Micromorphological Analysis of Sediments from Meadowcroft Rockshelter, Pennsylvania: Implications for Radiocarbon Dating

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Meadowcroft Rockshelter (36WH297), in Pennsylvannia, is an important site in North American prehistory because of its long, continuous sequence of occupation and its controversial pre-Clovis dates. While a geoarchaeological analysis of the site has been conducted over twelve seasons of excavation between 1973 and 1999, questions have remained concerning the potential for groundwater contamination of the lowest levels that could have contributed to falsely early radiocarbon dates. The present study employs a micromorphological analysis of sediments to clarify the depositional and post-depositional history of the site. The results largely confirm the original work of the excavators, pointing to deposition by attrition, roof fall, and sheet wash, and reveal no evidence of groundwater contamination of the early levels.

Introduction

Excavations conducted at the site of Meadowcroft Rockshelter (36WH297) from 1973 to 1999 revealed floral, faunal, and artifactual evidence of human occupation that spanned a period of at least 10,000 to 12,000 years. Since the original publications of the site (Adovasio et al. 1975, 1977, 1978), the earliest levels ("Strata I/IIa interface" and Stratum IIa) have been the subject of considerable controversy (Dincauze 1984; Haynes 1980, 1987, 1991; Mead 1980). The dating of this site is pivotal to the understanding of the prehistoric settlement of the Americas. If accurately dated, this site could predate the Clovis sites in the Southwestern United States. These layers produced radiocarbon ages of 31,400 ± 1200 (OxA 363) to 8010 ± 110 b.p. (SI 2064, TABLE I),[1] among the earliest cultural dates found within North America (Donahue and Adovasio 1990). Some have suggested that the carbon samples from these layers were contaminated by "old carbon" (either particles or humates) transported through the sediments by groundwater (Haynes 1980, 1987; Tankersley, Munson and Smith 1987; Tankersley and Munson 1992). The source of the contaminants has been thought to be coal and organic rich beds interspersed within the sandstone formation into which the rockshelter developed. Crucial to resolving the dating controversy is a thorough understanding of the depositional and post-depositional factors acting at the site.

Previously published information on the sediments at the site included detailed field observations and grain-size analysis (Beynon 1981; Beynon and Donahue 1982; Stuckenrath et al. 1982), which provided an initial understanding of formation processes acting at the site. This paper supplements previous sedimentological work and uses soil micromorphology, an effective means of analyzing with great resolution the depositional and post-depositional processes operating at archaeological sites (Fisher and Macphail 1985; Courty, Goldberg, and Macphail 1989; Gé et al. 1993; Macphail and Goldberg 1995). This

1. All dates are given here as uncorrected radiocarbon years.

Table 1. Published radiocarbon dates of Stratum I/IIa interface through Stratum V from Meadowcroft Rockshelter (Donahue and Adovasio 1990). All samples, except where noted, were charcoal.

Stratum	*Lab no.*	*Uncorrected date b. p.*	*Corrected date*
V	SI 3024	1665 ± 65	A.C. 285 ± 65
	SI 3027	1790 ± 60	A.C. 160 ± 60
	SI 3022	1880 ± 65	A.C. 70 ± 65
	SI 2362	2075 ± 125	125 ± 125 B.C.
	SI 2487	2155 ± 65	205 ± 65 B.C.
IV	SI 2051	2290 ± 90	340 ± 90 B.C.
	SI 1674	2325 ± 75	375 ± 75 B.C.
	SI 2359	2485 ± 350	535 ± 350 B.C.
	SI 3031	2655 ± 120	705 ± 120 B.C.
	SI 1665	2815 ± 80	865 ± 80 B.C.
	SI 1668	2820 ± 75	870 ± 75 B.C.
	SI 1660	2860 ± 80	910 ± 80 B.C.
	SI 2049	3050 ± 85	1100 ± 85 B.C.
III	SI 2066	2930 ± 75	980 ± 75 B.C.
	SI 1664	3065 ± 80	1115 ± 80 B.C.
	SI 2053	3090 ± 115	1140 ± 115 B.C.
	SI 3030	3100 ± 90	1150 ± 90 B.C.
	SI 2046	3115 ± 70	1165 ± 70 B.C.
	SI 1679	3255 ±115	1305 ± 115 B.C.
IIb	SI 1681	3210 ± 95	1260 ± 95 B.C.
	SI 1680*	3770 ± 90	1820 ± 90 B.C.
	SI 2063	3950 ± 240	2000 ± 240 B.C.
	SI 2058	3970 ± 85	2020 ± 85 B.C.
	SI 2054	4005 ± 85	2055 ± 85 B.C.
	SI 2356	4380 ± 500	2430 ± 500 B.C.
	SI 1685	4820 ± 85	2870 ± 85 B.C.
	SI 2358	6290 ± 355	4340 ± 335 B.C.
	Pitt 122	6315 ± 280	4365 ± 280 B.C.
	Pitt 292†	6630 ± 70	4680 ± 70 B.C.
	SI 2055	6670 ± 140	4720 ± 140 B.C.
	SI 2056	5300 ± 130	3350 ± 130 B.C.
IIa	SI 2064	8010 ± 110	6060 ± 110 B.C.
	SI 2061	9075 ± 115	7125 ± 115 B.C.
	SI 2491	11,300 ± 700	9350 ± 700 B.C.
	SI 2489	12,800 ± 870	10,850 ± 870 B.C.
	SI 2065	13,240 ± 1010	11,290 ± 1010 B.C.
	SI 2488	13,270 ± 340	11,320 ± 340 B.C.
	SI 1872	14,975 ± 620	12,975 ± 620 B.C.
	SI 1686	15,120 ± 165	13,170 ± 165 B.C.
	SI 2354	16,175 ± 975	14,225 ± 975 B.C.
	SI 2062	19,100 ± 810	17,150 ± 810 B.C.
	SI 2060	19,600 ± 2400	17,650 ± 2400 B.C.
	DIC 2187	21,070 ± 475	19,120 ± 475 B.C.
I/IIa interface	SI 2121	21,380 ± 800	19,430 ± 800 B.C.
	SI 1687	30,710 ± 1140	28,760 ± 1140 B.C.
	OxA 363	31,400 ± 1200	29,150 ± 1200 B.C.
	OxA 364	30,900 ± 1100	28,950 ± 1100 B.C.

* Sample was composed of carbonized basketry fragments.
† Sample was composed of black walnut charcoal.

paper clarifies some of the issues surrounding the sedimentological history and dating of the site by examining the sediments from Meadowcroft micromorphologically.

Background

Meadowcroft Rockshelter is located about 48 km sw of Pittsburgh, Pennsylvania (FIG. 1), on the north side of Cross Creek, a minor tributary of the Ohio River, which flows through western Pennsylvania and West Virginia. It is situated 15 m above the present level of Cross Creek and 259.9 m above sea level (Carlisle et al. 1982). The shelter was formed during the middle to late Wisconsinan glaciation by erosional downcutting through the massive Morgantown-Connellsville Sandstone. This formation is a Pennsylvanian aged sandstone of fluvial origin that fines upward, with a double point bar sequence that rests on a basal shale (Carlisle et al. 1982; Donahue and Adovasio 1990). The current overhang covers an area of approximately 65 sq m, and is 13 m above the present-day colluvial surface of the site, with an approximate E–W orientation. The roughly 4 m thick colluvial sequence excavated at Meadowcroft consists of poorly to moderately sorted sands and clayey sands that are punctuated by a number of both individual and massive rock falls as well as cultural features including firepits, firefloors, burned areas, refuse and storage pits, and concentrations of ceramics, lithics, animal bone, and human remains (Sciulli 1982).

Stratigraphy

The excavators of the site recognized eleven strata numbered I (earliest) to XI (latest); all except Stratum I contain cultural features or artifacts. According to Adovasio et al. (1980; see also Stuckenrath et al. 1982), Stratum I consists of a shale unit. Above this are sediments that have been denoted as the "Strata I/IIa interface deposits" (Stuckenrath et al. 1982: 70). These deposits consist of a bluish silty-clay mixed with roof spall that the excavators thought represented overbank flooding and ponding when Cross Creek was associated with a higher base level prior to 21,300 B.P. Previous reports have frequently discussed what the excavators refer to as a thin "mung" layer from the top of the Stratum I/IIa interface. This deposit has often been described as a dark, organic clay layer, but accounts of it have varied considerably (Adovasio et al. 1980, 1998; Stuckenrath et al. 1982; see also Haynes 1991 for a discussion of the discrepancies). The overlying four meters of sediments were identified by the excavators as colluvium and attributed to three distinctly different mechanisms— attrition, rock fall, and sheet wash.

