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Cover Photo: Sketch of an extinct Bush Ox (*Eucera therium sp.*) discovered in Musk Ox Cave, Carlsbad Caverns National Park in February, 1976, by the Cave Research Foundation. The bones were removed in July, 1976 and are under study at the Smithsonian Institution.

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Fossil Man in India: The "Missing Link" in Our Knowledge of Human Evolution in Asia

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ABSTRACT

In exploration of caves and rock-shelters in India and Pakistan, palaeontologists have not been rewarded with the rich harvest of fossil bones of Pleistocene man such as has been recovered from natural shelters in much of Europe, Africa and Asia. It was at the close of the Ice Age and onset of geologically Recent times that prehistoric populations of South Asia began to occupy these formations. The predecessors of these Late Stone Age (Mesolithic) peoples lived most often in open-air camps, as the archaeological record of their Early and Middle Stone Age (Palaeolithic) stone tools testifies by an artifact distribution in open country rather than in caves. Apart from some interesting exceptions to this trend in habitat preference, where Pleistocene man lived is reflected in a failure on the part of South Asian prehistorians to find the skeletal remains of the contemporaries of Neanderthals, *Homo erectus* and other Pleistocene members of the human family. This paper discusses those strategies of palaeontological investigation which, if pursued, could result in filling the hiatus in our knowledge of early man in South Asia. The significance of post-Pleistocene cave and rock-shelter habitation is discussed as well. Specific natural formations visited by the writer in his quest as an anthropologist for the bones of ancient man in Indian are described.

A FEW days ago, while compiling a list of general texts published in this country on the subject of human evolution and the fossil record, I counted at least a score which have appeared within the past twelve months. Including revised editions of some older works, this abundance of sources might give the impression that the public's enthusiasm to read about new discoveries in human palaeontology provides stiff competition for the publishers of more serious works by that great anthropologist Ann Landers or the experts on vaginal politics, virtures of vitamin C, and real estate costs in Plains, Georgia.

Varied as these anthropological efforts are from one another, they share a single feature—a conspicuous absence of data concerning the fossil evidence of human evolution in the vast subcontinent of South Asia (Fig. 1). Those of us old enough to have labored through Boule's *Les Hommes Fossil* while preparing for a language examination in French will remember that an identical situation pertains to that venerable tome. We seem to have an enduring problem here. Why has a record of fossil man in India, Pakistan and Sri Lanka (Ceylon) been so elusive during the past century of research in human palaeontology, while scholars excavating and collecting prehistoric specimens in Europe, Africa and in other parts of Asia have been more richly rewarded for their efforts?

I doubt if a failure to recover the skeletal remains of early man in this part of the world is due to the existence of any peculiar conditions of preservation of human bone in local geological contexts. A kind of Eastern fatalism is expressed sometimes in the notion that there is an inevitable destruction of ancient organic remains in Indian soils of reputed dissolving capabilities. However, the bones of organisms other than man are preserved in ancient deposits, for example *Bos namadicus* and *Hippopotamus* in Pleistocene beds, and human bones are not so different from these in their organic and inorganic constituents.

Nor can I accept that old saw that searching has not been extensive enough to allow for an opportunity to uncover the remains of ancient man in this part of the world. But I do think that explorations may have been carried out in the wrong places. Any suggestion that early man had not inhabited South Asia can be refuted immediately by reference to the archaeological evidence of Acheulean handaxes, choppers and other kinds of Palaeolithic tools which are to be found in almost every corner of the subcontinent. Indeed, the archaeological evidence of prehistoric man is very well documented for South Asia.

No, I think the explanations lie elsewhere; and perhaps, by being mindful of the points I'll make here, the student of ancient man may

enhance his luck in adding South Asian hominids to the picture of human evolution which has been drawn already from discoveries made beyond the borders of the Himalayas.

First of all, many early man sites which have been reported in South Asia since 1863, when Robert Bruce Foote found a handaxe near Madras, are no longer recognizable. Excessive collecting of surface finds and a dearth of records about exact locations of find sites have meant that many rich areas of prehistoric human activity are lost of us forever. To date only one primary Palaeolithic site has been excavated in India. I refer to the excellent work of Gûdrun Corvinus of the University of Tübingen at Chirki on the Pravara River which was begun in 1965. But the tens of thousands of stone tools which are preserved in museum collections in Europe and America are seldom documented as to their provenience. If the bones of the manufacturers of these palaeoliths were deposited near these collecting areas, traces of their burial remain unknown to us today.

A second reason may be that we have been looking for the bones of early man in inappropriate places in South Asia. What was so innovative and significant about the survey carried out by the late Theodore D. McCown of the University of California, Berkeley, along the banks of the Narmada River a decade ago was that the searching

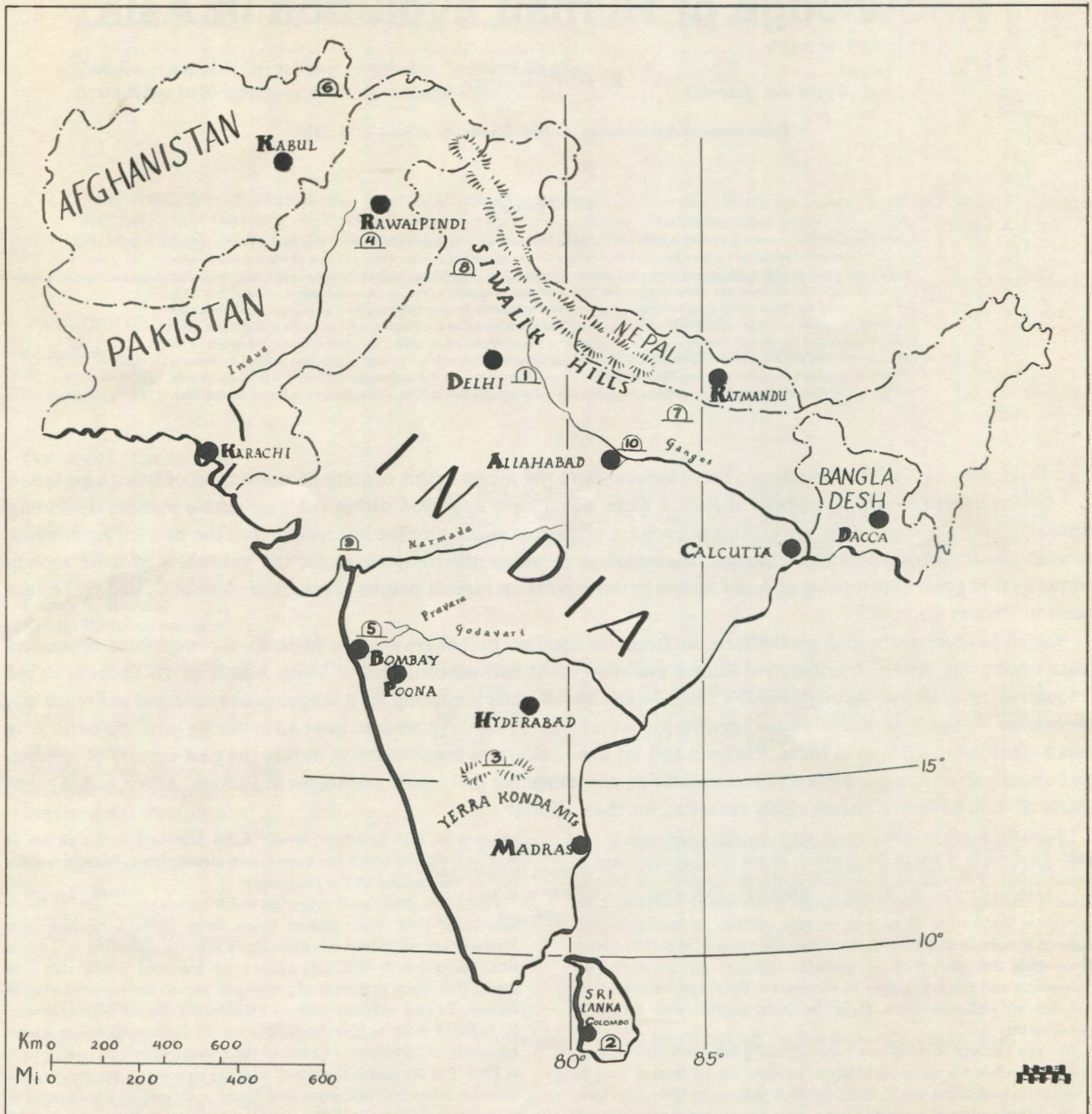**Figure 1.** Map of South Asia, showing places mentioned in the text. 1. Ahirpura, 2. Bellanbandi Palassa, 3. Billa Surgam, Pedda Pavuralla Badde, 4. Chinji, 5. Chirki, 6. Darri-I-Kur, 7. Gorakhpur, 8. Haritalyangar, 9. Jalampur, 10. Sarai Nahar Rai.

for new sites was conducted along the tops and sides of the ancient terraces cut by the river and not within the channel being cut by the present river. The Palaeolithic tools which appear in the modern bed have been washed in from above and do not represent true samples of integrated and specific industries. Collecting along the more ancient terraces was rewarded by the finding of some pristine assemblages where the degree of post-depositional disturbance has been slight. Here is the type of situation where undisturbed skeletal remains of ancient man are most likely to be encountered.

