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Geochronology of Sandia Cave

C. Vance Haynes, Jr.
and George A. Agogino

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ABSTRACT

Haynes, C. Vance, Jr., and George A. Agogino. Geochronology of Sandia Cave. *Smithsonian Contributions to Anthropology*, number 32, 32 pages, 7 figures, 2 tables, 1986.—Excavations in Sandia Cave, New Mexico, in the late 1930s provided the first recognized stratigraphic evidence for a pre-Folsom culture in North America. This, the Sandia complex, is represented by diagnostic projectile points found in a loose deposit underlying a limonite ocher deposit which, in turn, underlies a cave breccia containing Folsom artifacts and reportedly sealed by an overlying dripstone. Our investigations in the 1960s revealed that the Sandia deposit (unit X) is in fact, a rodent deposit created by bioturbation of the limonite ocher (unit C) and contains material derived from most of the other deposits. A second dripstone (unit D) is recognized as being much older (preoccupation) than the post-Folsom dripstone, instead of being a contemporary facies as originally reported. Its absence from the deposits near the mouth of the cave is believed to be due to removal during the mining of the yellow ocher by Paleo-Indians.

Paleoclimatic interpretations of the stratigraphic units include (1) a warm moist period for the derivation of the ocher by leaching from a pedalferic paleosol formed during a previous cool moist period, (2) desiccation of the ocher during a dry climate, (3) formation of the lower dripstone during a cool moist period, (4) gypsum precipitation (unit E) due to either a dry period or opening of the cave or both, and (5) accumulation of dust and debris (units F and H) under dry conditions alternating with dripstones (units G and I) and breccia cementation under wet conditions. From 14,000 B.P. on, the cave interior was accessible to man and animals. Accumulation of dust and debris (unit F) occurred during a dry period during which a portion of the lower dripstone was removed, presumably by Paleo-Indians in order to extract ocher. During the sbusequent moist period the artifact-bearing debris became cemented by cave drip where not protected by the lower dripstone. Under recent climatic conditions another loose debris layer (unit J) has accumulated during the middle and late Holocene and has always been connected to the lower loose-debris deposit (unit X).

We conclude that Sandia points are definitely less than 14,000 years old and suggest they may be specialized Clovis or Folsom artifacts used for mining ocher. However, we cannot preclude a pre-Clovis age or even post-Folsom. Undisturbed cave strata provide valuable paleoenvironmental data, but redeposition and bioturbation is the rule rather than the exception for most, if not all, cave deposits that were once unconsolidated debris.

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Contents

Foreword

In 1936, when Wesley Bliss and Chester Stock discovered the first Sandia point in Sandia Cave, Paleo-Indian studies were in their infancy. Less than a decade had passed since the discovery of Pleistocene fauna associated with human artifacts at the Folsom site in New Mexico. Some estimates for the age of Folsom culture exceeded 25,000 years. But, the potential antiquity of these finds was not totally accepted by many prehistorians. Clovis artifacts, also recently discovered at Dent, Colorado, and Blackwater Draw, New Mexico, were considered to be Folsom variants, perhaps contemporaneous, or a different facies of the same cultural group. The new finds at Sandia Cave, with a cultural level below Folsom and thus possibly older than 25,000 years, had a revolutionary impact on the archaeological profession. Especially excited of course was Dr. Frank C. Hibben, who was the principal investigator of the site. Based on his interpretation of the data from the Sandia Cave deposits, Hibben proposed a new theory of Solutrean origins for New World cultures.

At that time, even in the Old World, only a rudimentary chronological framework had been worked out for the paleolithic stage of human cultures. Time estimates for the paleolithic cultures of Eurasia, with an evolved flint-working technology, seemed to be directly comparable to the newly discovered Paleo-Indian data. But the barren wastes of Siberia and Alaska were virtually unknown to archaeologists. Without the Siberian and Northeast Asian archaeological link between the Old and New Worlds, only unfounded speculation about inter-hemispheric cultural relationships was possible. It was thought logical that discovery of the descendants of the European paleolithic hunters might soon be made in Asia as well as North America. The plausibility of this expectation greatly increased with the finding of the Sandia projectile points, which had a single shoulder, very similar to the Font Robert variety of Solutrean projectile points found in Western Europe.

Through the ensuing decades, as the Siberian archaeological gap closed and as the amount of available information for North America increased, additional evidence for a Solutrean affinity to Sandia (or for that matter the New World in general) was not forthcoming. Furthermore, a tremendous amount of controversy developed concerning the status of Sandia Cave as well as the proposed Sandia culture itself (see Stevens and Agogino, 1974 for complete details). Unfortunately, in the fifty years that have elapsed since the discovery of Sandia Cave, only one other Sandia site has been discovered. This is the Lucy site, also located in New Mexico and excavated under the direction of Dr. Hibben. This site, as well as Sandia Cave, has a great amount of controversy surrounding the validity of its Sandia component. Therefore, other than a few surface finds of putative Sandia points, there are few external data to confirm the status of Sandia culture. Nevertheless, chronological charts in many prehistory textbooks place Sandia as the earliest cultural complex in the New World. In fact, the problems surrounding Sandia cave have not been resolved, and even the question of the antiquity of the human occupation of the New World still remains basically unresolved. Although it is now known that Clovis predates Folsom by as much as half a millennium, there are only vague hints of the existence of any cultural groups that may have preceded Clovis in North and South America. Thus, it can be seen that the evidence from Sandia Cave could be extremely significant, but the many ambiguities surrounding that evidence need to be resolved before its full potential can be realized.

The controversies that surround the evidence from Sandia Cave center primarily on three key issues: (1) the exact nature of the relationships of the various geologic strata, (2) the validity of the reported radiocarbon dates and (3) the typological validity, if any, of the Sandia projectile points. This last issue holds extreme importance to anthropological theory. However, without the resolution of the first two problems, further discussions of a "Sandia Culture" will remain meaningless.

The following report by Drs. C. Vance Haynes and George A. Agogino is the result of over twenty years of field and laboratory research directed towards resolution of the problems of the geochronology of Sandia Cave. Of course the main concern was to establish a date for the Sandia horizon and to determine its relationship to the overlying Folsom stratum, and thereby establish with as much certainty as possible the validity of a "Pre-Clovis" occupation of the New World. These goals have to a great extent been achieved; however, the cultural questions remain very much enigmatic. In the main, this volume establishes the sequence of geologic events in the cave, and based on a series of radiocarbon dates establishes the upper and lower limits of the time of the potential Sandia occupation. The research, however, was not able to affirm the validity of the Sandia Culture as an independent entity, although it does present a hypothesis concerning the "Sandia Projectile Points." Assuming that these artifacts represent a Paleo-Indian cultural phenomenon, Haynes and Agogino suggest that they may have been used as implements for mining the deposits of ocher that occurred below the Folsom travertine. Although this hypothesis would explain many of the mysteries surrounding the distribution, or scarcity, of Sandia points, it too is beset with difficulties. The final proof will be provided when another in situ Sandia site has been found and properly excavated with modern scientific techniques.

This research report is presented in the Smithsonian Contributions to Anthropology Series as part of the Paleo-Indian research program. Because the original 1941 monograph on Sandia Cave by Frank C. Hibben was published in the Smithsonian Miscellaneous Collections Series, we take pleasure in publishing this revised study of the geochronology, which resolves many of the ambiguities introduced into the archaeological record in the original monograph.

Dennis Stanford
Curator North American Archaeology
Smithsonian Institution
Washington D.C.

Preface

In 1961 we entered Sandia Cave with the naive thought that we could collect bone samples from the Sandia and Folsom levels for radiocarbon dating and thereby solve the question of the ages of these two important cultures. We also intended to update geologic-climatic interpretations. Our first surprise was a pleasant one. We found that remnants of the strata still existed in the excavated forward portion of the cave. The second surprise was stratigraphy more complex than we had anticipated. It was not until the second visit that we became convinced that there had been at least two periods of dripstone formation separated by a significant period of time. On the third visit a remnant of the "Folsom breccia" was found that covered a broken edge of the lower dripstone adhering to the north wall. Clearly, the breccia, topped by a dripstone, was inset against an older sequence topped by another dripstone. This proof of the prehistoric removal of the lower dripstone made more understandable the differences in stratigraphy described by different investigators.

At this point and because of the controversies that had developed in the literature (Stevens and Agogino, 1975) we decided that in order to objectively arrive at our own conclusions we had to ignore previous work and proceed anew. Laboratory investigations and radiocarbon analyses were interrupted by relocation of the senior author, and subsequent career developments prevented writing up the data for several years. In the meantime, even though more data were obtained from time to time, we each became more committed to other projects and teaching so the manuscript lay idle and unfinished. Returning to the cave in 1972 to check some of our conclusions regarding the stratigraphy we found it sealed by a masonry wall at meter 13 presumably made by the Forest Service.

Another reason for the delay is that we hoped to repeat some of the radiocarbon dates on bone using more advanced techniques that more effectively remove contaminants than the pretreatment we used. The senior author is still conducting research to find more reliable methods for dating bone. At this time, there is no foolproof method of positively isolating indigenous bone carbon from contaminant carbon in leached bone. There is now great hope for sophisticated techniques that may solve these problems in the near future (Haynes, 1978). We have decided not to date more bone until then.

Not until sabbatical leave was taken by the senior author did time allow the completion of the manuscript, but there has not been enough time to completely revise it in the light of much scientific literature, particularly on cave research, that has appeared in the past decade. We have, therefore, decided to submit the manuscript for publication after minor revision and rewriting of only the last three sections.

We have striven to keep facts separate from interpretation and have offered multiple hypotheses wherever we feel the data do not support firm conclusions. From these data the reader will understand why there is no simple answer to the question of age of the Sandia artifacts.

We do not wish to argue for or against past interpretations because the stratigraphy, which is basic to establishing the chronosequence, was not adequately understood by previous investigators. This may be due, in part, to inadequate exposures until excavations had revealed critical stratigraphic relationships. In fact the original excavations in the forward part of the cave ended at meter 24. We found much of the deposits removed to meter 27 where the two major dripstones could be seen superposed. It is advisable for anyone concerned with the geology or prehistory of Sandia Cave to have a thorough grasp of the literature before reading the present work, and it may be even more enlightening to read it again afterward.

In addition to the geochronological objectives we hope that this work will restore Sandia Cave to its rightful place in American archaeology.

Geochronology of Sandia Cave

C. Vance Haynes, Jr.
and George A. Agogino

Introduction

Sandia Cave (35°15′30″N, 106°24′W), a natural solution tunnel 138 meters long and 2 to 4 meters in diameter, is in the Magdalena limestone of Pennsylvania age. The mouth is in a nearly vertical cliff some 100 meters above the floor of Las Huertas Canyon in the Sandia Mountains of New Mexico (Figure 1).

Archaeological investigations of the deposits in Sandia Cave were conducted in the late 1930s and early 1940s by the University of New Mexico. Preliminary excavations in 1936–1937 were conducted by both Frank C. Hibben and Wesley L. Bliss. Subsequent work in 1938–1941 was under the direction of Frank C. Hibben. This work resulted in the recognition of what was thought to be a pre-Folsom complex in America. Unfortunately, almost from the start, the literature reporting the results of these investigations has been plagued with controversy and conflicting statements of reported facts (Hibben, 1937; Bliss, 1940a; Brand, 1940; Bliss, 1940b; Hibben 1940, 1941a, 1941b; Byers, 1942; and Stevens and Agogino, 1975). Further confusion pertaining to radiocarbon dating of the cultural levels ensued in the late 1950's (Hibben, 1955; Crane, 1955; Johnson, 1957; Hibben, 1957; Krieger, 1957; and Stevens and Agogino, 1975). The result is that data from one of the most important sites to American archaeology and to Pleistocene geology is held in doubt by many scientists.

The only geological report on Sandia Cava was presented by the late Kirk Bryan (1941) in Hibben's (1941b) monograph. While Bryan's conclusions were based upon two brief visits to the cave and the archaeologist's notes (1941: 45, 46, 52), his evidence for climatic change based upon elevation shifts of paleosols and vegetation zones was a pioneering effort in paleoclimatology. In the beginning of his report on the geology of Sandia Cave Bryan (1941: 46) stated: "As further knowledge of the Pleistocene and particularly of the late Pleistocene is acquired, the precision of the chronology of climatic fluctuations will increase. Present correlations may be confirmed or may be shifted, either forward or backward." In spite of the fact that the stratigraphy as reported was incomplete and that many of the scientific tools used today were not then available it will become apparent to the reader of the present work that most of Bryan's geological interpretations and correlations, except regarding the Sandia level per se, stand as essentially correct today.

The present investigations were undertaken as an attempt to determine the geochronology of the strata by (1) conducting fresh and independent investigations of the cave stratigraphy, (2) radiocarbon dating all suitable materials, and (3) reconstructing the late Quaternary climatic his-

C. Vance Haynes, Jr., Departments of Anthropology and Geosciences, University of Arizona, Tuscon, Arizona 85721. George A. Agogino, Department of Anthropology, Eastern New Mexico University, Portales, New Mexico 88130.