Attrition or grain-by-grain release of sand particles from the roof of the shelter is a slow, continuous process that provides gradual accumulation of sediment to the surface of the colluvial slope within the boundary of the dripline. Rock fragments fall from either the ceiling, interior walls,

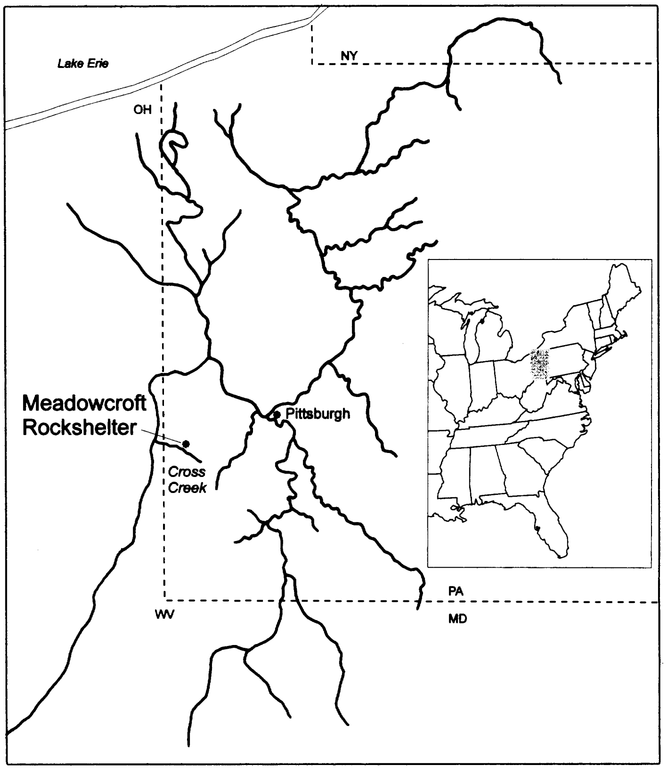


Figure 1. Map showing location of Meadowcroft Rockshelter and the late Pleistocene drainage pattern (after Adovasio et al. 1978: 634, fig. 2).

or entrance of the rockshelter and from the cliff face. This last locus provides a more consistent and higher rate of rock fall causing the development of a raised drip line ridge. Periods of very abundant rock fall appear episodic in nature and depend on the physical configuration of a shelter. At Meadowcroft, abundant rockfall occurred during the accumulation of the Strata I/IIa interface, Stratum II, and Stratum III (between ca. 30,000 and 3000 b.p.); and the accumulation of Strata V, VI, and VII (between 2200 and 900 b.p.). The earlier rock fall period is associated with both the original development of the shelter and an old roof fall on the west side of the overhang, while the later rock fall period marks a large new roof fall on the east side of the shelter. The irregular surface produced by rock fall was thought by the excavators to have been gradually infilled, predominantly by attrition during accumulation of Strata I, II, and III and by sheet wash and attrition during accumulation of Strata V, VI, and VII (Stuckenrath et al. 1982).

Sediments derived from sheet wash can accumulate during rain storms when water and sediment are transported from upland surfaces over the cliff edge and down to the colluvial surface immediately outside of a shelter's dripline. Where re-entrants, indentations along the cliff edge, have developed along a shelter's edge by the release of large rock falls, such as the old and new roof falls at Meadowcroft, water and sediment accumulate along the dripline. Sheet wash cones can develop with the apex located at the re-entrant. These deposits have a steep slope and are laminated. At Meadowcroft, this type of sedimentation was thought to have become well developed after the roof fall during the accumulation of Stratum V, VI, and VII (Beynon and Donahue, 1982).

Chronology

According to an interim Meadowcroft report (Adovasio 1982), the rockshelter would have been available for use after the mid-late Wisconsinan (21,300 B.P.), once Cross Creek had retreated. Of the 52 dated charcoal samples, 39 are later than 12,800 B.P. (Donahue and Adovasio 1990: 238–239). The remaining 13 dates come from both the earliest cultural level (IIa) as well as the underlying sterile level (I/IIa) and span the period from 31,500–12,800 B.P. These dates are controversial, with some researchers arguing for the possibility of contamination of the carbon samples by either coal particulates or by soluble humates derived from the coal (Haynes 1987, 1991; Mead 1980; Tankersley, Munson, and Smith 1987). A list of radiocarbon dates from the strata discussed here are presented in Table 1. For a complete list of radiocarbon dates from Meadowcroft see Adovasio et al. (1998) and Donahue and Adovasio (1990).

Haynes (1991) has argued that in most sedimentary environments a sedimentological break should be visible at the Pleistocene/Holocene transition. "Without radiocarbon dating the Pleistocene/Holocene boundary (PHB) at Meadowcroft Rockshelter would logically be placed at the base of Stratum IIa, which directly overlies Stratum I" (Haynes 1991: 9). His argument is at odds, however, with the radiocarbon dates that indicate that the Pleistocene/Holocene transition occurs just below the IIa/IIb interface. The excavators noted no stratigraphic hiatus within Stratum II, although there was a major roof spalling event that separates IIa and IIb, as well as additional roof spalling events within both stratigraphic subunits.

Micromorphology

Micromorphology, the study of thin sections made from undisturbed blocks of sediment or soil (Courty, Goldberg, and Macphail 1989), can disclose the interplay between depositional and post-depositional processes that are not visible to the unaided eye in the field and that bulk analysis will not readily reveal. Since the sampled, consolidated blocks of sediment retain their structure and orientation, it is possible to study the three-dimensional organization of the sediments, including the relationship between the solid material and the empty spaces, called voids. Air and water flow through sediments and soils via the void system. Thus if the sediments at Meadowcroft had been contaminated with groundwater, it would have passed through the void network. In the descriptive terminology for shapes and sizes of voids, those in the Meadowcroft sediments typically occur as vughs (small, irregularly-shaped), chambers (large, rounded), or channels (long, narrow). These types of voids, by definition, all occur within the sediment aggregates called peds, but other types of voids can occur outside of peds. Fissures are elongated, planar voids that separate peds and result in a blocky structure (Bullock et al. 1985; Jungerius and Rutherford 1979; Fitzpatrick 1991).

Other important features described by micromorphologists include the coarse and the fine fraction (also called the matrix) of the solid material, and the relationship between these two, called the related distribution. Observation of the related distribution allows us, for example, to differentiate between primary and secondary clay. Similarly, we can recognize the difference between primary and secondary carbonates and the presence of other secondary features, such as iron staining (addition) or iron depletion.

By observing the spatial relationships between voids and fine and coarse fractions, it is often possible to distinguish a relative chronology of the processes that operated within the deposit. A basic chronological framework could identify depositional processes such as those discussed for Meadowcroft which resulted in the accumulation of the bulk of the sediment. Post-depositional processes occur after the depositional events, but how closely after can vary considerably. Those processes that occur within a "short" time, on the order of days, months, or a few years are called penecontemporaneous events. These can be depositional, erosional, or involve chemical transformations (Karkanas et al. 1999). The term syndepositional is used to refer specifically to penecontemporaneous depositional events.

The effects of groundwater, for example, could be manifested micromorphologically by extensive depletion or segregation features associated with voids (Vepraskas 1995), or by extensive textural features, such as filling of voids by fine material carried in suspension by the groundwater.

Methods

A total of 25 sediment samples was collected for micromorphological analysis from Meadowcroft Rockshelter in September, 1994 when Paul Goldberg and Jack Donahue (University of Pittsburgh) visited the site during maintenance operations (TABLE 2, FIG. 2). Samples were collected from Strata I/IIa interface and Stratum IIa, the two layers that some have argued may have been contaminated by humates or particulates; no samples were taken from the controversial "mung" layer because it was not exposed. Micromorphology samples were also collected from the non-controversial Strata IIb, III, IV, and V. These samples were included in the analysis to provide control and to present a more complete picture of sedimentary processes operating at the site.

After collection, the blocks of sediment were impregnated with polyester resin and thin sections were produced from these consolidated blocks following the procedures outlined in Courty, Goldberg, and Macphail (1989). Thin sections were examined with both a conventional microfiche reader and a petrographic microscope, using plane (PPL) and crossed (XPL) polarized light at magnifications of 15×, 20×, and 40×. Additional observations were made using blue episcopic illumination (490 nm excitation filter, 510 nm dichroic mirror, 525 nm barrier filter), and ultraviolet (540 nm excitation filter, 400 nm dichroic mirror, 580 nm barrier filter). Terminology follows that of Bullock et al. (1985) and Courty, Goldberg, and Macphail (1989).

