energy depositional agency locally available. This generally was water, providing either fluvial or lacustrine transport. Then, a karst/soluble-bedrock

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§ The generic term, "carbonate rock", is meant here to include most readily soluble sedimentary rocks, including limestone, calcareous sandstone, dolomite, gypsum and anhydrite. The term, "karst", is used here to describe a terrain in which the topography is chiefly formed by the dissolving of rock. Carbonate rocks may or may not be karsted; virtually all such rocks exhibit karst features to some degree.

association is inferred if the drainage system originated in such terrain. The location and extent of these areas were taken from Herek and Stringfield (1972) for Europe and America, from Bishop and Clark (1967), Flint (1970) or Houghton (1963) for Africa, and from various sources for Asia (*e.g.* Soetarjo, 1962; Richtoffen, 1912).

Where these conditions were not met, fossil provenance is recorded as a non-karst/soluble-bedrock occurrence.

Distribution of Karst/Soluble-Bedrock Terrains

Bedrock, in this context, is defined as the indurated rock exposed at the surface, if denuded, or as the rock directly underlying the soil, if soil is present. Only one worldwide estimate of the amount of calcareous rock so located on the terrestrial masses is known. Sweeting, citing Ham (1973, pp 6-7), says that 75% of the total land area is directly underlain by sedimentary rocks and that 15% of these sedimentary rocks are carbonates (limestones and dolomites); thus 11.25% of the total land surface is composed of carbonate rocks. This estimate is confirmed by Fairbridge, who says (Chilingar, Bissell, and Fairbridge, 1967, p 1):

> "Carbonate rocks constitute some 10-15% of the sedimentary rocks of the earth's crust. . . some estimates run as high as 25% by volume. . . at the present time none of the estimates is likely to be correct by ± 10%".

To check the 11¼% estimate of Sweeting, the writers estimated distributions for a number of localities, including East and West Germany 25% (Pfeiffer and Hahn, 1972), Madigascar 25% (Decary and Keiner, 1971a and 1971b), England 5% (Cullingford, 1962), and the United States 15% (Davies and LeGrand, 1972). Figure 1 shows the distributions of both karst and of soluble bedrocks for the United States. It can be consulted to gauge the accuracy of the estimate and to visualize the relationship of karsted to non-karsted soluble rock. Since Sweeting's estimate included only calcareous rock we have added an additional 1-2% to her estimate to include all soluble rocks, making a total of 12-13% of the land surface to which the hominids were confined.

It should be recognized that karsted and non-karsted soluble rocks are in no way restricted to desirable climatic or altitudinal zones. They occur at all latitudes, longitudes and elevations, and the only distribution pattern that can be assigned them is that they originated at the bottoms of ancient seas (and lakes). For the last reason, they are more frequent in coastal areas—the Mediterranean Basin is a classic example—than in continental interiors. Prehistoric hominids inhabited karst/soluble bedrock terrains from 37° south to 53° north latitudes, at elevations to 6000 ft, both on the littoral and in the interior.

Sampling Bias

The possibility that the anomalous distribution of fossil hominids might be due to sampling bias is untenible. Such an argument must inevitably be based on the assumption that more cave earth has been processed in the search for fossils than earth at other kinds of sites. This argument fails on two basic counts: (1) It is unthinkable that the total amount of earth excavated in all the caves ever investigated approaches by many orders of magnitude the amount of earth processed in excavating materials for a single large city. It could be said that these are not archaeological investigations and therefore much might be missed; in fact a great many of the fossils were found in just this way: the original Neanderthal specimen, the

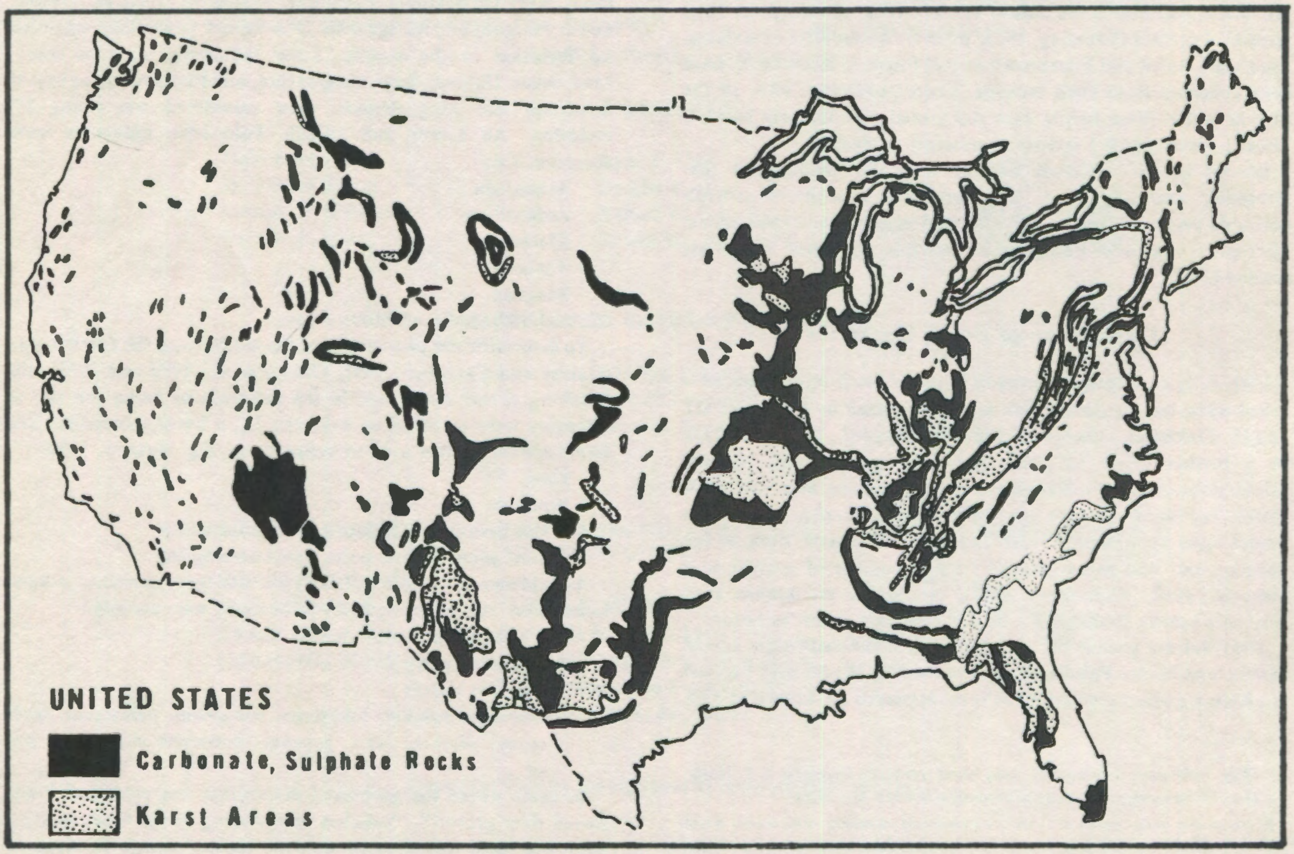


Fig. 1. Distribution of soluble bedrock and karst areas in the United States, taken from Davies and Legrand, 1972. The authors estimate that approximately 15% of the terrestrial surface is composed of such lands.

Swancombe specimen, the Břno specimens, the Mauer specimen, the Gibralter fossils, etc., etc. (2) It also is unlikely that there exists a dedicated compulsion by archaeologists to investigate only caves. The 'Sutton Principal' in economics is based on the reply given by Willie, "The Actor", Sutton when asked why he robbed banks. He replied, "Because that's where the money is". The authors suggest that the reason archaeologists investigate caves is simply because that's where the fossils are.

Karst/Soluble-Bedrock Terrains

Caves are but one manifestation of a karst, but it has long been assumed that man was drawn to them, alone, because they provide a convenient shelter. It is obvious that the prehistoric men who lived in caves had also to come to terms with the terrain, itself. Karst has been variously described, but the underlying theme remains constant: it is an area of soluble bedrock, in which solution by water predominates over other landform processes. More specifically, it is an (usually limestone) area characterized topographically by caves, cutters, and sinkholes and which contains a characteristic soil and soil distribution, flora, fauna, drainage system, geomorphology, and attendant subsystems. Karsts are very restricted in occurrence, and their true domain is a matter of recognition and definition (Jennings, 1972, pp 1-8).

The best assessment, in the literature, of the uniqueness of karst as it affects the hominids is given by LeGrand (1973, pp 859-863):

> "Moreover in most regions the influence of climate is so great that it tends to mask the more subtle influences of underlying rocks except for certain special situations. Limestone terranes form one such exception...
>
> "The interplay between carbonate rocks and climate, geologic, topographic, and hydrologic factors creates a wide variety of environments, ranging from the subsurface to the surface and particularly determining soil patterns and water distribution. These environments, in turn, have had their effect on the local development of plants and animals and on the culture and history of man...
>
> "Some of the characteristic problems of carbonate rock terranes, such as those related to scarcity of soils, scarcity of surface streams, and rugged topography, are obvious and somewhat distinctive; these characteristic features are developed by natural processes. In fact, natural processes in some carbonate regions may have caused a greater restriction in the development of biota than man can ever be suspected of causing. There are complex, insidious problems that develop as man disturbs the natural balance of geologic and hydrologic conditions in carbonate rock terranes...
>
> "Carbonate rocks are exposed and karstified in glacial, temperate, and tropical settings that range from wet to very dry. Karst in arid regions, such as the Western Desert of Egypt and the Nullarbor Plain of Australia, is mostly a relic of development during an earlier and more humid period...
>
> "Karst topography is uneven...While undergoing karstification, many carbonate rocks have little insoluble residue, and their soils are regenerated more slowly than those on insoluble rocks. Once carbonate rocks on upland slopes have been stripped of soil they tend to remain denuded, even in humid regions where soil-forming processes are favorable. Soils of upland karst regions are washed into sinkholes and other karst lowlands. In some low-lying areas, the soils are protected from further removal long enough to form laterite and even bauxite...
>
> "The permeability of the entire carbonate rock system is important because while caverns and other openings are enlarging and while permeability is increasing, the water table is progressively lowering itself to greater depths below the land surface...but many practical problems in carbonate areas are related to permeability. These include 1) scarcity and poor predictability to groundwater supplies, 2) scarcity of surface streams, 3) instability of the cavernous ground...In most karst regions of the world the permeability is too high or too low for water supply needs... The dependence of some biota on streams and the convenient uses that man has made of streams is well known and need not be reviewed here...The centralization of water discharge as large springs...
>
> "We often assume that there was a fair degree of ecological balance in all regions of the world before man significantly changed the landscape. Yet in karst regions, more than in any other specialized environment, ecological conditions were already skewed and the biota were developed in specialized and sometimes erratic ways. The scarcity of soils, the scarcity of water at the land surface, the rugged terranes are not conducive to a flourishing and expansive environment..."

Non-Karst/Soluble-Bedrock Occurrence of Fossil Hominids

The results of the study of the occurrence of the fossils are described fully in Tables II, III, and IV and were summarized in the introduction. Exceptions to the general rule of confinement to karst/soluble-bedrock terrains must be considered. Most of these exceptions occur in the rift valley deposits of East Africa. Although a few caves are known in the rift valleys (Gambel's and Lion Hill caves, for example), this huge district is certainly not a karst nor is the bedrock calcareous.

Most of the fossils are australopithecines, but *Homo erectus* is also present and the new, very early *Homo sp.* of Richard Leakey comes from the east Lake Rudolph area. *Kenyapithecus wickeri* specimens from Ft. Ternan and Rusinga Island, almost certainly ramapithecines, provide an early date (Upper Miocene) for the hominid occupation of the area; the period represented extends from around 12,000,000 to later than 1,000,000 years B.P. It cannot be argued, then, that the rift valley district represents a chance utilization during a short period of time or that the fossil compliment—more than 30 individuals—is so limited as to make it a special case.

Geologically, the fossiliferous deposits can be described as lacustrine (generally) or fluvial (occasionally) beds composed of indurated or loose sediments mostly of volcanic origin (Bishop and Clark, 1967). The obvious association is with former water sources.

The hydrology of the rift valley system provides a unique case. Tectonics resulting from relative motion between the African, Arabian and Indian plates has produced active vulcanism and great vertical displacement of the land surface. The net effect is an elongated basin that acts as a catchment for runoff from the surrounding upland. Drainage is toward the basin and groundwater control over this great area is exercised by the lakes at its bottom—functions that are assumed by the oceans and seas in most other contexts. This hydrological regime has produced a very rugged landscape, one incised by deep gorges and containing few surface water occurrences besides the great lakes themselves. The lakes have varied greatly in depth and aerial extent as the crust under them went up and down. Two conclusions are drawn from the special circumstances that attend the occurrence of the fossils: 1) The area has always (since the lower Miocene) entertained a singular hydrological environment; 2) The nature of the drainage system has tended to concentrate and preserve, rather than to disperse and destroy, mammalian remains. Reinforcing the latter aspect is the fact that most of the sites are located in desert areas adjacent to temporary lake levels where preservation is regarded as optimum, particularly when associated with deposit on or under volcanic sediments. The potential of the area in this regard can be judged by the existance of 28 major Tertiary fossil sites in the eastern and western rift valleys of the Congo, Kenya, and Uganda alone (Bishop and Clark, 1967).

Occurrence of Non-Hominid Fossils in Europe

To test the hypothesis that the relationship between early man and karst/carbonate terrains may have been one of preference, the occurrence of other Plio-Pleistocene mammalian fossils were investigated. The rationale being that, if a substantial number of other mammals of the Late Tertiary and Quaternary were to have been found in non-carbonate contexts, then the hypothesis would be strengthened.

It is Halstead's contention (1969, 1971) that lowland areas offer the best preservation conditions and that highland species are often excluded from the fossil record because they inhabit zones of maximum erosion. He amplifies this by remarking that highland animals are only preserved in limestone terrains, because their bones are caught in caves and fissures and, thus, are protected from the mechanically destructive effects of erosion. It is obvious from the context that he is considering the Cenozoic era as a whole and is, therefore, dealing with a preservation period (average length 34,000,000 years, based on a 68 x 10^6 year Cenozoic) much longer than the total time of hominid existence.