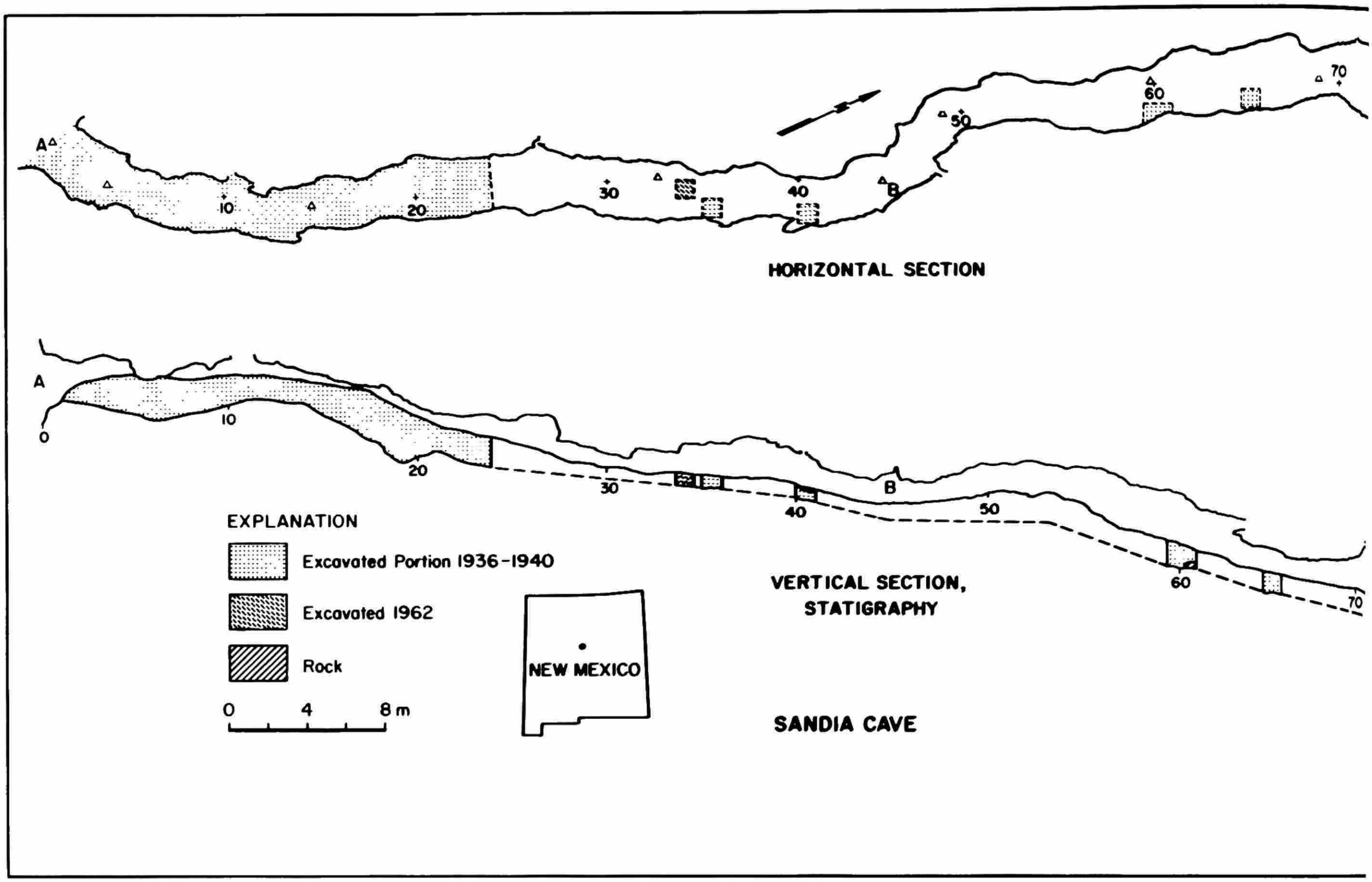
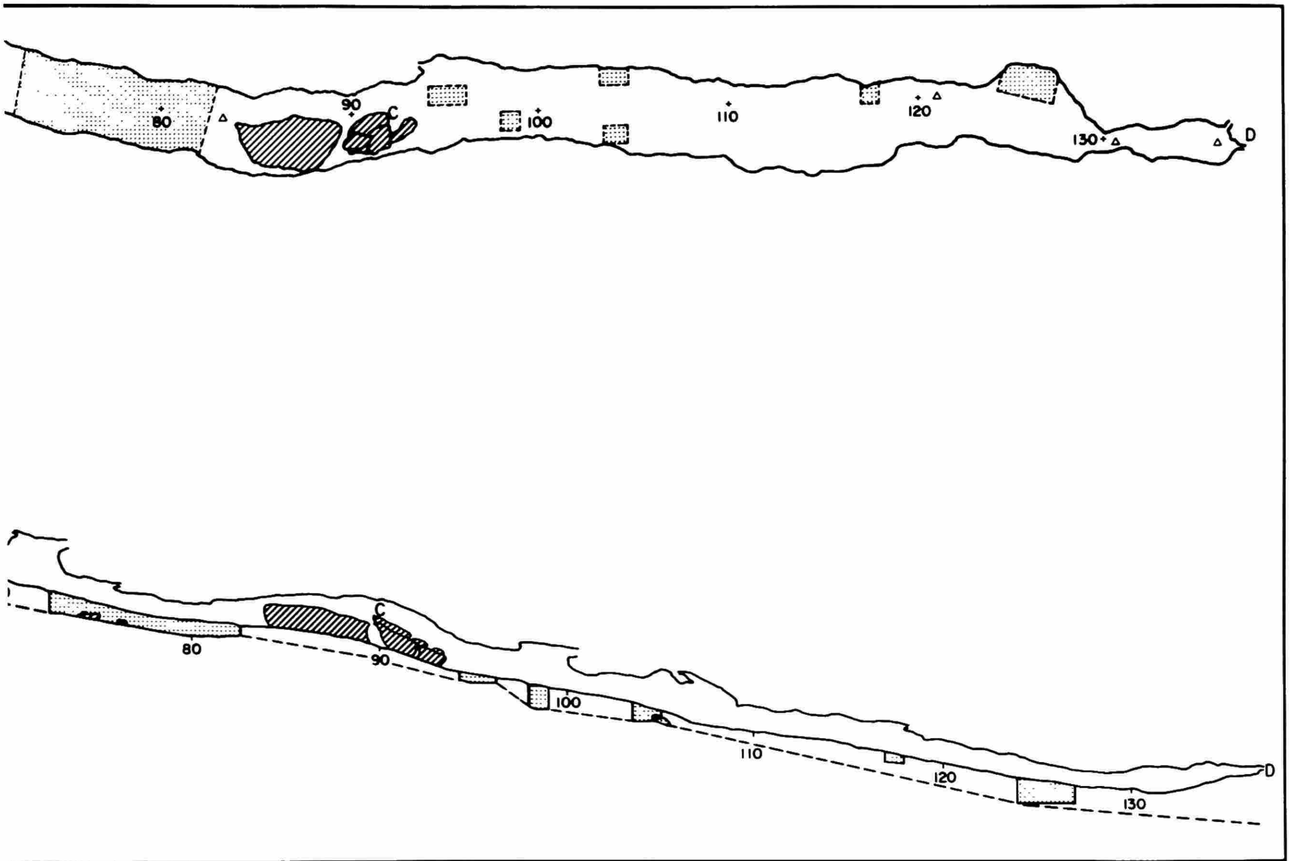


FIGURE 1.—Sandia Cave map and longitudinal profile.

tory of the cave deposits. During the period 1961–1962 a total of 10 days were devoted to geological investigation and to temperature and humidity measurement in the cave. Two days were spent examining paleosols in the Sandia Mountains, and laboratory investigations, including radiocarbon dating, required approximately two months of work. The cave has been visited on several occasions since 1962. Because most of the benchmarks of the Hibben excavations remain intact, all positions in this report refer to this survey (Hibben, 1941b).

Numbers in parentheses, with 1-, 2-, or 3-letter prefixes, refer to laboratory samples.

ACKNOWLEDGMENTS.—These preliminary investigations were made possible by a grant from the National Geographic Society and by permission of the U.S. Forest Service, Francis J. Monighan, Director, Cibola National Forest. Dr. F.C. Hibben, University of New Mexico, is largely responsible for our enthusiasm and interest in Early Man and helped us by providing specimens and advising us on matters pertaining to the earlier investigations. Identification of the fossil bacteria was performed by Eugene T. Oborn of the U.S. Geological Survey, Denver, Colorado. N.C. Schieltz, Colorado School of Mines, did the X-ray analyses of fossil bone and Jack Allen, University of Arizona Geochronology Laboratories, analyzed fossil bone for uranium. Identification of fossil vertebrates was performed by Paul Wood, Stephen F. Austin State College, and Bob Slaughter, Southern Methodist University. Special mention is due Paul Damon and Austin Long for making the facilities of the University of Arizona radiocarbon laboratory available to



the senior author. Experimental uranium-series dates were provided by B.J. Szabo, U.S. Geological Survey, Denver, Colorado, and H.P. Schwarcz, McMaster University, Hamilton, Ontario. Paul Damon, Emil Haury, John Lance, Luna B. Leopold, L.K. Lustig, Alex Krieger, Fred Wendorf, and H.M. Wormington critically reviewed various stages of the manuscript. The manuscript was substantially improved by the comments and suggestions of the official reviewers, W.R. Farrand and D.M. Hopkins. The interpretations offered herein are solely the responsibility of the authors.

Financial assistance of the National Geographic Society and the National Science Foundation (GA-1288 and 12772) is gratefully acknowledged. Special appreciation is expressed to Luna B. Leopold and the U.S. Geological Survey for partial support for the senior author for fieldwork during the summer of 1961.

Present Climate Inside Sandia Cave

At noon 24 December 1961, the temperature and relative humidity outside the cave was 6.5°C and 23 percent, respectively. These measurements varied from 11°C and 27 percent 8 meters inside the mouth to 11°C and 88 percent at meter 115. At the same hour on 2 July 1962, outside measurements were 18°C and 85 percent (raining); 18.5°C and 70 percent at meter 8; and 10.5°C and 80 percent at meter 75.

The only active drip water observed in the cave today is weak intermittent dripping at meter 1 during times of heavy rain or snow melting. This apparently flows in from the face of the cliff.

Stratigraphy

The stratigraphy of Sandia Cava as reported by Hibben (1941b) consisted, from top to bottom, of recent deposits, calcium carbonate crust, Folsom breccia, yellow ocher, Sandia breccia, and clay. From our investigation we observed and differentiated ten units from top to bottom; upper loose debris, upper dripstone, upper breccia, intermediate dripstones, lower breccia, gypsum crust, lower dripstone, limonite ocher, lower loose debris, and limestone residuum. Comparisons of the stratigraphy of various authors are given in Table 1.

Most of the strata in the central part of the cave passage between the mouth and meter 24 were removed by the archaeological excavations, but enough stratigraphy can be observed in remnants adhering to the walls to allow accurate observations of pertinent stratigraphic relationships. Between meters 27 and 70 most of the deposits remain undisturbed (Figure 1).

Reconstructed stratigraphic relationships are shown in Figures 2, 3, and 5 and were determined from remnants left along the cave walls between meters 8 and 23 and from test pits between meters 27 and 40. Additional examinations were made throughout the rest of the cave. Descriptions of stratigraphic units are presented below.

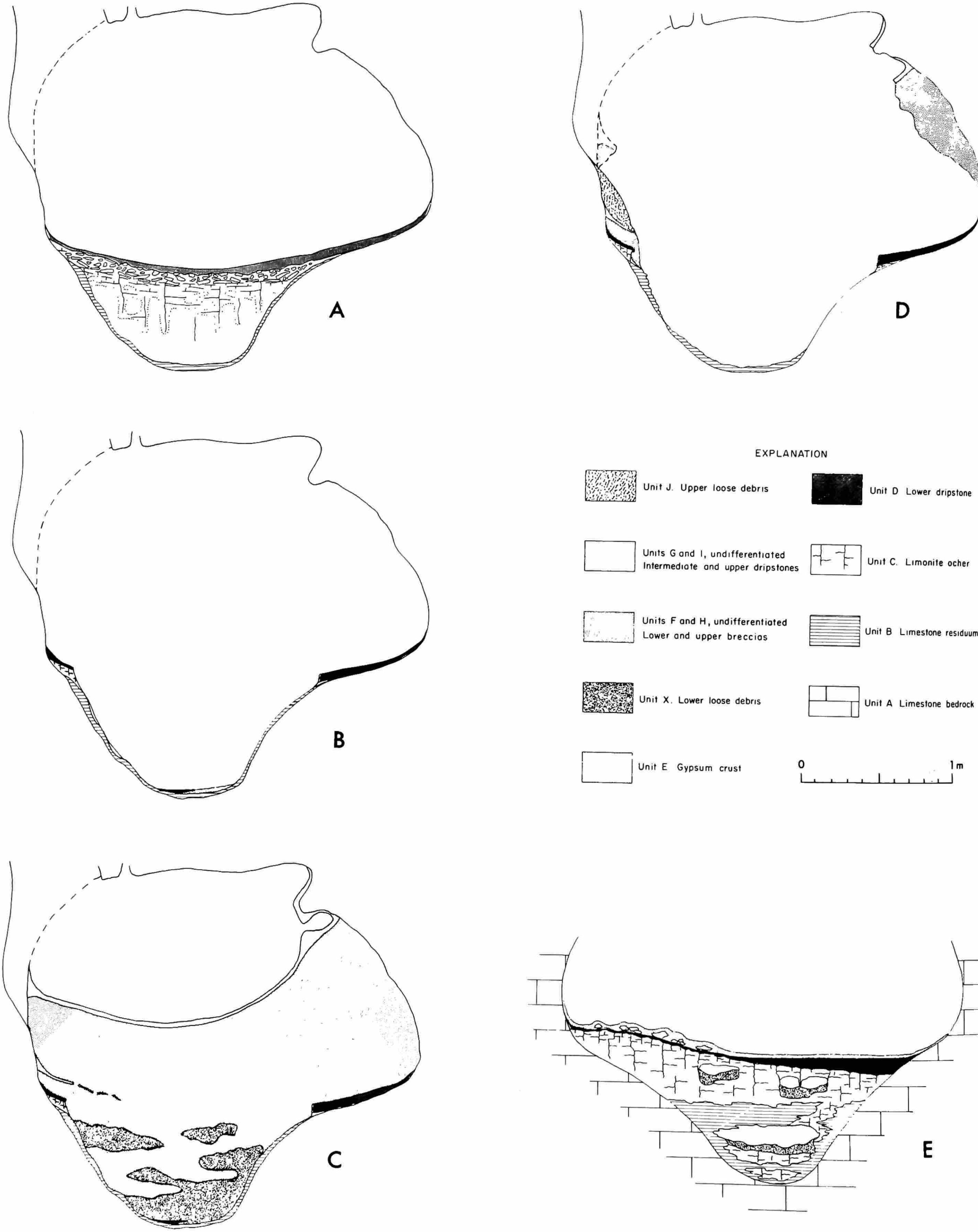
UNIT J, UPPER LOOSE DEBRIS.—Mixed loose organic and inorganic dust intermixed with rock fragments, bones, sticks, twigs, dung, and other vegetable matter commonly cemented by amberrat, contains cultural material of late Holocene age. Most of this deposit was removed by the

TABLE 1.—Comparison of descriptions of Sandia Cave strata by various authors (* rear of cave; † front of cave).