The successful cave research that has characterized prehistoric studies of Europe does not have a parallel in South Asia. Limestone caves are few in India, and those which have been studied do not appear to contain the remains of Pleistocene man. A good case in point is the Billa Surgam Cave complex of Kurnool District, South India (figs. 2, 3). Since the 'eighties when Foote, then Superintendent of the Geological Survey of India, and his son Henry, an army Lieutenant, commenced their excavations at these magnificant natural caverns, teams of excavators have paid visits to the complex and moved quite a bit of earth from one place to another. This work was at first the responsibility of M.E. Grant Duff, Governor of Madras, who in turn had been requested by the British anatomist Thomas H. Huxley to see to the exploration of the caves of the Yerra Konda range as reported by their discoverer Captain T. Newbold in 1844. For forty years the Billa Surgam Caves were lost. Foote re-discovered them while surveying portions of Kurnool District. It is ironic that they should have disappeared from geological records given the fact that the geographical coordinates of the caves were contained in the title of Newbold's report published in 1884 in the *Journal of the Asiatic Society of Bengal!* The Footes confirmed Newbold's observation that the caverns of Billa Surgam were fossiliferous, but their hopes that the traces of Pleistocene man might be found here were never realized. For many years the faunal collections were lost in the Madras Museum, and upon finding them in 1916, the elder Foote argued as he had earlier that some bones exhibited evidence of human workmanship. His contention that these splintered pieces were evidence of a "Magdalenian" Palaeolithic culture finds few supporters among present-day prehistorians. Foote himself came to modify his view when the palaeontologist R. Lydekker, then in Calcutta, suggested that the bone markings were the traces of rodent gnawings.

Continued digging at the Billa Surgam and other caves in Kurnool District has revealed that their most ancient use is no earlier than Neolithic times. We visited this region in the spring of 1972 and had the opportunity to see excavations in progress at Pedda Pavuralla Badde by a team of archaeologists from Deccan College, Poona. Neither my co-worker, Güdrun Corvinus, who is a geologist, nor I saw any evidence at these caves to convince us that they had been occupied by man before the time when agriculture and herding were introduced in this region around 2000 B.C. Neolithic-type pottery of wheel-made pattern and
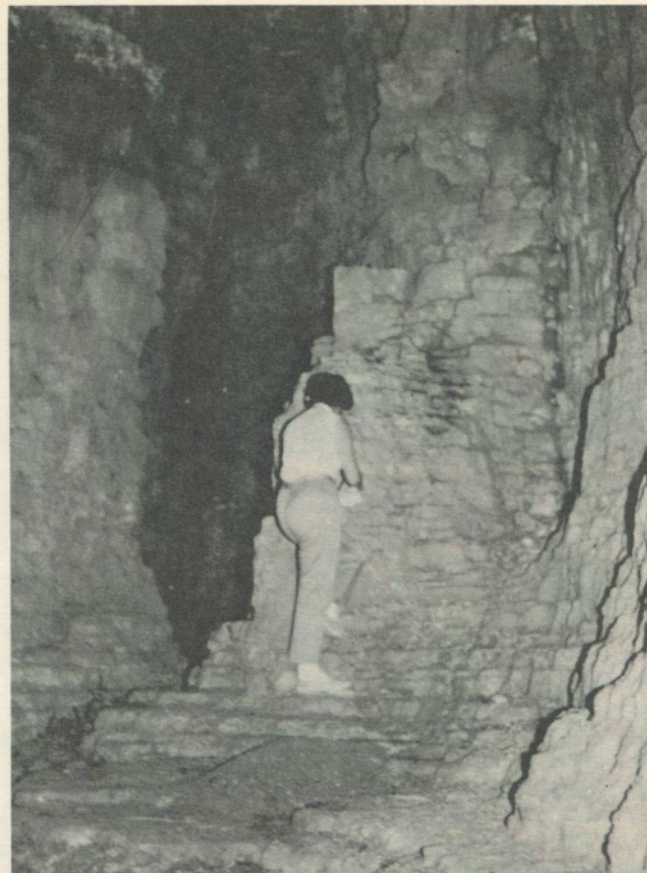

Figure 3. Billa Surgam Caves, Kurnool District, South India. "High Altar" in Cathedral Cave. Before excavation in 1884-85, the original cave floor was at a level just above the head of the standing figure. Photo by K.A.R. Kennedy.

some Iron Age points were removed from deeper deposits within the cave at Pedda Pavuralla Badde. In 1926 a Collector of Kurnool District, L. A. Cammiade, suggested in an article that Foote had failed to locate the hearths and stone tools of early man because his excavations were carried out deep within the caves and not at the places of entrance. Subsequent excavations have neither confirmed nor rejected Cammiade's thesis, but there persists a strong bias that these caves must have been the abodes of Pleistocene man.

Rock-shelters were inhabited by prehistoric communities, and their frequency is much higher than caves in parts of India. I have visited a great number of these rock-shelters in Central and South India and admired the drawings in red ochre of animals and anthropomorphic figures which appear on flat surfaces of rock walls (Fig. 4). But again, the palaeontological results are disappointing as we search for the remains of Pleistocene hominds. The predominant stone industry associated with these natural formations dates to Late Stone Age or post-Pleistocene times. Early phases of this prehistoric horizon are 10,000 years old, but in some parts of India there is good evidence to indicate that this lithic industry and the economy of a hunting-gathering lifeway persisted well into the historic period, pehaps as late as the end of the first millenium A.D. Rock-shelters are no longer used by remaining hunting-gathering tribal groups in India, but until about fifty years ago the aboriginal Veddas of Sri Lanka were inhabiting rock-shelters.

Related to this matter of looking in improper places is the continuing practice of turning to those remote hill and jungle areas inhabited today by tribal populations as a suitable place to find the remains of early man. Surely with these aboriginal peoples must lie the solution to knowing more about the earliest hunting bands of the subcontinent! Our own visits to these relict hilly tracts have led me to conclude that it

Figure 2. Billa Surgam Caves, Kurnool District, South India. Purgatory and Charnal House Caves seen from mouth of Cathedral Cave. Debris removed by excavators is in middle foreground. Photo by K. A. R. Kennedy.

Figure 4. Rock-shelter wall painting along Betamcherla-Kurnool road, Kurnool District, South India. Two male figures. Photo by G. Corvinus.

was not until relatively recent times that these jungle areas were occupied by man. The ancestors of living tribal peoples lived in the lowland plains which were once rich in game and various edible vegetable products, but with the presence of agricultural populations moving into these fertile areas the Late Stone Age hunters migrated to those marginal and less desirable highland regions where we find them today. Archaeological data indicate an abundance of lithic assemblages in the lowland areas now inhabited by farmers, but there is very meager if any prehistoric artifact material to be found in regions presently occupied by tribal communities.

Another facet of our problem is the sad fact that in those few cases where the actual vestiges of fossil man have been discovered in this part of Asia, the bones have not always been recognized or collected for study. The result has been the loss of these specimens in museums in South Asia and in Europe. I am convinced that Upper Pleistocene hominid remains were found at Gorakhpur in the middle of the nineteenth century and perhaps even earlier along the banks of the Ganges, for the published records of the excavations in which the specimens were found indicate an Upper Pleistocene geological and faunal depositional context in both cases. The geologist W. Theobald reported in the decade of the Footes' work at Billa Surgam the presence of a human skull from Gorakhpur which had been taken to the Museum of the Asiatic Society in Calcutta, but before he had an opportunity to examine the specimen it had disappeared, whither one knows not to this day. Similar tragedies are associated with provocative discoveries at Ahirpura and Jalampur, also in India.

I have painted a bleak picture of fossil man studies in South Asia, but it is not without its glimmers of light too. Let's look now at a few situations where success has been encountered. Perhaps we shall find here a remedy in the formulation of new strategies of exploratory research into the broader problems of human evolution in South Asia.