Results

Below we summarize the stratigraphy of the site as drawn from the published reports, followed by a description and interpretation of the most significant aspects of the micromorphological samples from each stratum. Concise descriptions of each sample are provided in Table 3. The results of the fluorescence microscopy and the implications of the micromorphological analysis for the site as a whole are presented more fully before the "Discussion."

Stratum I/IIa Interface

FIELD DESCRIPTION

The Stratum I/IIa interface is the basal sedimentary unit at the site (FIG. 2), and appears both inside and outside the modern dripline. It is a silty clay layer containing fragments of roof spall and rounded shale clasts that is presumed to be continuous across the site, but has no cultural associations (Beynon and Donahue 1982). Early field and laboratory work suggested that Stratum I/IIa interface deposits were deposited during flood events at a time when Cross Creek was still at a level close to the floor of the rockshelter. The four radiocarbon dates obtained from this stratum span a period from 31,400 ±1200 (OxA 363) to 21,380 ±800 b.p. (SI 2121; TABLE 1). The dates from this stratum have been considered as controversial and possibly contaminated with old carbon.

Table 2. List of sample locations by stratum.

Stratum	*Sample no.*	*Coordinate* *Northing*	*Coordinate* *Westing*	*Elevation below PDM* (m)*	*Strata/ features*	*Level (cm)*
V	MR-94-19	10.417	16.423	2.186	F14	4–8
IV	MR-94-20	10.417	16.423	2.266	F16	3–10
	MR-94-21	10.417	16.423	2.336	F16	10–13
	MR-94-22	10.417	16.423	2.336	F16	13–23
	MR-94-23	10.417	16.423	2.466	F16	23–33
	MR-94-24	10.417	16.423	2.566	F16	33–41
	MR-94-25	10.417	16.423	2.646	F16	42–49
	MR-94-16	10.620	16.882	2.776	F130 III	
	MR-94-17	10.620	16.882	2.826	F167 I, II,III	
III	MR-94-7A	7.210	17.818	4.304	F18	40–50
	MR-94-5	2.775	17.877	3.267	F18	5–15
	MR-94-10	5.726	17.182	3.504	F18	40–47
	MR-94-11	5.726	17.182	3.574	F18	47–55
	MR-94-12	5.726	17.182	3.644	F18	55–61
	MR-94-13	5.726	17.182	3.704	F18	61–71
IIb	MR-94-18	10.753	16.820	2.716	F46	0–8
	MR-94-8	2.930	17.712	3.669	F46	0–10
	MR-94-6	1.992	17.663	3.967	F46	0–10
	MR-94-3	2.255	17.769	4.308	F46	40–50
IIa	MR-94-1	4.546	17.942	4.171	F46	60–65
	MR-94-2	4.082	17.956	4.268	F46	65–75
	MR-94-4	2.218	17.759	4.415	F46	50–60
	MR-94-9	3.349	20.741	4.954	F46	90–95
I/IIa interface	MR-94-15	11.160	18.128	3.494	F99	0–10
	MR-94-14	10.868	18.963	3.754	F99	0–10

* PDM = Permanent Datum Marker

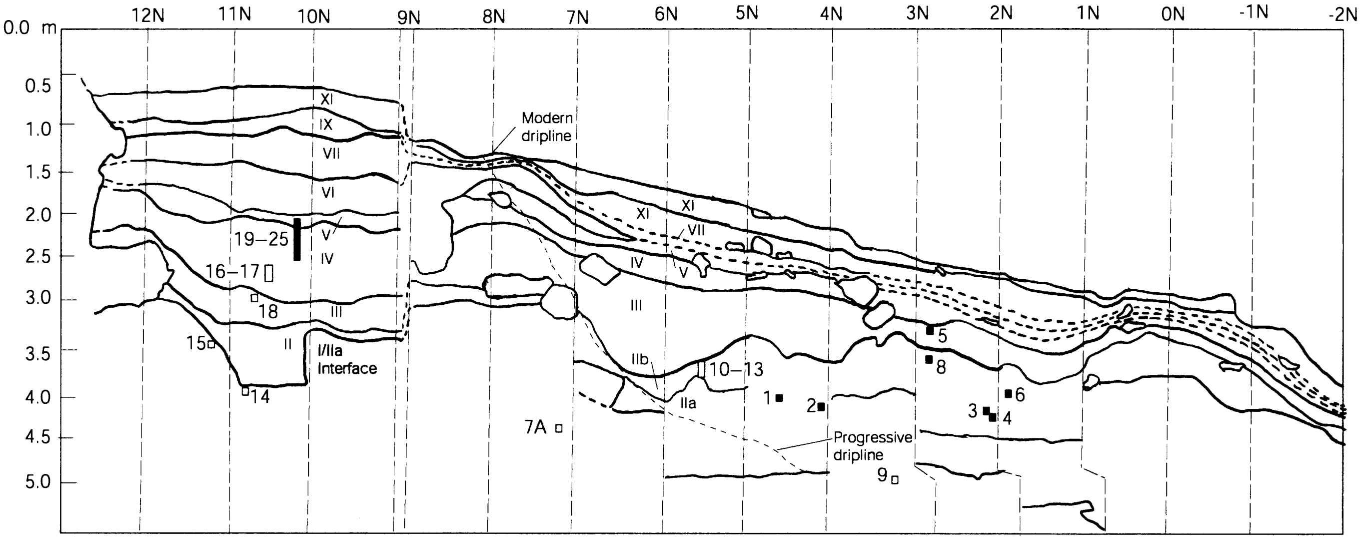


Figure 2. Composite drawing of the N–S profile of the rockshelter (after Adovasio and Donahue 1990: 236–237, fig. 7). Shown are relative depth and lateral distribution of samples collected for micromorphological analysis. Solid squares represent samples taken from the profile shown here; outlined squares indicate samples that were taken from profiles not depicted. The IIa/IIb division extends across the site, but extant drawings depict it only in the central part of the profile, as shown here.

Table 3. Concise description of micromorphological samples examined in this study (terminology is taken from Bullock et al. 1985 and Courty, Goldberg, and Macphail 1989).

Sample no.	*Stratum*	*Dripline**	*Microstructure and gross organization*	*Coarse fraction*	*Micromass*
MR-94-19 †	V	I	Loose, vughy structure with open porphyric to gefuric related distribution.	Randomly distributed sand- to silt-size quartz grains; occasional rock fragments, including a possible hematite or ochre fragment.	Fine fraction of light brown silty clay with accumulations of darker, dustier clay.
MR-94-20	IV	I	As in MR-94-17.	As in MR-94-16, but rock fragments less common.	As in MR-94-16, but with less carbonate; deposits of dusty reddish clay.
MR-94-21	IV	I	As in MR-94-17.	As in MR-94-16, but rock fragments less common.	As in MR-94-16, but with less carbonate; deposits of dusty reddish clay.
MR-94-22	IV	I	As in MR-94-16, but vughs more common.	As in MR-94-16, but rock fragments less abundant and, on average, larger.	As in MR-94-16.
MR-94-23	IV	I	As in MR-94-16, but with only traces of bedding.	As in MR-94-16.	As in MR-94-16.
MR-94-24	IV	I	As in MR-94-16.	As in MR-94-16.	As in MR-94-16.
MR-94-25	IV	I	As in MR-94-16.	As in MR-94-16.	As in MR-94-16.
MR-94-17 †	IV	I	Very loose, vughy structure with gefuric related distribution; clear bedding of coarse and fine fractions.	Similar to MR-94-16, but rock fragments are much less common.	As in MR-94-16.
MR-95-16	IV	I	Vughy structure with open porphyric related distribution; clear bedding of coarse and fine fraction.	Randomly distributed, well sorted sand to silt-size quartz grains; abundant shale and sandstone rock fragments.	Fine fraction of light brown silty clay with a high carbonate content.
MR-94-7A †	III	I	As in MR-94-12, but lower part of sample with more vughs.	As in MR-94-13.	As in MR-94-13 but more calcareous than other samples from stratum III; relatively little clay in upper portion of sample.
MR-94-5	III	O	Massive with irregular vughs and chambers.	Angular sand grains and a few granule-sized siltstones.	Fine silt and clay.
MR-94-10 †	III	O	As in MR-94-12, but bedding is less prominent.	As in MR-94-13.	As in MR-94-13.
MR-94-11	III	O	Similar to MR-94-12, but related distribution more gefuric and bedding more disturbed.	As in MR-94-13.	As in MR-94-13.
MR-94-12	III	O	Vughy to pellicular structure with porphyric to gefuric related distribution; coarse bedding of coarse and fine fraction.	As in MR-94-13.	As in MR-94-13.
MR-94-13	III	O	Very loose, vughy structure with a gefuric related distribution; traces of bedding, disturbed; pellicular grain coatings.	Randomly distributed sand- to silt-size quartz grains; occasional shale and sandstone rock fragments.	Fine fraction of light brown material, much siltier than in Stratum II, and reddish limpid clay deposits; granostriated and reticulated b-fabrics.