Hibben, 1937*	Hibben, 1937†	Bliss, 1940†	Hibben, 1941a	Bryan, 1941	This report
Accumulated dust	Bat guano, pack-rat dung, leaves, sticks and artifacts	Unconsolidated aeolian and animal deposition	Recent deposits: wind-blown dust, bat guano, pack-rat dung, small rocks and vegetable materials	Dust, guano and trash (f): decreasing in thickness from 6 ft. near mouth to thin dust layer at meter 70	Recent debris (J): dust mixed with rock fragments, bones, sticks, twigs, dung, and vegetable matter
Consolidated breccia of limestone, clay, dirt, cherty concretions and yellow ocher cemented by calcium carbonate	Hard crust of calcium carbonate	Laminated stalagmitic floor near front to breccia with calcite crystals	Calcium carbonate crust: varies from laminated lime to crystalline travertine. Extends in continuous crust from mouth to extreme rear	Stalagmite layer (e): granular and crystalline; in places chalky; small Tivoli-type cups on surface	Upper dripstone (I): laminated white, microcrystalline calcite with included small rock and bone fragments; discontinuous
	Slightly damp soft brown dirt mixed with small fragments of bones	Rodent debris of dung, pinon nut, paper, burned matches, sticks, and bone fragments	Folsom deposit: consolidated mixture of stone, bone, ocher, charcoal, and flint fragments cemented by calcium carbonate	Upper breccia (d): fragments of limestone, ocher, bone, and artifacts cemented by crystalline calcium carbonate as parallel films and stalagmite layers	Upper breccia (H): light brown, calcareous, porous breccia of dust, rock fragments, and bone fragments; more consolidated at top. Thin (1 cm) cemented dust at meter 28

TABLE 1.—Continued.

Hibben, 1937*	Hibben, 1937†	Bliss, 1940†	Hibben, 1941a	Bryan, 1941	This report
					Intermediate dripstones (G): same as unit I but commonly more dense, thinner and discontinuous
					Lower breccia (F): same as unit H but thicker and less cemented in places
					Gypsum crust (E): coarse, porous, 2 cm thick layer of gypsum in vicinity of meter 34
					Lower dripstone (D): dense brown, translucent, coarse crystalline calcite; occurred throughout cave
Several strata of yellow ocher		Unconsolidated sediments containing bone fragments, artifacts and hearth in situ	Yellow ocher: finely laminated, light and dark, yellow ocher	Yellow ocher (c): uniformly fine grained; banded and laminated limonite ocher	Limonite ocher (C): brownish yellow, friable, laminated, silicious rythmite; jointed; brecciated at top
			Sandia deposit: finely divided, less consolidated dust with bones, artifacts, dirt, vegetable and animal matter. No breccia as in Folsom deposit. Friable, noncrystalline mass	Lower breccia (b): bone, artifacts, charcoal, stones; limonite fragments near top; more cemented in upper part; in places not cemented at base	Loose debris (X): yellowish brown, dust with rodent dung, artifacts, teeth, and fragments of rock, bone, twigs, pinon nuts, and acorns in tunnels in, on, and under ocher and limestone residuum (B)
	White disintegrated limestone clay		Clay, laminated and sterile except for crinoid fragments	Basal clay (a): gray with partly dissolved limestone and crinoid fragments	Limestone residuum (B): gray clay to yellow-stained coarse-grained calcite sand
Limestone bedrock	Limestone bedrock	Limestone bedrock	Limestone bedrock	Limestone bedrock	Limestone bedrock (A)


A
D
B
C
E
EXPLANATION
Unit J. Upper loose debris
Units G and I, undifferentiated Intermediate and upper dripstones
Units F and H, undifferentiated Lower and upper breccias
Unit X. Lower loose debris
Unit E Gypsum crust
Unit D Lower dripstone
Unit C. Limonite ocher
Unit B Limestone residuum
Unit A Limestone bedrock
0
1m

original excavations. A remnant of this unit on the north wall at meter 13 (Figure 2D) was sampled for radiocarbon dating. The total organic matter, less solubles and carbonates, dated 870±110 B.P. (A-370) (Table 2).

UNIT I, UPPER DRIPSTONE (Figure 3A,B, 4A).—White microcrystalline, platy sheets of friable calcium carbonate with a maximum thickness of 15 cm or more, indicated by remnants on the cave walls between meters 8 and 26, in some places encases bones of small animals. The laminae commonly part along dust-covered surfaces. This unit does not extend farther back than meter 26; however, carbonate impregnating the cave floor in places farther back may be of equivalent age. Between meters 23 and 26 the upper dripstone thins to nothing and forms the top of a wedge of carbonate-cemented dust that is apparently the equivalent of the cave breccias (units H and F), described further on. This thin wedge, 3 cm thick where the old excavations terminated at meter 23, is the rearmost occurrence of the cultural breccias in the cave and rests on the lower dripstone (unit D). Petrographic examination of unit I reveals diffuse laminae and irregular patches of microcrystalline calcite (checked by X-ray against aragonite) with widely dispersed angular grains of quartz up to 66 microns in diameter, fragments of bone, and a few patches of weak limonite staining. Some voids are lined with microcrystalline calcite.

Radiocarbon analyses of organic and inorganic fractions of the top 1 cm of this carbonate yielded apparent ages of 19,100±900 B.P. (A-443) and 24,600±1000 B.P. (I-404) respectively (Table 2), but these dates cannot be correct because of the archaeology and the dating of more reliable materials in the underlying units. Contamination by approximately 80 percent ancient carbon is indicated.

UNIT H, UPPER BRECCIA (Figures 3A, 4A).—Whitish gray to light brown, calcareous, consolidated, porous breccia made up of clay, silt, fine organic matter, fragments of limestone, chert, bone, crinoid stems, and very sparse charcoal all well cemented by calcium carbonate attains a maximum thickness of 46 cm. This material occurs as small remnants beneath the upper dripstone crust from meters 9 to 22. Petrographic examination reveals fragments of limestone, chert, and bone; disseminated, unidentified dirt specks (organic?); and numerous, dispersed, quartz fragments up to 100 microns in maximum dimension, all in a matrix of microcrystalline calcite. Some portions are limonite stained.

A sample from the north wall at meter 12 was removed to the laboratory, pyrolyzed, and leached free of all carbonates. The remaining organic carbon was radiocarbon dated at 9,100±500 B.P. (A-368) (Table 2). Bone fragments removed from a transition zone between units H and G on the south wall between meters 18 and 21 gave a radiocarbon age of 12,830±400 B.P. (A-367) and a uranium-series age of 73,000±4,000 B.P. (B-60) (B.J. Szabo, pers. comm.). The U-series date cannot be supported archaeologically.

UNIT G, INTERMEDIATE DRIPSTONE (Figure 3A).—White, laminated, microcrystalline calcite

FIGURE 2.—Time-sequential, transverse, geologic cross sections of Sandia Cave between meters 11 and 13 reconstructed from remnants of strata adhering to cave walls (A–D) and transverse geologic cross section between meters 33 and 34 as it appears today (E) (reconstructions A–D are stratigraphically accurate but not precise as to detail): A, Cross section at end of lower dripstone (unit D) deposition showing cracked and disrupted limonite ocher (unit C) partly cemented by calcium carbonate (dotted outlines), and overlying limestone residuum (unit B). B, Cross section after breaking away of lower dripstone (unit D) and removal of limonite ochre (unit C). Rodents (pack rats, pocket gophers, etc.) were probably active in cave before this stage. Sandia hearth (excavated by Bliss and Stock) was made on floor of cave sometime during this stage. C, Cross section after cementation of breccias (units F and H) by calcium carbonate and dripstones (units G and I) showing pockets of lower loose debris (unit X) in rodent passageways. D, Cross section as it appears today showing remnants of strata adhering to cave walls and truncation of units B, C, and D before deposition of subsequent units. E, transverse geologic cross section of Sandia Cave at meter 34 as it appears today showing voids in limestone residuum (unit B) and limonite ocher (unit C) partly filled by lower loose debris (unit X). Limestone fragments on lower dripstone (unit D) are covered by gypsum crust (unit E).

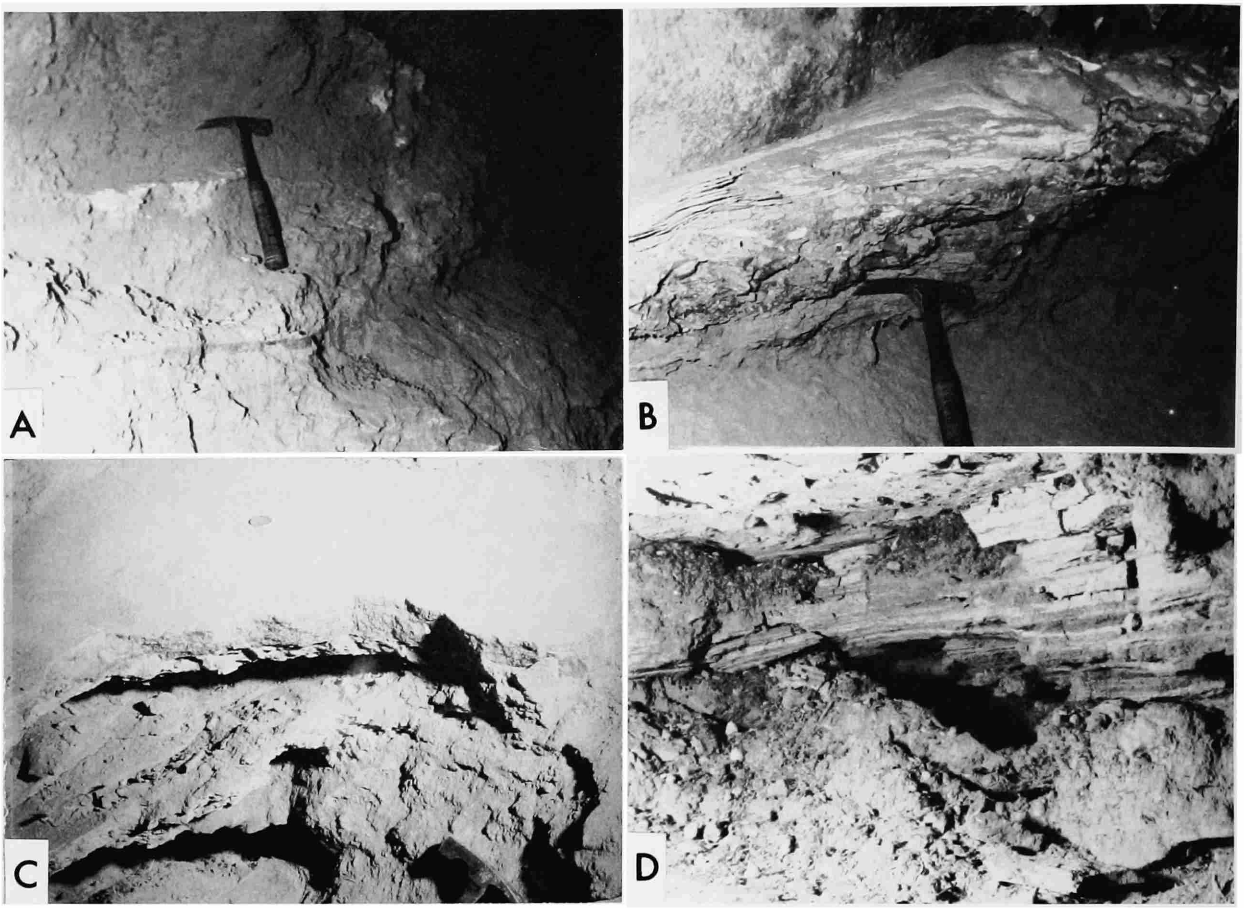


FIGURE 3.—Sandia Cave strata: A, remnants of units B, C, D, F, G, H, and I on south wall in vicinity of meter 19. Bone fragments from unit H breccia for radiocarbon date A-367 were collected along this wall. B, remnant of upper dripstone, unit I, on south wall at meter 16 provided radiocarbon samples A-443 and I-404. C, stratigraphy at meter 34 showing lower dripstone (unit D) overlying limonite ocher (unit C) limestone residuum (unit B) and lower loose debris (unit X) partly filling tunnels within units C and B. A one-inch thick crust of gypsum (unit E) has been removed from flat and level surface of unit D. Radiocarbon sample I-337 collected here. D, lower loose debris (unit X) occupying voids within laminated limonite ocher (unit C). Radiocarbon sample A-371 collected here.

layers and lenses up to 2 cm thick are interbedded with breccia remnants between meters 9 and 22 and in places merge into the bottom of the upper dripstone and into each other. These relations are visible in Figure 6 (Bliss, 1940a, fig. 2). Except for greater density the lithology is the same as unit I above. These observations indicate that the intermediate dripstones, where sufficiently extensive, merge with the upper dripstone and are included in it in some places. This unit is best developed separately on the north wall between meters 11 and 13, is weakly developed along the south wall from meters 16 to 20, and is not developed separately elsewhere. A radiocarbon analysis of this unit (Table 2) yielded an apparent age in excess of 30,000 years (I-471) but the dating of more reliable materials and the archaeology above and below this unit show the date to be in error.