There is, for instance, the recovery of teeth and jaw fragments of the possible proto-hominid Ramapithecus from the Siwalik Hills of North India, Pakistan and Nepal. The deposits of Haritalyangar and Chinji date to Miocene-Pliocene times. The Gigantopithecus mandible described by Elwyn Simons and his colleagues also gives us hope of other discoveries to come. But from the time of the emergence of Ramapithecus to the date of the next most ancient hominid specimen from India is a temporal hiatus of over 10 million years. We do not know if early hominids of the genus Australopithecus existed in South Asia, although claims of the presence of this hominid inhabiting other parts of Asia make this a strong possibility, if such claims turn out to be true.

Prehistoric research in Afghanistan carried out between 1959 and 1966 under the direction of Louis Dupree led to the finding of a broken right temporal bone from the cave of Darra-I-Kur. This specimen was found in a cultural context dated to 30,000 ± 1900-1200 years B.P., as

determined by radiometric assay. The cultural deposit is Mousterian or Middle Palaeolithic. This fragment has been carefully described by J. Lawrence Angel of the Smithsonian Institution, and I had the privilege of examining the temporal bone myself. Angel has concluded, after a comparative study of the bone with skulls from series of Neanderthals and modern men, that the Darra-I-Kur temporal would fit into a partly Neanderthal population such as Skhūl in Israel as well as into a modern Homo sapiens sapiens population. Its most unusual feature is a very massive vascular foramen on the medial wall of the pyramid where the large cavern of the internal acoustic meatus has a diameter of almost three times that of the usual cross-sectional area: 160.6 mm. in contrast to 62.5 mm. using πr^2. It is tempting to conclude, as Angel has done with caution, that the increased size of the vascular foramen may have a connection with the slight vascular hypertrophy needed at high altitudes. The Darra-I-Kur cave is situated in the limestone foothills of eastern Afghanistan.

At Sarai-Nahar-Rai rock shelter near Allahbad in Uttar Pradesh, North-Central India, a fossilized collection of bones of a burial complex was found six years ago. Bone samples from this alluvial deposit have been dated by radiocarbon methods to 10,345 ± 110 years B.P. The associated cultural remains consist of microlithic flakes and crude pottery, all assignable to the Late Stone Age. The geological evidence has been interpreted to indicate a dry post-Pleistocene climatic phase. The complete skull of one male adult specimen is described in a brief report in Nature. In all anatomical features the skull shows traits which fall within the normal range of metrical and morphological variation for modern man.

A third series of human skeletal specimens of some antiquity is from the Late Stone Age open-air site of Bellanbandi Palassa in Sri Lanka. At the time we described the majority of these specimens several years ago, dating was based upon samples of charcoal provided from the upper levels of the site. At that time the occupation was assumed to be second century B.C. In 1972 Kenneth P. Oakley, now retired from the British Museum of National History, London, published the results of his thermoluminescent dating of fired rock crystal directly associated with one of the skeletons. A date of 6500 years B.P. with an error limit of plus or minus 700 years at the 68 percent level of confidence was obtained.

These are the most ancient specimens of prehistoric man known in South Asia at the present time. There are about twenty-five other Late Stone Age sites in India and Sri Lanka which have human skeletal material, but dating analyses of these are not yet underway. The skeletal record for Neolithic, Chalcolithic, Harappan (Bronze Age) and Iron Age populations of the subcontinent is larger and better understood, and it has been possible for the writer to be involved directly in the excavation and anatomical study of some of these prehistoric series. For the past 5000 years the records are more complete in South Asia with respect to the bony remains of human beings.

In considering these factors involved in the search for fossil man in South Asia, we may now pose the question of what our past frustrations and present successes might teach us about prospects of future research in this part of the world. We have noted that caves and rock-shelters were first occupied in post-Pleistocene times and not earlier, save for a few exceptions such as Darra-I-Kur. This suggests that Pleistocene man in India was living rather extensively in open-air camps, particularly in those regions beside river courses where his handaxes and choppers are found today in greatest number. As in Europe prior to the onset of the Würm I glacial advance, so in South Asia were caves and rock-shelters less frequented as year-round habitations. The open-air primary camp and factory sites, such as Chirki, hold the greatest promise of yielding finds of ancient human bones. Indeed, bone preservation is excellent at Chirki, although to date all specimens are of non-human species.

Areas which are relatively in isolation today have not been productive of either palaeontological or archaeological evidence and the dates of first occupancy of these highland tracts must be rather recent. More

hopeful areas of discovery are those parts of the subcontinent where there existed in the Pleistocene ecological settings for large game and extensive watercourses. Perhaps we can compare the present tribal areas of India to those relict portions of Europe during the Pleistocene, although the climatic and geological stresses were quite distinct.

It was the extension of the tropical belt some eight to ten degrees northward of its present limit during the Pleistocene that may explain in part this behaviorial preference for open air camps, for climatic conditions did not become a stress factor in forcing South Asia's nomadic hunters to seek more permanent and warmer abodes. With the retreat of this tropical zone in the geological Recent, we find that rock-shelters become particularly important as the loci of permanent camps. Equally important to the factor of absence of climatic stress is the use of the natural formations as a demographic response to increasing population size and density in areas of developing high cultural specificity, more permanent residence patterns, and relatively restricted territoriality—all effects of the more intensive exploitation of the food resource base through the manufacture of more efficient hunting weapons and experimentation in incipient agriculture and keeping of animals as a food reserve. By Neolithic times food-production and animal domestication were a full-time preoccupation with sedentary villagers who maintained a symbiotic relationship

with remaining hunting peoples who were the suppliers through trade of flesh foods and forest products.

We are describing here a general trend in habitat preference among prehistoric peoples of South Asia: future explorations of caves may reveal a higher frequency of their use by Pleistocene man than is indicated by present evidence. Erosional agents of geologically more recent times have erased the surface traces of ancient caves and rock shelters in some regions of the subcontinent.

The search for early man in this part of Asia has only begun, and much of the pioneering of this effort will be in the hands of the nationals of the South Asian countries. Foreign scholars continue to be welcome providing that they work with native colleagues, and this is as it should be. But the traditional ways of looking for the fossils of our ancient ancestors, based as they were on European archaeological and palaeontological models of Pleistocene cave archaeology, particularly with reference to British practices, will no longer satisfy the goals of the human palaeontologist conducting research in South Asia. What is demanded by the "new palaeontology" of early man is a sensitivity to the importance of the osteological data as well as to the critical implications of palaeo-ecology and palaeo-demography. Here lies the new adventure and, I believe, a promise of success.

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A Growth Rate For Cave Gypsum Needles

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ABSTRACT

Gypsum (selenite) needles in an Iowa cave grew to an average mass of 0.0056 g and a maximum mass of 0.0160 g in 90 years or less. This represents a mean and a maximum growth rate of 0.062 and 0.18 g/1000 years, respectively. If this maximum growth rate is applicable to needles in other caves, then, one of a frequently encountered large size (15 cm long and 5 mm wide, weighing 5 g) would require about 28,000 years for its formation. Such long development times argue strongly for the preservation of these fragile cave deposits.

Many observations have been made on the rate of growth of calcitic stalactite and stalagmite deposits in caves (Hicks, 1950; Hill, 1976; Moore, 1962; Moore and Nicholas, 1964). In contrast, little is known about the rates of deposition of the various growth forms of gypsum ($CaSO_4.2H_2O$), the second most common secondary mineral in caves (Broughton, 1971, 1972; Hill, 1976; White, 1976). Most of the literature on cave gypsum is concerned with gypsum flowers and wall crusts, and with the origin of the sulfate ion in cave systems (Pohl and Born, 1935; Pohl and White, 1965; White, 1968, 1976). The purpose of this note is to report the presence and rate of formation of gypsum needles (selenite crystals) in caves in Dubuque County, Iowa and to relate this rate to other gypsum needle occurrences.

Gypsum occurs in various forms in many caves in the United States and elsewhere. A scattered literature on these forms and occurrences exists; it is cited in the above references, in various issues of NSS publications, and in the Speleo Digest. One such gypsum growth-form is gypsum needles. These are clear, multiple-twinned crystals (selenite) that are loosely connected to and protrude from the clay of the cave floor. They range in size from 0.2 to 10 mm and more in diameter and from less than 1 cm to over 1 m in length (Hill, 1976).

Gypsum needles up to 16.5 cm long and about 5 mm wide occurred on clay cave floors in some of the "spar caves" south of Dubuque, in the lead mining district of Dubuque County, Iowa (Brown and Whitlow, 1960, p. 10; Calvin and Bain, 1900, p. 509; Leonard, 1897, p.36). Heyl, *et al.* (1959, p. 93) mention gypsum needles in abandoned sections of nearby mines in Illinois and Wisconsin, but give no data on the size of the crystals.

In 1960, in Webers Cave, a spar cave south of Dubuque, I found selenite needles protruding from the side of a trench cut in clay fill. The cave was originally discovered through an artificial shaft in the late 1860's and the trench, in a remote section of the cave, was probably not dug before 1870. Therefore, the crystals formed and grew to the extent in which I found them in 90 years or less.