A more realistic estimate of the geological conditions conducive to the preservation of hominid fossils can be gained from Kurtén (1968). Unfortunately, his data—which cover the Late Pliocene and Pleistocene of Europe—cannot be quantified because the numbers of individuals of each species are not enumerated. As a general statement regarding the preservation of the Villafranchian fauna, he remarks (*op. cit.*, p. 8):

> "Deposits containing fossils of Villafranchian age have been found at many sites in Europe. Some of the best known lie in Central and Southern France and Northern Italy and include both fluviatile and volcanic deposits. In addition, Villafranchian cave deposits are common in a belt further east, especially in Hungary and neighboring areas. The correlation between the eastern and western localities is difficult, for the *cave sediments mostly contain the bones of small animals*, whereas larger forms are predominant at open air sites." (emphasis added)

In order to specify actual occurrences, the writers have taken from Kurtén (*ibid.*: Fig. 1 and pp. 1-39) the most important Astian, Villafranchian, Middle and Upper Pleistocene faunal sites and correlated them with bedrock geology (Herek and Stringfield, 1972). The French and German sites are indicated on the maps, Figures 2 and 3. In this way, karst/carbonate associations can be calculated. The lists of sites that follow include the type of deposit and the bedrock association, where they could be determined:

About one-half of the sites in Table I are associated with karst/carbonate-derived deposits. The remaining half cannot be related in any way to carbonate rocks. The results tend to support our thesis: despite the mechanically (and chemically) better preservation conditions on carbonate rocks only about 50% of Late Tertiary and Quaternary fossil mammal sites of Europe occur in this domain. As noted earlier, 99% of European hominid fossil sites are found in karst/carbonate domains.

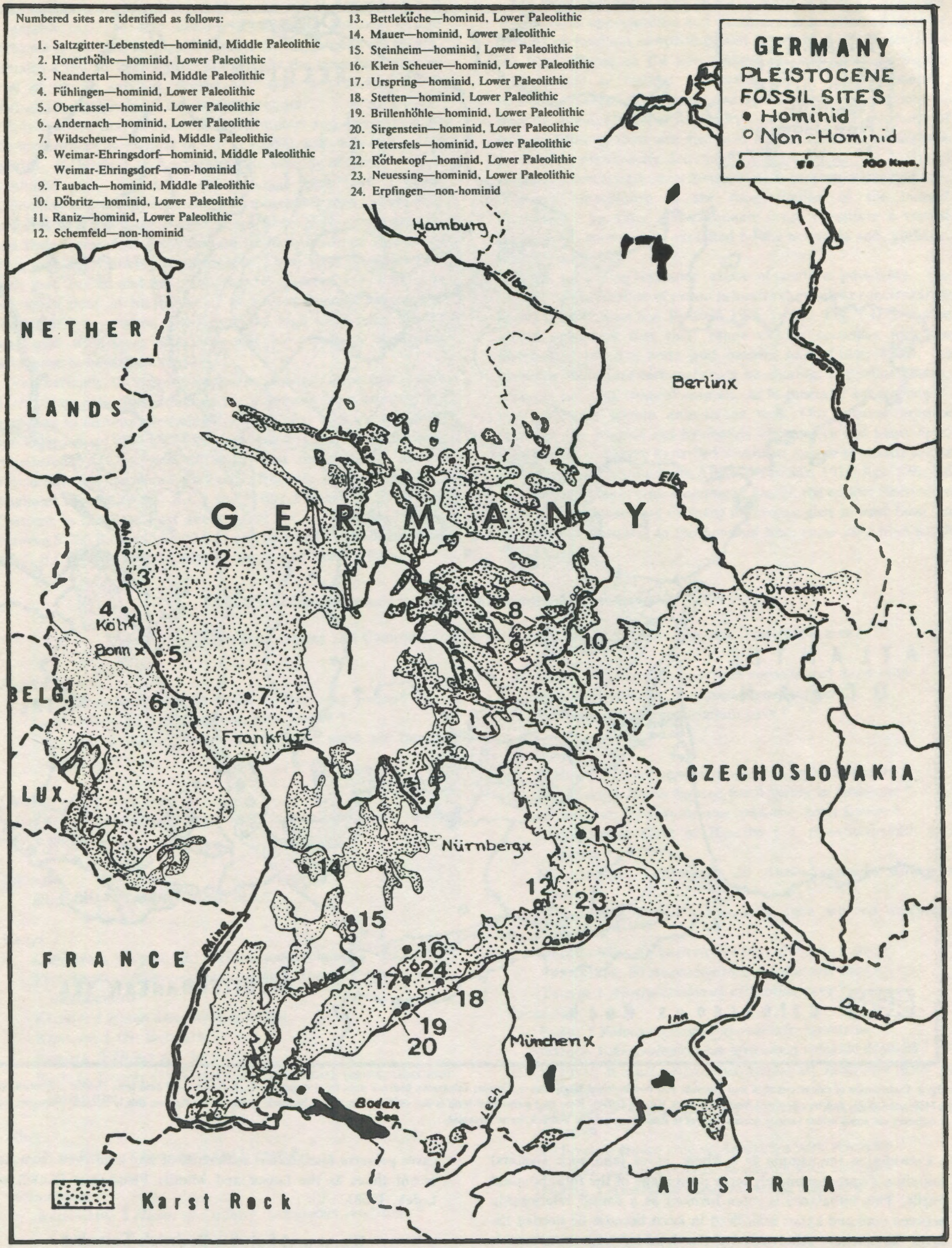
When large animals are known primarily from karst deposits—note that caves tend to contain smaller individuals, per Kurtén (above)—they often are given the specific or subspecific designation *spelaeus*, or a variant of the same. Thus, *Ursus spelaeus, Crocuta crocuta spelaea, Felis leo spelaea* and *Myotragus balearicus*, the cave bear, cave hyena, cave lion and cave antelope are considered karst animals. European Pleistocene hominids are similarly restricted in occurrence. Serving to amplify this association is the fact that non-cave human fossils of this period are often found in the open karst sites with cave animals—as at Steinheim, Mauer and Ehringsdorf (Kurtén, 1968, pp. 60-277). It is also significant that the only other surviving European primate species, *Macaca sylvana* (the Gibralter "ape") is known only in fossil form from cave sites (*ibid.*, pp. 30-31).

There is another line of evidence that is equally suggestive of the karst/carbonate hominid association. An important source of Pleistocene fossils are the sites at which catastrophic events resulted in massive kills. Although few in number, such sites are important because they are considered to preserve a cross-section of all species occurring in the area. Vulcanism is the usual destructive agency and Seneze on the Rhone River is an example of this kind of site. Oakley *et al.* (1972, p. 107) list only one known prehistoric hominid fossil originating from this kind of deposit and it is of uncertain date and authenticity.

TABLE I

Country	Site	Type of Deposit and Bedrock
Spain		
	Valverde de Calatrava	?, probably carbonate *
	Villaroya	fluvial, carbonate bedrock *
England		
	East Anglia Crags	marine gravel deposits, limestone bedrock *
	Swanscombe Ilford	fluvial gravels, drainage on limestone *
France		
	Mt. Perrier	fluvial deposits, non-carbonate drainage
	Chatillon Saint-Jean	Fluvial deposits, non-carbonate drainage
	Seneze	volcanic beds, carbonate bedrock *
	Vialette	fluvial deposits, non-carbonate sedimentary formation
	Salles	fluvial deposits, non-carbonate sedimentary formation
	Saint Vallier	loess beds, igneous bedrock
	Chagny	fluvial deposits, igneous bedrock
Netherlands		
	Teglen	fluvial deposits, drainage on limestone *
Italy		
	Villafrance de Asti	fluvial deposits, non-carbonate drainage
Italy (cont'd)		
	Leffe	fluvial deposits, non-carbonate drainage
	Val d'Arno	fluvial/lacustrine deposits, non-carbonate bedrock
Germany		
	Erpfingen	cave*
	Steinheim	fluvial deposits, karst drainage *
	Schernfeld	karst fissure *
	Ehringsdorf	fluvial deposits, karst drainage *
Hungary		
	Villany	karst fissure *
Poland		
	Rebielice	karst fissure *
	Kadzielnia	sinkhole *
Romania		
	Olet	fluvial deposit, karst drainage*
U.S.S.R.		
	Mariupol	fluvial deposits, non-carbonate drainage
	Taganrog	fluvial deposits, non-carbonate drainage

* Indicates a karst/carbonate bedrock association with the fossil site.



Numbered sites are identified as follows:

1. Saltzgitter-Lebenstedt—hominid, Middle Paleolithic
2. Honerthöhle—hominid, Lower Paleolithic
3. Neandertal—hominid, Middle Paleolithic
4. Fühlingen—hominid, Lower Paleolithic
5. Oberkassel—hominid, Lower Paleolithic
6. Andernach—hominid, Lower Paleolithic
7. Wildscheuer—hominid, Middle Paleolithic
8. Weimar-Ehringsdorf—hominid, Middle Paleolithic
   Weimar-Ehringsdorf—non-hominid
9. Taubach—hominid, Middle Paleolithic
10. Döbritz—hominid, Lower Paleolithic
11. Raniz—hominid, Lower Paleolithic
12. Schemfeld—non-hominid
13. Bettleküche—hominid, Lower Paleolithic
14. Mauer—hominid, Lower Paleolithic
15. Steinheim—hominid, Lower Paleolithic
16. Klein Scheuer—hominid, Lower Paleolithic
17. Urspring—hominid, Lower Paleolithic
18. Stetten—hominid, Lower Paleolithic
19. Brillenhöhle—hominid, Lower Paleolithic
20. Sirgenstein—hominid, Lower Paleolithic
21. Petersfels—hominid, Lower Paleolithic
22. Röthekopf—hominid, Lower Paleolithic
23. Neuessing—hominid, Lower Paleolithic
24. Erpfingen—non-hominid

Fig. 2. Distribution of karst areas and of hominid and non-hominid fossil sites in East and West Germany; karst information taken from Pfeiffer and Hahn (1972), hominid fossil data from Oakley, Campbell, and Molleson (1972), and non-hominid fossil data from Kurtén (1968).

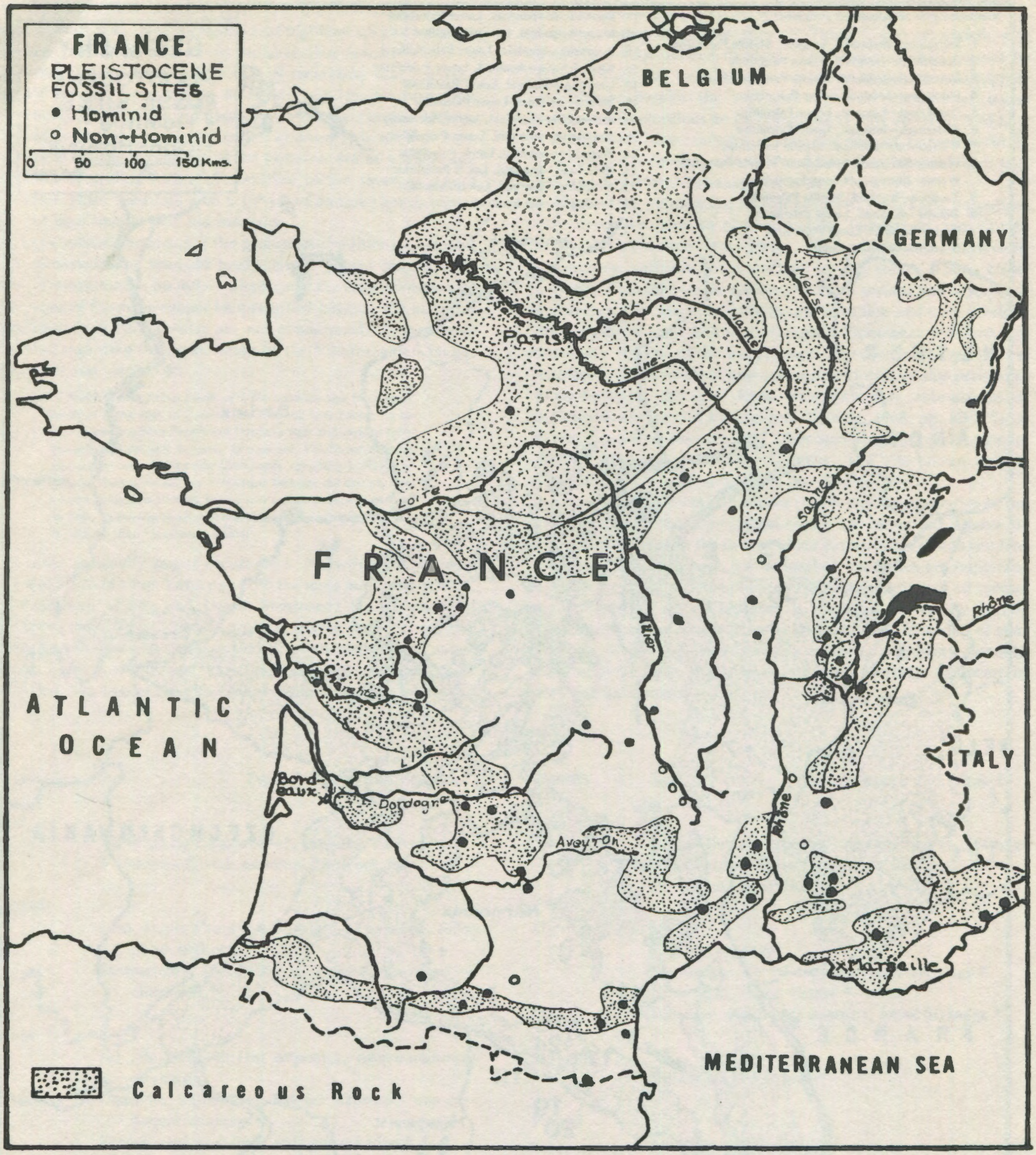


Fig. 3. Distribution of calcareous rock and hominid and non-hominid fossil sites in France; calcareous bedrock data from Avias (1972), hominid fossil data from Oakley, Campbell, and Molleson (1972), and non-hominid fossil data from Kurtén (1968). Note that a standard term is not used to identify the bedrock in any of the figures; this is because geologists from different countries utilize various nomenclatures in describing soluble bedrock/karst terraines.