UNIT F, LOWER BRECCIA (Figure 3A).—Light brownish gray to tan, calcareous, consolidated, porous breccia made up of clay, silt, fine sand,

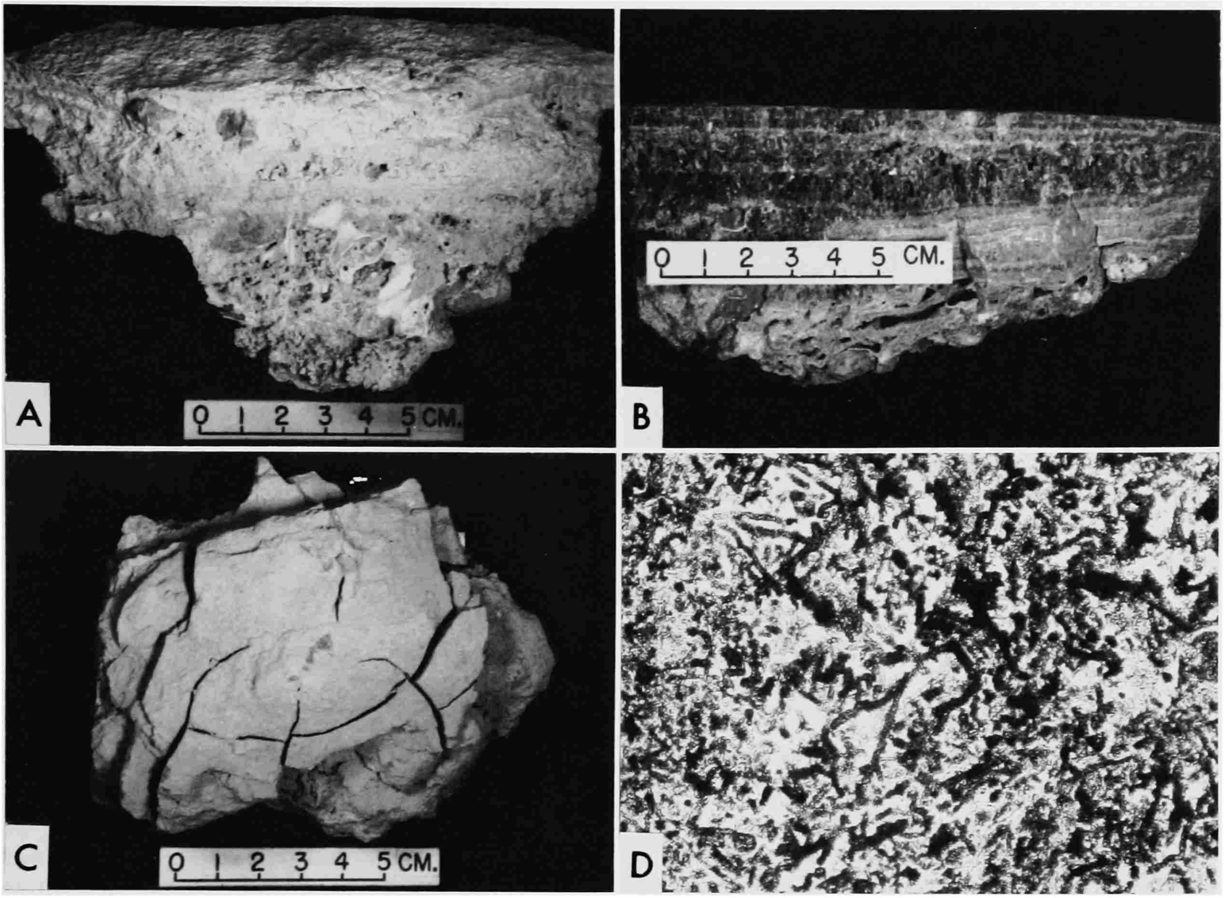


FIGURE 4.—Sandia Cave stratigraphic specimens: A, specimen of upper dripstone (unit I) and upper cave breccia (unit H) under meter 21. Bone fragments in unit H are typical of those collected for radiocarbon sample A-367. B, specimen of lower dripstone (unit D) from meter 34 showing flat upper surface, layering, and carbonate-cemented ocher on the bottom. Second prominent layer from top provided sample for radiocarbon date I-337. C, top view of specimen of limonite ocher (unit C) from meter 27 showing shrinkage cracks. D, photomicrograph of silicified limonite ocher (unit C) from meter 34 showing fossil remains of the iron-depositing bacteria *Leptothrix ochracea*. (× 150; photo by E.T. Oborn, USGS.)

and organic matter and fragments of chert, limestone, bone, limonite ocher, lower dripstone, crinoid stems, and very sparse charcoal all well cemented occurs as a few scattered remnants left along both walls between meters 8 and 23. It is apparent that it was much more extensive than the upper breccia, that the lower portions were weakly cemented to uncemented, and that the maximum thickness probably exceeded a meter in some places.

On the north wall at meter 11 a remnant of the lower breccia overlaps and covers a broken remnant of the lower dripstone (unit D) (Figure 2D). This, plus the occurrence of fragments of unit D and the ocher (unit C) within the breccia, clearly indicates the lower dripstone and underlying ocher were broken through and disrupted prior to deposition of the lower breccia.

Organic carbon in this breccia from the north wall between meters 11 and 12 produced a radiocarbon date of 12,000±400 B.P. (A-369.1) (Table 2). Lower loose portions of this unit do not exist in situ but are dispersed within unit X to be described later.

TABLE 2.—Radiocarbon dates and chemical analyses from Sandia Cave (numbers in parentheses with prefixes = laboratory numbers).

Unit	Material dated		^{14}C Age (Years B.P.)	Loss on pyrolysis*	Solubles	Residual carbon	Ash	Total
J	organic debris		870±110 (A-370)	–	–	–	–	–
I	dripstone carbonate		24,600±1000 (I-404)	–	–	–	–	–
I	dripstone organics		19,100±900 (A-443)	1.2	96.5	0.11	3.3	101.1
H	breccia organics		9,100±500 (A-368)	1.3	73.7	0.06	lost	–
H	bone organics		12,830±490 (A-367)†	12.8	84.5	0.43	1.7	99.4
G	dripstone carbonate		>30,000 (I-471)	–	–	–	–	–
F	breccia organics		12,000±400 (A-369)	2.6	84.4	0.14	12.6	99.8
F	bone		too small	14.2	84.0	0.19	1.5	99.9
X	charcoal lump		1890±90 (SMU-77)	–	–	–	–	–
X	wood stick (*Pinus* sp)		2250±50 (SMU-76)	–	–	–	–	–
X	small animal bone in	1	8,520±300 (A-381)	19.1	76.7	2.6	1.7	100.1
	order from least (1)	2	11,880±280 (A-383)	16.1	79.2	2.3	1.2	98.8
	to most (3) corroded	3	13,450±150 (A-382)	13.9	82.7	1.9	0.3	98.9
X	large animal bone in	1	13,700±400 (A-384)	18.1	79.5	1.0	1.3	99.9
	order from least (1)	2	11,850±1000 (I-301)	19.5	78.8	0.6	1.0	99.9
	to most (3) corroded	3	12,920±400 (A-385)	16.2	81.8	0.5	0.9	99.4
X	bone volatiles		9,480±150 (A-726B)	–	–	–	–	–
D	dripstone carbonate		32,300±2000 (I-337)‡	–	–	–	–	–
C	ocher organics		7,520±460 (A-371)	–	–	–	–	–

* Percentages based upon initial dry weight.
† Uranium-series date is 73,000±4000 by B.J. Szabo, U.S. Geological Survey, Denver.
‡ Uranium-series date is 226,300±16,200 by H.P. Schwarcz, McMaster University, Ontario.

UNIT E, GYPSUM CRUST.—White, translucent, tabular crystals of gypsum form localized, porous, crystal aggregates, resting directly on the crystalline calcite crust of unit D (Figure 3C) and in places extend as much as 30 cm up the cave walls. This crust apparently is centered between meters 23 and 40, and thickens toward the latter where it is 5 cm thick. Other remnants were observed elsewhere, but because of its soft, friable nature much of it has probably been worn away by the movement of man and animals. Dust particles are common in the gypsum. This unit was not recorded by previous investigators.

UNIT D, LOWER DRIPSTONE (Figures 3C, 4B).—Dense, translucent, brown crust, less than 2 mm to 30 cm thick, is composed of fine- to medium-grained, elongated, scalenohedral, calcite crystals extending perpendicular to surfaces of attachment, producing a columnar structure. This material is one of the most persistent formations in the cave and evidently extended over all or most of the underlying cave deposits, although, as pointed out before, it was broken in the forward part of the cave prior to deposition of the overlying breccias. It extends into the underlying ocher as drusy crusts around fragments. In the vicinity of meter 73 no pure calcite crust occurs, and only carbonate-impregnated ocher and ocher breccia have formed instead. In some places it is a flowstone resting directly on limestone where the walls bulge out toward the center of the cave (Figure 2). At these occurrences the upper surface is horizontally rippled. At meter 34 the upper surface is absolutely flat and level over an area of at least 3 square meters (Figures 2E, 3C). The upper 1 cm of this unit shows three distinct layers of columnar calcite crystals, each separated by a fine layer of calcareous yellow dust. Below this the calcite occurs as elongated scalenohedral crystals radiating from surfaces of disrupted ocher or limestone (Figure 4B). Near the end of the cave, which is also one of the lowest portions of the cave, the calcite is horizontally banded in cross section and has a maximum thickness of 30 cm. Microscopic examination of the upper lamina from the flat area at meter 34 reveals the upper crystal terminations to be absolutely flat and coated with limonite dust-like particles. Optically clear, scalenohedral calcite from the second layer (3 mm thick) down from the top of this unit provided a radiocarbon date of 32,300±2,000 B.P. (I-337) (Table 2). If corrected for 50 percent ancient carbon this becomes 27,500 B.P., which could be of the correct order as discussed later on. This is in conflict with a uranium-series date of 226,300± 16,200 obtained by H.P. Schwarcz (pers. comm.). Unit D beyond meter 24 was considered by previous investigators to be equivalent to unit I from the vestibule to meter 24.

UNIT C, LIMONITE OCHER (Figures 3D, 4C,D).—Yellow to yellowish brown, soft, friable, calcareous and siliceous, laminated, limonite ocher, up to 30 cm or more thick, extended throughout the entire length of the cave and occupies solution chambers and irregularities in the underlying limestone residuum (unit B). It is thickest in depressions, commonly shows vertical shrinkage cracks (Figure 4C), and in the upper 2 to 4 cm is fragmented and cemented with calcium carbonate. Interstices are commony lined with drusy calcite, and cracks are filled with a fine dust-like material cemented with calcium carbonate and considerably harder than the pulverulent ocher. Calcium carbonate has impregnated the ocher in many places, but some of the deeper remnants of pure ocher show no carbonate reaction with hydrochloric acid. Ocher unaffected by carbonate impregnation is very friable and has a low bulk density. The laminations in the ocher are due to color variations and possibly to variations in grain size. Because of the alternating light and dark laminae, 1 to 3 mm thick, the ocher can best be described as rhythmite. In most places the ocher layer is traversed by tunnels and interconnecting chambers roughly circular in cross section and 10 to 25 cm or more in diameter (Figure 3C,D). These spaces are more or less filled with loose dirt and debris described below as unit X. Within the ocher near meter 24 there are localized layers of blackened limonite 2 to 5 cm thick. The fine-grained black material is an oxide of manganese that superficially resembles charcoal. In places within the ocher there are flat tabular plates or lenses of silicified ocher that can properly be classified as ferruginous chert.

Petrographic examination of the contact zone between units C and D reveals a mixture of microcrystalline calcite and limonite granules with a few dispersed angular quartz particles. Some limonite occurs as fine tubules and some as colloform jackets around calcite grains and in voids. A few widely disseminated black grains are probably an oxide of manganese, and some veinlets are filled with anhedral, interlocking crystals of calcite producing a mosaic texture. The pure ocher shows irregular to subrounded granules and short tubular fragments of limonite with a high percentage of interstitial voids.

Siliceous lenses of ferruginous chert that occur in the laminated ocher are composed mainly of microcrystalline quartz (confirmed with X-ray by Harry Tourtelot, U.S. Geological Survey, Denver, Colo.). The tubular forms are longer and best preserved in the silicified portions of the ocher (Figure 4D). Some are straight and others crooked with diameters averaging 6 microns. These forms suggested biochemical deposition by iron-depositing "thread" bacteria and for this reason specimens of pure ocher and silicified ocher from meter 34 were submitted to Eugene T. Oborn, U.S. Geological Survey, Denver, Colo. for identification and ecological interpretation. His report follows.

Name of bacteria:		
Leptothrix ochracea Kützing		*Gallionella ferruginea* Ehrenberg
% present (approximate)	99	1
Ecology:		
(a) Temperature		
Minimum	0°C	Same

Optimum	15–20°C	"
Maximum	30°C	"
(b) Light conditions: Grow best in direct light.		Predominate in darkened waters in conduits and tunnels.
(c) pH: Grow best in slightly acid to neutral environments.		Same
(d) Quiet or flowing water: Organism grows unattached to precipitated mineral or other substrata. Quiet water essential.		Organism grows attached to precipitated mineral or other substrata. Flowing water characteristic.
(e) Iron deposition habits: Organically complexed iron is metabolized by the bacteria and iron oxide is excreted into the mucilaginous envelope surrounding the chitinous sheath.		Same, except no sheath or muscilaginous envelope present.

The growth presence of these organisms is indicative of the presence or physiological availability of complexed organic iron.

It is noted that dilute hydrochloric acid treatment dissolves the iron oxide sheath leaving the original chitinous sheath of the organism exposed.

The last statement suggested that organic carbon from the chitinous sheaths might still be present, so a large sample was pretreated for radiocarbon dating. The small amount of insoluble carbon and the anomalously young date of 7,520±460 (Table 2) show the carbon to be secondary; probably derived from rodent urine.

UNIT B, LIMESTONE RESIDUUM (Figure 3A,C).—Grayish white to pale yellow limestone residuum is composed of loosely cemented, medium-grained, fossil fragments gradational upwards to fine- to medium-grained calcite sand that is further gradational to calcareous clay. These subunits attain a maximum individual thickness of 5 cm, and the sequence may repeat itself two or more times. Total thicknesses of a half meter or more occur in a channel cut in the limestone floor of the cave.

UNIT A, BEDROCK.—At the cave the Magdalena Formation consists of biohermal limestone composed of crinoids, bryozoans, and brachiopods in a dense aphanitic ground mass and occasional masses of dark gray chert.

UNIT X, LOWER LOOSE DEBRIS (Figure 3D).—Loose, yellowish brown, fine dust, divided ocher, rock fragments, artifacts, bone fragments, mammal teeth, rodent dung, and pieces of vegetable fiber, pinon nuts, acorns, corncobs, and twigs, all slightly damp, occur as a filling in tunnels and chambers in and under the ocher. In some places this material apparently extends to the cave floor. In other places it is divided into several levels separated by layers of calcareous, silty clay of unit B. A part of a unifacially flaked knife was found in this material near meter 27 and was turned over to the University of New Mexico. Because the material of this unit is a mixture derived from other units it is designated unit X instead of in sequence with the units just described. As discussed later, rodent bones from this unit yielded dates of 8,500 to 13,500 years old (Table 2), but some are obviously modern having dried tissue still attached. The mixed nature of the deposit is demonstrated further by a small piece of wood (*Pinus* sp.) that dated 2250±50 B.P. (SMU-76) and a lump of charcoal that dated 1890±90 B.P. (SMU-77) (Table 2). Hibben (1941b) considered this unit to be the primary matrix of the Sandia artifacts.

Stratigraphic Interpretation

As suggested by Bryan (1941), the premise for interpreting the origin of the deposits inside Sandia Cave is that the conditions of deposition were dependent, in large part, on those outside of the cave. Except for the limestone residuum there is nothing to suggest that aqueous solutions entering this cave had any source other than drainage into the mouth and seepage from overlying rock and soil. By understanding the limiting geochemical conditions for deposition of the various cave deposits evaluation of these conditions in terms of possible climatic conditions outside of the cave might be useful for estimating paleoclimatic conditions and for correlation.

LIMESTONE RESIDUUM.—The granular fossil fragments of this material (unit B), the horizontal and vertical gradations in particle size, and the position of this material on the floor of the cave and in a channel cut into this floor suggests dissolution of limestone, and deposition and sorting of the less soluble parts of the limestone by stream action. Apparently this took place at some time during the transition from the phreatic stage of the cave history to the subareal stage. The limestone residuum deposit is itself channeled and tunneled apparently by later water movement. That the deposit was partially indurated prior to the later period of water movement is suggested by the uncollapsed nature of the solution tunnels and secondary channels. Further dissolution and sorting of limestone residuum probably occurred during subsequent periods of water movement. From the complex nature of this deposit it is entirely possible that several periods of water movement, solution, deposition, sorting, and cementation occurred.