A sample of the largest crystals averaged 13.9 mm long and 0.9 mm wide (range: 9 to 19 mm long and 0.3 to 1.5 mm wide). The average crystal mass was 0.0056 g, and the largest had a mass of 0.0160 g (Table 1). These represent a mean and a maximum growth rate of 0.062 and 0.18 g/1000 years, respectively.

Landis (1961) reported selenite crystals which had grown about $7 \pm$ mm in a maximum of 100 ± 5 years from the clay wall of an excavation dug by saltpeter miners in Cove Knob Cave, West Virginia. The mass of these crystals was not given, but it seems that they had a growth rate only half that of the Webers Cave sample.

If we take the above mean and maximum depositional rates as those representing the average and the most favorable conditions for selenite needle growth, we can easily calculate, through a simple

TABLE 1. Maximum dimensions and weights of the largest selenite crystals that grew in 90 years or less from the side of a mining trench in Weber's Cave, Iowa.

	Width (mm)	Length (mm)	Weight (gm)
	1.5	16	0.0160
	1.0	11	0.0035
	0.7	16	0.0028
	1.0	11	0.0064
	0.3	9	0.0028
	0.7	19	0.0023
Means	0.9	13.7	0.0056

ratio, a suggested time required for the formation of needles in other caves. Thus, the mean and minimum time needed to form the largest of the reported Dubuque region crystals, estimated to weigh 5 g (by comparison with weighed crystals of similar dimensions), is about 81,000 and 28,000 years respectively. This 5 g size is one that I have frequently encountered in caves with extensive selenite needle deposits. Of course, larger crystals would require a proportionately greater time of formation. A large crystal from Tennessee, 255 x 20 x 10 mm and weighing 68.14 g, would thus require about 380,000 years for its formation at the above maximum rate. Larger crystals, such as those up to 1 m long reported from Falls Cave, Arizona, would require even greater formation times.

Of course, the validity of these greater ages should be open to question. But, at least, in most caves in the southeastern United States, the larger crystals occur in caves that are comparatively old, occur beneath an impervious and protective cap rock, and are far removed from areas of rapid and massive ground water percolation. Consequently, these cave areas may have conceivably been stable sites for slow and continuous selenite needle growth for the suggested times, even in the light of the known dramatic fluctuations of Pleistocene climates and their effect on regional precipitation and ground water percolation rates. Other conditions influencing growth rates, such as the nature of the clay cave floor and its permeability to calcium and sulfate ions and the retarding effect of limited sulfate availability, are not known. The mechanisms of ion transport, crystal formation, and growth of these needles from cave clays are undoubtedly different from those proposed for gypsum crystals formed on cave carbonate ceilings and walls (Pohl and White, 1965).

The Webers Cave selenite crystal growth rate may be a reasonable maximum that is unlimited by sulfate availability, because the sulfate is here in abundant and close supply. Calcium bearing solutions are reacting with oxidizing iron sulfides (marcasite, FeS_2) in veins directly above the Webers Cave passages,

less than 2 m from the site of the crystals.* In many of the drier parts of the cave, careful examination shows gypsum hairs lying directly on an iron oxide (limonite and/or goethite) boxwork with an unoxidized marcasite core (Fig. 1).

Figure 1. Selenite gypsum crystals on iron oxide boxwork formed from oxidation of marcasite in Webers Cave. Scale line equals 2 mm.

The growth rate suggested here is not applicable to the large selenite crystals from the "Cave of the Swords" or Maravilla Mine, Naica, Chihuahua, Mexico (Foshag, 1927; Stewart, 1940). Some of these crystals are up to 1.5 m long; a smaller specimen (in the U.S. National Museum), 7 x 4 x 45 cm, weighs 2.36 kg. These crystals were not formed by slow basal deposition of ions moving through a cave clay floor, but developed while completely submerged (Moore and Nicholas, 1964; Hill, 1967).

The slow rate of growth of gypsum needles, much slower than that of calcite formations, argues even more strongly for the protection of the few remaining unvandalized occurrences of these crystals.

Additional observations of cave selenite needle growth rates are in order, as well as study of the conditions that determine the rates and quantities of sulfate percolation through cave clays, and the mechanism determining the site of initiation and the maintenance of crystal growth.

ACKNOWLEDGEMENTS

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Post-Wisconsinan Vertebrate Remains from a Fissure Deposit near Ripplemead, Virginia*

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ABSTRACT

Fissures in a quarry wall near Ripplemead, Virginia have yielded fragmentary remains of at least 33 species of vertebrates (26 mammals, one bird, three reptiles, two amphibians, and one fish). Most of the fauna is considered characteristic of post-Wisconsinan time (<10,000 BP) except for remains of horses, tapirs, and peccaries. Although the possibility cannot be rigorously excluded that there has been a postmortem mixing of Wisconsinan and post-Wisconsinan animal remains, it is considered more likely that these three species were contemporaries of the rest of the fauna and thus survived into post-Wisconsinan time in southwestern Virginia.

VERTEBRATE remains have been recovered near Ripplemead, Virginia, from three fissures in an abandoned limestone quarry adjacent to the old U.S. 460 bridge on the south bank of New River (Fig. 1). The fissures trend northeast and are about 60m above the river. They contain red clay, limestone breccia, New River stream gravels, landsnail shells, and vertebrate remains. Most of the vertebrate fauna was collected from the northernmost fissure. The sparse faunas of the other two, more southerly, fissures duplicate parts of the fauna found in the northernmost fissures. Remains were collected by surficial examination of both the fissure and the fissure outwash, as well as by acid preparation of fallen, calcite-cemented blocks from the northernmost fissure. The matrix in the fissures is not stratified; therefore, relative ages of the accumulated vertebrate remains could not be determined.

Attempts to determine the age of the fissure deposit so far have met with limited success. Bone fragments were submitted for carbon-14 age determination, but carbon-14 in the sample was insufficient for a reliable date to be obtained. Likewise, matrix samples were submitted for palynological analysis, but no palynomorphs were present. Therefore, the age of the deposit for now must be surmised from the vertebrate content of the fissures.

Microtine remains are of characteristic Wisconsinan and post-Wisconsinan species (Guilday, 1971; Guilday and Hamilton, 1973 and written communication). No characteristic Wisconsinan large mammal remains (for example: mammoth, mastodon, sloth) and no characteristic arctic or subarctic small mammal remains were found, yet many temperate-zone small mammals are represented. Therefore, we conclude that the fissure probably was filled in post-Wisconsinan time (<10,000 BP). Because no remains of domestic animals, red foxes, or opossums were found, and because horse (see page 108), tapir, and peccary teeth are present, the deposit appears to be entirely pre-Colonial. The raccoon is the only member of this fauna ever considered to be a fairly recent immigrant to eastern North America (Handley, 1971). As this animal presumably migrated into eastern America from the southwest, it may well have reached southwestern Virginia significantly earlier than it reached areas of Pennsylvania,
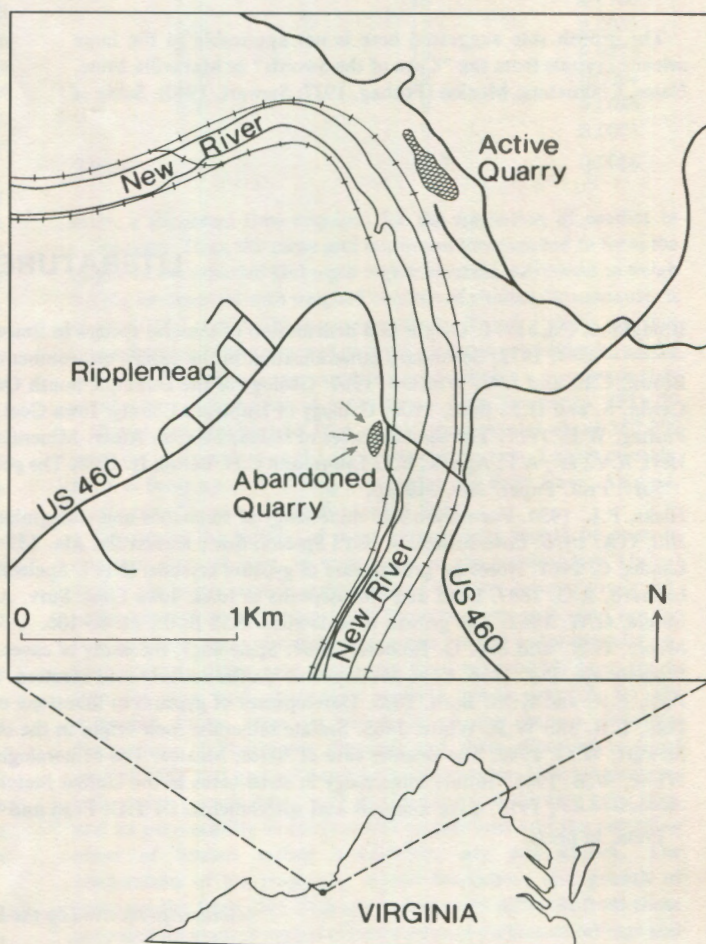
Figure 1. Map showing the location of the Ripplemead quarry. An active quarry is on the northeast side of the River; the abandoned quarry is on the west side of the river, southeast of Ripplemead. The arrows point to the approximate locations of the three bone-bearing fissures on the southern half of the west wall of the quarry.