* I = inside the modern dripline. O = outside the modern dripline.
† Sample shown in illustrations.

Textural pedofeatures	Other secondary features	Organic material
Rare, localized dusty clay void coatings.	–	Rare bone, eggshell and charcoal fragments.
Abundant dusty clay void coatings.	Occasional carbonate crusts.	Occasional bone, eggshell, and charcoal fragments.
Localized dusty clay void coatings.	–	Rare eggshell and charcoal fragments.
Localized, thin, dusty clay void coatings.	Rare carbonate hypocoatings.	Rare bone, eggshell, and charcoal fragments.
–	Occasional carbonate hypocoatings.	Rare charcoal fragments and domains of ash.
–	Rare iron concretions.	Rare eggshell, bone, and charcoal fragments.
–	–	Rare eggshell and charcoal fragments.
–	Occasional iron staining; carbonate hypocoatings.	Rare eggshell and bone fragments; coarse and fine charcoal fragments (the latter commonly interbedded with very fine silt and ash).
–	Rare localized iron depletion and concentration zones; carbonate crusts and hypocoatings.	Abundant bone and eggshell fragments; charcoal fragments, very broken up; ash.
Dusty red clay bridges, but few intercalations or void coatings.	Secondary iron staining; micritic hypocoatings and domains.	Rare shell and bone fragments.
Reddish brown clay intercalations; occasional isolated void fillings.	Iron depletion and concentration features; occasional indications of bioturbation.	–
As in MR-94-12, but intercalations are more massive.	As in MR-94-13; manganese crust; indications of gleying.	Rare bone fragments; charcoal and organic matter present.
As in MR-94-12.	As in MR-94-13.	As in MR-94-12.
Reddish clay inter-calations and void coatings; the former often distributed in a rectilinear fashion; the latter frequently associated with large, linear voids.	As in MR-94-13.	Rare charcoal fragments.
Intercalations of clay; more massive accumulation of primary clay than in Stratum II, particularly associated with large voids.	Localized iron depletion and concentration zones.	Rare bone fragments; rare charcoal fragments.

(cont.)

Table 3. (cont.)

Sample no.	*Stratum*	*Dripline**	*Microstructure and gross organization*	*Coarse fraction*	*Micromass*
MR-94-18 †	IIb	I	Structure looser and vughier than in other Stratum II samples, with enaulic to gefuric related distribution; porosity 20–30%; packing voids and vughs.	Similar to MR-94-9, but quartz fraction finer grained, and includes two very large (2 × 2 cm) sandstone fragments.	Fine fraction contains a much higher carbonate content and much less clay.
MR-94-8	IIb	O	As in MR-94-4, but with a greater porosity (20–30%), including several large chamber voids.	As in MR-94-9, but with a higher percentage of rock fragments.	Similar to MR-94-9.
MR-96-6	IIb	O	As in MR-94-9, but with closed porphyric related distribution.	As in MR-94-9.	As in MR-94-9.
MR-94-3 †	IIb	O	As in MR-94-4, but with greater porosity (20–30%).	Similar to MR-94-9, but sand-size quartz is less abundant.	Similar to MR-94-9, but fine fraction more abundant, siltier, and lighter brown with very little organic material.
MR-94-1	IIa	O	As in MR-94-9, but with higher percentage of vertically oriented chamber voids and channel voids.	As in MR-94-9.	As in MR-94-9, but fine fraction slightly less abundant; dustier and more micaceous than previous samples.
MR-94-2	IIa	O	As in MR-94-9.	As in MR-94-9, but quartz grains slightly coarser; sandstone rock fragments, coarser than in MR-94-9.	Similar to MR-94-9, but much less abundant, lighter in color and with less organic matter.
MR-94-4	IIa	O	Vughy structure with closed porphyric related distribution; porosity 10–20%, predominately vughs with occasional chambers.	As in MR-94-9.	Similar to MR-94-9.
MR-94-9	IIa	O	Vughy to spongy structure with open porphyric to chitonic related distribution; porosity 20–30%, vughs and chambers.	Randomly distributed sand- to silt-size quartz, with occasional (5–10%) fragments of sandstone and shale; occasional iron concretions; several large (1–3 cm) sandstone fragments.	Abundant dark brown silty matrix; granostriated and reticulated b-fabrics.
MR-94-15 †	I/IIa interface	I	As in MR-94-14.	As in MR-94-14, but rock fragments are more common.	Lower percentage of fine fraction than in MR-94-14; localized calcareous domains.
MR-94-14 †	I/IIa interface	I	Open, vughy structure with open porphyric related distribution; high porosity (30–40%); packing voids and vughs.	Randomly distributed sand- to silt-size quartz, occasional (5–10%) cm-sized rounded shale and micaceous siltstone; rare partially dissolved limestone fragments.	Light brown silty matrix intermixed with domains of darker brown, organic rich material; bridges and coatings of silty reddish-brown clay between coarse grains.

* I = inside the modern dripline. O = outside the modern dripline.
† Sample shown in illustrations.

MICROMORPHOLOGY

Two samples were studied from the Stratum I/IIa interface, MR-94-14 and MR-94-15 (TABLES 2, 3; FIG. 2); both located inside the modern dripline. Both samples are composed of a sandy and silty material with rounded fragments of shale that initially appeared consistent with the original interpretation of the stratum as a deposit from single or multiple flood events (Beynon and Donahue 1982). These samples, however, do not appear to be of fluvial origin because they are poorly sorted and there is no trace of bedding that would indicate such a sedimentary environment. Both samples contain deposits of silty, reddish-brown clay that coat sand-sized grains and form bridges between the grains, indicating colluvial deposition (FIG. 3).

Textural pedofeatures	*Other secondary features*	*Organic material*
–	Secondary carbonate pendants on base of rock fragments.	Scattered bone fragments and eggshell fragments of varying thicknesses; mm-sized charcoal fragments; domains of ash.
As in MR-94-4, but with late stage limpid yellow intercalations and void coatings.	Some iron staining.	–
As in MR-94-4, but intercalations less common; void coatings more common.	Occasional iron staining.	–
Similar to MR-94-4.	Occasional iron staining.	Randomly scattered, isolated charcoal fragments, more abundant than in lower samples.
As in MR-94-4, but with silty clay void coatings that are more common, darker in color, and thicker.	Occasional iron staining; possible secondary silica.	Rare, randomly scattered, isolated silt-size fragments of charcoal.
As in MR-94-4, abundant intercalations.	–	Rare, randomly scattered, isolated fragments of charcoal.
Intercalations of reddish clay; rare dusty clay void coatings.	Localized iron staining and depletion domains.	Rare charcoal fragments (up to 1.5 mm).
Abundant intercalations, both silt and clay; the latter in two phases, dark dusty reddish-brown and limpid, yellowish brown clay; rare dusty clay void coatings.	–	Rare, charcoal fragments.
–	–	Randomly scattered bone, burned eggshell, and small fragments of charcoal.
–	–	–

The presence of bone and burned eggshell in MR-94-15 (FIG. 4) is notable since this stratum had been considered culturally sterile (Adovasio et al. 1978). While the origin of these remains may be natural (e.g., roosting of birds), their presence may also suggest human activity in this stratum; downward reworking from overlying deposits seems remote because there is no evidence of bioturbation.

Stratum II

FIELD DESCRIPTION

This stratum is continuous across the site, and is subdivided into Stratum IIa and IIb, separated by a layer of roof spall (FIG. 2). Attrition and rockfall were identified as the main depositional agents (Donahue and Adovasio 1990).