LIMONITE OCHER.—As mentioned previously the ocher (unit C), where not contaminated with secondary carbonate, is made up almost entirely of the siliceous, limonitic, fossilized remains of the iron bacteria *Leptothrix ochracea*. According to Oborn (1960, and pers. comm.) *Leptothrix* can thrive in water containing as little as 0.5 ppm iron at 15° to 20°C although 0° to 30°C is given as the known temperature range. It is said to prefer quiet waters and commonly occurs in deep mine waters (Harder, 1919) indicating that light is not essential. The presence of organic matter is necessary for the growth of *Leptothrix*, which also is believed to remove CO_2 from solutions. It has an affinity for manganese as well as iron and seasonal changes in iron and manganese deposition have been observed. As Oborn has stated (1960:16), the conditions favoring the biochemical deposition of iron by *Leptothrix* are light, quiet or gently flowing waters, with a pH of 7 or less. The bacteria are also said to keep the CO_2 content of the water low (Zapffe, 1931:802).

The preference of *Leptothrix* for direct light is not consistent with its occurrence in Sandia Cave because beyond meter 14 no direct light can reach the floor and indirect light is very weak. Beyond meter 27 there is almost total darkness. Furthermore, the absence of foreign matter in the ocher suggests that the cave entrance was either very restricted or much farther away at the time of ocher deposition. It is therefore possible that the bacterial growth took place in water at or very near the entrance. Because the organism grows unattached (Oborn, pers. comm.) deposition farther back in the cave would result from flowing water carrying the ferruginous filaments down the gentle slope of the cave floor to areas of ponding. Between ponds the filaments might accumulate as a slime.

Oborn found about 1 percent of the bacteria to be *Gallionella ferruginea*, which prefer darkness and which grow attached to conduit surfaces carrying flowing water. Apparently this form was living in the cave and became mixed with the *Leptothrix* remains being carried back into the cave from near the entrance.

Leptothrix may actually have thrived in a pond that was partially outside of the cave mouth and exposed to direct sunlight. There is a rise in the floor at meter 12 which would dam water from going farther back in the cave until it had reached a depth of 0.5 meters or more at meter 6, a low spot from which the floor rises both toward the mouth and toward the dam. At the present time the floor at the mouth does not reach the elevation of the dam. Therefore, at the present slope, the floor must have extended 2 m farther out at some time in the past in order for

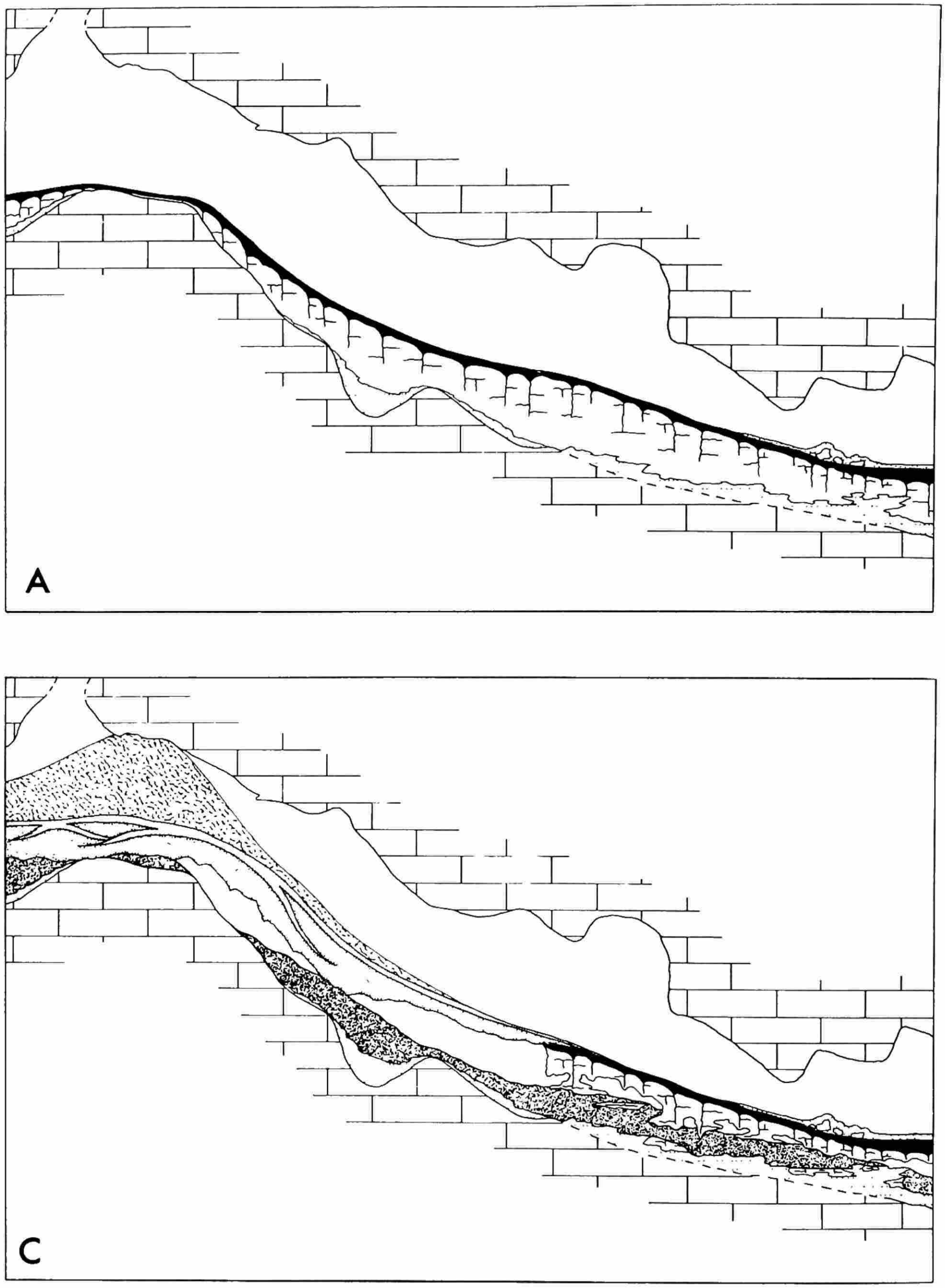
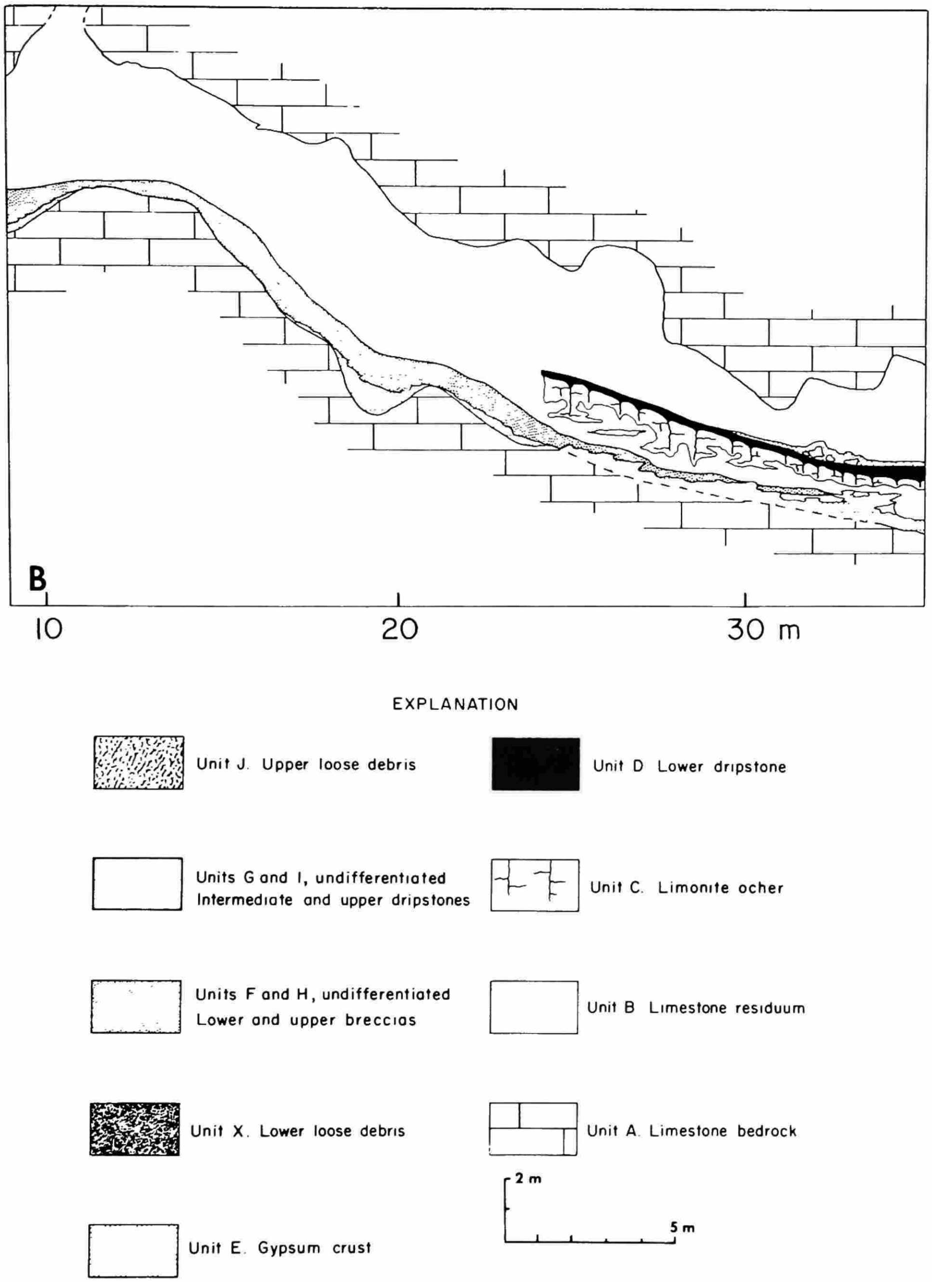


FIGURE 5.—Time-sequential, longitudinal, geologic cross sections of Sandia Cave between meters 9 and 35; reconstructions stratigraphically accurate but not precise as to detail. A, Cross section at end of gypsum (unit E) deposition showing shrinkage cracks in limonite ocher (unit C) and sealing by lower dripstone (unit D). B, Cross section after breaking away of lower dripstone (unit D) and before cementation of lower breccia (unit F) showing rodent excavated voids and partial in-filling by unconsolidated loose cave debris. C, Cross section as it would appear today showing incorporation of unconsolidated cave debris into unit X, cementation of units F and H, and intercollation of dripstones G and I.



water carrying *Leptothrix* remains to flow into the cave beyond meter 12.

There is evidence of an even earlier stand of water requiring a much higher floor at the mouth than now exists. In the front portion of the cave between meters 7 and 10 there is a small remnant of a calcite crust adhering to the walls. This remnant is approximately 1 cm thick and forms a small ledge projecting a centimeter or so from both walls. In one place this ridge-like projection is covered by a remnant of the consolidated upper cave breccia (unit H). In other places it is covered by the crystalline calcite flowstone of the lower dripstone (unit D), hence predates it and probably the ocher as well. It indicates that the cave had an earlier filling covered by a carbonate crust. The fact that the remnants form an absolutely level "bathtub" ring on opposite walls and the sloping ceiling farther back in the cave suggests that the filling was water. This horizontal plane, when projected, extends through the present cave mouth and is evidence that the entrance was farther out. The projection intersects the general slope of the cave floor 10 or more meters outside of the cave.

Color differences between laminae in the ocher are apparently due to the form of oxidation or hydration and to the MnO_2 content. The rhythmic nature of the deposit may reflect variations of the activity of thread-bacteria in response to seasonal changes. These matters require further investigation, but tentatively it is concluded that during the period of limonite deposition the cave was very wet and the entrance was restricted in part by a pond at the mouth.

The apparent requirement of organically complexed iron by *Leptothrix* could be met by leaching from a soil. The organically complexed iron previously referred to by Oborn is the form of mobile iron to be expected by eluviation from a pedalfer.

Oborn and Hem (1961) have demonstrated the extreme importance of soil microorganisms in bringing iron into solution and have pointed out that, between 5° to 35°C, the microbiological activity doubles in rate for each 10°C rise in temperature. Bryan, noting limonitic soils in the Sandia Mountains, has described the pedological processes with specific reference to Sandia Cave (1941:55, 56).

If a pedological source for iron and silica in the ocher is assumed, it is possible to estimate the type of pedological process and, therefore, the climatic conditions that would permit the dissolution and transportation of iron. A general account of the geochemistry of iron in soils is given by Cornwall (1958:193, 194). Between pH 3 and 5.5 iron can be transportable in solution as a colloidal sol. Below pH 3 it can exist in true solution. Flocculation of humic acids occurs at pH 3.9 or below. Above 4.9 they can mobilize the iron up to pH 5.5 whereupon precipitation of iron would begin unless occlusion of colloidal iron by silicic acid prevents flocculation at higher pH values. If the silica in the ocher is also pedogenic, as seems most likely, its solubility as silicic acid increases with rise in temperature, with rise in pH above 5.5, and with greater precipitation (available H_2O). Because acid conditions are required for the iron to enter solution it appears that warm temperatures were more influential than higher pH in forming soluble silica. Also, Lovering (1959:799) has pointed out the possible influence of biochemical activity in overcoming acid conditions in the formation of soluble organic complexes of silica.

As pointed out by Bryan (1941:54), pedalfers characterize the forest zones generally above 7,500 feet in the Sandia Range while pedocals exist in the lower woodland zone. While the cave is within the woodland zone it is apparent from paleosols that the forest zones were at lower elevations in the past and that a pedalfer existed on the ridge over Sandia Cave during pluvial periods. It is concluded, therefore, that the iron and silica of the ocher were derived from a pedalfer. A relatively cool moist climate would favor the development of this type of soil at the elevation of the cave, and iron would be retained in the B horizon. Warm moist conditions would favor microbiochemical activity and the solution of silica to form colloidal sols that would peptize ferric hydroxide (Cornwall, 1958:77). Thus mobilized they would be carried to the cave from descending vadose water.

It is suggested, therefore, that a cool moist climate preceded deposition of the ocher and that iron and silica were later leached from the pedalfer under warm moist climatic conditions. Upon entering the cave in solution, precipitation of iron and silica underwater was augmented by the biochemical activity of *Leptothrix*.