Maryland, northern Virginia, and northern West Virginia where early post-Wisconsinan faunas have been found and extensively collected. Thus, in view of the presence of the horse, tapir, and peccary, an age in the range of 7,000 to 9,000 BP would seem to be a reasonable estimate, though the deposit may have accumulated over a longer period, and a more recent date is possible. Because most collecting was done on outwash from the fissures, some recent material may have been introduced.

Most of the vertebrate remains consist of unidentifiable broken and rodent-gnawed vertebrae and ribs. These could not be studied meaningfully because they lacked diagnostic features. Some better preserved post-cranial remains, jaw fragments, and many isolated teeth did allow recognition of at least 33 different animals (Table 1). The deposit contains a preponderance of rattlesnake remains. Strings of vertebrae and ribs of these animals constituted the only partially articulated material in the fissures. Next most abundant were teeth and jaws of voles, wood rats, and white-footed mice and teeth of Virginia deer. Jaws of short-tailed shrews and rabbit teeth were found

occasionally, whereas other animals were represented by only one to five bones or teeth. Some salamander vertebrae and fish scraps were present, but there were no turtle remains. Bats seem to have been strikingly rare, being represented only by a single jaw of the silver-haired bat. This species roosts frequently in rocky crevices and is not known to roost in caves (Jackson, 1961).

Dentitions and bones of smaller mammals are often fairly complete and well preserved. In contrast, larger mammals are represented only by isolated teeth. Though this difference in quality of preservation may be purely a function of the relative size of the remains, large and small mammal remains may have had different modes of collection and/or preservation or else represent different time intervals of accumulation. If we assume that all the remains accumulated at the same time, the proportions of remains and the animals represented suggest that the fissures were relatively dry, at least partially open to light and air, and were inhabited by rattlesnakes. Bones scattered on surrounding slopes were gnawed by rodents and then were washed or fell into the fissures. Much small mammal material, as well as the fish scraps and

Table 1. Vertebrates from the Ripplemead Fissures
(collection donated to the Smithsonian Institution).

OSTEICHTHYES

Nondiagnostic vertebral centra and jaw fragments (9 specimens)

AMPHIBIA

Bufo fowleri or *woodhousi* (toad) (4 vertebrae)

Cryptobranchus alleghaniensis (hellbender) (5 vertebrae)

REPTILIA

Lacertilian (lizard) (anterior caudal)

Family Colubridae (5 vertebrae)

Crotalus horridus (eastern timber rattler) (more than 100 vertebrae and vertebral strings, 8 fangs)

AVES

Family Strigidae (medium-sized woods owl) (1 phalange)

MAMMALIA

Parascalops breweri (hairy-tailed mole) (left mandibular ramus, left humerus)

Blarina brevicauda (short-tailed shrew) (2 left mandibular rami and 1 right mandibular ramus with teeth)

Sorex fumeus (smokey shrew) (left mandibular ramus with dentition)

Lasionycteris noctivagans (silver-haired bat) (left mandible with M_3)

Lepus sp. or *Sylvilagus sp.* (rabbit or hare) (9 cheek teeth)

Tamias striatus (eastern chipmunk) (right mandibular ramus with incisor; right mandible with incisor, M_1, M_2, M_3)

Castor canadensis (beaver) (one lower molar or premolar fragment)

Marmota monax (woodchuck) (right lower M_1 or M_2)

Erethizon dorsatum (porcupine) (heavily worn molar or premolar)

Pitymys sp. (pine voles) (right mandible with M_1-M_2; two right M_1; one left M_1)

Clethrionomys sp. (red-backed mice) (left maxilla with M_1-M_2)

Synaptomys cooperi (southern bog lemming) (right mandible with M_1-M_2, broken M_3; right M_1)

Synaptomys (probably *cooperi*) (left and right M_1; single molar)

Microtus pennsylvanicus (meadow vole) (left M_3)

Microtus cf. pennsylvanicus or *chrotorrhinus* (left mandible with M_1-M_2; left M_1)

Neotoma floridana (eastern wood rat) (37 molars; 4 right mandibular rami; 1 right mandible with M_1-M_2; 1 right mandible with M_2; 1 right mandible with M_2-M_3; 1 left mandible with M_2; 1 left mandible M_2-M_3; 1 left mandible with M_1-M_2; 2 left maxillae with M_1-M_2; 1 left maxilla with M_2-M_3; 2 right maxillae with M_1-M_2; 1 right maxilla with M_1-M_3)

Ondatra zibethicus (muskrat) (1 molar fragment)

Peromyscus leucopus or *maniculatus* (white-footed mice) (7 left mandibles with incisor; left mandibular ramus with incisor and M_1; left mandibular ramus with incisor and M_3; left mandibular ramus with incisor and M_1-M_2; left maxilla with M_1-M_2)

Procyon lotor (raccoon) (upper [?]right canine, lower left M_2)

Spilogale putorius (spotted skunk) (right mandible with P_2-M_1)

Martes pennanti (fisher) (left mandibular fragment with P_4, roots of M_1)

Canis lupus (gray wolf) (upper right M_1; molar fragment)

Urocyon cinereoargenteus (gray fox) (upper right P_4)

Ursus americanus (black bear) (lower [?]right P_1; lower left I_3)

Tapirus sp. (tapir) (3 upper cheek teeth)

Equus sp. (horse) (2 milk molars and 1 milk incisor)

Mylohyus sp. (peccary) (1 lower P_1; 1 fragmentary cheek tooth)

Odocoileus virginiana (Virginia deer) (3 right lower M_3; 2 right lower M_2; 1 right lower M_1; 2 right lower P_3; 1 right lower P_2; 2 left lower P_2; 1 right upper M_3; 2 right upper M_1; 2 right upper P_2; 1 right upper P_1; 2 left upper M_3; 1 left upper M_1; 1 upper milk molar; 1 lower milk molar; 16 fragmentary cheek teeth)

salamander vertebrae, were probably introduced as meal remnants dropped on the slopes above the river by predatory mammals and/or birds, most probably owls.

Of the mammalian species recognized according to Jackson (1961), the fisher, porcupine, wolf, and bear prefer dense woodlands or brushy thickets. The silver-haired bat and raccoon prefer wooded areas near swamps or rivers, as do the tropical to subtropical living tapirs (Hall and Kelson, 1959). The muskrat and beaver clearly prefer an environment near permanent water. Chipmunks, however, prefer open forests, especially rocky wooded limestone bluffs. The deer, moles, and rabbits are quite compatible with the rest of the fauna but have wider environmental tolerance. Their presence does not reflect any one set of environmental conditions. The living peccaries *Dicotyles* and *Tayassu* are found from deserts to jungles (Hall and Kelson, 1959), although the recently discovered peccary *Catagonus* (Wetzel and Dubos, 1975) seems to prefer scrub thorngrass associations. Thus, the extinct peccary *Mylohyus* can be referred to no obvious habitat. The fisher and porcupine generally prefer forests containing some conifers, but most of the other animals show a strong preference for temperate hardwood forest. The lizard remains indicate that the climate was as warm as the present climate, or only slightly cooler, and most of the mammals are or historically were inhabitants of the State (Handley and Patton, 1947).

Thus, a picture of the environment would be a permanent river bordered by a flood plain covered mainly by a dense, brushy, preponderantly hardwood forest, more open and less brushy land being found on the flanks of the flood plain. This environment is probably similar to that which existed in early historic time before the bottom lands adjacent to the river were cleared. Only the horse seems somewhat anomalous in this setting. Three explanations are possible: (1) The horse may represent a farm animal from historic time accidentally or purposefully introduced into the fissure. (2) The fissures are on what was then an exceptionally moist slope; other nearby slopes were drier and grassy. (3) The native eastern American horse may have been tolerant of forest habitats. Possibly (1) seems unlikely in the absence of any other recent species introduced by or because of man. Possibility (2) also seems to be unlikely because the slope on which the quarry was developed faced east instead of north. Pronounced differences in vegetation are fairly common, even in the present Appalachians, where the contrast is between northern and southern exposures, but such effects are subdued or absent where slopes face east and west. Thus, possibility (3) seems to be the most likely choice in view of the rest of the fauna with which the horse teeth are associated. Probably western Virginia was heavily forested at the time the Ripplemead fissures were entombing vertebrate remains and had a climate comparable with that of today, or only slightly cooler. The persistence of tapirs, peccaries, and horses, therefore, probably is attributable either to these extinct species' tolerance of heavily forested environments or to their ability to survive on only small patches of grassland. Such areas of grassland easily could have persisted in the form of either natural "balds" or as fire-cleared areas produced by Indians. This explanation is compatible with the apparent carry-over of only medium-sized animals from the Wisconsinan. Thus, although this assemblage can be explained by assuming that the remains are of mixed age, it is equally if not more likely that tapirs, peccaries, and horses did persist in southwestern Virginia until well after the end of the Wisconsinan ice age.