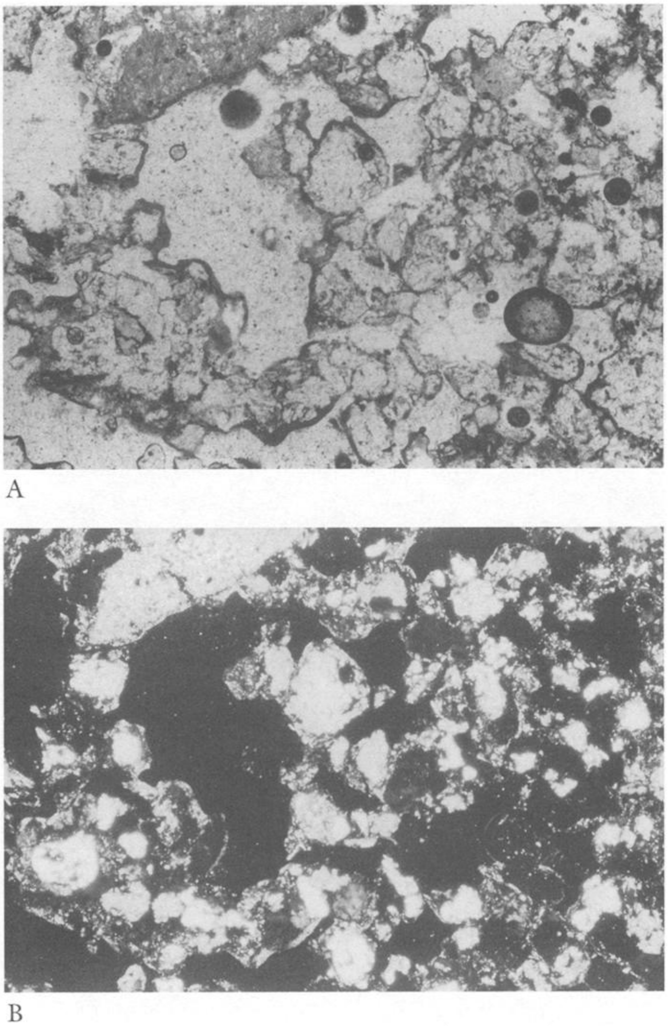


Figure 3. a) Microphotograph of sample MR-94-14 showing dusty clay bridges between grains (Plane polarized light. Field of view is ca 3 mm); b) The same view as shown in a) but in cross-polarized light (Field of view is ca 3 mm).

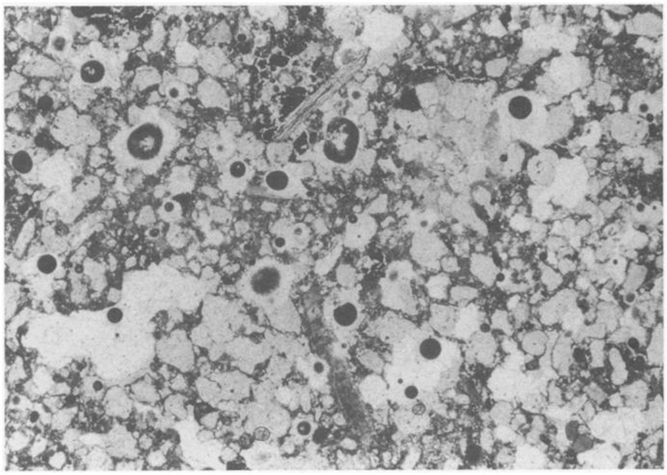


Figure 4. Microphotograph of sample MR-94-15 showing burned eggshell (bottom center) and bone (top center), typically indicative of cultural material. The black area in the lower right is charcoal (Plane polarized light. Field of view is ca 6.5 mm).

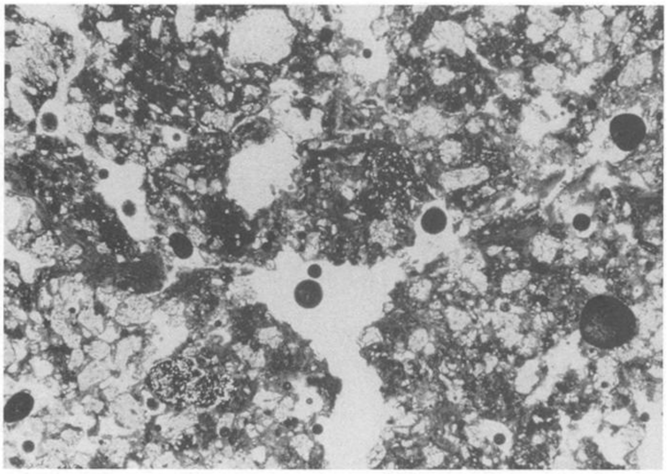
Firepits, firefloors, storage and refuse pits, stone tools, shell, and floral and faunal remains were found in both Stratum IIa and IIb (Stuckenrath et al. 1982.).

The radiocarbon dates from Stratum IIa span a period from 21,070 ± 475 (DIC 2187) at the I/IIa interface to 8010 ± 110 b.p. (SI 2064) at the top of the layer. Stratum IIb spans a period from 6670 ± 140 b.p. (SI 2055) to 3210 ± 95 b.p. (SI 1681). The dates from Stratum IIa, like those from Stratum I/IIa interface have been considered by many to be too old and possibly contaminated with old carbon (Haynes 1980; Tankersley and Munson 1992; Tankersley, Munson, and Smith 1987). Some critics have also questioned the validity of the radiocarbon dates from Stratum IIb, believing that these may also have been subjected the same contamination processes. Stratum II is also where evidence of the Pleistocene/Holocene boundary might be expected. If Haynes (1991) is correct, this break would occur at the base of IIa, but if the radiocarbon dates are accurate the transition occurs just below the IIa/IIb transition.

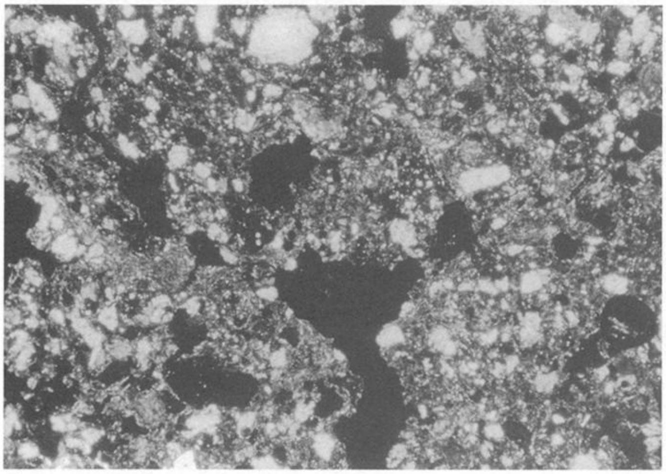
MICROMORPHOLOGY OF STRATUM IIA

Four samples were collected from Stratum IIa (TABLES 2, 3; FIG. 2; MR-94-4, MR-94-2, MR-94-1, MR-94-9). In general, these sediments are composed of a mixture of matrix-supported sand and silt. Linear accumulations of clay, called intercalations (FIG. 5; Bullock et al. 1985), are widespread within the matrix, and by definition these features are unrelated to voids. In fact, the absence of clay in most of the voids found within these sediments indicates that the intercalations formed syndepositionally, perhaps accumulating seasonally when clay-enriched water filtered downward through cracks in dry sediments. It is not possible to determine definitively the source of this water; possibilities include sheet wash from upslope, or, to a lesser extent, water dripping off the brow. It is likely that water was derived from multiple sources.

Charcoal and bone tend to occur as isolated fragments, randomly scattered throughout the sediments. This distribution may result from bioturbation, although there are few other micromorphological indications of this process. The distribution and the fragmentation may also relate to the effects of trampling by humans or other animals, and may be syndepositional (Gé et al. 1993; Matthews 1995).



A



B

Figure 5. a) Microphotograph of sample MR-94-3. The intercalations of clay are visible in the center of the photo. A piece of charcoal is also visible in the lower (left) (Plane polarized light. Field of view is 6.5 mm); b) The same view as in Figure 5a but in cross polarized light. (Field of view is 6.5 mm).

MICROMORPHOLOGY OF STRATUM IIB

Four samples were collected from Stratum IIb (TABLES 2, 3; FIG. 2). In general the three samples from the exterior of the modern dripline (MR-94-3, MR-94-6, MR-94-8) are very similar to those from Stratum IIa, although intercalations are less common and a few void coatings are present. The clay in both the intercalations and the voids ranges from the silty, reddish-brown material seen in the previous layer to a limpid, yellowish clay. The difference in color and texture of the two clay types indicates a shift in the source or in the energy of the depositional process, but it is a minor change. The presence of clay within void coatings likewise indicates a change in the depositional regime, or at least in its timing, and it is likely that these coatings formed post-depositionally. These changes, although present and noteworthy, are subtle and do not indicate any major change in the depositional processes during the accumulation of Stratum II.