As mentioned previously, the upper 2 or 3 inches of the ocher deposit are fragmented. The fragments increase in size downward and also are less disoriented. The underlying ocher is traversed by vertical cracks as much as 1 cm thick and is divided into large blocks by these cracks. The cracks are now filled with cemented granules of secondary microcrystalline calcite intermixed with limonite and manganese particles. The fillings are harder than the ocher. The cracks and breccia are apparently the result of shrinkage of the limonite ocher deposit concomitant with desiccation. Judging from the occurrence of lenses of ferruginous chert it is likely that colloidal limonite and silica originally solidified as a gel that cracked upon drying in a manner similar to that described by Oehler and Schopft (1971). The observation that no foreign matter exists either in the ocher itself or in the cracks suggests that the cave must have had a restricted entrance. The atmosphere in the cave must have been quite stagnant, but the evidence of desiccation indicates that water vapors could escape. The cracking and flaking suggest the drying up of the ocher deposit and imply a change to a drier climate outside of the cave.

Lower Dripstone.—The purity and clarity of the crystalline calcite suggest that both the solution bearing the calcium carbonate and the atmosphere in the cave were free of dirt, dust, and other foreign matter throughout most of the time of formation of the lower dripstone. Therefore a continuing period of isolation of the cave interior from the outside is strongly indicated.

The flat-surfaced areas are difficult to explain by any means other than crystallization in a quiet pond. Further evidence of crystallization from standing solution is observed where the calcite is thicker in the lower part (bottoms) of voids and depressions in the disrupted limonite ocher. The rippled surface of the crust (flowstone) on sloping surfaces indicates crystal growth from flowing solutions.

The crystalline calcium carbonate cementing the ocher fragments and filling cracks within the ocher represents the early stage of growth of the lower dripstone.

The deposition of the lower dripstone probably took place from solutions charged with calcium bicarbonate according to the equation

$$Ca^{++} + 2\ HCO_3^- \rightleftharpoons CaCO_3 + H_2O + CO_2.$$

The cave calcite would grow in response to either a loss of CO_2 from solution or evaporation of water from solution. Calcite crystals will continue to grow as long as the solution is replenished with calcium and bicarbonate ions from water entering the system and as long as loss of CO_2 prevents the concentration of carbonic acid. The source of these ions could involve either the leaching of a pedocalic horizon, or the dissolution of limestone by water made acid by soil-forming processes, or both.

Holland and others (1964) have investigated the chemical composition of cave waters and point out that rainwater intermixing with soil gas, containing several orders of magnitude more CO_2 than the atmosphere, is the chief process whereby vadose waters become charged with CO_2 to form carbonic acid. The capacity of rainwater to dissolve carbonate rocks may be thus increased by two orders of magnitude, and calcium ions are acquired through this mechanism. Upon reaching the cave environment equilibration of cave water and cave air occurs and calcium carbonate flowstone forms either as a result of loss of CO_2 from solution or evaporation of the water. Holland and others (1964:42) found that, in the caves they studied, exchange of CO_2 between solution and the cave atmosphere was the dominant process. Biochemical mechanisms for the deposition of carbonates in caves have been suggested but are poorly understood (Gerundo and Schwartz, 1949; Caumartin, 1957).

Obviously the relative humidity inside Sandia Cave during deposition of the lower dripstone was at least as high as it is today, which ranges from 30 percent at meter 8 to 88 percent at meter 115. It appears certain, therefore, that calcium carbonate was precipitated more in response to loss of carbon dioxide from solution than from evaporation of water. The purity of the calcite crystals suggests that the cave was sufficiently sealed to prevent the entering of either dust particles or animals, but the loss of CO_2 from solution requires either the cave to have been incompletely sealed so that CO_2 could escape or a decrease in the partial pressure of CO_2 in the cave atmosphere relative to that in the rock fissures and soil through which the bicarbonate-bearing solutions seeped into the cave.

The climatic implications of the lower dripstone are even less known than the possible mechanisms of precipitation. Certainly moisture is required to form the solution. No such deposit is forming in the cave today, therefore the climate must have been wetter than today, assuming the catchment has not changed. A climate with an overall higher relative humidity than that of today is also implied and provides additional support for the importance of loss of CO_2 relatives to evaporation in precipitating crystalline calcite in the cave.

The temperature range of crystallization of calcite is too wide to be of much use in indicating ambient temperature in the cave, but Moore (1956) finds evidence suggesting that calcite is the more common dripstone mineral in caves having average temperatures less than 15°C and that aragonite is more common in caves with higher temperatures. Murray (1954) found experimentally that higher ambient temperatures favored deposition of aragonite. X-ray analyses of dripstones have not revealed aragonite in Sandia Cave.

Calcium carbonate in the lower dripstone came from either soil over the cave or from dissolution of limestone. After the drier climate implied by ocher desiccation and upon the return to another wet climate indicated by the dripstone there was no return to any significant iron deposition in the cave. This implies that the climate had turned colder as well as wetter, under which conditions iron and silica would be likely to remain fixed in the soil, especially if the iron oxides had become less hydrated during the implied dry interval (Cornwall, 1958:194). It is suggested, therefore, that the time represented in the cave by desiccation and shrinkage of the limonite ocher was a dry and possibly warm climatic period outside of the cave, and was followed by a change to more moist and/or cooler climate under which water leached carbonates from soil and/or dissolved limestone as it percolated into the cave to deposit the calcite crust and cement portions of the limonite ocher.

Before a reasonably accurate interpretation of the end of calcite deposition can be made, the significance of the gypsum layer that in places overlies the crystalline calcite crust must be properly evaluated.

GYPSUM CRUST.—The discontinuous gypsum layer (unit E) consists of a porous mass of loosely intergrown crystals of variable size from a fine powder to feather-like growths a centimeter or more in length. The contact of this gypsum layer with the underlying calcite layer is sharp, and in flat places the gypsum layer can be lifted in a single sheet from the lower dripstone (Figure 3c). The bottom of the gypsum crust lifted from the smooth, flat calcite surface is slightly undulatory. Locally, the gypsum layer extends up the walls of the cave for as much as 30 cm. In some places there are fragments of limestone on the lower dripstone that are covered by the gypsum crust. The presence of disseminated, fine-grained mineral matter as impurities in the gypsum and in greater amounts towards the top suggests that the cave was sufficiently open to provide access of dust-laden air from outside.

From the foregoing observations, a replacement origin for the gypsum does not seem worthy of further consideration. They are more suggestive of an efflorescent crust formed by evaporation.

Present indications are that the gypsum deposits of the cave are confined to local depressions. This further suggests that the deposit formed from the evaporation of standing water. Two possible sources for the sulfate-bearing water are considered, (1) a new set of climatic conditions outside of the cave led to a change in composition of descending water from carbonate-bearing to sulfate-bearing, (2) the sulphate-bearing water was derived from a residual solution from the calcite-depositing carbonate water.

The first possibility requires sudden and rather drastic changes in outside conditions in order to account for the relatively high concentration of sulfate ions and exclusion of carbonate in the cave water. It appears unlikely that climatic change alone could account for this by the formation and leaching of sulphates by pedological processes. A sudden increase in sulfate could derive from volcanic gases. There are volcanoes of Pleistocene age in the region, but their more specific age is unassessed at present.

The most tenable explanation for the gypsum crust is that it is the result of evaporation of residual solution left after calcium carbonate crystallization. The end of calcite deposition probably resulted from depletion of the carbonates in the solutions. The absence of alternating layers of calcite and gypsum suggests that additional solutions were probably not being added to the cave. Some time after calcite deposition had ceased, rocks fell from the cave roof and are now observed either resting on the lower dripstone or penetrating it. This may have been caused by an earthquake. An earthquake could also account for the indicated reopening of the cave. This reopening, in turn, promoted relatively sudden evaporation of the residual solutions held in shallow basins and depressions on the cave floor. Calcium sulfate crystallized upon evaporation of the solution to form the gypsum crust. As would be expected, the gypsum crust is thicker in deeper depressions. The precipitation of calcium sulfate after calcium carbonate from evaporating solutions is to be expected from their relative solubilities in water (Clark, 1924: 180).

Thus the rock fragments on the dripstone floor, the gypsum crust, and the dirt in the crust are all apparently the result of several sequential events. In chronological order these are (1) cessations of cave drip upon climatic shift to dry conditions, leaving ponds of residual solutions enriched in dissolved calcium sulfate, (2) seismic disturbance causing rock falls throughout the cave and widening of the cave mouth, (3) free air circulation that accelerated evaporation and brought in airborne dust and dirt particles. The rock falls breaking the lower dripstone and the hypothetical breaking away of some of the cave mouth both would have made the lower levels of the stratigraphy accessible to rodents at this time if they were not already so.

Cave Breccias and Dripstones.—The gypsum crust is increasingly contaminated with dust and dirt towards the top. This crust is not observed in the front part of the cave; i.e., from meter 23 to the mouth. In this part of the cave remnants of the lower dripstone are overlain by the cave breccias (units F and H), which together constitute the Folsom breccia of Hibben (1941b) and, as described previously, consist of dust, dirt, rock fragments, and bone fragments cemented by microcrystalline carbonate. The breccia is mostly hard and dense, but in places it is soft and friable. When ignited this material gives off a strong pungent odor of burning organic matter. These cave breccias give every indication of having been, at one time, typical accumulations of loose cave debris similar to those now observed as recent fills in many caves throughout the southwestern United States. Sandia Cave itself contained such a fill (unit J) at the time of its discovery. These recent cave fills are commonly composed of organic and inorganic dust and dirt intermixed with rock fragments, bone fragments, sticks, twigs, dung, and other vegetable matter. Such deposits are the result of airborne matter intermixed with spalled cave rock and the living debris of man and animals. The organic materials are preserved under arid conditions. Under moist conditions they decay.

It is suggested, therefore, that the cave breccias of Sandia Cave represent similar deposits that accumulated under climatic conditions that are not unlike those of today in the Sandia Mountains. During the time of accumulation the cave was intermittently occupied by man and animals. The cementing of this material by calcium carbonate and the lack of identifiable organic materials other than bone are indications that the climate upon turning more moist renewed dripwater activity in the cave which impregnated the cave debris, deposited carbonates, and caused the decay of most of the vegetable and animal matter. The continued deposition of carbonates eventually reduced the permeability of the upper part of the lower breccia such that the rate of evaporation of the dripwater exceeded its rate of penetration and a travertine or dripstone crust (unit G) began to form. The soft, friable, microcrystalline, and platy nature of the dripstones and included dust particles are indicative of deposition from dripping solutions under more aereated conditions than the lower dripstone (unit D), and initially the precipitated carbonates may have been in the form of hydrocalcite as described by Marschner (1969). The absence of human refuse in the dripstones indicates that at these times man had ceased to use the cave, but the occurrence of rodent bones within layers of dripstone indicates that these animals continued their occupancy in spite of wetter conditions in the cave.

The separation of parts of the breccias by intermediate dripstones (unit G) indicates that a dry-wet cycle occurred at least twice. The thicker, more widespread occurrence of the upper dripstone (unit I) in the cave relative to the intermediate dripstone does not necessarily indicate the final wet period to have been wetter or longer. The underlying deposits had become impermeable such that all of the precipitating carbonate was added to the dripstone crust instead of being absorbed by porous sediments. The intermediate dripstone may represent only localized areas of cave drip, and the small isolated remants of the upper breccia may represent either the waning phase of continuous occupation of the cave or a second period of occupation. In either case the upper dripstone indicates conditions too wet for comfortable occupation of the cave by man.

The source for carbonates in the upper and intermediate dripstone (units G and I) is considered to have been at least in part pedological. The carbonates of a pedocal accumulate under semiarid conditions (Birkeland, 1974:232–234; Bryan and Albritton, 1943), conditions such as those indicated by the dust and debris of the breccias. Under moist conditions the carbonates of soils can be carried away by descending waters and redeposited as dripstones in caves. For at least some cave dripstones this process has been cyclically controlled by seasonal variations in climate (Broecker and others, 1961). Because rainwater acquires its highest CO_2 charge from the soil gas in the A and B horizons of a pedocal, the most readily available carbonate would be those existing in the underlying calcic horizon or "caliche." As observed by Bryan (1941:56), some of the soil profiles of the woodland zone at Las Huertas Canyon show polygenetic profiles in which powder of calcium carbonate has replaced limonite films and some deeper zones show plates of crystalline calcium carbonate. It is possible, therefore, that part of the calcium for the dripstones had a pedogenic source.

Upper Loose Debris.—As mentioned previously, the accumulation of loose cave debris (unit J) that formed the uppermost stratum in Sandia Cave is typical of cave fills in the Southwest that have accumulated over at least the last 6,000 years under semiarid or arid climatic conditions. It is reasonable to assume that if the climate were to turn moist, cave drip would be renewed, the loose material would become cemented by carbonate, and eventually a dripstone crust would form.

Lower Loose Debris (Unit X).—It is apparent that the lower loose debris (unit X) is a secondary deposit that postdates the lower dripstone (unit D). It lies within and below the ocher and is composed chiefly of yellowish brown, slightly damp, limonitic dust. It contains abundant fecal pellets, small animal bones, pinon nuts, acrons, fragments of large animal bones, teeth of extinct animals, and artifacts.

The Sandia level has been described as follows. Hibben (1937:262–263):

Beneath the hard crust (calcium carbonate) is a stratum of varying thickness, for the most part composed of slightly damp, soft, brown dirt. This, in places, overlies the original rock surface of the cave floor, and in other sections, small lenses of white disintegrated limestone clay which lie in the original water channel on the floor of the cave. The layer of brownish dirt beneath the calcium carbonate crust is very thickly mixed with bones, almost all of which are in small fragments.

Bliss (1940a:201):

The third layer consists principally of unconsolidated sediments in which a number of fragments of Pleistocene animal remains have been found . . . .

Bliss (1940b:77):

Channels connected both of these breaks with the underlying deposits where rodent dung, pinon nut shells, small fragments of paper, burned matches, and small sticks of wood were found.

Hibben (1941b:16):

The material of this layer is more finely divided and less consolidated than that of the Folsom. It is composed of rock fragments, finely divided rock dust, bones, artifacts, charcoal, crinoid stems, and brownish-color dirt, evidently windblown and mixed with vegetable and animal material. This stratum, because of the cultural items included, and its lower and distinct position in this cave, has been termed the Sandia level.

Hibben (1942:47):

The Sandia stratum is of loosely consolidated breccia, softer than the Folsom matter and in many places of considerably greater thickness . . . . Occasional pieces of yellow ocher consolidated into a friable stone also occur. The material has been compressed by dampness but is not water laid. A definite cave floor lies at the base of the Sandia stratum and the material contained in the layer is cave debris, both cultural and from the lairing of animals.