ACKNOWLEDGEMENTS

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Evidence for Relict Caves from Passage Development Along Dipping Strata?

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These comments on relict caves (Campbell, 1977) are not to question the existence of relict ("fossil") caves. As surely as caves exist today, they must have existed during much of the past, and it would be highly unusual if by now all such relict caves had been obliterated by geologic processes. The problem is one of identification, and I agree with Campbell that "proving" a cave relict is not easy. It is especially difficult because a cave, being the absence of rock, is a non-entity which leaves no *corpus delecti* for post mortem examination. Campbell properly resorts to lines of inferential evidence, but I do not agree that passages following inclined bedding surfaces were likely formed long ago, before the bedding was inclined by subsequent tectonic forces.

Campbell's statement ". . . writers have shown that caves developed in steeply dipping limestones are usually oriented across the bedding, along the water table" (p.52) can be misleading. It is possible for a *cave* to display a modest, uniform slope, perhaps correlated with a river terrace, and at the same time it is possible for each individual passage in that cave to be structurally or lithologically controlled. In discussing cavern development in folded limestones in West Virginia, Davies (1960, p.7) states: "In evaluating the slope it should be borne in mind that the slope referred to is that for a *system of passages* at a given level" (italics added). But nowhere does Davies document a *passage* cutting through bedding surfaces under pure hydrologic control. (It does occur in W.Va., but it is very much the exception rather than the rule.)

In Greenbrier County in southeastern West Virginia, there are many large caves in Mississippian limestones (Rutherford, 1971) which were folded and faulted during the Appalachian orogeny. Passages in these caves usually follow the bedding surfaces. In the Greenbrier Caverns, for example, passage development follows bedding surfaces (among other things) down both limbs of a syncline toward the axis, both along a basal limestone-shale contact and along a higher stratigraphic horizon (Rutherford and Handley, 1976). On both levels plus a higher third one, remnants of a compacted, breccia-like fill can be found in ceiling

and wall pockets, suggesting that the cave was once extensively filled and later re-excavated. A related situation prevails in nearby Ludington's Cave (Palmer, 1974). Here, development follows bedding surfaces along or near a folded and faulted limestone-shale contact, and Palmer concluded that passage orientation in this cave is controlled by stratigraphy and structure. Curiously, Campbell's section of Lillyguard Cave (p.50) gives hint of possible structural control. The strata are not shown, but the central part of the cave appears to follow a dipping bedding plane to an area of brief horizontal and then vertical development, followed by development along a similarly inclined plane. However, the final plane appears lower and different from the former one (unless a fault or monoclinal fold is in between, suggesting structural control), with a possible indication of a third stratigraphically higher plane in the upper entrance portion.

In the Mendip Hills of England, Ford (1965) describes water table control of cavern development, but in all of his example caves the particular passage development is mainly along bedding planes and faults. Taking his section of St. Cuthbert's Swallet as an example (p.113), the vertical shaft complex at the entrance denies a possibly tilted relict cave. By the same token, however, if one could demonstrate cavern development along substantially dipping bedding which also includes classic shaft development which is non-vertical and normal to the bedding, *then* one could make a strong case for the tilting hypothesis.

Based on extensive observations in Greenbrier County, W. Va., where the bedding is sometimes level, sometimes tilted, folded, and faulted, the evidence is that, usually, particular passage orientation is controlled by stratigraphic and/or structural factors. One need only look closely to find them. Accordingly, although I believe relict caves exist, I believe that the probability is remote of proving their existence by documenting that formerly-horizontal bedding plane-controlled development (a) occurred long ago phreatically, (b) was preserved by filling, (c) was later tilted through tectonic uplift, and (d) has recently been revealted by re-excavation (or drilling records).

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Sweden: Caves in Crystalline, Insoluble, Igneous Rocks

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ABSTRACT

Sweden is underlain almost entirely by Archean granites, gneisses, and porphyries. Calcareous rocks very rarely crop out at the surface, being limited to the Danian formation in Scania, the Silurian formations in Gotland, and some pre-Cambrian limestones in Dalecarlia and in Lapland.

Many years ago, the author proposed the following classification of cave-like features in non-carbonate terranes: 1. "original caves" along widened joints and other fractures; 2. caves formed by frost wedging, cavernous weathering, and abrasion, and 3. "glacial caves," i.e. potholes, talus caves, and caves among heaps of glacial erratics. That Swedes have dealt mainly with these kinds of caves has caused them to develop a special branch of speleology.

RÉSUMÉ

Cet article décrit la singulière situation géologique de la Suède, où des roches primitives non-calcaires de granites, gneisses et porphyres debordent entre quelques tres rare formations de chaux, comme le Danien en Scanie, le Silurien dans l'île de Gotland, et quelques traits épars de Pré-Cambrien en Dalecarlie et dans la Laponie. L'auteur a proposé, il-y-a plusieurs ans, une spécification comme suit des phénomènes spéléologiques: 1. des grottes originelles des types Diaclases et Paraclases; 2. des formes causés de gerçures, décomposition ou abrasion; et 3. des monuments précis encore existants de l'Inlandsis quaternaire, c'est-à-dire des roches fracturées, des marmites et des cavités intersticielles dans de tas d'erratic blocs.

ZUSAMMENFASSUNG

Die Abhandlung beschreibt die eigenartige geologische Situation Schwedens, wo die Grundgesteine hauptsächlich Granite, Gneisse und Porphyre sind, und wo nur bescheidene Formationen von Kalksteinen vorkommen [Danienkalk in Schonen, Silur auf der Insel Gotland, und einzelne präkambrische Kalksteine in Dalekarlien und Lappland]. Der Verfasser hat folgende Einteilung der speläologischen Phänomene deshalb vor Jahren vorgeschlagen: 1. Originalhöhlen, die bei Diaklasen und Paraklasen, Verschiebungen, Kluftüngen und Spaltungen ursprunglich entstanden sind; 2. Kavitaten die durch Frostsprengung. Verwitterung und Abrasion entstehen; und 3. die jenigen meistenfalls vom quartären Inlandseis erzeugt worden sind, wie Riesenkessel, Höhlen in zerdrückten und zermalten Felsen, in Steinhaufen und unter erratischen Blöcken.

WHEN I first encountered soluble calcareous rocks, in Moravia shortly before the First World War, the sight of previously unimaginable erosional phenomena was really astonishing. I was lucky enough to begin my life-long work as an amateur speleologist in the area of Macocha, north of Brno.

My first thought, as a tourist and novice, was that my own Sweden might be the last place to contain similar features. Since boyhood, I had visited many "robbers' caves" in the woods of my home province, but those were mainly fault and fissure openings in archean igneous rocks. Calcareous formations there are very rare.

The Czechoslovaks stopped upon meeting with granitic walls or blocks within the limestones, believing that these signified the ends of even the most promising passages. As late as the '50's, my dear bio-speleologist friend, Dr. Knut Lindberg of Lund, believed it pointless to speak of Swedish "speleology" because we possess so few exposures of calcareous rocks.

Lindberg changed his mind after discoveries such as the large Balsberg Cave in Scania, extensive new passages in the long-known Lummelunda caves in Gotland, and those of Dr. Gunnar Rasmusson beyond the Artic Circle in the Lullihatjårro at Abisko. In fact, he wrote a first report on this matter for *Rassegna Speleologica Italiana* (Lindberg, 1956). Nevertheless, he couldn't imagine a speleology dealing with non-carbonate rocks, even though non-carbonate caves became the central interest of the highly active Swedish Speleological Society (SSF) after its founding in 1966.

The proof for this fact is the some 1000 Swedish caves described in four catalogs between 1963 and 1974, in the *Archives of Swedish Speleology*. The most of these are in non-carbonate rocks. How could it be otherwise?