Considering the sample as a whole, caves (and rock shelters) contain a disproportionately large percentage of the total hominid fossils. This imbalance is often invoked as a causal relationship between man and karst: man lived in karst because he needed the caves for shelter. Alternatively, the lopsided representation is explained as preferential preservation. While the former may have some validity, the latter is doubtful because caves often offer poor survival potential for bone of any kind (Caumartin, 1963; Kopper and Creer, 1973). Further, it has long been recognized that few caves preserve fossiliferous sediments of any kind even from such recent times as the Lower and Middle Pleistocene (Kukla and Ložek, 1958).

Karst and Soluble Bedrock Terrains as Human Habitats

If early man lived largely in karst/soluble-bedrock areas, as seems the case, what special conditions did this habitat provide? A unique hydrology is certainly one obvious common denominator; it is notable that the only non-karst carbonate bedrock terrain occupied by the early hominids in force, the east African rift valleys, contains a similar hydrological domain. At the most fundamental level of species survival, subsistance, such a hydrology offers distinct advantages to an omniverous primate.

It is assumed that all hominids were hunters and gatherers until the invention of agriculture (8,000 to 12,000 years ago in the Old World). To hunters and gatherers, the scarcity of surface water combined with other karst features may have been a boon. Vegetation is generally restricted to topographic lows, where soils have developed and where water is available. Herbiverous animals and their carniverous predators are similarly confined because of their food and drinking requirements. Thus, both the game that early man hunted and the plants that he gathered were limited to restricted areas of his range... and were, therefore, easier to predict and to monitor. Obviously, the high local relief usually associated with these terrains would have been a significant advantage to human hunters.

Very certainly, these lands became increasingly important to man during later prehistoric times as he progressed from hunting and gathering to farming. Probably, his familiarity with the somewhat specialized flora and fauna of these regions was at least partly responsible. At any rate we know that most of the earliest agriculture was developed in karst/carbonate regions: Northern Thailand around 10,000 B.C.; the "Hilly Flanks" of the Fertile Crescent in the Near East about 8,000 B.C.; Tehuacán, Mexico between 5,200 B.C. and 3,400 B.C.; Greece and the Balkans about 4,500 B.C. and somewhat later in Egypt and North Africa.

But larger questions must be asked if our hypothesis is correct. What unique opportunities and constraints were imposed by these terrains on hominid morphology and behavior? Much speculation has been offered on the development of such distinctly human achievements as bipedal locomotion, rapid brain expansion, profound changes in dentition and spoken language, coöperative hunting, manipulation of the environment and other attributes of culture. Most of these are discussed as they relate to subsistance procural in climatically determined biomes. Is not, as LeGrand suggests (above), carbonate bedrock, as it controls water and soil, of equal importance in the determination of the biome? Specifically, do karst and carbonate lands constitute a special econiche?...an econiche exploited by the hominids and, perhaps, other primates?

Some tantilizing evidence exists of such a possibility. The worldwide distribution of extant primates shows their concentration in just these regions (*i.e.* Birdsell, 1975, p. 183, Fig. 7-1). It can be quickly observed that their range exactly coincides with the distribution of terra rossa and bauxite soils (Creer, 1968), the insoluble residues of carbonate rock weathering. The primates may, thus, be not only tropical animals, as is generally acknowledged, but carbonate terrain animals as well. Our nearest primate relatives, the pongids and hylobatids (the greater and lesser apes) are confined to heavily karstified Southeast Asia or to laterite soil or karst regions of SubSaharan Africa (Reynolds, 1971, figs. 3-9). All 30-plus examples of *Gigantopithecus blacki*, the extinct Pleistocene giant "ape", considered by many anthropologists to have been the closest of all primates to the hominid line, came only from south China caves.

TABLE II. African Hominid Fossils of the Pliocene and Pleistocene to 30,000 B.P.

The data are taken from Oakley and Campbell (1967), with genus and species designations from that source.

Algeria
Afalou-Bou-Rhummel; 50 *Homo sapiens*; rock shelter*
La Mouillah; 15 *Homo sapiens*; rock shelter *
Ternifine; 3 *Atlanthropus mauritanicus*; sand pit (marine origin ?) *

Chad
Yayo; 1 *Tchandanthropus uxoris* (australopithecine): fluvial sands

Ethiopia
Diredawa; 1 Neanterthaloid; cave*

Kenya
Chemeron; 1 *Homo sp.*; surface, unassociated
Fort Ternan; *Kenyapithecus wickeri* (ramapithecine); open, unassociated
Kanam; 1 *Homo kanamensis*; fluvial
Kanapoi; 1 (?); lacustrine
Kanjera; 5 *Homo sp.*; lacustrine
Rusinga Island; (?) *Kenyapithecus wickeri* (ramapithecine): lacustrine

Libya
Haua Fteah; 2 Neanderthaloid; cave *

Mozambique
Kassimatis; 1 *Homo sp.*; quarry, calcareous sandstone *

Morocco
Dar es-Soltan; 2 *Homo sapiens*; cave *
Jebel Ighoud; 2 *Homo neanderthalensis*; karst fissure in mine *
Mugharet El-'Aliya; 2 *Homo neanderthalensis*; cave *
Rabat; 1 *Homo sp.*; quarry in consolidated dune sands *
Sidi Abderrahman; 1 *Atlanthropus sp.*; cave *
Temara; 1 Pre-neandertalian; cave *

South Africa
Boskop; 1 *Homo capensis*; open site in karst terrain *
Florisbad; 1 *Homo helmei*; fossil spring in limestone *
Kromdraai; 6 *Paranthropus robustus*; karst fissure *
Makapansgat Cave of Hearths ; 1 Neanderthaloid; rock shelter *
Makapansgat Limeworks; 30 *Australopithecus africanus*; cave *
Saldanha; 1 *Homo saldanensis*; open site on calcareous bedrock *
Sterkfontein; 40 *Australopithecus africanus*; cave *
Swartkrans; 60 *Australopithecus robustus*; cave *
Taung; 1 *Australopithecus africanus*; cave *

Tanzania
Eyasi; 2 *Palaeoanthropus njarasensis*; lacustrine
Garusi; 1 *Australopithecus africanus*; volcanic deposits
Olduvai; 6 *Australopithecus africanus*; lacustrine with volcanics
Olduvai; 3 *Australopithecus robustus*; lacustrine with volcanics
Olduvai; 3 *Homo erectus*; lacustrine with volcanics
Olduvai; 3 *Homo erectus;* lacustrine with volcanics
Peninj; 1 *Australopithecus robustus*; lacustrine

(continued on page 24)

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* Indicates karst/carbonate bedrock association with fossil, as interpreted by the present writers.

TABLE II (Cont'd)

Zambia
Broken Hill; 3 *Homo rhodesiensis*; cave *

Ethiopia & Kenya—Adeenda
Omo River; 10 *Australopithecus africanus*; fluvial and open sites
Omo River; 3 *Australopithecus robustus*; fluvial and open sites
Lake Rudolph; 30 Australopithecines; lacustrine and open sites

Total sites—31
Total sites with karst/calcareous bedrock associations—22
Percent karst/calcareous bedrock association—70

Total fossils—234
Total fossils with karst/calcareous bedrock association—204
Percent karst/calcareous bedrock associations—87

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* Indicates karst/carbonate bedrock association with fossil, as interpreted by the present writers.

TABLE III. European Hominid Fossils of the Pliocene and Pleistocene to 30,000 B.P.

The data are taken from Oakley, Campbell and Molleson (1972), with genus and species designations from that source.

Belgium
Engis; 4 *Homo neanderthalensis*; cave *
Fond-de-Forêt; 1 Neanderthaler; cave *
La Naulette; 1 Neanderthaler; cave *
Spy; 3 Neanderthalers; cave*

British Isles
Kent's Cavern; 1 *Homo sp.*; cave *
St. Brelade; 2 *Homo breladensis*; cave *
Swanscombe; 1 *Homo protosapiens*; fluvial gravel, limestone drainage *
Pontnewydd; 1 *Homo sp.*; cave *

Czechoslovakia
Břno; 3 *Homo sapiens*; loess, karst drainage*
Gánovce; 1 *Homo neanderthalensis*; quarry in limestone *
Kúlna; 1 *Homo neanderthalensis*; cave *
Mladeč; 10 *Homo sp.*; cave *
Ochoz; 1 *Homo primagenus*; cave *
Palffy; 1 *Homo sp.*; cave *
Pavlov; 3 *Homo sapiens*; open site in karst *
Předmosti; 30 *Homo sapiens*; open site in karst *
Šala; *1 Neanderthaloid*; fluvial, karst drainage *
Silická Brezova; 1 *Homo sapiens*; karst fissure *
Šipka; 1 *Homo neanderthalensis*; cave *
Sv. Prokop; 1 *Homo sapiens sapiens*; cave *
Svitávka; 1 *Homo sapiens sapiens*; clay deposit in karst *

France
Angles sur L'Anglin; 1 *Homo neanderthalensis*; rock shelter. *
Arago; 12 *Homo sp.*; cave *
Arcy-sur-Cure; 25 *Homo sapiens*; cave *
Bau de L'Aubesier; 2 *Homo sapiens*; rock shelter *
Baume des Peyards; 2 *Homo sapiens*; rock shelter *
Caminero; 1 *Homo neanderthalensis*; cave *
Castelmerle; 4 *Homo sapiens sapiens*; rock shelter *
La Cave; 1 *Homo sapiens neanderthalensis*; rock shelter *
La Chaise; 17 *Homo sp.*; cave *
1 *Homo sapiens sapiens*; cave *
La Chapelle-aux-Saints; 1 *Homo neanderthalensis*; cave *
Châteauneuf-sur-Charente; 3 *Homo neanderthalensis*; cave *
La Combe; 1 *Homo sapiens sapiens*; cave *
Combe Capelle; 1 *Homo sapiens*; rock shelter *
Combe-Grenal; 1 *Homo sapiens*; cave *
Le Cottés; 2 *Homo sapiens*; cave *
Cro-Magnon; 5 *Homo sapiens sapiens*; rock shelter *
La Crouzade; 1 *Homo sp.*; cave *
La Ferrassie; 6 *Homo neanderthalensis*; rock shelter *
Fontéchevade; 3 *Homo sapiens*; cave *
3 *Homo neanderthalensis*; cave *
Genay; 1 *Homo neanderthalensis*; open site, calcareous bedrock *
La Gravette; 1 *Homo sapiens sapiens*; rock shelter *
Hortus; 38 *Homo sapiens neanderthalensis*; cave *
Le Lazaret; 3 *Homo sp.*; cave *
Macassargues; 3 *Homo neanderthalensis*; cave *
Malarnaud; 3 *Homo sp.*; cave *
Marillac; 2 *Homo neanderthalensis*; cave *
La Masque; 3 *Homo sp.*; cave *
Monsempron; 7 *Homo neanderthalensis*; karst fissure *
Montmaurin; 3 *Homo sp.*; sinkhole *
Le Moustier; 2 *Homo neanderthalensis*; rock shelter *
Organac-L'Aven; 3 *Homo sp.*; cave *
Pair non Pair; 3 *Homo sapiens sapiens*; cave *
Pech de L'Aze; 1 *Homo neanderthalensis*; cave *
Le Petit-Puymoyen; 6 *Homo neanderthalensis*; cave *
Le Placard; 1 *Homo neanderthalensis*; cave *
Grotte Putride; 1 *Homo sapiens neanderthalensis*; cave *
La Quina; 10 *Homo sapiens neanderthalensis*; rock shelter *
3 *Homo sapiens sapiens*; rock shelter *
Regourdou; 1 *Homo neanderthalensis*; cave *
René Simard; 3 *Homo neanderthalensis*; cave *
Rigabe; 1 *Homo sapiens neanderthalensis*; cave *
Roc de Marsal; 1 *Homo neanderthalensis*; cave *
Les Roches; 2 *Homo sapiens sapiens*; rock shelter *
La Rochette; 6 *Homo sapiens sapiens*; rock shelter *
Les Rois; 2 *Homo sapiens sapiens*; rock shelter *
Soulabé-les-Maretas; 1 Neanderthaloid; cave *
Vergisson; 3 *Homo neanderthalensis*; cave *

Germany
Honerthöhle; 2 *Homo sapiens sapiens*; cave *
Mauer; 2 *Homo heidelbergensis*; fluvial, karst drainage *
Neanderthal; 1 *Homo neanderthalensis*; cave *
Neuessing; 1 *Homo sp.*; rock shelter *
Salzgitter-Lebenstedt; 1 *Homo sp.*; fluvial, karst drainage *
Sirgenstein; 2 *Homo sapiens sapiens*; cave *
Steinheim; 1 *Homo steinheimensis*; fluvial, karst drainage *
Tauback; 2 *Homo sp.*; travertine quarry *
Weimar-Ehringsdorf; 9 *Homo sp.*; travertine quarry *
Wildscheuer; 2 *Homo neanderthalensis*; cave *

Gibraltar
Devil's Tower; 1 *Homo neanderthalensis*; cave *
Forbes Quarry; 1 *Homo neanderthalensis*; limestone quarry *
Genista Cave; 1 *Homo sp.*; cave *

Greece
Petralona; 1 *Homo sapiens neanderthalensis*; cave *

Hungary
Istállóskö; 1 *Homo sapiens sapiens*; cave *
Subalyuk; 2 *Homo sapiens neanderthalensis*; cave *
Tapolca; 1 *Homo sapiens sapiens*; rock shelter *
Vértesszöllös; 2 *Homo erectus*; travertine quarry *

Italy
Bisceglie; 1 _Homo neanderthalensis_; cave *
Camerota; 1 _Homo neanderthalensis_; cave *
Ca'Verde; 2 _Homo sp._; clay pit, karst drainage *
Circeo; 4 _Homo neanderthalensis_; cave *
Leuca; 1 _Homo neanderthalensis_; cave *
Pofi; 1 _Homo sp._; lacustrine deposits on carbonate bedrock *
Quinzano; 1 _Homo sp._; cave *
Saccopastore; 2 _Homo Neanderthalensis_; fluvial, karst drainage *
San Bernardino; 1 _Homo sapiens_; cave *
Sedia del Diavolo; 1 _Homo sp._; limestone quarry *
Uluzzo; 1 _Homo neanderthalensis_; cave *
2 _Homo sapiens sapiens_; cave *

Netherlands
Beegden; 2 _Homo sapiens neanderthalensis_; fluvial, karst drainage *

Portugal
Columbeira; 1 _Homo sapiens neanderthalensis_; cave *
Salemas; 2 _Homo sapiens_; karst fissure *

Romania
Ciolovina ; 1 _Homo sapiens_; cave *
Ohaba-Ponor; 1 _Homo neanderthalensis_; cave *

Spain
Barranc Blanc; 1 _Homo sapiens_; cave *
Carigüela; 6 _Homo sapiens_; cave *
Cova Negra; 1 _Homo neanderthalensis_; cave *
Lezetxiki; 1 _Homo sapiens neanderthalensis_; cave *

Switzerland
Saint-Bras; 1 _Homo sapiens neanderthalensis_; cave *

U.S.S.R.
Akhshtyr'; 1 _Homo sp._; cave *
Azykhskaya Peshchera; 1 Neanderthaler; cave *
Dzhruchula; 1 Neanderthaler; cave *
Kiik-Koba; 2 Neanderthaler; cave *
Rozhok; 1 _Homo sapiens_; open site, bedrock unknown
Starosel'e; 2 _Homo sapiens_; open site, carbonate bedrock *
Teshik-Tash; 1 Neanderthaler; cave *

Yugoslavia
Krapina; 14 _Homo neanderthalensis_; rock shelter *
Velika Pečina; 1 _Homo neanderthalensis_; cave *
Veternica; 1 _Homo sapiens_; cave *

Total sites—114
Total sites with karst/calcareous bedrock association—113
Percent karst/calcareous bedrock association—99.1

Total fossils—353
Total fossils with karst/calcareous bedrock association—352
percent karst/calcareous bedrock association—99.9

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* Indicates karst/carbonate bedrock association with fossil, as interpreted by the present writers.