When the description of unit X is compared with these descriptions of the "Sandia level" (Table 1) it becomes readily apparent that they are one and the same thing.

It is further apparent that unit X is in large part derived from the transportation and accumulation of cave debris by rodent activity. Of 30 small animal mandibles and skulls collected from this unit and identified by Dr. Paul Wood, University of Georgia, 50 percent are pocket gopher (*Geomys*), 20 percent are pack rat (*Neotoma*), 10 percent are rabbit (*Lepus* and *Sylvilagus*), 10 percent are squirrel (*Citellus*), 7 percent Mustelidae, and 3 percent are marmot (*Marmota*). Passageways and chambers in soft portions of the ocher, and presumably the breccias, as will be discussed below, were obviously excavated by rodents.

In order to obtain some idea of how long rodent activity had persisted in Sandia Cave, quantities of their bones were collected from unit X for radiocarbon dating. On the basis of their physical appearance these were divided into three groups: (1) least, (2) intermediate, and (3) most corroded and stained. After careful pretreatment including washing, surface leaching, pyrolysis, and carbonate removal these dated 8,520±300 B.P. (A-381), 11,880±280 B.P. (A-383), and 13,450±150 B.P. (A-382) respectively (Table 2). It is understood that these ages are not for single animals but represent mixtures of animals of various ages. Nevertheless, it is clear that rodents have been active in Sandia Cave for at least 13,500 years. The group of least corroded rodent bones could have contained specimens of modern age.

ORIGIN OF UNIT X.—All fossil bone in Sandia Cave postdates the lower dripstone (unit D) as none occurs in situ either in or below it. Had any bones occurred in the cave prior to ocher deposition they would have long since perished under the aerobic and acid conditions of ocher deposition. To test the possibility that the large animal bone fragments of unit X were originally a part of the cave breccias, bone fragments were collected from unit X for radiocarbon dating by a procedure similar to the one described for the small animal bones. Groups 1, 2, and 3 dated 13,700±400 B.P. (A-384), 11,850±1,000 B.P. (I-301), and 12,920±400 B.P. (A-385) respectively. These are all close to being within two standard deviations of each other, which suggests a general time period of between 11,000 and 14,000 years ago for the deposition of large animal bones in the cave.

Radiocarbon dates of 9,100 and 12,000 on breccias H and F respectively have already been mentioned and are presumed to be in the correct range as opposed to the uranium-series date of

73,000±4,000. The large animal bones from the lower loose debris are 12,000 to 14,000 years old. It is apparent, therefore, that the large animal bones overlap in time with the lower breccia (unit F) and were removed to unit X through the activity of rodents. If the extinct animal bones and teeth were so derived, then so could the Sandia artifacts have been derived.

That some bones from loose portions of unit F were redeposited into unit H before it was indurated by calcium carbonate is indicated by the date of 12,830±490 (A-367) on bone fragments therefrom. It is obvious that mixing between units has taken place during several periods in the cave's history.

Evidence that the large animal bones of unit X came originally from dry deposits is found in chemical analyses of bone from the various units (Table 2). Bone from the cemented breccias contains more carbonate and less organic carbon than bone from unit X which is the same age or older. This is just what would be expected if bone from the bottom parts of the lower breccia had been protected from dripwater by overlying cemented breccia and had, therefore, remained in a looser and drier matrix, one susceptible to rodent disturbance.

Occupation of the cave by rodents and humans was possible any time after deposition of the gypsum crust (unit E), but rodent penetration of the ocher was not likely until after the lower dripstone had been broken by natural rock falls or possibly by man to acquire yellow ocher for use as a pigment (red when burned). As mentioned previously (p. 7), there is ample evidence that the lower dripstone was broken and the ocher disrupted prior to accumulation of the lower breccia (unit F).

In fact Bryan (1941:511), speaking of the Sandia level, states, "not only was calcium carbonate deposited, but also limonite (yellow ocher) which, however, was largely *broken up and incorporated in the breccia as fragments*" (italics ours), and Hibben (1942:47), speaking of the same stratum, said it contained "occasional pieces of yellow ocher." Thus this "breccia" must postdate deposition of the ocher. Furthermore, Bliss (1940a) did not find an ocher stratum in his excavations in the first 11 meters of the cave. Instead a "laminated stalagmitic floor" was found to overlay "unconsolidated sediments" in which a number of fragments of Pleistocene animal remains were found (see Table 1) as well as the first Sandia projectile point. The resemblance of our units F–I can be clearly seen in fig. 1 of Bliss (1940a) althought the captions of figs. 1 and 2 are reversed as Bliss (1940b) later noted. This is reproduced herein as Figure 6.

It is concluded that materials from the uncemented portions of the breccias, units F and H, presumably containing the original Sandia artifacts have been available for rodent and gravitational transport from their moment of deposition in the cave. From the evidence presented previously these materials have been thusly transported and have been intermixed with disrupted ocher and dripstone of earlier deposits and loose debris of later deposits, including the upper loose debris (unit J); all to make up unit X as it appears today. There is also evidence that bone fragments from uncemented portions of unit F or unit X were redeposited into unit H before its induration.

Materials from the breccias were not available for transport or mixing once the breccias had become cemented. This might account for the indicated gap in the radiocarbon ages between group 1 and group 2 rodent bones of unit X and the indicated absence of fossil large animal bones younger than about 12,000 years in unit X. This is not to suggest that such aged materials are totally absent from unit X, only that it represents a significantly smaller amount. This would also explain the exclusion of Folsom artifacts from unit X. Folsom points were not abundant to begin with and were only briefly available for transport before being cemented in the breccia. Sandia artifacts could have been redeposited in the "Folsom" breccia prior to cementation, but none are reported.

ORDER OF STRATIGRAPHIC EVENTS.—There are certain discrepancies between the stratigra-

FIGURE 6.—Photograph of Sandia Cave deposits at meter 13 showing upper and intermediate dripstones (units G and I) interbedded with breccia (units F and H) with tunnels partially filled with loose debris (unit X). Original Sandia point, a hearth with four stream-rounded cobbles, and bovid mandible were found in front of and to right of trowel point on limestone residuum (unit B). After Bliss (1940a).

phy recorded herein and that reported by previous investigations as can be seen in Table 1. Bryan's stratigraphy is based upon two brief visits to the cave and on the archaeologists' records (1941:45, 46, and 52).

From the present investigation, the cause of one discrepancy is easily understood. At no place in the cave were all strata present in stratigraphic superposition (Figure 7). The lower dripstone (unit D) was broken and disrupted before accumulation of the lower breccia (unit F) in the front part of the cave. It was not encountered by the excavators from meter 23 to the entrance. On the other hand, the upper dripstone (unit I) extended from near the mouth to meter 27 where it is little more than a film. Beyond this it, and possibly unit G as well, is represented as cement in discontinuous deposits of rubble and as thin coatings thereon. Unit D when encountered from meter 27 on back has been mistakenly correlated with unit I from meter 23 to the entrance (Hibben, 1941b:12).

The limonite ocher (unit C) was not recognized in the forward part of the cave (Hibben, 1937: 262, 263; Bliss, 1940a:200, 201) because after breakage of the lower dripstone (unit D) the underlying ocher was disrupted and partially incorporated into the accumulation that became the lower breccia (unit F) and the lower loose debris (unit X). The ocher may have been mined by Paleo-Indians who could be expected to recognize its exceptional qualities as a pigment. It is bright brownish yellow in its natural state and rouge red when roasted. Use-wear analysis of

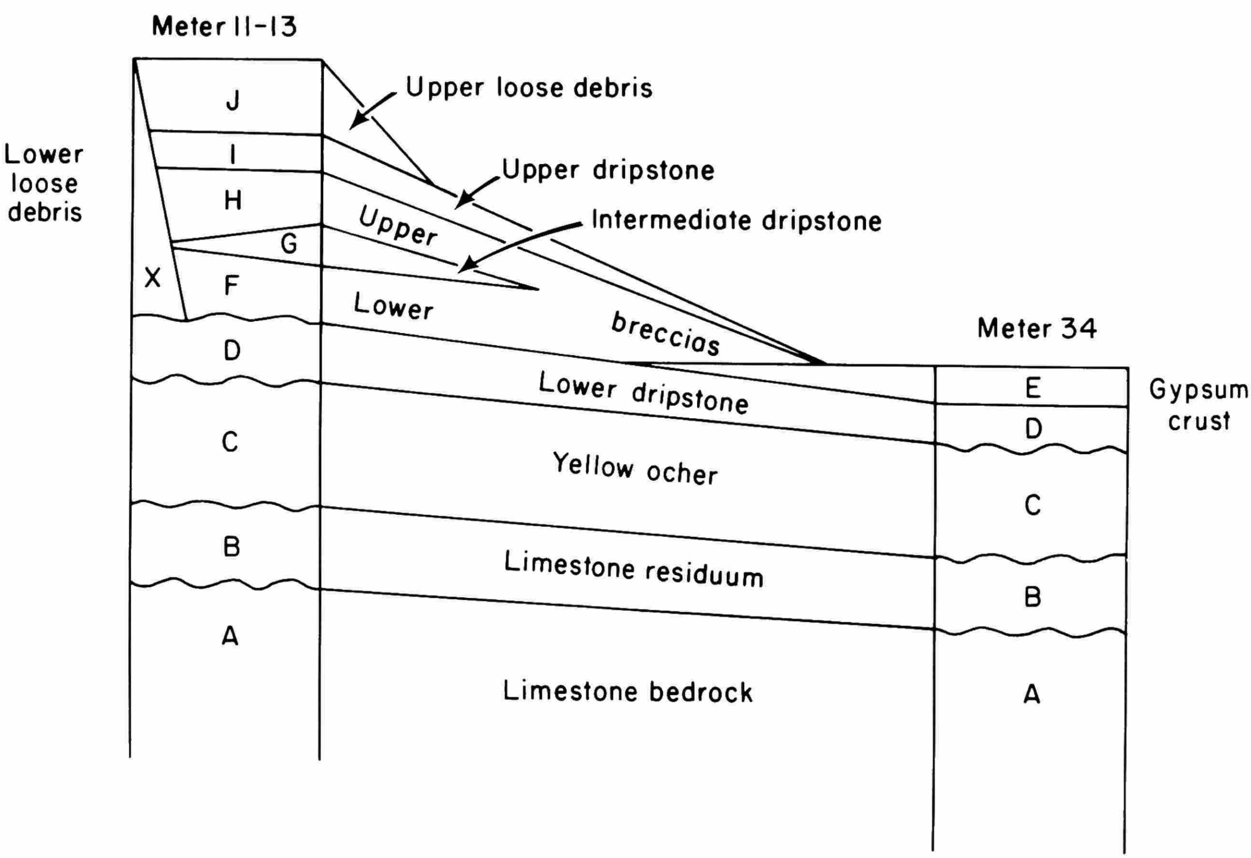


FIGURE 7.—Correlation diagram showing age relationship between units in front and intermediate parts of Sandia Cave.

Sandia points is consistent with this possibility (Gibson, 1977). Paleo-Indian mining would also explain the breaking out of the lower dripstone back to meter 23.

In the rearward positions of the cave, meters 72 through 83, the highly jointed and fragmented ocher is cemented by calcium carbonate that may represent both the lower dripstone (unit D) and the upper dripstones (unit G and I). In this cemented rubble a bifacial tool was found along with sparse remains of Pleistocene animals (Hibben, 1937:262, 263; Bliss, 1940a;200, 201) and is on display at the University of New Mexico.

Once the stratigraphic relationships are understood the order of stratigraphic events becomes clear. This sequence is shown in Figures 2, 5, and 7 and is described as follows.

Preoccupation Stratigraphy (Figures 2A, and 5A): Deposition and partial dissolution of the limestone residuum (unit B) were followed by biochemical deposition of limonite ocher (unit C) underwater. Subsequent desiccation and shrinkage of the ocher were followed by deposition of carbonate dripstone (unit D) that impregnated upper parts of the ocher and filled shrinkage cracks. After cessation of dripwaters gypsum (unit E) was deposited in localized areas. The cave became dry and suitable for human occupation.

Early Occupation Stratigraphy (Figures 2B and 5B): In the forward portion of the cave breaking away of the lower dripstone, possibly by man, was followed by formation, after 14,000 B.P., of the originally loose lower breccia (unit F) composed of disrupted ocher, cave dust, organic debris, and possibly Sandia artifacts, fragments of dripstone, limestone, and bone.

Middle-to-late Occupation Stratigraphy (Figure 2C): The upper cave breccia (unit H) accumulated during an intermediate period of occupation (ca. 10,000 B.P.?), was partially mixed with the lower cave breccia, and was interrupted by periods of intermediate dripstone deposition (unit G). The breccia became impregnated and cemented with calcium carbonate to varying depths. After deposition of the upper dripstone (unit I) the cave became dry and the upper cave debris (unit J) accumulated during late occupation.

Present Stratigraphy (Figure 2D,E): The forward part of the cave has been excavated back to meter 23 leaving remnants of the ocher, breccia, and dripstones attached to both walls. Except for test pits and an excavation between meters 72 and 83 the lower dripstone and cemented ocher protects underlying loose debris (unit X) in burrows throughout much of the remainder of the cave. Unit X has been accumulating since the beginning of deposition of unit F and contains Sandia artifacts as well as modern material.

The secondary deposition of unit X through rodent activity in the soft portions of the ocher (unit C) probably began immediately after the abrupt opening of the cave indicated in the stratigraphy by the gypsum crust (unit E) and the dust therein. This was undoubtedly before the first human occupation of the cave, and the incorporation of foreign matter by animals and man has been going on ever since.

Geochronology and Correlations

On the basis of the Folsom and Agate Basin artifacts in the breccias and the known age-range of these cultural complexes we correlate the units F, G, H, and I with the transition from the final part of the Pleistocene (Wisconsinan (glacial) Stage) to the Holocene (Frye et al., 1968). The lack of precise knowledge of the stratigraphic provenance of the artifacts and the poor precision of radiocarbon dates preclude more detailed correlation to geologic-climatic units such as those at the type Clovis site in Blackwater Draw, New Mexico (Haynes, 1975).

The association of the breccias with dry episodes in the cave environment and dripstones with wet episodes seems obvious, but correlations with similar environments (climates) outside of the cave is not so obvious. Considering current trends in thought regarding glacial climates (Brakenridge, 1978), it is conceivable that the breccias could be related to cold, dry climates in the Sandia Mountains.