Most limestones in Sweden were destroyed during the several epochs of continental glaciation. Devonian, Carboniferous, and Permian are totally absent from surface exposures. Only a few outcroppings remain of Triassic and Jurassic limestones, all of them in southern Sweden. Were Swedish speleologists confined to these occurrences of limestone, there would be no possibility for the development of an indigenous speleology, either practical of theoretical, in Sweden.

Fortunately, there are many striking non-karst speleological features developed in igneous rocks. These caves are often large and contain many interesting features, although they rarely equal solutional caves in length. Solutional features such as Rillen and Karren do occasionally appear on granites and other silicate rocks, however, and one must not ignore the frequent discovery of interbedded schists and slates in cavernous limestones. In the latter case, caves develop through the insoluble layers by "incasion" (Bögli, 1969a & b).

Caves in silicate rocks should therefore never be thought so rare as they are often conceived to be as a result of speleologists' predominant interest in solutional caves. Speleological interest in non-karst caves has recently increased. For example, the UIS Commission on Terminology has divided cavernous terranes into karstic, parakarstic, and pseudokarstic forms.

Pseudokarst studies often deal with really intriguing new cave forms. In many countries, these caves form an important element of the landscape. Those in the Caledonian highland of Scotland are described in Tony Oldham's wonderful book, "The Caves of Scotland." I, myself, very early tried to identify the more outstanding pseudokarstic features of Sweden.

I proposed the following divisions of caves in non-calcareous, insoluble rocks to the 4th International Spelelogical Congress in 1961, using examples from Sweden:

Type I: Diaclase, paraclase, cleft, and crevice caves.

Crevices in archean igneous rocks can be large enough to be called "caves" from the moment of their creation. They were formed by tectonic and seismic forces, perhaps as early as the Karelium, but mostly during the Caledonian and Variscan orogenies. By such movements, fast or slow, joints, faults, overthrusts, and founderings occurred. Many of the caves formed thusly in granites, gneisses, porphyries, leptites, and other similar rocks still exist and are accessible today. Others have been wholly or partly buried under later deposits, especially by glacial drift.

Type II: Frost-wedging and corrasion caves.

These caves are initiated by frost, when water sinks from the land surface into porous, cracked, or fissured rocks and later freezes. Running water may enlarge fissures opened by frost until they become large enough for man to enter. In old, decayed granites and other weathered silicates, the annual cycle of freezing is still widening fissures and cavities.

Type III: Glacial caves.

This is the type of greatest interest for Swedish speleologists. The several continental ice sheets greatly transformed the Swedish landscape. Their weight and irresistible motion crushed whole hills and distributed the debris widely, in addition to planing off and polishing the bedrock, generally. Caves often exist among the boulders of rocky moraines. Glacial meltwater created potholes ("giants' cauldrons"). Glaciation also produced recesses at the bases of cliffs and cavities in shattered rock exposures.

Figure 1. Type I: Diaclase. Skarpneck at Stockholm.

Many hundreds of Swedish caves are of the first sort, including some that are very large. In the south, in Scania, there are in the isolated hill of Kullen (Kullaberg) caves such as Söfting, Valdemar, and Visit. These all originated from joints in the gneiss, afterwards widened by abrasion, frost-wedging, and corrasion. In nearby Bleking, there are also many diaclases and paraclases in the Fenno-Scandian shield, for example Skafteskär and Björnamåla. In Halland, the large Bursa's Cave, at Kungsbacka, is a 3-level system along an enlarged joint.

The province of Bohuslän contains many narrow fissures in granite, locally called "Klovor" in which morainic boulders are wedged. Very deep and narrow joint caves are found in the basaltic hill, Halleberg, on the shore of Lake Wener in Westergothland. In Smaaland, near Eksjö, is the widely-known tourist attraction of Skurugata, a 1-km long enlarged joint. On the edge of Lake Wetter, in Ostrogotha, is the famous Rödgavel Cave in the prophyritic hill, Omberg. North of my home town of Norrköpping, is a typical little joint cave in the hill, Kolmård, which I used to show to foreign friends.

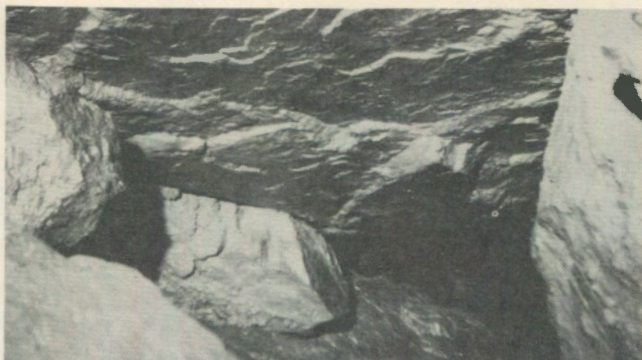Figure 2. Type II: Frost-wedging. Visit Cave at Kullaberg.

Figure 3. Type III:1: Glacial (submorainic) cave at Froesoe, Oestersund.

Figure 4. Type III:2: Glacial (erratic) cave, Solltorp.

Figure 5. Type III:3: Glacial (pothole) cave, "Perkels kittel," Tjellmo.

One might go on like this, studying diaclase and paraclase caves all over Sweden, even adjacent to the Norweigian border far above the Artic Circle. I will mention only one example in the north of Sweden, the Skallberg Cave system in Gideá. At the present, it is the largest non-karst cave known in Sweden. Some passages are over 200m long.

The well-known severe climate of Sweden favors the development of all kinds of cryogenetic features, including Type II caves. All rock openings connected with the free atmosphere are influenced more or less by frost-wedging, including karst caves. The "mantle process" (Gèze, 1969) preserves and expands the profile of all caves by the uniform shallow decay of the cave walls and ceiling. The effect is more pronounced in silicate rocks, in the caves of which each winter precipitates a new layer of decayed and rotten rock upon the floor.

Type II caves can be found all over Sweden, but an especially noteworthy example occurs in the coarse-grained gneiss of the Kullaberg where small fissures have developed into large caves by the work of frost. Another good example of cryogenic cave is the Sulnäs Cave, on the edge of Lake Fjälaren in Ostrogothia, which was entirely developed by frost.

The third type of cave, glacial cave, includes three sub-categories: 1. caves developed in talus and shattered outcrops, 2. caves in blocky moraines or among glacial erratics, and 3. witches' or giants' cauldrons, grooves, and furrows. These features are common and widespread throughout Sweden.

In the old days, people believed glacial erratics to be evidence of battles among giants, for how could such huge stones otherwise have come to lie so far from rocky hills or mountains? And as for the cauldrons, these were so smoothly formed in the hard rock that none but giants or witches could have made such fine things!

The highly ground and polished rock edges in Bohuslän display glacial action very well. Exposed hills and ledges all over Sweden have been similarly abraded, planed, and polished on the stoss side. Rooms and passages in blocky moraines and talus may be inhabited by beasts as well as men. A great many caves are of this type. Some are very long. The labyrinth of Göljhult, at Vimmerly, totals 180m.

Giants' cauldrons at Ålanda, between the Anten and Mjörn seas in Westergothland, reach 18m in diameter and 10m in depth. The local caving club in Ostrogothia has exhumed a cauldron with an elliptical width of 2 to 3 m and a depth of 12m. Most cauldrons are vertical, but horizontal ones also exist. A small horizontal pothole occurs at Rossjö, near Bona in Ostrogothia. The largest horizontal pothole of Räckeberga kyrka, at Torsböle in northern Sweden, is 25m long, 8m high, and 6m wide; two adjacent ones are also quite large. Whole series of cauldrons may be found in ancient river beds, as at Degerfors and in Ragunda.

From the foregoing, the reader may conclude that the usual notion of "cave" is not so self-evident as generally supposed, especially among students of calcareous terranes. A little reflection may suggest that there are legitimate non-karst caves in lava beds, unconsolidated sands and silts, and ice, as well as those in the igneous rocks discussed above. Indeed, there are vast regions of the Earth from which thick sedimentary blankets were swept during the epochs of continental glaciation, exposing Archean granitic, gneissic, and prophyreous rocks to non-karstic speleogenetic processes. It is to these small and peculiar caves, created by tectonic and seismic movements in the earth's crust, by dislocations and faults, by glacial and cryogenetic phenomena, and by other non-karstic events, that Swedish speleology owes its existence.

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Soda-Niter in North Central Arizona Earth Cracks

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ABSTRACT

Soda-niter ($NaNO_3$) occurs as bitter tasting, white efflorescent crusts in Malmquist and Dangling Flake Fissures, Wupatki National Monument, North Central Arizona, and in Buffalo Crack, approximately 15km southeast of the Monument. The occurrence of this comparatively rare mineral is related to the low relative humidity of these caves.