TABLE IV. Asian and American Hominid Fossils of the Pliocene and Pleistocene to 30,000 B.P.

The data are taken from Oakley, Campbell and Molleson (1975), with genus and species designations from that source.

Peoples Republic of China
Changyang; 1 _Homo sp._; cave *
Choukoutien; 49 _Homo erectus_; cave *
Kwangsi Province (?); 2 _Homo erectus_; bedrock unknown
Keiyuan; 1 _Ramapithecus punjabicus_; coal deposit *
Lantian; 2 _Homo erectus_; open site on carbonate bedrock *
Liukang; 1 _Homo sapiens_; cave *
Mapa; _Homo solensis_; cave *
Tingtsun; 1 Neanderthaler; bedrock unknown

India
Haritalyangar; 6 _Ramapithecus punjabicus_; riverine sandstones *

Indonesia
Kedungbrubus; 1 _Homo erectus_; fluvial deposits, carbonate bedrock *
Modjokerto; 1 _Homo erectus_; fluvial deposits, carbonate bedrock *
Ngandong; 14 _Homo solensis_; fluvial deposits, carbonate bedrock *
Sambungmachan; 1 _Homo sp._; fluvial deposits, carbonate bedrock *
Sangiram; 24 _Homo erectus_; fluvial deposits, carbonate bedrock *
Trinl; 9 _Homo erectus_; fluvial deposits, carbonate bedrock *

Iran
Bisitun; 1 Neanderthaler; cave *
Tamtana; 1 _Homo sp._; cave *

Iraq
Shanidar; 7 _Homo sapiens neanderthalensis_; cave *

Israel
Wadi Amud; 5 _Homo sapiens neanderthalensis_; cave *
Djebel Kafzeh; 9 _Homo sp._; cave *
Geluah; 1 _Homo sp._; cave *
Hozorea; 5 _Homo erectus_; open site on carbonate bedrock *
Me 'Arat Shovakh; 1 Neanderthaler; cave *
Mugharet El-Kebarah; 7 _Homo sapiens_; cave *
Mugharet Es-Skūl; 10 _Homo sapiens_, cave *
Mugharet et-Tabun; 11 _Homo sapiens neanderthalensis_; cave*
2 _Homo sp._; cave *
Ubeidya; 5 _Homo sp._; open site on carbonate bedrock *

Lebanon
Antelias; 4 _Homo sapiens_; cave *
Ksar 'Akil; 1 _Homo sp._; cave *
Masloukh; 1 Neanderthaler; cave *
Ras el-Kelb; 1 _Homo sp._; cave *

Malaysia
Niah; 1 _Homo sapiens sapiens_; cave *

Pakistan
Attock, Chinji, Domeli, Kanatti; 5 _Ramapithecus punjabicus_; riverine sandstones *

Philipine Islands
Tabon; 6 _Homo sapiens_; cave *

(continued on page 26)

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* Indicates karst/carbonate bedrock association with fossil, as interpreted by the present writers.

TABLE IV (Cont'd)

Canada
    Taber; 1 *Homo sapiens sapiens*; glacial till

U.S.
    San Diego; 3 *Homo sapiens sapiens*; fluvial deposits

Total sites—37
Total sites with karst/soluble bedrock associations—33
Percent karst/soluble bedrock association—89.2

Total fossils—203
Total fossils with karst/soluble bedrock associations—196
Percent karst/soluble bedrock association—96.6

Cumulative Totals, Table II, Table III and Table IV

Total sites—182
Total sites with karst/soluble bedrock associations—168
Percent karst/soluble bedrock association—92.3

Total fossils—790
Total fossils with karst/soluble bedrock associations—752
Percent karst/soluble bedrock association—95.2

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* Indicates karst/carbonate bedrock association with fossil, as interpreted by the present writers.

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Potential Gas Accumulation in Caves in Bowling Green, Including Relationship to Water Quality

L.P. Elliott*

ABSTRACT

Although surface air and water pollution have attracted considerable attention, little research has been done in subterranean areas. The accumulation of methane and other gases in caverns may be related to the degree of pollution of the cave water. This project proposed to determine: (1) the extent to which methane gas accumulates in the cave systems under Bowling Green, and (2) the influence of cave water pollution upon methane gas production.

To accomplish these objectives, it was necessary to monitor the physical, chemical, and biological characteristics of the cave water, as well as to analyze the cave air for gases. The tests included those for turbidity, apparent color, temperature, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, total organic carbon, pH, coliforms, fecal coliforms, methanogenic bacteria, carbon dioxide, alkalinity, hardness, total residue, chlorides, sulfates, phosphates, nitrates, iron, and maganese; gases monitored included ammonium, carbon monoxide, hydrogen sulfide, and methane.

This study of seven caves extended over a period of three months during the summer of 1973 and included the following caves: State Trooper, Lost River, Big Bertha, Livingston, Lampkin (collectively known as the Lost River Complex) Field's and X Cave (Hunts).

The average turbidity in cave waters was 31 JTU's. The water in the caves had an average apparent color of 20 APHA color units. Average water temperature in the Lost River Cave complex was 15.1° C (with slight fluctuations). Average water temperature for Field's Cave was 18.7° C and for Hunts was 18.1° C. Average cave air temperature for the Lost River Complex was 15.7° C. Cave air temperature in Field's averaged 17.8° C and in Hunts, 19.1° C.

A definite sewage odor was detected at sampling points B of Lost River and Big Bertha. A paint thinner smell in both water and air was detected at point B in Big Bertha. Automobile exhaust fumes and gasoline odors were detected in Hunts.

The dissolved oxygen concentrations of the Lost River Cave complex averaged 8 mg/l, excluding sampling points B of Lost River and Big Bertha. Hunts Cave averaged 4.9 mg/l and Field's cave 4.4 mg/l, in dissolved oxygen.

Five-day (20° C) BOD concentrations for seven of the 10 sampling sites averaged under 1.0 mg/l. Concentrations at site B in Big Bertha fluctuated in value from 0.16 mg/l to 105.4 mg/l, indicating an inconsistent discharge of waste into the water. The chemical oxygen demand at Big Bertha averaged 89.76 mg/l, whereas the rest of the sampling sites never had values greater than 50 mg/l.

The total organic carbon value for the Lost River Cave complex water was 19.91 ppm. The water of Field's had an average value of 21.76 and of Hunts, 23.84 ppm. The drinking water of Bowling Green had an average value of 10 ppm.

The average CO_2 value for the cave water of the Lost River complex was 37.3 mg/l, that of Field's was 34.4 mg/l, and that of Hunts was 44.3 mg/l. The water in all seven caves had hardness values between 150 mg/l and 300 mg/l.

The total residue in all of the cave waters (except Lampkin) exceeded the Federal Drinking Water Standards (not more than 200 mg/l). Chlorides in the cave waters averaged 7.5 mg/l, sulfate concentrations averaged 15.9 mg/l.

The total phosphate concentrations in the cave waters averaged 0.48 mg/l. Nitrates averaged 6.9 mg/l. Both nitrate and phosphate concentrations were in ranges which would contribute to eutrophication.

The iron concentration in the cave waters averaged 0.41 mg/l. The manganese concentrations in the cave waters averaged 0.13 mg/l. No cave air contained ammonia or hydrogen sulfide, but air in Hunts contained carbon monoxide. Methane was detected in all cave air samples, but not in high concentrations. When concentrations of methane found in caves were compared to those of surface air samples (control), statistically significant concentrations were found at site B in Lost River, in Big Bertha, and in Hunts.

The coliform count for waters (excluding Lampkin) averaged 18,690/100 ml, while fecal coliform counts averaged 4,144/100 ml. All cave waters enriched for *Methanobacterium* were positive, except on three occasions. Only seven enrichment cultures for *Methanococcus*-like organisms were positive.

Since the cave waters studied were considered polluted, the Federal Water Pollution Control Administration and the Kentucky Water Control Commission should pass effective regulations to keep the water from being further polluted. The city of Bowling Green should determine who is dumping and littering in the caves and prosecute those responsible. Where sewage and industrial pollutants are found entering the caves, an attempt should be made to determine where these originate and to prosecute the offenders. Sufficient data has been gathered on the cave water to establish a baseline for water quality during summer months, but the water quality measurements should be continued to determine the effect of winter flow on the physical, chemical, and biological qualities of the water, plus the changes that might occur in the cave air.

An experimental digester which simulates cavern conditions should be designed to determine if methane could build up to concentrations that might be explosive. In the future, methane organisms in the cave water should be quantified. A study of the methane concentration in cave air would be facilitated by a portable gas chromatograph that could be taken into the caves. Since Warren County has abundant sinkholes and old gas wells which could be giving off methane, parking lots should be properly ventilated for the release of gas, particularly. All residents of the city who use flush toilets should be forced to connect to the sewer system that is available.

Introduction

Increased nutrients in polluted cave water may enhance the activity of methane-producing cave microörganisms, thus increasing the atmospheric methane in polluted caves. Caves will be classified as "polluted" or "clean" on the basis of biological and chemical criteria and their degree of pollution will be correlated with methane production in them. All maps of caves except those of X Cave (Hunts) and of Field's Cave are from George (1973). Cave locations are shown on a map of the city (Fig. 1).

Sample Stations

State Trooper Cave

Figure 2 shows our entrance (starred) and gas and water sampling points A and B. The entrance is conspicuously marked by a dump and by the two-inch pipe used by a farmer to take out water. The sampling points will be designated "STA" and "STB" throughout this report. The gas samples were taken as near the roof of the cave as possible. The stream in this cave has been traced to the Lost River resurgence.

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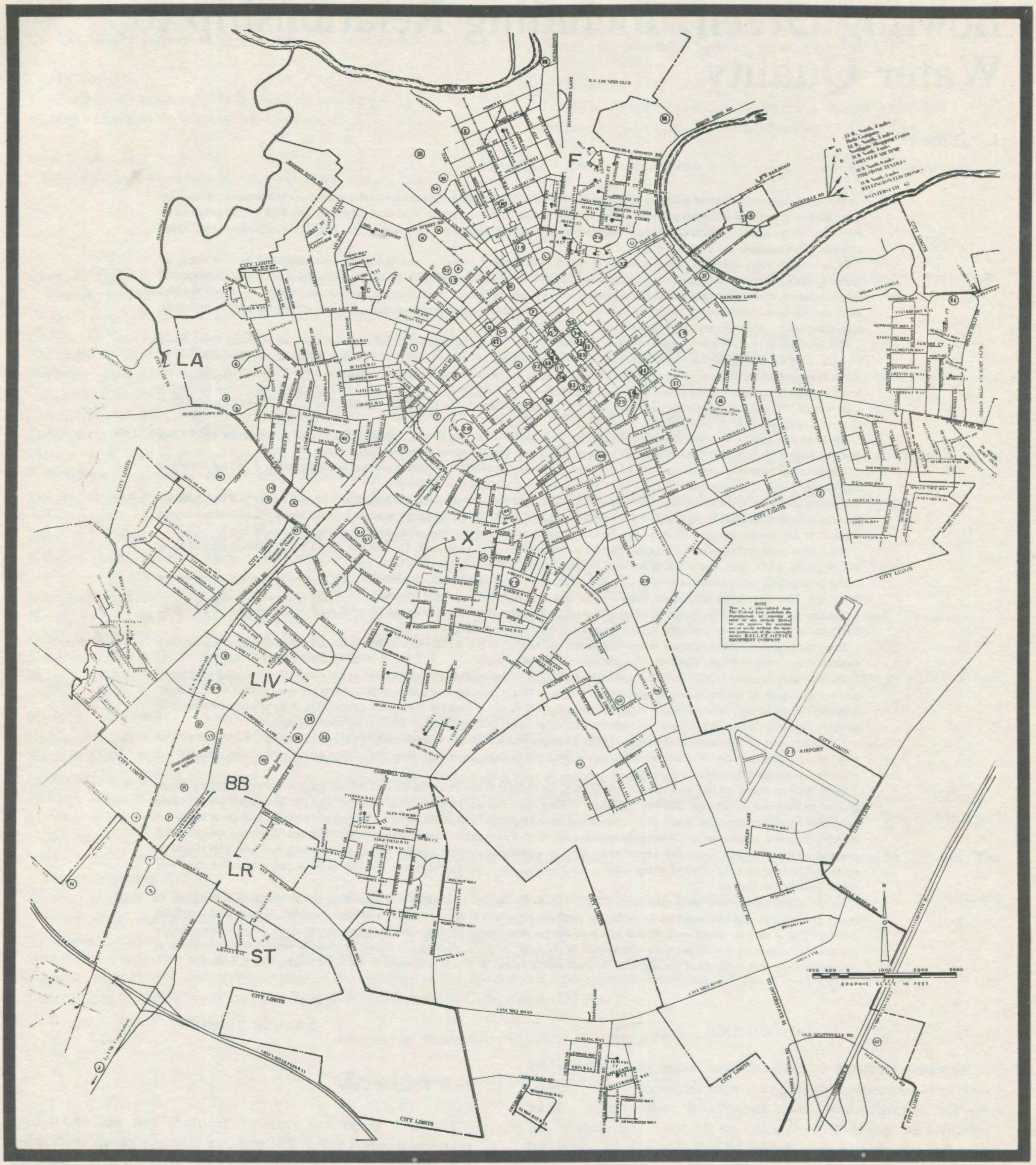