As stated in the previous section, we believe that the breccias accumulated after 14,000 and before 9,000 years ago and became partially cemented during a later part of this period, which includes the end of the Woodfordian Substage of Wisconsinan Stage, the Twocreekan Substage of glacial recession, and the early part of the Greatlakean (glacial) Substage (Evenson et al., 1976). This represents an epicycle and a half of climatic fluctuations be they cold-warm-cold or wet-dry-wet. The absence of a sedimentary response in the cave to climatic fluctuation outside may have been due to a lack of sufficient amplitude in this part of the southwestern United States, but there is good evidence to the contrary (Wendorf and Hester, 1975; Bachhuber, 1970). Bachhuber's lacustrine sequence for the Estancia Valley is essentially at the back door of Sandia Cave. The lower breccia spans the top of his Zone F representing full glacio-pluvial conditions, a presumably drier interval between Zones F and E, and part of Zone E, representing a glacio-pluvial phase.

Perhaps the breccia and bone radiocarbon dates from Sandia Cave are too old and units F and I all correlate with Holocene Zones D and C in the Estancia Valley. Bone samples have been notoriously unreliable for radiocarbon dating (Haynes, 1967b) and the Sandia samples were processed by the senior author in a manner (pyrolysis) considered obsolete today. Contamination of such samples is usually with younger carbon, but in the geochemical environment of the cave there is an abundant supply of "dead" carbon, both organic and inorganic, in the Paleozoic limestone. This could be tested in future research on Sandia Cave.

Perhaps our difficulty in arriving at convincing correlations is due to geomorphic changes to the catchment for water entering the cave. The lower dripstone (unit D) formed throughout most of the cave by water flowing down the walls whereas the upper and intermediate dripstones formed from water flowing along the roof and down the sides mostly in the forward part of the cave. From the time the cave mouth opened, represented by the E/D contact, until the beginning of the accumulation of loose debris that became unit F, there may have been no catchment directing water to the mouth. The upper and intermediate dripstone (units I and G) may indicate that sometime between 10,000 and 11,000 years ago a catchment for renewed drip had been established.

The radiocarbon date on carbonate ions at the top of the lower dripstone (unit D) is 32,300± 200 (Table 2). This must be considered as an apparent age because of an unknown amount of "dead" carbon likely present in the bicarbonate ions from which the carbonate formed. The optical clarity of the calcite scalenohedrons making up the laminae is believed to preclude exchange with younger carbonate ions. Therefore, unit D can be interpreted as representing the Woodfordian Stage 13,000 to 22,000 B.P. or the glacio-pluvial represented by Zone F of the Estancia Valley. On the other hand, a uranium-series date on the top of unit D by Henry P. Schwarcz (pers. comm.) is 226,300±16,200 B.P. If unit D is this old it means that from then until 14,000 B.P., about 200,000 years, no deposition occurred in Sandia Cave other than the gypsum crust, presumably due to gradual evaporation from a semiclosed system. In this unlikely case the roof fragments between units D and E do not reflect opening of the cave mouth as hypothesized earlier. Opening by 14,000 B.P., however, is valid provided the bone dates are correct.

The uranium-series date, if correct, would make the ocher unit (C) even older, and correlation of either unit C or D at such an early date is too equivocal for us to attempt. If, however, the lower dripstone represents all of early and middle Wisconsinan time, the ocher layer might represent the Sangamonian interglacial stage when iron and silica were leached from a pedalfer under a warm moist climate as suggested earlier. We prefer this interpretation with the understanding that this does not make it any more valid. It is based simply upon our lack of complete understanding of uranium-series dating and our contention that the radiocarbon dated layer of unit D was not contaminated with younger carbon.

The high percentages of ancient carbon indicated in the dripstones of Sandia Cave is unusual for natural carbonate systems (Broecker and Walton, 1959). They could be due to mechanical incorporation of limestone dust or to recycling of carbon dioxide released from the cave waters. The first explanation is untenable for the lower dripstone because it is composed of optically clear calcite, and the absence of foreign matter indicates the cave was sufficiently closed to inhibit the entrance of dust. Post-depositional exchange with old CO_2 is unlikely because of the coarse crystalline nature and clarity of the calcite.

The absence of any correlative speleothems on the cave ceiling or upper walls plus the etched appearance of these surfaces suggests that descending waters may have dissolved limestone from the upper half of the cave cross-section and deposited it on the lower half in much the same manner as laminated caliche jackets form on the bottom of limestone pebbles at the expense of the tops (Bretz and Horberg, 1949:494).

It is concluded, therefore, that vadose water entering the cave must have acquired additional CO_2 from the cave atmosphere which, because of the restricted ventilation, was high in ancient carbon dioxide. The combination may have resulted in dissolution of limestone from the cave walls and joints in the limestone and eventual precipitation on the cave floor and sides as carbon dioxide left the solution to further enrich the cave atmosphere in ancient carbon.

Another possibility is that the lower dripstone is actually as old, or nearly so, as the radiocarbon analysis indicates. This would indicate more than 10,000 years for which there is no record of any sedimentation in the cave.

The intermediate dripstones (unit G) are relatively thin and some contain megascopically visible limestone fragments. It is assumed, therefore, that a radiocarbon date of >30,000 B.P. (I-471) is meaningless.

There is no doubt that the upper dripstone (unit I) is contaminated with "dead" carbon, but if clastic limestone is present it is not obvious even under microscopic examination of thin sections, and more than 80 percent limestone dust ought to be obvious. Recycling of ancient CO_2 as suggested for unit D is quite unlikely in this case because of the indicated aerated conditions prevailing after 14,000 B.P. Another possible explanation might be the occurence of old CO_2 in the soil gas, or a combination of these factors may be responsible. In any case it is clear from these discrepancies, as well as others (Broecker and Olson, 1961:203), that the chemical systems of speleothem deposition are not adequately understood.

At the Lucy site in New Mexico, the only other site where Sandia points have been found in a stratified context, Roosa (1956) found the Sandia artifacts to be distributed in the upper portion of a deposit of aeolian sand wedged between late Pleistocene lake deposits and early Holocene pond deposits (Harbour, 1958 and pers. comm.) with a radiocarbon date of 14,300±650 B.P. (M-1434) on calcium carbonate (Crane and Griffin, 1968). Carbonate dates being notoriously unreliable, we are inclined to consider it to be too old. A Holocene age for the pond deposits seems more likely. If the correlations are correct the Sandia occupation of the Lucy site is at either the end of a dry period or at the beginning of the earliest Holocene wet period. Contemporaneity with the Clovis culture would be consistent with this interpretation as would a correlation of Harbour's unit 4 dunes with the desiccation of Bachhuber's terminal Pleistocene playa (zone D) and desiccation in Sandia Cave represented by units E and F.

Sandia Artifacts

AGE.—From the archaeological investigations, it is apparent that the cemented portions of the breccias contained Folsom points and other projectile points (Hibben, 1941b, pl. 6) that could now be classified as Agate Basin and Milnesand. Krieger (pers. comm.) has suggested that one base (Hibben, 1941b, pl. 6d) may be a Clovis point, but the broad flute and complete marginal retouch are more like some Folsom points. The archaeological complexes represented by these point types are now dated between 9,000 and 11,000 B.P. (Haynes, 1967a), with Folsom being the older type, but if there was stratigraphic separation between these types within the cave breccias it was not reported.

Published radiocarbon dates for the Sandia occupation have been questioned (Crane, 1955; Johnson, 1957; Krieger, 1957), and the dates presented herein unfortunately do not resolve the question. The whole-rock radiocarbon dates from the breccias (units F and H) range from approximately 12,000 to 9,000 B.P. with the older date being from the lower breccia, whereas bone from upper breccia dated approximately 13,000 B.P. This plus the 14,000 to 12,000 B.P. range for large animal bone fragments from the lower loose debris (unit X) suggests that the large animal bones and the breccias were thoroughly intermixed by the time they were cemented by calcium carbonate. The earliest possible date for human occupation of the cave would be after the enlarging of the cave mouth indicated by the rockfall and gypsum crust. The dates of these vents are unknown, but are probably quite close to the earliest dates on small animal bones of between 14,000 and 12,000 B.P. Human occupation of the cave would have been possible starting in the same time range. At present nothing directly associated with such occupation has been dated unless the large animal bones were in part human refuse, but this may not have been the case. Most large animal bones from Sandia Cave are in the form of small fragments or small elements such as teeth (Hibben, 1941b:32) that could all have been derived from carnivore lairing and pack rat activity in the cave. Many show evidence of rodent gnawing.

It is apparent that because portions of the lower breccia were never cemented rodents have been active in these areas and in the tunnels excavated in the limonite ocher for the past 14,000 years, as evidenced by the radiocarbon dates on mixtures of their bones. And because all of the diagnostic Sandia artifacts are from the rodent-created deposit (unit X) all that can be said with assurance is they must be younger than 14,000 B.P.

Because diagnostic Sandia artifacts were not found cemented in the breccias (units F and H) it can be assumed that Sandia occupation was not during the period when cementation was taking place (11,000 to 9,000 B.P.?). If Sandia occupation was before Folsom occupation it is surprising that no diagnostic Sandia artifacts were found in the breccias, especially so because fragments of bone of pre-Folsom age did occur in unit H if the radiocarbon dates are acceptable.

The other possibility that must be considered is that the Sandia artifacts from the lower loose debris postdate cementation of the breccias and are, therefore, less than ca. 9,000 years old. Whereas this possibility would explain the absence of Sandia artifacts from the breccias, it appears unlikely because no Sandia artifacts are reported from the upper loose debris (unit J) and the Sandia artifacts at the Lucy Site are considered to have been associated with mammoth bones (Roosa, 1956). Furthermore, the first Sandia point was found by paleontologist Chester Stock while excavating a lens of charcoal considered to be a hearth on the bedrock floor of Sandia cave (Hibben, 1937:263; Bliss, 1940a:201, and pers. comm.). Apparently all witnesses considered the point, four rounded cobbles, and a bovid mandible to be in situ and associated with the hearth (Figure 6).

Tentatively, it is suggested that Sandia occupation of Sandia Cave was contemporaneous with the accumulation of the lower breccia (unit F) or, in other words, between 14,000 years when the first animal remains appeared in the cave, and 11,000 years ago, the older end of the known range of Folsom occupation. However, a caveat that should be kept in mind is that the detailed stratigraphic relationships between units F through I were destroyed by the former excavations in the central part of the transverse cross sections shown in Figure 2. In fact no subdivisions within either these breccias or these dripstones were indicated by the earlier investigators but the interfingering of these strata is clearly shown in Figure 6. It is entirely possible that the central portions of unit F had been trampled down or pushed aside by man and animals such that unit H was inset into unit F. Remnants high up on the walls as shown in Figure 2D do not necessarily mean that the dripstone floor was as high as shown in Figure 2C. Such remnants could actually be of unit F instead of unit H as we have assumed. This is an alternate explanation for the anomalously old bone date from unit H shown in Table 2. If such were the case the Sandia point and hearth excavated by Chester Stock could have been at the base of the upper breccia and therefore could be about 10,000 years old.

Another caveat that must be considered is the possibility that what was thought to be "finely powdered charcoal" (Hibben, 1937) in a hearth may have been a concentration of biogenic manganese oxide related to the ocher layer. As stated earlier black lenses of manganese oxide were observed within laminae of unit C. Such a lens may have occurred on the floor at meter 7. In spite of about 20 years of experience with most aspects of radiocarbon dating, we still encounter natural concentrations of manganese oxides that are difficult if not impossible to distinguish from some forms of carbon without laboratory testing. If the Sandia concentration was manganese oxide and not charcoal then the first Sandia point, anomalous stones, and bovid mandible might have been accidental associations at the base of the loose debris, in which case all that can be said about the age of Sandia artifacts is that they are no older than 14,000 B.P.

RELATIONSHIPS.—If Sandia points are specialized Clovis or Folsom tools we hypothesize that they were used in extracting the soft, pulverluent ocher from the cave. The use of ocher by Paleo-Indians is known from the Anzick site in Montana (Lahren and Bonnichsen, 1974) and the Gordon Creek burial in Colorado (Breternitz et al., 1971). How the tools were actually used is, of course, unknown, but they could have been used as knives to outline blocks of ocher by scoring deep grooves and then breaking away the block along a bedding plane. By careful wrapping in leather or woven mats and packing in grass the blocks could be transported without crumbling and used for barter.

A problem with this scenario is that the lithic technology manifest in most of the Sandia points is not like that of either Clovis or Folsom. Much of the flaking on Sandia points was done by percussion, apparently with a hard hammer in some cases, producing a rather crude biface. Pressure flaking is apparent on a few, usually in the form of marginal retouching, and even fewer show careful pressure flaking over most of their surfaces. Taken as a whole, the Sandia Cave Sandia point collection is unlike any single-component site assemblage we have ever seen. It appears to be a mixture of several different flaking techniques. If the collection from the Lucy site (Roosa, 1956) is included the mixture becomes even more bizarre, because these include fluted forms as well as one point that exhibits fine, parallel, collateral flaking that is as well executed as on some of the finest Plano (Yuma) types. Perhaps they represent ocher mining tools of several Paleo-Indian cultures over several millennia.

If Sandia points are pre-Clovis in age they could still have served as ocher-mining tools, but they would be of much greater significance to the history of the peopling of the New World. A possibility worth considering is that the cruder Sandia points represent a pre-Clovis culture that upon making contact with Clovis people tried fluting on their Sandia points. The percussion bifacial flaking technology seen on some Sandia points is not unlike that seen on San Dieguito bifaces from farther west that are at least 9,500 years old. The date and place of origin of the San Dieguito culture is unknown. Its origin is believed by some archaeologist to be pre-Clovis, but compelling evidence is lacking.

Until more stratified and datable Sandia sites are found and properly studied the relationships to the Clovis culture, if any, can not be ascertained from the data at hand.

Conclusions

The most significant conclusions to be derived from these investigations are (1) the Sandia level is not a primary sedimentary deposit but is a bioturbated mixture of deposits, (2) the Sandia artifacts from this deposit are no older than 14,000 B.P., (3) they probably predate the Folsom occupation but could be contemporaneous, and (4) the stratigraphic succession reflects both regional climatic variations and physical changes in the cave itself.

It is suggested that Paleo-Indian utilization of Sandia Cave was at least partly for the purpose of mining ocher. In this regard it is possible that Sandia points are specialized Clovis or Folsom tools used in cutting out blocks of ocher. We firmly believe that no deposition in Sandia Cave after it became accessible to man and animals was free of redeposition. Furthermore, we suggest that in most, if not all, cave deposits that were once unconsolidated, redeposition is the rule rather than the exception.

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