Sample MR-94-18 from the interior of the modern dripline, is noticeably different from the other samples from this layer, and, in fact, resembles the samples from the Stratum I/IIa interface (also from inside the modern dripline), although intercalations and void coatings are completely absent. This absence may result from the fact that the depositional agents that would produce them did not extend to the back of the cave. The coarse fraction is similar to that seen in other samples but also includes two centimeter-sized siltstone pebbles, both of which have micritic pendants, indicating the better preservation of calcium carbonate within the modern dripline. Both primary calcite, derived from the rockshelter walls and eggshells (FIG. 6), and secondary calcite, such as the pendants, have been preserved.

The sample also contains bone, isolated charcoal fragments, and ashes. None of these elements, however, appears to preserve their expected sub-horizontal orientation. This lack of preferred orientation may be the result of bioturbation, but again it may owe more to the disruptional effects of trampling during the deposition of the material.

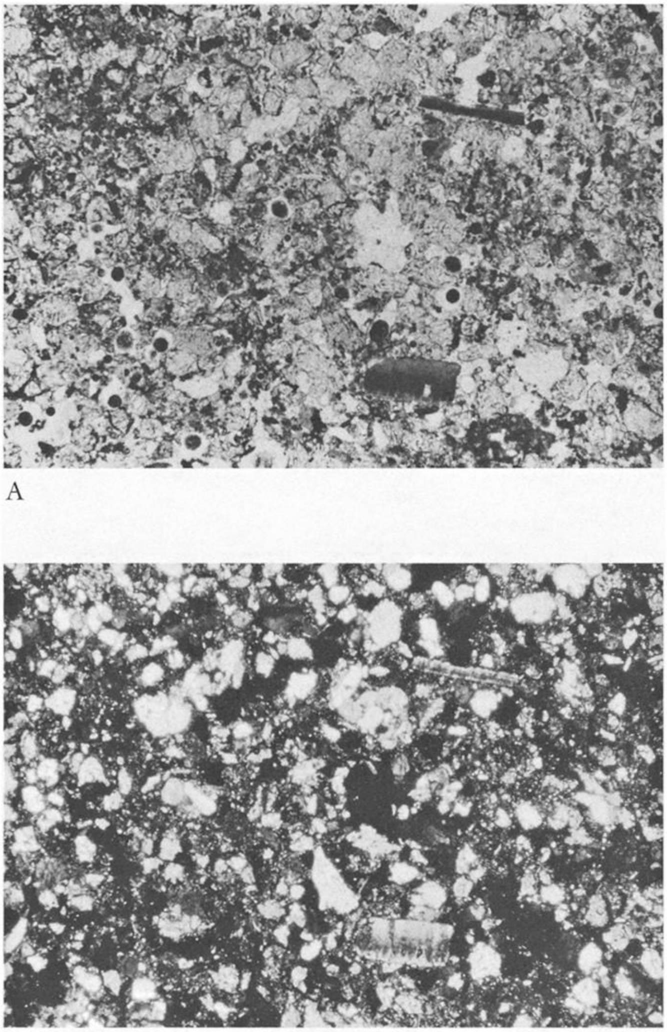
Stratum III

FIELD DESCRIPTION

This stratum, like the two overlying strata (IV and V; see below), is not controversial but supplies background and comparative information for the controversial layers. Stratum III is continuous across the site (FIG. 2). Inside the modern dripline, the sediments are polymodal (containing sand, silt, and clay), with a high percentage (5–8%) of carbonate; outside the dripline, they are a more uniform mixture of silt and clay with less carbonate. The stratum contains a significant component of rock fall. Sheet wash and attrition were identified as the other major depositional agents (Donahue and Adovasio 1990). Numerous cultural features reported by Stuckenrath et al. (1982) include firepits, firefloors, flaked and ground stone, bone, floral remains, and shell. Radiocarbon dates from this layer span the period from 3255 ± 115 (SI 1679) to 2930 ± 75 b.p. (SI 2066; TABLE 1).

MICROMORPHOLOGY OF STRATUM III

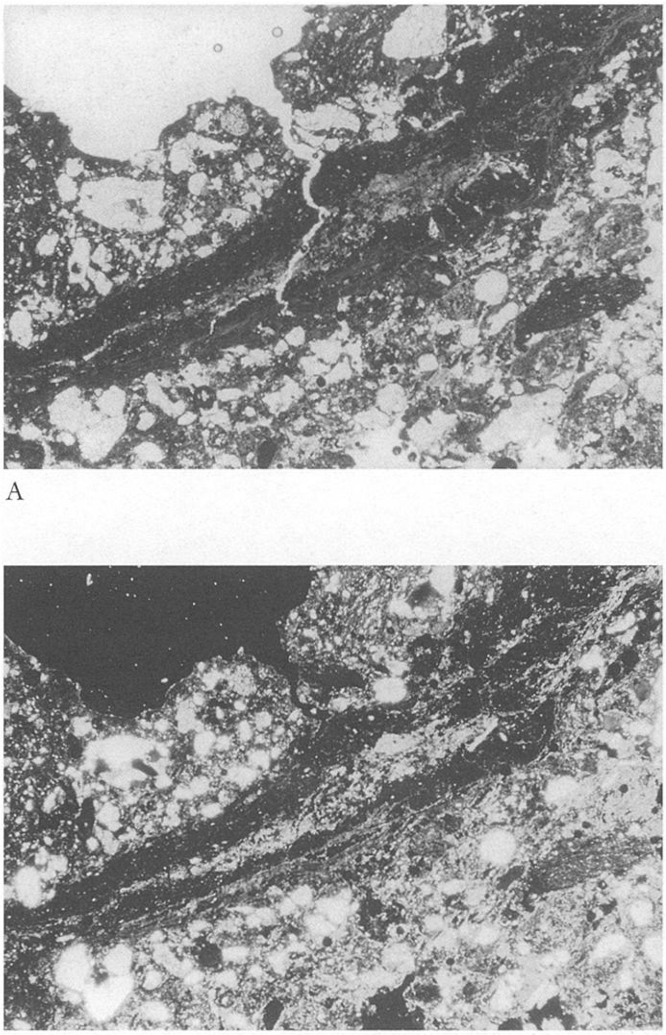
Six samples from this stratum were studied (TABLES 2, 3; FIG. 2), all except MR-94-5 were from areas within the *paleo*dripline. Samples MR-94-5, MR-94-10, MR-94-11, MR-94-12, and MR-94-13 are all from the same square



A

B

Figure 6. a) Microphotograph of sample MR-94-18. Note the different thicknesses of the eggshells, pointing to both different species of birds, and the overall calcareous nature of the sediments from within the modern dripline (Plane polarized light. Field of view is 6.5 mm); b) The same view as Figure 6a but in cross polarized light (Field of view is 6.5 mm).



A

B

Figure 7. a) Microphotograph of the manganese crust in sample MR-94-10. Visible are the calcareous layer within the crust, and the clay layer at its base (Plane polarized light. Field of view is 3 mm); b) The same view as in a) but in cross polarized light. (Field of view is 3 mm).

meter outside of the *modern* dripline. In contrast, sample MR-94-7A was collected from inside the modern dripline. Unlike the Stratum IIb samples, however, there were few differences among samples from inside and outside of the modern dripline.

All of the samples from outside of the modern dripline except MR-94-5 are very similar and contain an abundance of rock fragments composed of fine-grained silts and clays, in contrast to the sandstone rock fragments found in underlying layers. These rock fragments may be derived from shales and siltstones that stratigraphically overlie the sandstone that forms Meadowcroft shelter, and indicate transportation by sheet wash flows that originated above the shelter.