Fig. 1. Map of the City of Bowling Green, Warren County, Kentucky, showing the locations of the caves discussed in this paper. © 1967 Kelley Office Equipment Co., used by permission. BB—Big Bertha Cave, F—Field's Cave, LA—Lampkin Cave, LIV—Livingston Cave, LR—Lost River Cave, ST—State Trooper Cave, X—Hunts Cave

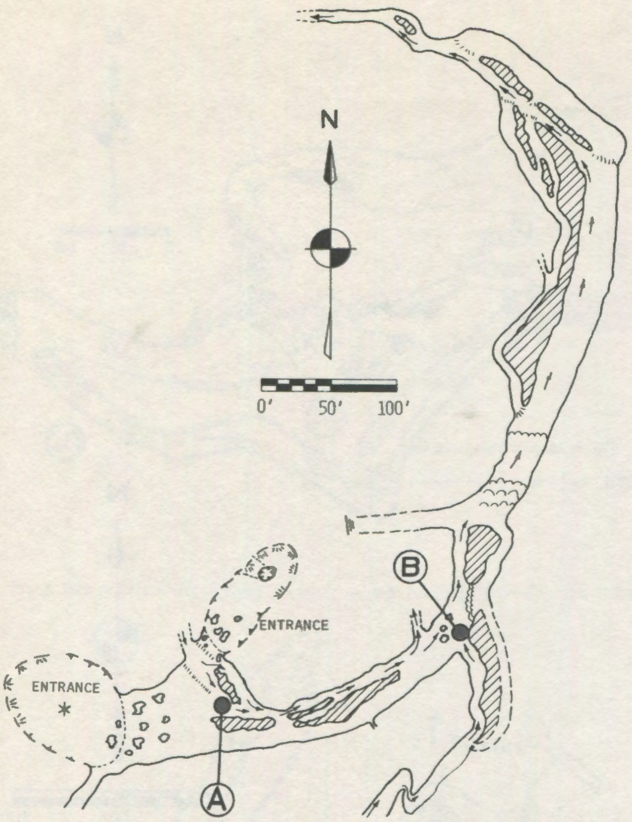

Fig. 2. Map of State Trooper Cave.

Lost River Cave

The Lost River Cave is one of the best known karst features in Kentucky. In 1796, a water grist mill and wool carding machine were constructed and operated in the mouth of the cave. In 1930-31, the Canyon Amusement Center built a hydroelectric plant with a new dam here; the floor of the cave was excavated and a modern dance floor built. The cave also had a cafe and small private dining rooms inside.

Lost River Cave drains approximately 50 square miles on the Sinkhole Plain. There are 2,850 ft of passage known in the cave. Figure 3 indicates our water and gas sampling points A and B. From the smell and consistency of the water, it appeared that the water at Site B was effluent from a septic tank. The hydroconnection between Lost River Cave and Big Bertha Cave was proved by a dye test. The sampling points will be designated "LRA" and "LRB" from this point forward in this report.

Big Bertha (Detrex) Cave

Big Bertha Cave (Fig. 4) is a segment of the Lost River Cave trunk passage leading toward the Dishman Mill rise on Jennings Creek. It is about 3000 ft northwest of Lost River Cave. The 4 ft wide, 5 ft high entrance is just below the Mall Apartment parking lot. Although no samples were taken from this passage (point C), from its smell and consistency, the water coming down over the flowstone appeared to be effluent from septic tanks. The sampling points henceforth will be designated "BBA" and "BBB".

Livingston Cave

Livingston Cave was discovered in 1965 by Dr. David Livingston, whose home is near the cave entrance. The crawlway entrance was used during this project. Water samples were taken at point A. For brevity in the Tables and Graphs, this cave will be designated "Liv".

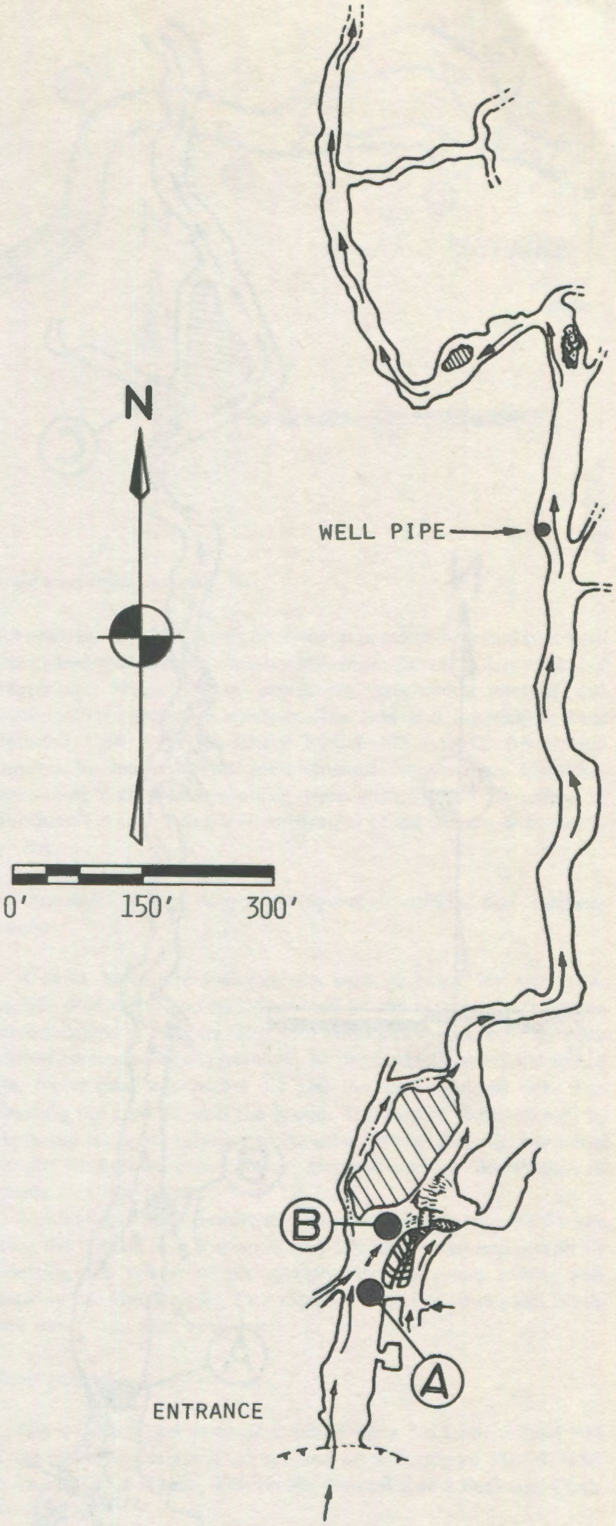

Fig. 3. Map of Lost River Cave.

Lampkin (Horshoe) Cave

Behind the baseball field in Lampkin Park is Lampkin Cave. A

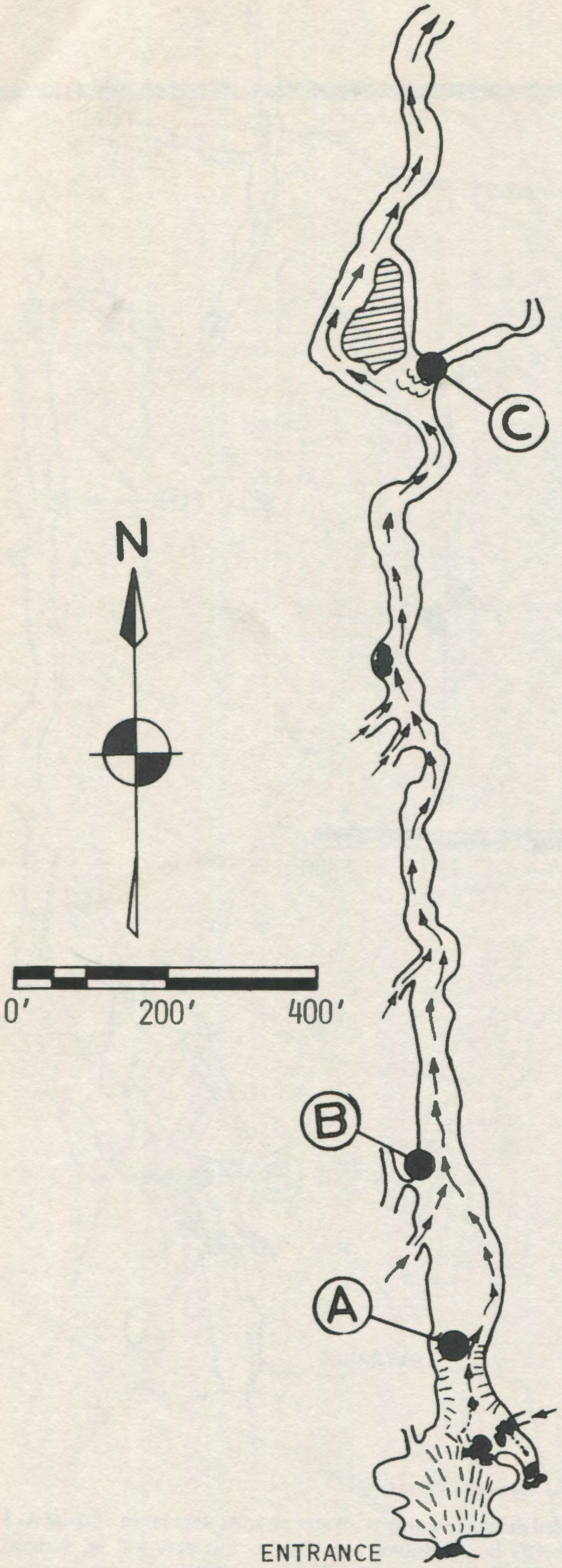

Fig. 4. Map of Big Bertha Cave.

small "bathtub" collects water dripping from above at point A; two water samples were taken here. The three gas samples were taken at equal intervals throughout the cave and as close to the roof as possible. This cave will be designated "La" in the Tables and LA in Graphs.

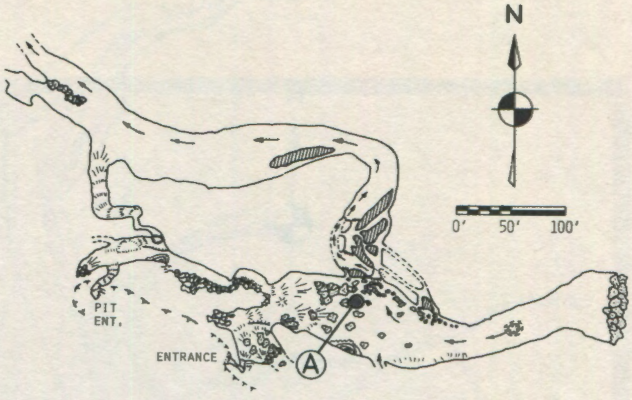

Fig. 5. Map of Livingston Cave.

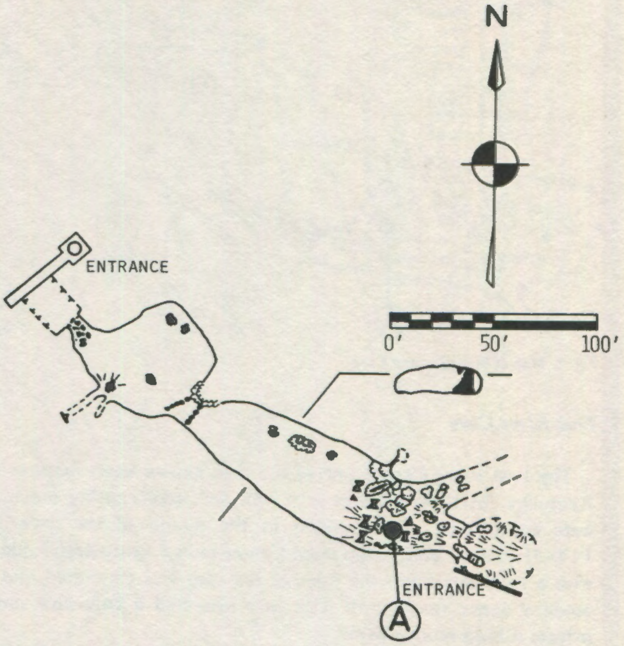

Fig. 6. Map of Lampkin Cave.

Cave X (Hunts Cave)

Hunts Cave (Fig. 7) is in a clump of trees at the intersection of Hogle Drive and U.S. Highway 31. Nearby is a "Pilot" gasoline station. Our gas and water sampling point was at the second pool. This cave will be designated "X" in all Tables and Graphs.

Field's Cave

Field's Cave (Fig. 8) is located off Boatlanding Road, beneath the Field Packing Co., Inc. Gas sampling points were at the drip line and at the bottom of the cave.

Materials and Methods

Sample collection

Lampkin Cave water was sampled only twice, since the cave is basically dry; gases were sampled three times. Point B in Big Bertha was not always sampled, because of high water. Cave water samples were collected from the predesignated points in acid-cleaned bottles. The water for bacteriological analysis was collected in sterilized dilution bottles.