INTRODUCTION

FEW DETAILED descriptions of nitrate minerals in caves exist. Previous documentation consists of either very old (early 1800 articles or scattered, later reports with limited detail. Niter (KNO_3) was reported by Davy (1821) as efflorescent wall encrustations, by Mansfield (1927) as white efflorescences and crusts in a sandstone cave and by Mansfield and Boardman (1932) in the lava tubes of Socorro County, New Mexico. A single report of ammonia-niter (NH_4NO_3) from Nicojack Cave, Tennessee, exists (Shepard, 1857). Ross (1914) mentioned the presence of very pure, elongated, white crystals of nitrocalcite ($Ca(NO_3)_2 \cdot 4H_2O$) in a Southwest guano cave. Palache, *et al.* (1951) reported nitrocalcite and nitromagnesite ($Mg(NO_3)_2 \cdot 6H_2O$) from Kentucky and Indiana caves but added that these localities needed verification. Soda-niter ($NaNO_3$) was briefly mentioned by Bailey (1902) as "an incrustation in a small cave that gave some good cabinet specimens", by Mawson (1930) as a minor constituent with niter in a central Australian cave and by Gale (1912) as "coatings or even stalactites" with niter on cave walls and ceilings. The only modern description of a cave nitrate mineral is for darapskite ($Na_3(NO_3)(SO_4) \cdot H_2O$) intermixed with halite ($NaCl$) in a Texas cave (Hill and Ewing, 1977).

Figure 1. Entrance to Malmquist Fissure, Wupatki National Monument, Arizona. (right)

Figure 2. Pocket of soda-niter in the Kaibab Limestone, Malmquist Fissure. Alan E. Hill photo. (below)


OCCURRENCE

Malmquist Fissure, located in Wupatki National Monument, North Central Arizona (Fig. 1), has a surveyed depth and length of 20m and 80m, respectively; Dangling Flake Fissure, located approximately 0.4km north of Malmquist Fissure, is 40m long and 45m deep (Bridgemon, 1976). Buffalo Crack is located approximately 15km southeast of the Monument and has a depth and length exceeding 30m and 1000m, respectively. All three caves are developed in the Kaibab Limestone of Middle Permian age and are recent, tectonic features (known locally as "earth cracks") associated with the nearby Tertiary San Francisco volcanic fields.

In Malmquist Fissure, the soda-niter occurs as cotton-like tufts adhering to the upper and lower surfaces of small ledges located about 3m above the floor and 10m from the main entrance. Temperatures and relative humidities in Malmquist, measured in October and February, varied between 15 and 20°C and 50 and 80%. In Dangling Flake Fissure, the soda-niter occurs as white crystalline masses in the entrance alcove. October temperatures and relative humidities in Dangling Flake were 14 to 16°C and 39 to 48%. In Buffalo Crack, the soda-niter occurs as a flour-like substance on small ledges 1m above the floor, at a distance of about 200m from the entrance. The temperature and relative humidity in Buffalo Crack in February were 18°C and 70%. In all three locations, the soda-niter is developed along slightly recessed, horizontal bedding plane pockets and seams in the limestone wallrock (Fig. 2). The soda-niter crystals are colorless, clear, and possess prismatic to acicular habit (Figs. 3 and 4).

Figure 3. Close-up of soda-niter crystals in a wall pocket, Malmquist Fissure. Length of longest crystal is approximately 2mm. Alan E. Hill photo. (above)

Figure 4. Acicular crystals of Soda-Niter. Length of longest crystal is approximately 2mm. (right)
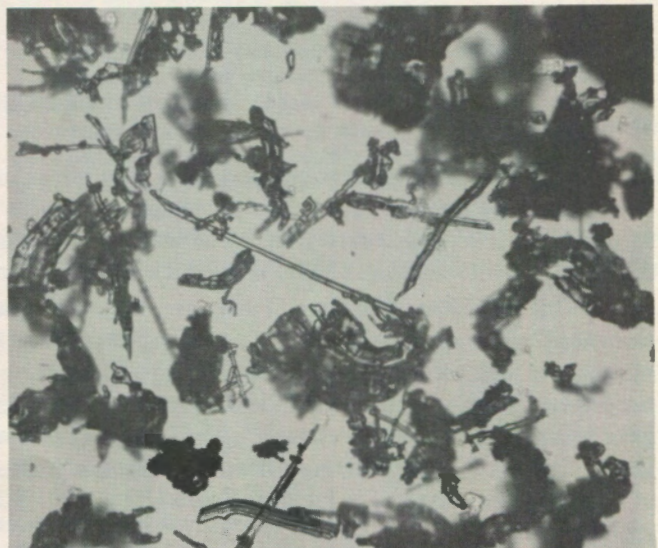
IDENTIFICATION TECHNIQUES

Preliminary identification was made by the distinctive bitter-cool taste, high solubility in water, a strong positive flame test and a strong positive nitrate test (phenoldisulfonic acid method [Black, 1965]). Verification was afforded by optical microscopy, infrared spectroscopy, melting point, and X-ray powder diffraction (Table 1). The data unambiguously identify the mineral specimens in Malmquist Fissure, Dangling Flake Fissure, and Buffalo Crack as soda-niter.

DISCUSSION

Mawson (1930) thought that percolating groundwater brought nitrate minerals into the cave of his study, because nitrate also "occurs...as saturations in the cave rock". High nitrate values in a drill core (22.5cm depth), Malmquist Fissure, indicate that nitrates occur as saturations in the Kaibab Limestone (Table 2). Downward seeping groundwater probably transports the nitrate into bedrock pores and cracks and also into the cave, where it crystallizes as efflorescences along bedding plane seams. Possible sources of nitrate to the groundwater may be surface vegetation, regional volcanics, or primary nitrate within the Kaibab Limestone. Rat guano (sparsely distributed on cave ledges) is considered an unlikely source of the nitrate, since dry cave conditions preclude nitrate movement up to 22.5cm into the wall limestone.

The crystallization of soda-niter in the Arizona fissure caves is a result of low humidity conditions. The relative vapor pressures of water over saturated solutions of various nitrate minerals (at 20°C) are listed in Table 3. When the relative humidity of the cave air reaches these vapor pressure values, the nitrate minerals will absorb moisture from the air (become hygroscopic) and may take up sufficient water to dissolve (deliquesce). The relative humidities of the Arizona fissure caves usually remain below 75% and therefore the caves contain crystallized soda-niter. On one visit to Malmquist Fissure, the relative humidity was 80%; on this occasion, the soda-niter had deliquesced and disappeared into the surrounding cave soil and bedrock.

Table 1. Characterization Data for Soda-Niter from Malmquist Fissure, Dangling Flake Fissure, and Buffalo Crack.

Parameter	Observed	Previously reported	Reference
Crystal system	Uniaxial negative	Uniaxial negative hexagonal-trigonal	Larsen and Berman (1934)
Refractive indices ($\in$, ω)[a]	1.330, 1.586	1.336, 1.587	Larsen and Berman (1934)
Melting point°C[b]	270	306.8	Palache, et al. (1951)
Out of plane deformation frequency (cm^{-1})[c]	834	831	Bhagavantum and Venkatarayudu (1939)
Principle lines in X-ray diffraction pattern	3.34[d](10) 3.03 (100) 2.80 (15) 1.90 (15) 1.89 (10)	3.03 (100) 2.81 (15) 1.90 (16) 1.89 (16)	Smith (1972)

a. Determined by the oil immersion method.
b. The somewhat low melting point for the specimen is attributed to its slightly impure nature.
c. Measured on a nujol mull.
d. The line 3.34 is the principle line of quartz.

Table 2. Nitrate Values (parts per million) for a Drill Core, Kaibab Limestone, Malmquist Fissure.

0-2.5cm	2.5-5cm	5-7.5cm	7.5-10cm	10-12.5cm	12.5-15cm	15-17.5cm	17.5-20cm	20-22.5cm
323	115	204	213	213	177	75	155	75

Table 3. Relative Humidities of Nitrate Minerals in Equilibrium with Their Saturated Aqueous Solutions at 20°C.

Mineral	Relative Humidity	Reference
Niter (KNO$_3$)	95%	Erdey (1963)
Soda-Niter (NaNO$_3$)	75%	Erdey (1963)
Ammonia-Niter (NH$_4$NO$_3$)	63%	Erdey (1963)
Nitrocalcite (Ca(NO$_3$)$_2$·4H$_2$O)	54%	Ewing (1927)
Nitromagnesite (Mg(NO$_3$)$_2$·6H$_2$O)	54%	Ewing, Klinger and Brandner (1934)

Caves of the Southeast have relative humidities greater than 90%. Therefore, niter should be the only nitrate mineral able to crystallize in these caves. The older literature which reports nitrocalcite, nitromagnesite and ammonia-niter in the saltpeter soils of Kentucky and other eastern caves must therefore be viewed with suspicion.

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