Significantly, these sediments, except those in MR-94-5, are characterized by the presence of bedding, which was absent from Stratum II. They also have a higher clay content than those from Stratum II. This clay, a limpid reddish-brown unlike that found in the underlying strata, is found in relatively more massive accumulations in intercalations, within large voids, and as bridges between individual grains. The clay accumulation does not seem to have been deposited by groundwater, since the composition of the clay is not consistent with that seen in the underlying layers. The massiveness of some of the clay deposits, their lack of bedding, and better sorting, all suggest a rapid accumulation of clay, perhaps in the form of a clay-rich slurry that percolated downward through the upper portion of existing deposits. It does not appear in the underlying strata since it is formed roughly penecontemporaneously with the accumulation of the coarse fraction. Some features also indicate local puddling, including the presence of iron depletion and concentration features and, most notably, the prominent crust at the top of sample MR-94-10 (FIG. 7). Sample MR-94-5 lacks the bedding seen in these other samples and is most notable for the presence of extensive depletion features. There are also indications of bioturbation of the sediments.

Sample MR-94-7A from inside the modern dripline contains the same general components, but clay void coatings and intercalations are less common and there is a noticeably higher percentage of primary and secondary calcium carbonate (FIG. 8).

All of the above observations largely support the original statements regarding depositional mechanisms for Stratum III (Beynon and Donahue 1982; Donahue and Adovasio 1990). Sheet wash, routed down the re-entrant formed by the release of roof fall, likely delivered rain water now bearing mud and shale and siltstone fragments into the interior of the shelter from the west.

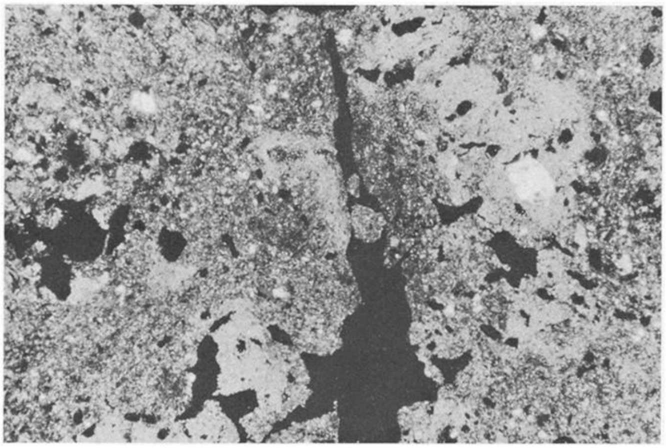


Figure 8. Microphotograph of MR-94-7A showing hypocoatings of calcite around voids (Cross polarized light. Field of view is 6.5 mm).

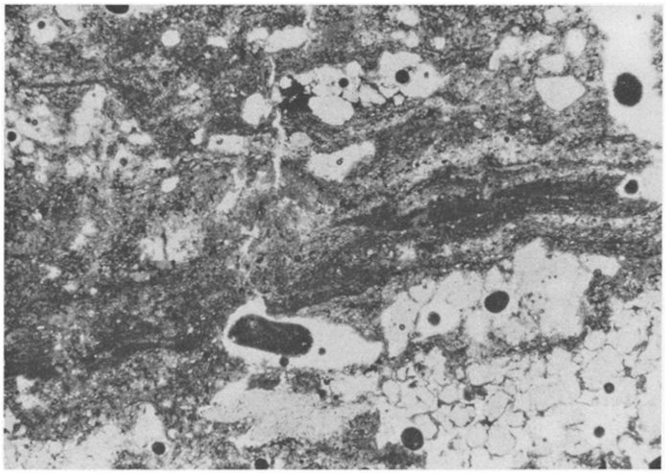


Figure 9. Microphotograph of sample MR-94-17. Note the bedding of the fine grained material in the center of the photograph (Cross polarized light. Field of view is 6.5 mm).

Stratum IV

FIELD DESCRIPTION

Stratum IV is continuous across the site (FIG. 2). The grain size distribution is bimodal (silt/clay and sand). The sedimentation appeared to the excavators to be dominated by sheet wash and attrition processes (Donahue and Adovasio 1990). Both the roof and cliff edge were relatively stable during accumulation of Stratum IV. Cultural associations include firepits, firefloors, flaked and ground stone, aboriginal ceramics, bone, floral remains, and shell (Stuckenrath et al. 1982). The radiocarbon dates span the period from 3050 ± 85 (SI 2049) to 2290 ± 90 b.p. (SI 2051; TABLE 1).

MICROMORPHOLOGY OF STRATUM IV

Eight samples were taken from Stratum IV (TABLES 2, 3; FIG. 2). Samples MR-94-20 to MR-94-25 were collected as a vertical series from a single locale inside the modern dripline. Samples MR-94-16 and MR-94-17 were taken from the same square meter as the others, but laterally adjacent to them. The sediments comprise varying percentages of sand-sized quartz, rock fragments of fine-grained shale and limestone, and micritic grains.

Several factors indicate that sheetwash activity was a significant depositional agent for the sediments that make up Stratum IV. All are clearly bedded, some more extensively than others. Samples MR-94-16 and MR-94-17, in particular, appear to have been subjected to standing water, likely local puddling, with the latter containing a micropan (a thick horizontal coating of silty clay exhibiting graded bedding; FIG. 9). Several samples, including MR-94-24 and MR-94-16 also contain calcium carbonate slaking crusts and hypocoatings, and micropans, all typical indicators of standing water.

Clay coatings are noticeably absent from the lowermost Stratum IV samples (MR-94-16, -17, -23, -24, -25), but some clay coatings are present in samples from the upper portion. These are comprised of dusty clay that is distinct from that found in the underlying strata, however, thus implying a different source or type of deposition.

There is also a larger percentage of calcium carbonate in these samples, as is to be expected within the modern dripline and closer to the rockshelter walls. Eggshell, bone, ashes, and charcoal fragments are also evident in many samples. The presence of charcoal in almost all of the samples accords well with the identification of many firepits and firefloors during excavation. In general, sediments from this stratum contain a noticeably stronger anthropogenic component than was seen in the underlying strata.

Stratum V

FIELD DESCRIPTION

This stratum is continuous across the site (FIG. 2). Inside the modern dripline, the grain size distribution is trimodal (clay, silt, and sand; Beynon and Donahue 1982), while the sediment outside the modern dripline more closely resembles that in Stratum III and IV. Sheetwash was identified as the dominant source of sediments within the dripline with a lesser component of attrition and rock fall from the shelter walls. Cultural remains consist of firepits, firefloors, flaked and ground stone, aboriginal ceramics, bone, floral remains, and shell. The radiocarbon dates from the layer span the period from 2155 ± 65 (SI 2487) to 1665 ± 65 b.p. (SI 3024; TABLE 1).

MICROMORPHOLOGY OF STRATUM V

Only one sample was taken from Stratum V, MR-94-19 (TABLES 2, 3; FIG. 2). The sample comes from inside the modern dripline, and was taken from the same square meter as the samples from Stratum IV. This sediment is, on the whole, very similar to that of Stratum IV, although the bedding is less apparent, suggesting that sheetwash may have been a less significant source of sediments. Dusty clay void coatings are present, but they are very localized. The distribution of broken fragments of charcoal throughout, suggest bioturbation or trampling. This sample exhibits the most numerous indications of cultural activity, containing more charcoal, bone, shell, and eggshell than pre-Stratum V deposits. Visible also is a pink concentration that is likely hematite or ochre. This stratum also contains the first indication of what could be an intact occupation surface, a line of unbroken charcoal (FIG. 10).

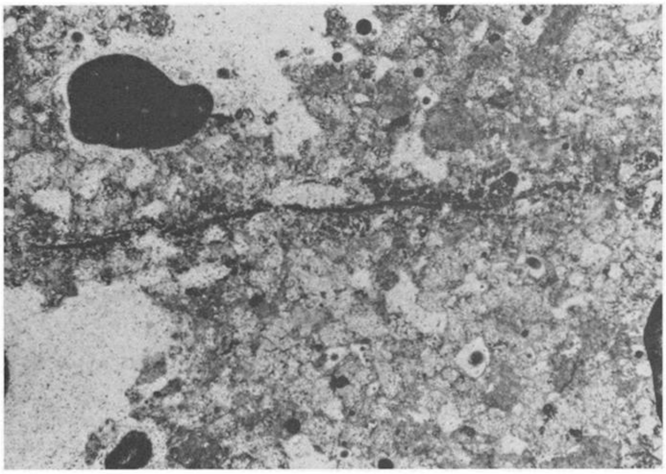


Figure 10. Microphotograph of sample MR-94-19. Broken line of charcoal indicates a possible surface. (Plane polarized light. Field of view is 6.5 mm).