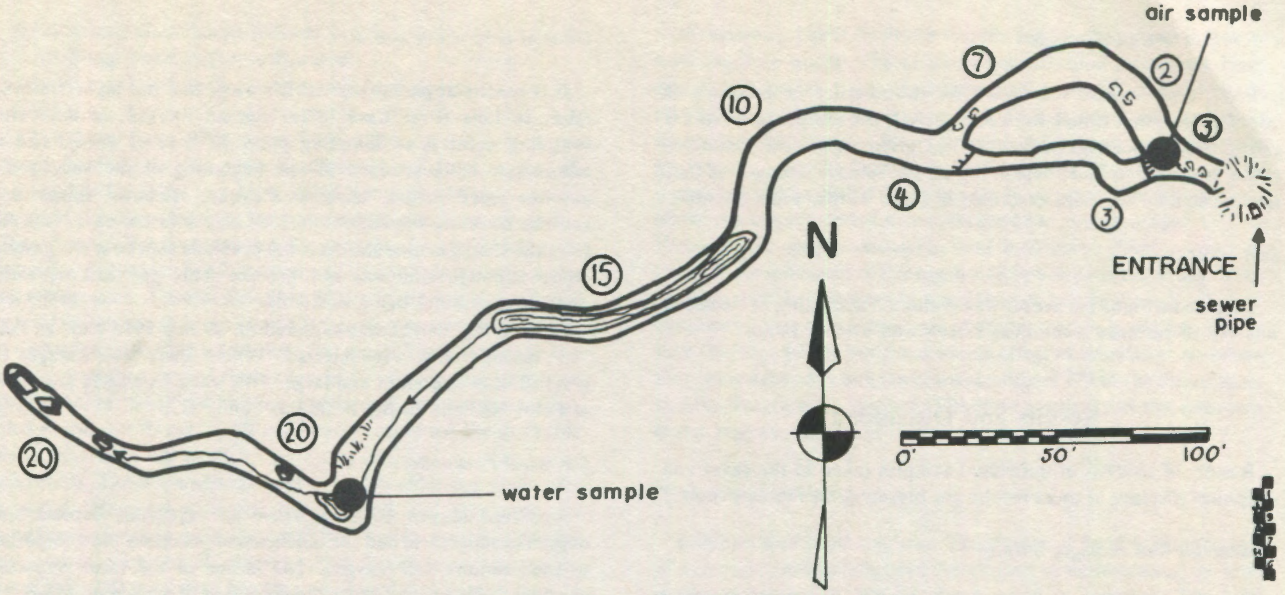

Fig. 7. Map of Cave X (Hunts Cave). Compass and tape survey by James Cubbage, James Weimer, and Ricky Downs, November, 1974.

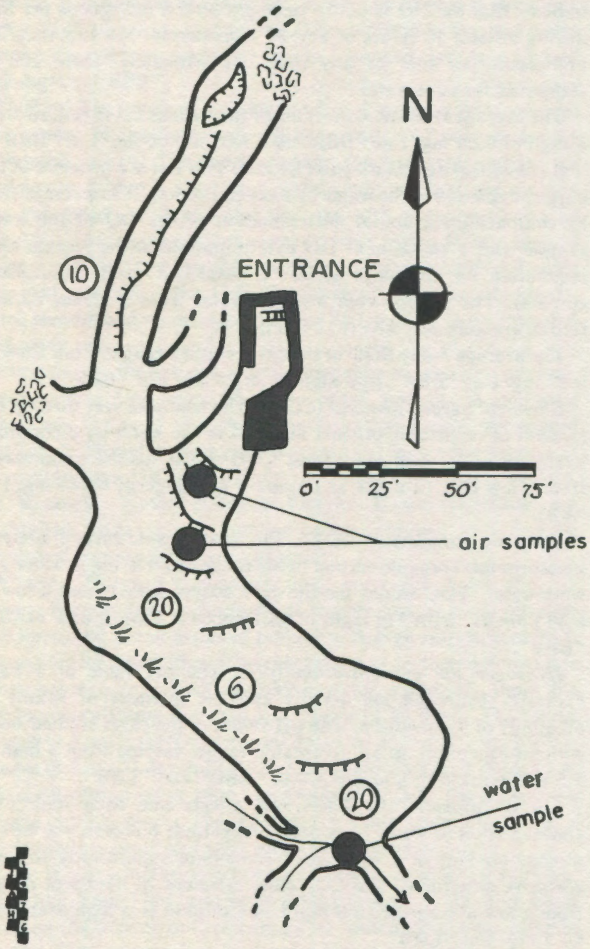

Fig. 8. Map of Field's Cave, by James Weimer, Larry Elliott, and James Cubbage, 4 December 1974.

Physical, chemical, and biological analysis of water

All of the samples were brought to the laboratories of the Ogden College of Science and Technology of Western Kentucky University for analysis. The laboratory analyses were made in accordance with the procedures given in *Standard Methods for the Examination of Water and Waste Water*, except for trace metal analysis and methanogenic organism analysis. The iron and manganese were detected with a Perkin-Elmer Model 303 Atomic Absorption Spectrophotometer. The methanogenic organisms, *Methanobacterium* and *Methanococcus*, were cultivated as described in Skerman's *A Guide to the Identification of the Genera of Bacteria*, p. 266.

Ammonium, carbon monoxide, hydrogen sulfide, and methane analysis

A MSA Monitaire Sampler was used to assay for ammonia, carbon monoxide, and hydrogen sulfide. the samples for methane were collected in ball jars filled with water and topped with two tube outlets connected by a tygon tube. At the sampling spot, one end of the tygon tube was pulled off and the water poured out, thus drawing the cave air into the bottle. The bottles were resealed by replacing the tygon tubing over the other fitting. Initially, the lids of the jars were sealed with stopcock grease to prevent the diffusion of gasses from the bottle.

A one ml gas-tight Hamilton syringe was used to transfer the gas from the bottles to a Varian Model 204 B gas chromatograph by inserting the needle of the syringe into the tygon tubing and drawing out the sample. Two samples were run from each bottle and the results were averaged.

Total carbon

The waters tested were determined on a Beckman Model 915 Total Organic Carbon Analyzer and on a Beckman Model 215A Infrared (IR) Analyzer, with results displayed on a Beckman Chart Recorder.

Meteorology

Relative humidity at the cave sites was measured with a sling psychrometer. Temperatures at the cave sites, inside the caves, and of the cave water were determined with a thermometer. Barometric pressure at the cave site was determined with a barometer. Past-24-hour precipitation data were obtained from the local weather station.

Odor of cave water and air

Each water sample was tested for the absence or presence of odors by smelling. If no odor was observed, the sample received a 0 rating. If an odor was present, it was given an arbitrary number rating from one to four, depending on the relative strength of that odor. The odor was also described in a few words, when possible.

Statistics

Data on methane in cave air was evaluated according to standard analysis of variance techniques (Steele and Torrie, 1960).

Results and Discussion

Results of analysis of individual samples taken in the caves and graphical displays of these results are presented in the Appendix.*

Hydrologic and ecologic settings

The Kentucky karst region (like those in Tennessee and Missouri) is characterized by a slight structural dome which has brought to the land surface Middle Paleozoic carbonate rocks concentrically surrounded by younger Paleozoic noncarbonate rocks (Le Grand, 1973). Streams are fairly scarce, most being fed by large springs. Many wells are polluted because of effluent from septic tanks.

Turbidity

Turbidity is the degree of opaqueness of the water due to the amount of matter in suspension, which may be in colloidal to silt-sized particles. The overall average of the turbidity of the cave waters studied was 31 Jackson Turbidity Units (JTU). Past-24-hour precipitation was included in the Turbidity Table, since this had some effect on turbidity of the water (demonstrated many times during this study).

Color

Color due to suspended material in water was termed "apparent" color, while color due to organic colloidal suspension was termed "true" color. The water varied in average color from a high of 38 at Site B in Big Bertha Cave to a low of 5 at Lampkin Cave.

The color of the water followed a pattern similar to that of turbidity and, generally, rose with increased precipitation.

Temperature

The average water temperature for the Lost River complex was 15.07° C, with little fluctuation. The average water temperature for Field's Cave was 18.7° C. Cave X had an average water temperature of 18.1° C.

The average cave air temperature for the Lost River complex was 15.7° C, while in Field's it was 17.8° C and in Cave X it was 19.1° C. Cave X is nearer the surface than are the other caves, which explains its higher temperature.

Relative humidity and barometric pressure

Data for both of these parameters was obtained, but was not analyzed.

Odor of cave water and air

It is readily apparent that BBB's water had the highest average odor. In Lost River Cave, there was an increase in odor from sampling point A to sampling point B. Cave X always had an automobile exhaust smell at the beginning of the cave and a gasoline smell further back in the cave. Exhaust fumes from vehicles traveling the Highway 31 W seep into the cave. Gasoline from the Pilot gasoline station is the probable source of the gasoline odor, although this was not proven. This gas leak is rather dangerous, besides being wasteful.

Most of Big Bertha was explored on 30 July 1973 and, at Point "C", sewage odor was detected. Where there was sewage, the crayfish were abundant and large. This was also true in Lost River at Point "B" and in Big Bertha at Point "C".

Chemical Parameters

Dissolved oxygen (*DO*). Because all organisms depend upon oxygen in some form and the biochemical processes most important to man require free oxygen, DO is one of the most important considerations in evaluating the condition of a body of water. The Water Quality Standards for Interstate Water for Kentucky indicate that the DO is not to be less than 5.0 milligrams per liter during at least 16 hours of any 24 hour period, nor less than 3.0 milligrams per liter at any time. Unfortunately, there are no standards for cave water.

The average DO concentrations of the various caves ranged from a high of 9.08 mg/1 at "BBA" to a low of 3.05 mg/1 at "BBB".

Biochemical oxygen demand (*BOD*). This test is a measure of the oxygen depletion of the water by bacterial action. It is accomplished by comparing the initial determination of the DO of the water sample with a subsequent DO determination on the sample after incubation for five days at 30° C (excluded from atmospheric contact). The results from tests on water from a clean, natural source are generally less than 0.5 mg/1.

The average 5-day BOD of the caves studied ranged from a low of 0.27 mg/1 at "BBA" to a high of 36.23 mg/1 at "BBB".

Chemical oxygen demand (*COD*). The test measures directly the amount of oxidizable organic material in the water by dichromate oxidation under acid conditions. COD values for the caves varied from a low of 1.12 mg/1 at Lampkin to a high of 89.76 mg/1 at "BBB".

Total organic carbon (*TOC*). The total organic carbon analyzer measures total organic carbon in the range of 1-150 mg in water and wastewater. TOC values for the cave waters varied from a low of 6.14 ppm at "BBA" to highs of 48.19 ppm at Cave X and 74.56 at "BBB".

Hydrogen ion concentration (*pH*). The pH value of a water expresses hydrogen ion activity and the intensity of acidity or alkalinity of the medium. The pH values of the caves studied were, without exception, in an acceptable range, varying from a high of 7.5 at Lampkin to a low of 7.0 at "BBB" and "LRB".

Carbon dioxide. No deleterious effects due to a high CO_2 concentration in water have been recognized; however, the carbon dioxide content of a water may contribute significantly to some corrosive situations. The CO_2 concentrations in the caves ranged from a low average of 10.0 mg/1 in Lampkin to a high average of 64.2 mg/1 at "LRB".

Alkalinity. The alkalinity of a water is a measure of the capacity of that water to neutralize acids and is used to a great extent in waste water treatment practice. The Federal Water Quality Criteria suggest a range from 30 mg/1 to 500 mg/1 as satisfactory for a public water supply. The greatest average alkalinity was 252.1 mg/l in Cave X and the lowest was 135.9 mg/1 in Lampkin.

Hardness. Hardness, as a quality of water, was originally defined in terms of the capacity of soap to lather in the water. Hardness may

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* Unabridged copies of the Appendix are available free of charge from: NSS Cave Files Committee, Cave Avenue, Huntsville, Alabama.

be quantitatively classified as follows:

0-75 mg/1 as $CaCO_3$—soft water
75-150 mg/1 as $CaCO_3$—moderately hard water
150-300 mg/1 as $CaCO_3$—hard water
>300 mg/1 as $CaCO_3$—very hard water

Water hardness in the caves studied ranged from a low of 156.8 mg/l in Lampkin to a high of 264.9 mg/l in X.

In all of the caves studied, the water was in the hard category.

Total residue. Total residue was the amount of material left after evaporating a sample of definite size and drying it in an oven at an exact temperature. Federal Drinking Water Standards recommend that total dissolved solids not exceed 500 milligrams per liter (mg/l) and that a desirable level is less than 200 mg/l. Total residue in the cave waters studied ranged from a low of 66 mg/l in Lampkin to a high of 2,270 in "BBB". With the exception of Lampkin Cave water (which averaged 170 mg/l), all cave waters exceeded the desirable Federal criteria of 200 mg/l.

Chlorides. There are several ways in which chlorides may enter the water. Some are dissolved from topsoil and from mineral formations. Sewage effluent and industrial wastes contain considerable amounts of chlorides.* A chloride concentration greater than 250 mg/l may produce an objectionable salty taste in the water; however, this taste is variable and depends upon the chemical composition of the water. It may be absent if there is a high level of calcium or magnesium. The chlorides in the cave water samples ranged from nondetectable in Lampkin Cave to a high of 60.5 mg/l at "BBB".

Sulfates. The source of sulfates in natural waters is from mineral soils, rocks, atmosphere, and the degradation of organic matter containing sulfur. The laxative dose for hydrated sodium or magnesium sulfate is about 2 g. This would occur if the average man consumed 2½ l of water per day with a concentration of 300 mg/l. The average sulfate concentration varied from a high of 35 mg/l at Field's to a low of 4.2 mg/l at Livingston Cave. All water remained well below the U.S. Public Health Service Standards, which recommend a maximum limit of 250 mg/l in water intended for human use.

Phosphates. Phosphates are undesirable in aquatic environments, since they may stimulate algal growth in nuisance quantities. The total phosphate concentration should not exceed 0.015 mg/l. Phosphate concentrations ranged from a low average of 0.1 mg/l in Lampkin Cave to a high of 1.7 mg/l in "LRB". To date, the Kentucky Water Pollution Control Commission has not established limits on the amount of phosphorous that may be discharged to receiving bodies of water.

Nitrates. Nitrogen compounds may enter the water through sewage. Prior to the development of bacteriological tests, nitrogen tests were used as indicators of pollution. A high nitrate content is responsible for a condition in infants known as methemoglobinemia "blue babies". Therefore, drinking water standards limit the nitrate concentration in terms of nitrogen to 10 mg/l. The lowest average (4.6 mg/l as NO_3 nitrogen) occurred at "LRB"; the highest average (8.9 mg/l) was in "LRA". Livingston Cave had yielded low results on several other tests but averaged next to the highest on nitrates at 8.7 mg/l. The Lost River Cave complex drains a substantially agricultural area which is fertilized regularly.

Iron. Iron is a highly objectionable constituent in water supplies, a limit of 0.3 mg/l has been set in drinking water. This value is not based on the toxicity but, rather, on its undesirability for esthetic reasons. The average iron concentration varied from a high of 0.99 mg/l at "BBB" to a low of 0.27 mg/l at "LRB". All the cave waters were above the recommended level for iron concentration except "LRB", which definitely has been shown to be polluted by other parameters tested.

Manganese. The U.S. Public Health Service limits manganese to 0.05 mg/l in water. The criterion for drinking water has been established on the basis of esthetic and economic considerations rather than physiological hazards. It has been reported that manganese will turn the fat on finished chickens to an undesirable green color. The highest manganese concentrations (0.61 mg/l) were observed in "BBB" waters. All average concentrations were above the recommended concentrations for human usage.

Ammonia, carbon monoxide, and hydrogen sulfide analysis of cave air. No ammonia or hydrogen sulfide was detected in any of the caves, and carbon monoxide was detected only in Cave X. Carbon monoxide levels at this low level of concentration is not harmful to man (Astrup, 1972), but the ultimate effect of inhalation of carbon monoxide depends upon the concentration of CO in the atmosphere and the duration of exposure. The close proximity of this cave to a major highway helps CO being in this cave's air.

Biological parameters

Coliform and fecal coliform. The degree of fecal contamination of water has traditionally been determined by enumerating the total coliforms present in 100 ml of the water in question. The total coliform group merits consideration as an indicator of pollution, because these bacteria are always present in the normal intestinal tract of humans and other warm-blooded animals and are eliminated in large numbers in fecal material. Thus, a low reading total coliform bacteria is evidence of a bacteriologically safe water.

Unfortunately, some strains included in the total coliform group have a wide distribution in the environment, but are not common in fecal material. Further, some coliforms surviving sewage chlorination may increase by one or two logs within one or two days' travel downstream (Geldreich, 1967).

The Federal Water Pollution Control Administration Report on Water Quality Criteria (1968) indicated a permissible total coliform count of 10,000/100 ml and a desirable count of less than 100/100 ml for a surface water public water supply and a permissible fecal coliform count of 2,000/100 ml and a desirable count of less than 20/100 ml.

The Kentucky Water Control Commission allows no more than 5,000 total coliform /100 ml as a monthly arithmetical average. This number is not to be exceeded in more than 20% of the samples examined during any month, nor is the count to exceed 20,000/100 ml in more than 5% of the samples for a public water supply or for a food processing industry. For recreation (boating, fishing, etc.) purposes, these standards indicate that the total coliform count is not to exceed an average of 1,000/100 ml. The total coliform count may not exceed this number in 20% of the samples in a month nor may it exceed 2,400/100 ml on any day. The fecal coliform count in water used for recreation purposes from May to October are not to exceed 200/100 ml as a monthly geometric mean, nor may it exceed 400/100 ml in more than 10% of the samples examined during a month.

The total coliform count in the Lost River Cave system was generally highest at State Trooper Cave and decreased in count downstream, except for obvious pollution points at "LRB" and "BBB". All cave waters increased in total coliform count after a rain, particularly the State Trooper Cave water. This cave water probably includes coliforms from septic tanks that serve each of the houses in the nearby subdivision. Drainage from agricultural activity in the area would go into the cave water, also. Water from Lost River complex resurges near Dishman Mill on Jennings Creek, about 500 ft southeast of Lampkin Cave. In the summer of 1972, Kaurish and Rowe found that the total coliform count of Jennings Creek was so high that this creek would not be suitable for a water supply source or for recreational purposes. The average total coliform count was found to be 16,580/100 ml, which is similar to the count found in the Lost River system.

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* The average amount of chloride produced per person per day is six grams. This increases the amount of Cl in sewage about 15 mg/l above that of the carriage water.

Every site sampled except two ("LA" and "BBA") was found to have an average total coliform count of over 5,000/100 ml, which is the maximum allowed by the Kentucky Water Commission for a public water supply. Of course, no standards have been set for cave waters, but, since they eventually feed streams and rivers, one wonders why standards have not been set for them.

Fecal coliform in the cave waters ranged from nondetectable to 55,000/100 ml. The fecal coliform graph of counts followed the same pattern as the total coliform graph, reaching a maximum average count of 18,800/100 ml at "BBB". All fecal coliform densities (except in Lampkin Cave water) were greater than the recommended maximum of 200/100 ml for contact recreation in Kentucky. Again, no standards have been set for cave water. The low total coliform : fecal coliform ratios indicated that the organisms counted were of fecal origin. Note, particularly, that the ratio of "BBB" was 1.9:1.

Methane and methanogenic organisms. Methane is a colorless, odorless, tasteless gas which makes up the largest part of natural fuel gas (up to 97%). The explosive limits of methane in air are 5-15%, by volume. Methane is formed when plants decay in anaerobic environs. It is the dangerous "firedamp" of the coal mine and can be seen as the, so-called, "marsh gas" bubbling to the surface of swamps.

None of the cave air samples ever came close to the lowest concentration needed to be explosive in air. The least variation in concentration of methane was in Livingston Cave, which had the smallest entrance.

When the concentration of methane found in the caves was compared to surface air samples (control), significant statistical differences were found between "LRB" and control, "BBB" and control, and both sites in Cave X vs. control. "LRB" and "BBB" cave sites were known to have sewage contamination. Methanogenic organisms are known to occur in feces of man as frequently as $2 X 10^{10}$ colony-forming units per gram (Nottingham and Hungate, 1968). Both sample sites in Cave X were far removed from the mouth of the cave. The air and water temperatures were higher in this cave than in the others, except for Field's Cave. These higher temperatures would allow the methane bacteria to be more active. However, why was this not true for Field's Cave? Fecal contamination of the water was about the same, judging from average fecal coliform counts. The big difference between the two cave waters was that Cave X had more residue in the water and a higher COD and BOD than Field's. More organic compounds were available for oxidation by organisms. Another obvious difference between the two caves was that the air in Cave X contained carbon monoxide, which could be used as a substrate by methane bacteria for methane production (Schwartz, 1973). Obviously, methane could be produced in water by methane bacteria. Deuser, Degens, and Harvey (1973) found large quantities of this gas in the waters of Lake Kivu.

The mean control value of 2.3 ppm methane found in surface air was close to the 2.2 ppm reported by Magill (1956). The surface-air concentration of methane would be influenced by the many old gas wells, in the Bowling Green area.

In an attempt to determine the origin of the methane that was present in the caves, a chromatogram of pure tap methane (natural gas) was made. It showed a small concentration of propane, and this concentration was in a definite ratio to the methane present. Sensitive analyses of some of the cave air samples provided no conclusive evidence of propane in these samples.

Methane concentrations in the caves were not found to fluctuate with change in barometric pressure, although the pressure did not change much during our sampling times. Kissell *et al* (1973) found that coal mine gas explosions were distributed randomly throughout the year and were not influenced by barometric pressure.

This study conclusively demonstrated that methane-producing bacteria were present in cave waters. The substrates utilized by the methane bacteria fall into three categories: the lower fatty acids, containing from one to six carbon atoms; the normal and iso-alcohols, containing from one to five carbon atoms; and the three inorganic gases, hydrogen, carbon monoxide, and carbon dioxide.

The methane bacteria are represented by *Methanobacterium, Methanococcus* and *Methanosarcina*. They are found in the feces of man and are present in great abundance as components of the complex anaerobic microflora in the rumen of herbivorous mammals (Nottingham and Hungate, 1968; Paynter and Hungate, 1968). They are also found in mud, in sewage treatment plants, and in the deep layers of peat bogs (Schwartz, 1973); Lamanna, 1972). It seems possible that fecal material could serve as an inoculum in surface waters, which could then deposit the organisms in caverns.

The growth of these bacteria in caverns at low temperatures seems possible. Nemerow (1963) stated that there seem to be no specific temperature limitations between 0° C and 55° C, but, once the culture has been acclimated to a certain temperature, a sudden drop of two degrees could interrupt methane fermentation and render obstructive the accumulated acids. Johns and Barker (1960) found that *Methanobacillus omelianskii* cells retained their activity for at least seven days when stored in Thunberg tubes under vacuum at 3° C. Most studies have been made on cultures at 30-37° C (Polland, 1969; Standtman, 1967).

All enrichment cultures from cave waters were positive for *Methanobacterium*-like organisms, as demonstrated by the Gram stain of slides, except for "LA" (6/20/73), "BBB" (6/25/73), and "LRB" (7/30/73). All cultures produced methane, except "LA" (6/20/73). The average amount of methane found in the Lost River Cave system was 73.5 ppm. The average amount of methane produced by the enrichment culture of Field's Cave water was 143 ppm. Cave X had an average of 72.8 ppm. Field's Cave and Cave X had enough nutrients to support the growth of methanogenic organisms, and their warmer water and air probably allowed the organisms to multiply faster.

It seems quite probable that runoff water could have been inoculated with methanogenic bacteria from freshly deposited excreta or from septic tanks. This water could have inoculated a cavern, in which the methane bacteria could have continued to grow if its supply of oxygen was sealed off and nutrients were available. Nutrients should have been present in the sewage and water (methane bacteria are not fastidious). Nemerow (1963) stated that methane fermentation will take place in enriched cultures and is applicable to any type of substrate within a pH range of 6.5 to 8.0, except lignin and mineral oil.

Enrichment cultures for *Methanococcus* were mainly negative. Thus, *Methanococcus* was not contributing much methane to the cave air. It was obvious that *Methanobacterium* was producing much of the methane. How much methane could some of the cultures produce if they were allowed to reincubate for an additional period of time?

Eight cultures were reincubated and the average amount of gas produced during reincubation was surprisingly high: 176,313 ppm (18%), which could be a hazard. The amount of methane buildup that could occur in an unopened cavern possibly could be quite high and should be checked experimentally.

Another question that needed answering was, could an enrichment culture for *Methanobacterium* grow and produce methane at cave temperature? Time did not allow extensive experimentation, so a few cultures were incubated at 18° C for varying lengths of time. Of the four enrichments, one grew and produced 135,000 ppm of methane in 15 days. Why three of the cultures did not produce gas is highly speculative, but the success of the one sample in producing gas at cave temperature helped explain why methane gas was detected in the caves.

It seems obvious that, if the pollution problem worsens, the chance will become greater that methane build up in caves eventually could lead to an explosion. Far too many people consider a sinkhole or cave entrance nothing more than a convenient garbage pit. This attitude needs to be changed, particularly in Bowling Green, because water from the Lost River Cave System and from Field's cave water eventually runs into the Barren River, the city's drinking water source. Far too many people still use septic tanks. The reckless contamination of underground streams with sewage and other pollutants could upset the delicately balanced cave community. This happened in Stockton, Mo. (Hedges, 1959), where, during exploration of a cave beneath the business district, a strong propane odor was detected and warm water was found running into the cave via a fissure in the ceiling.

Other organisms. Cave crickets were present in all caves except Field's and Cave X. Field's has a building over the entrance and the temperature in Cave X was warmer than that of the others, which might explain the absence of crickets in the two caves. All caves had crayfish (*Orconectes* sp.), except Lampkin and Field's. A small segment of stream was visible in the bottom of Field's, but no crayfish were seen. Large crayfish (*Cambarus* sp.) were found in abundance where sewage effluent was entering Lost River and Big Bertha caves. Thus, an abundance of crayfish could be an indication of sewage pollution. Holsinger (1966) found large concentrations of the flatworm *Sphalloplana* and the isopod *Asellus recurvatus* in polluted cave waters; the amphipod *Stygobromus mackini* was missing. Fish were seen only in State Trooper Cave, but they could have been missed in the other caves. Bats were seen only in State Trooper and Lampkin caves, but bats in the other caves could have been overlooked.

Trash and debris. Definitions of water pollution are often subjective. Wolman (1971) defined it as any impairment of water which lessens its usefulness for beneficial purposes, or anything the public does not like, or even that which is getting worse. Variables used to describe water quality may be separated into two types: those associated with the water itself, and those associated with the water site. Many measurements have been made on the former, but rarely have site characteristics, such as amount of trash present, been recorded.

The cave having the most debris was Lampkin, its walls were marked and its formations marred. State Trooper had the most trash and debris at its mouth. Certainly, no dumping signs should have been posted and the trash cleaned up. Inside, State Trooper cave was fairly clean, particularly at sampling site B and further back. Since Lost River Cave used to be commercial, a lot of debris was found at the mouth and inside the entrance. During this project, the cave was not explored further than sampling point A. Big Bertha Cave had a lot of debris, such as old tires, shopping baskets, and cans at the bottom of the cave at sampling point A. The cave was in good condition from sampling point A on back. A lot of debris had been washed or carried into Cave X, but, at sampling point B and further back, the cave was in good condition. Field's Cave had a lot of broken bottles and bones since, several years ago, the company emptied its waste into the cave. The cave that had no debris or trash was Livingston Cave.

Summary

This study of the air and water of seven caves in Bowling Green, Kentucky, extended over a period of three months during the summer of 1973. The investigation included the air and water of State Trooper, Lost River, Big Bertha, Livingston, Lampkin, Field's and X Cave (Hunts).

Physical parameters

The average turbidity of the cave waters was 31 JTU's, while the average apparent color was 20 APHA color units. Average water temperature in the Lost River Cave complex was 15.1 C. Average water temperature in Field's was 18.7 C and in Cave X it was 18.1 C. Average cave air temperature in the Lost River Complex was 15.7 C, while in Field's it averaged 17.8 C and in Cave X, 19.1 C.

A definite sewage odor was detected at sampling points B in Lost River and Big Bertha caves. A paint thinner smell in both water and air was detected at point B of Big Bertha. Automobile exhaust fumes and gasoline odors were detected in Cave X.