Fluorescence Microscopy

In order to attempt to isolate any particulate or non-particulate organic contamination, the samples were examined under fluorescent light, a technique frequently used in coal petrology (Bustin et al. 1983; Pratt, Comer, and Brassell 1992; Taylor et al. 1998). The method had been previously used at Meadowcroft on a few samples from Stratum IIa and "the results were negative for the presence of coal or coal-associated microflora" (Adovasio, Donahue, and Stuckenrath 1990: 351).

It was thought that an examination of a more complete set of samples from the lower portion of the section and from the bedrock might reveal whether certain organic materials, identified by their fluorescence in the bedrock, would then be visible as isolated particle contaminants within the sediments. Similarly, it was suspected that non-particulate organic matter contamination might be expressed as broadly diffused areas with greater fluorescent intensity (Hutton 1991). Under blue illumination, fluorescence was visible in two samples of organic-rich, Stratum I bedrock that were collected from exposures adjacent to the entrance of the rockshelter, and in the sediment samples. The pattern of fluorescence, however, was different between bedrock and sediments. In the bedrock samples thin, short stringers of amber fluorescent material were scattered throughout. In the sediments, however, fluorescence was restricted mostly to the clay fraction, particularly in the intercalations and void coatings. This material fluoresced with two basic colors, greenish-white and pale red. Calcite, eggshell, secondary calcite and bone also fluoresced, generally as white or yellowish white.

The cause of the clay fluorescence is not obvious nor does this appear to be a subject with a well-developed literature. It could be due either to the presence of organic material within the clay or it may be associated with iron staining of the sediments. The latter appears possible because many areas that appear reddish-brown in polarized light fluoresce more strongly than areas that appear as a lighter brown. The ultimate source of the fluorescence, while interesting, is of secondary importance here. As the fluorescence patterns are consistent throughout the Meadowcroft sediments, they must have had one of two possible sources. They may have been something inherited with the original clay matrix since, in general, the fluorescence intensity follows the bedding of the intercalations and clay coatings. On the other hand, if the fluorescence is due to a post-depositional process, such as groundwater contamination, it affected all the sediments in the Strata I/IIa interface through Stratum V since the fluorescence is uniform throughout. This second scenario is contrary to hypotheses that the effects of groundwater contamination were restricted to the Strata I/IIa interface and Stratum IIa.

Discussion

Our micromorphological analysis has clarified some of the depositional and post-depositional processes operating at Meadowcroft Rockshelter. Some of these processes had already been inferred from field observations, although many of them are more prominent when viewed in thin section.

Depositional Processes

Micromorphology has confirmed the depositional processes identified by the excavators, including attrition and rockfall derived from the shelter walls, and sheetwash from upland surfaces. Rockfall and attrition are clearly recognized—the former by clasts of sandstone and siltstone and the latter by sand- and silt-sized grains. Sheet wash sedimentation is also clearly recognized by the appearance of smaller clasts of shale and limestone and by the well-bedded sediments in Strata III and IV. There is no evidence, however, of flood material derived from Cross Creek, as might be indicated by well-bedded, relatively well-sorted sands or silts. The examination of two samples from the Stratum I/IIa interface, where flood deposits are most likely (Beynon and Donahue 1982) did not reveal any evidence of sorted sands or silts, although this absence may be a consequence of the limited number of samples collected from this stratum.

Although the excavators documented many firepits, firefloors, and other cultural features within Strata II–XI, the anthropogenic component of the sampled strata is minimal at a microscopic level, particularly in the earlier strata. This absence may be due to the small number of samples collected, their distribution, or to the ephemeral nature of the occupation. A more systematic sampling of the features and strata in the future might clarify this question. Interestingly, the Stratum I/IIa interface, identified by the excavators as culturally sterile, did contain eggshell fragments, which could be interpreted as anthropogenic indicators, although they could also be derived from birds roosting along the cliff.

We comment here on some types of processes that have not been clearly noted elsewhere. Principal among these is the accumulation of reddish-brown clay as intercalations within joints and fissures and occasionally localized in large voids. Such clay accumulations are typically ascribed to soil forming processes, although this is certainly not the case here where they occur throughout 3 m of sediment. Moreover, they are not confined to simple vughs or voids, but more generally to larger scale features, such as chambers and fissures. In other words, the evidence points to the translocation of clay through larger voids and features rather than through smaller ones as occurs in typical soil-forming processes. The clay intercalations seen at Meadowcroft are typically found in sediments outside of the paleodripline and are virtually non-existent in samples from within the paleodripline. This distribution implies a link among clay accumulation, sediment, and water sources. The changes in the color and texture of the clay features are more suggestive of changes in the source of clay and the energy level of the depositional process. This accords well with a model of a changing rockshelter configuration.

Another feature that is relatively striking in thin section is the distribution of calcium carbonate. Stuckenrath et al. (1982) noted that sediments outside of the modern dripline tended to be relatively deficient in calcium carbonate compared to those from the interior. Our micromorphological analysis has confirmed this, but has revealed a more complicated picture. The majority of calcium carbonate is depositional, not post-depositional, in origin, and is tied to the presence of calcite-cemented quartz sandstone. We have also noted the presence of other calcareous elements, such as eggshell in sediments from within the modern dripline. Although the lack of eggshell in samples from outside of the dripline might be attributed to differences in activity by humans or nesting birds, the general absence of carbonate outside of the modern dripline indicates that there is a difference in the preservation of calcium carbonate and not simply in its deposition. We do note the presence of some secondary calcite in the form of hypocoatings (for example MR-94-16 and -17), but these are only minor. These microscopic features indicate that some or all of the dissolution has occurred fairly recently, since the retreat of the dripline to its present position. What is significant here is the importance of these processes in the preservation of not only eggshell, but also shells, wood ash, and other calcareous material of cultural origin.

Post-Depositional Processes

Other than secondary carbonate precipitation and dissolution, there is little evidence of post-depositional processes. The physical post-depositional features are very limited, although some of the observed vughs may be due to modern root activity. We do note the presence of iron/manganese concentrations and of depletion features, but these are rare.

Most significantly in terms of the Meadowcroft dating controversy, we see no evidence of the effects of groundwater saturation of the sediments, nor was particulate coal material visible in any sample. Had groundwater penetrated any or all of the strata it would have moved through the void system, and we would have expected to see some evidence of its effects, such as extensive gleying of the sediments or elutriation of the fine-grained material within the sediments and around the voids in particular (Bullock et al. 1985). These indicators are not invariably created by groundwater saturation, but expectation of their presence is highly reasonable, and relic hydromorphic features have been identified elsewhere (Vepraskas 1995; Vepraskas and Guertal 1992). The only two hypotheses that can explain this observation are 1) there was no groundwater saturation; or 2) the sediments were saturated by groundwater that deposited non-particulate contamination, but had no other effect on the sediments. It is logically impossible to prove a negative, but we see no evidence of groundwater saturation of any strata, nor do we see evidence of any other mechanisms by which particulate or non-particulate contamination could have been introduced into the sediments in general and into the charcoal samples in particular.

We have no explanation at this point for the presence of older humates in two of the charcoal samples from Stratum II (SI 2488 and SI 2354) as discussed in Haynes (1991) and Adovasio et al (1998). Observation of the thin sections in ultraviolet light revealed no extraordinary fluorescence that could be interpreted as humate or coal particulate contamination. The humates may have been introduced before the charcoal was deposited or, less likely, they may have been absorbed by the charcoal from surface runoff while the charcoal was exposed at the surface. Similarly, we cannot comment on the problems of removing such humates or other contaminants from charcoal samples.

Conclusion

This micromorphological study has accomplished three objectives. First, it has substantiated the site formation history proposed by the excavators, and has clearly documented certain depositional and post-depositional processes that had been less emphasized in the past. These include the syndeposition of fine reddish-brown clay as intercalations, the occurrence and distribution of calcareous elements such as eggshell, and the differential preservation of these elements, *viz.* their position with respect to the dripline. Second, it has cast reasonable doubt on the hypothesis of groundwater contamination of the sediments, as no signs of groundwater activity could be seen in any of the samples studied. Thus, we see no micromorphological reason to reject the published dates. Finally, this study has demonstrated the value of micromorphology as a technique for addressing geoarchaeological questions that can not be satisfactorily addressed by more conventional techniques.

Although the fluorescence results were inconclusive, fluorescent microscopy would seem to be a fruitful avenue for future research, provided systematic samples and reference samples are available. Such research might include more detailed sampling of different bedrock lithologies (including the "mung" deposits), modern soils forming on the surfaces above the rockshelter, and modern sediments situated near seeps. Such a strategy may help to further address the concerns raised by the radiocarbon dates.

Acknowledgments

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