Chemical parameters

The dissolved oxygen concentrations of the Lost River Cave complex averaged 8 mg/l, excluding sampling points B in Lost River and Big Bertha caves. Big Bertha "B" averaged 3.1 mg/l and Lost River "B", 4.3 mg/l. Cave X averaged 4.9 mg/l and Field's Cave, 4.4 mg/l.

Five-day (20 C) BOD concentrations for clean, natural waters should average less than 0.5 mg/l. Seven of the 10 sampling sites averaged under 1.0 mg/l. The other three sites, Cave X, Lost River "B" and Big Bertha "B", averaged 2.32 mg/l, 3.68 mg/l and 36.23 mg/l, respectively.

Because COD is principally a test for industrial waste waters, its major importance in evaluating the cave water studied was to detect and measure significant industrial pollution. Only one cave (Big Bertha) had a COD above 50 mg/l.

The Total Organic Carbon value for the Lost River Cave complex water was 19.91 ppm. The water in Field's Cave had an average value of 21.76 and that of Cave X, 23.84 ppm.

The pH values for the cave waters were within an acceptable range at every site on every sampling date.

All waters, except those of Lampkin Cave, were higher in CO_2 than 10 mg/l. All cave waters had hardness values over 150 mg/l and were classified as hard. The total residue in all of the cave waters, except Lampkin Cave water, exceeded the Federal Drinking Water Standards. The average total residue concentration of the Lost River Cave water was 395 mg/l, that of Field's was 284 mg/l, and that of X was 339 mg/l. The chlorides in the cave water samples ranged from nondetectable in those from Lampkin to a high of 60.5 mg/l in those from "BBB". None of these would have had an objectionable salty taste, which requires a concentration greater than 250 mg/l. All water remained well below the recommended sulfate concentration of the U.S. Public Health Service Standards, which recommend a maximum limit of 250 mg/l in water intended for human use. The phosphate concentrations ranged from a low average of 0.1 mg/l in Lampkin Cave water to a high of 1.7 mg/l in "LRB" water. Drinking water standards limit the nitrate concentration in terms of nitrogen to 10 mg/l. None of the cave waters ever exceeded this standard. A limit of 0.3 mg/l of iron has been set for drinking water. All cave waters (except that from "LRB") were above this recommended level. The U.S. Public Health Service limits manganese to 0.05. All average concentrations of manganese in the cave waters were above the maximum level of 0.05 mg/l recommended for human usage by the U.S. Public Health Service.

No ammonia or hydrogen sulfide was detected in any of the caves. Carbon monoxide was detected only in Cave X. Methane was detected in all cave air samples, but not in high concentrations. When concentrations of methane found in cave air samples were compared to those in surface air samples (control), statistically significant concentrations were found at Lost River "B", Big Bertha, and Cave X. Pollution of water was thought to enhance methane production in the caves.

The total coliform and fecal coliform counts indicated that none of the cave waters, except those of Lampkin Cave, would be suitable for a public water supply or for recreational purposes. Generally, total coliform and fecal coliform counts increased after rain.

All cave waters enriched for *Methanobacterium* were positive, except on three occasions. The methane concentrations from enrichment cultures for *Methanobacterium* after a one-week incubation at room temperature averaged 81.1 ppm. excluding that of Lampkin Cave. Eight enrichment cultures for *Methanobacterium* were allowed to reincubate at room temperature for an additional 8-15 days, and the average methane concentration, in this case, reached 176,313 ppm. One enrichment culture for *Methanobacterium* incubated at 18° C for 15 days produced 135,000 ppm methane.

Large crayfish were found where sewage effluent was entering Lost River and Big Bertha caves. The only cave not having trash and debris at the entrance or inside was Livingston Cave.

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Uranium-Series Dating of Speleothems: Discussion

Mike Shawcross*

The paper by Harmon *et al.* (1975) contains a number of errors and inaccurate data, mainly pertaining to the application of the figures obtained from the dating of speleothems in the Crow's Nest Pass area to determining the rate of cutdown of the Pass. The data in question are contained in Tables 3 and 5 and in the text on pages 30 and 31.

All but one of the caves under discussion in the Crow's Nest Pass area are in the Flathead Range and not in the High Rock Range, as stated on page 30. The altitude above sea level of each of the caves is stated incorrectly. In one case the figure is almost 300 m too high and the figure given for the local relief is more than 100 m too high.

In Table 3 and again in the text on page 30, the following data are given for the elevations of caves in the Crow's Nest Pass area:

Yorkshire Pot	2700 m ASL
Gargantua Cave	2675 m ASL
Coulthard Cave	2500 m ASL
Middle Sentry Cave	1950 m ASL
Eagle Cave	1350 m ASL

Since we do not have accurately computed elevations for any of these caves, we must rely mainly on topographical maps (1:50,000 Crowsnest sheet, 82 G/10 E, edition 1) for their altitudes. In the case of Yorkshire Pot and Gargantua, there is additional evidence from an unpublished topographic survey of the Ptolemy and Andy Good Plateaux carried out by James F. Quinlan (with myself as assistant) in 1971. For Coulthard Cave and Middle Sentry Cave, I also rely on published reports of the original exploration of these caves (Morris, 1970; Ford, 1971) and on personal communications from the explorers. For Eagle Cave, I rely on personal observation.

Based on information obtained from the above sources, far more accurate figures for the altitudes of these caves would be:

Yorkshire Pot	2409 m ASL
Gargantua Cave	2475 m ASL
Coulthard Cave, probably below	2300 m ASL
Middle Sentry Cave, probably below	1700 m ASL
Eagle Cave, approximately	1400 m ASL

Even using the "about 1600 m" figure for the local relief in the Crow's Nest Pass area given on page 30, the calculations on page 31 of the development of the present relief are inaccurate. Sixty percent of 1600 meters would be 960 m (not 900 m) and 85% of 1600 m would be 1360 m (not 1400 m). Using the data given in the article, 25% (85%—60%) of 1600 m would be 500 m. Since the correct figure for the local relief is 1464 m (Mt. Ptolemy, the highest peak in the Crow's Nest area is 2813 m; the pass is at 1349 m) the data given are meaningless anyway.

It is difficult to see how one could support the statement on page 30 that "the succession of ages indicates that the floor of the pass . . . was below1960 m ASL 275,000 years ago and below 1600 m ASL 200,000 years ago". 1960 m is close to the (incorrect) figure of 1950 m given for Middle Centry Cave and 275,000 years is close to the date of the "youngest" sample studied. The figure of 1600 m does not, however, appear to be taken from the data recorded. If 1350 m (the figure given for Eagle Cave) was intended, then to suggest that the pass was at that level 200,000 years ago means one has to discard the date obtained from one of the only two samples studied from Eagle Cave (E-1, greater than 300,000 years BP).

If one accepts that the data obtained from the analyses of speleothems from the caves of the Crow's Nest Pass area can be used to indicate the rate of cut-down of the pass, the final paragraph on page 30 and the first on page 31 should read:

> The succession of ages indicates that the floor of the pass to which the caves discharged was below 1700 m ASL 273,000 years ago and below 1400 m ASL 198,000 years ago. Given that valley floor elevations are maximum and their ages minimum, the data suggest that at least 76% (1113 m) of the present relief had formed at least 273,000 years ago and that at least 96% (1413 m) of the present relief had formed at least 198,000 years ago.

Finally, in Table 3, the age for sample 72030 (GV) is given as 145,300± 6000 years BP. In Figure 7, the same sample is given a date of approximately 190,000 years BP.

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Uranium-Series Dating of Speleothems: Reply

Derek C. Ford* and Russell S. Harmon†

Michael Shawcross has quite rightly taken us to task for an extremely slipshod interpolation. At a late stage in revising the manuscript, it was decided to add the section "Geomorphic Studies" and Table 3. To summarize the Crowsnest Pass findings, a précis of an earlier analysis was hastily dictated. That analysis used feet rather than meters and, as a first rough conversion, numbers were divided by three and rounded off. They were never corrected as they should have been. Mr. Shawcross' elevations are accurate except for the Middle Sentry Cave, which is closer to 1800 m altitude than the 1700 m he quotes. We cannot understand our very erroneous values for Yorkshire Pot and Gargantua.

More serious is the unexplained Eage Cave data, cited in Table 3. Specimen E-1 was a piece of flowstone thought to have come from Eagle Cave. This specimen gave an unexpected age of greater than 300,000 years BP. Because we were unsure of the exact location of the sample, we collected the Eagle Cave site (only one flowstone unit is present) and obtained an age of 145,000 years on the specimen collected. This is the age used in the denudation calculations. We apologize to the readers for the confusion over the two Eagle Cave dates.

The second paragraph discussing Crowsnest Pass should be amended to read "The succession of ages indicates that the floor of the pass to which the caves discharged was below 1800 m a.s.l. 275,000 years ago and below 1440 m a.s.l. 200,000 years ago." Percentages and ages quoted later in the published paragraph and conclusions drawn from them remain sufficiently correct.

A careful check indicates that metric dimensions and speleothem ages quoted elsewhere in the text of the paper are correct, given that they have been rounded off to avoid creating an impression of extreme precision that is unwarranted.

Our thanks to Michael Shawcross for these corrections and our apologies to readers for carelessness.

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Typhlichthys subterraneus Girard (Pisces: Amblyopsidae) in the Jackson Plain of Tennessee

David L. Bechler*

ABSTRACT

Three populations of *Typhlichthys subterraneus* are known to exist west of the Tennessee River, in Decatur County. All three localities lie in Silurian limestone bordered on the west by Cretaceous sediments marking the eastern edge of the Mississippi Embayment. Further westward distribution of *Typhlichthys* is considered improbable, because of the lack of massive limestones in the Cretaceous formations. An analysis of variation shows the Jackson Plain specimens not to differ significantly from other known populations.

Introduction

Although the western limits of the main range of the southern cavefish, *Typhlichthys subterraneus*, in Tennessee lie in the Highland Rim escarpment (Woods and Inger, 1957; Poulson, 1961), Cooper (1974) recorded the species west of the north-flowing arm of the Tennessee River. A single specimen was collected in Baugus Cave, Decatur County (Bath Springs, 7½′ Quadrangle, Barr, 1972)†, on 15 June 1972 by William A. Henne. Additional specimens have since been taken in this cave, and two more populations west of the river have been located. All three are approximately 27 km from the escarpment. These records verify the presence of *T. subterraneus* populations in the Jackson Plain and extend our knowledge of the distribution of this wide-spread, but rare, fish.

New Localities

On 16 and 22 July 1973, eight *Typhlichthys* were captured in Baugus Cave. Five were narcotized in a solution of tricaine methanesulfonate (Poulson, 1961) for measurement and then released. The remaining three specimens were preserved in 10% formalin immediately on capture. The total lengths of the specimens were 31, 33, 34, 39, 40, 42, 44, and 50 mm.

On 4 August 1973, *Typhlichthys* was discovered in Stewman Creek Cave, Decatur County (Thurman, 7½′ Quadrangle). This became the second known locality for the species west of the Tennessee River in Tennessee. Two fish, measuring 23 and 27 mm standard length, were captured and preserved. These and the specimens from Baugus Cave are in the collections of the Northeast Louisiana University Museum of Zoology, Monroe, Louisiana.

Jerald Ledbetter has observed *Typhlichthys* in a third cave lying along the Tennessee River approximately 3.6 km east of Jeanette (approximate location: Jeanette, 7½′ Quadrangle). To date, no specimens have been collected.

Discussion

Decatur County lies along the eastern edge of the Jackson Plain, which is separated from the West Highland Rim by the Tennessee River. Elevations rise from 114 m along the river to a maximum of 153 m west of the river. Caves to the west are poorly developed. Stewman Creek Cave, the longest in the county, is a maze approximately 500 m in length. The rear portion of the cave consists of solution channels, running at right angles to each other, which drop down approximately 2.5 m to lentic pools 20 cm deep. The bottoms of the pools are covered with fine silt and clay. Baugus Cave consists of a single passage, 280 m long. A small stream, consisting mostly of pools 15 to 45 cm deep, flows the length of the cave. The stream bed consists mostly of chert and gravel. The third cave, lying along the Tennessee River, is a single passage approximately 70 m long. The floor of the cave is composed of fine silt and clay, over which a lentic pool lies. The level of the pool is determined by the level of the river. *Typhlichthys* has been seen around a large sump hole at the rear of the cave.

All three caves are developed in Silurian limestone marking the eastern edge of the Jackson Plain. The (mapped) Silurian rocks, divided from top to bottom into the Decatur, Brownsport, and Dixon formations, include some overlying Lower, Middle, and Upper Devonian formations (Amsden, 1949; Dunbar, 1919). Immediately west of the Paleozoic formations, lie the Upper Cretaceous Selma chalk and clay and McNairy sand (Stearns, 1958). These sediments, rising from under Paleocene and Eocene sand and clay, mark the eastern edge of the Mississippi Embayment. The lack of massive, soluble limestone deposits within the Mississippi Embayment makes further westward distribution of *Typhlichthys* improbable in Tennessee.

In a morphological comparison involving specimens from throughout the range of *Typhlichthys* known at that time, Woods and Inger (1957) found no pattern of variation and considered all *Typhlichthys* to be conspecific. Poulson (1961) has also found considerable homogeneity among populations of *Typhlichthys*, especially along the western edge of the Cumberland Plateau and the East Highland Rim. Cooper and Beiter (1972), however, reported a population of *Typhlichthys* from Sloans Valley Cave, Pulaski County, Kentucky, which appears to differ in a number of ways from populations to the southwest. The specimens from the Jackson Plain were compared to 41 specimens loaned by the Northeast Louisiana University Museum of Zoology, the Chicago Museum of Natural History, the University of Michigan Museum of Zoology, and the U.S. National Museum. The specimens were grouped according to the following geophysical regions: Ozark Plateau, Pennyroyal Region, East Highland Rim, West Highland Rim, and Jackson Plain (Hunt, 1974). An analysis of variation, involving twenty-one meristic and morphometric characters used by Woods and Inger (1957) and Douglas (1972), was computed. This analysis shows them to be not significantly different from other known populations.

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† Exact cave locations on file with the NSS Cave Files Committee.

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