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CLASTIC SEDIMENTS IN THE BUTLER CAVE – SINKING CREEK SYSTEM, VIRGINIA, USA

KLASTIČNI SEDIMENTI JAMSKEGA SISTEMA BUTLER – SINKING CREEK, VIRGINIJA, ZDA

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Abstract UDC 552.51:551.44(75)

Daniel L. Chess, Catherine A. Chess, Ira D. Sasowsky, Victor A. Schmidt & William B. White: Clastic sediments in the Butler Cave-Sinking Creek System, Virginia, USA.

The Butler Cave - Sinking Creek System in Bath County, Virginia, consists of a master trunk passage along the axis of a syncline with a trellis arrangement of dip-oriented side caves. The western set of dip passages contain a sequence of massively and chaotically bedded sand and cobble sediments. Massive cobble fills also occur in the strike-oriented trunk passage. Cave passages on the eastern side of the syncline contain mostly sand and silt. The light fraction of the sediments consists predominantly of quartz and rock fragments. The sediments contain several percent heavy minerals composed of iron oxides, zircon, rutile, tourmaline and other minerals. Measurement of the visible and near infrared diffuse reflectance spectra shows at least three populations of sediments to be present: an iron-rich, clay-poor group; a clay-rich group; and a gypsiferous sediment. The iron minerals provided a paleomagnetic signal. Sediments from the trunk passage, deposited by recent underground drainage, contained a normal pole direction. Sediments from the dip passages were paleomagnetically reversed, showing the deposition dates from prior to 780,000 years. In one instance reversed polarity deposits overlie normal polarity, implying a minimum age of 990,000 years for the reversed sediments.

Keywords: Butler Cave, Burnsville Cove, Clastic Sediments, Heavy Minerals, Sediment Spectra, Paleomagnetism.

Izvleček UDK 552.51:551.44(75)

Daniel L. Chess, Catherine A. Chess, Ira D. Sasowsky, Victor A. Schmidt & William B. White: Klastični sedimenti jamskega sistema Butler – Sinking Creek, Virginija, ZDA

Jamski sistem Butler - Sinking Creek v okrožju Bath, Virginija, ZDA sestavljajo glavni rov, usmerjen po osi sinklinale, in mreža stranskih rovov, usmerjenih po vpadu plasti. Zahodni niz stranskih rovov vsebuje sekvence masivnega in neenakomerno plastovitega peščenega in prodnatega sedimenta. Masivna prodnata zapolnitev se pojavi tudi v glavnem rovu. Jamski rovi na vzhodni strani sinklinale vsebujejo predvsem pesek in melj. Lahko frakcijo sedimentov pretežno sestavljajo kremen in delčki kamnine. Sedimenti vsebujejo več odstotkov težkih mineralov kot so: železovi oksidi, cirkon, rutil, turmalin in drugi minerali. Merjenje vidnega in skoraj infrardečega difuznega odbojnega spektra kaže prisotnost vsaj treh populacij sedimenta: skupino bogato z železovimi minerali in revno z glino; skupino bogato z glino in skupino bogato s sadro in železovimi minerali. Železovi minerali so nosilci paleomagnetnega signala. Sedimenti iz stranskih rovov so bili paleomagnetno reverzni in kažejo na odlaganje pred 780.000 leti. V enem primeru reverzno polarizirani sedimenti ležijo na normalnih, kar pomeni najnižjo možno starost reverznih sedimentov, 990.000 let.

Ključne besede: jama Butler, Burnsville Cove, klastični sedimenti, težki minerali, spekter sedimentov, paleomagnetizem.

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INTRODUCTION

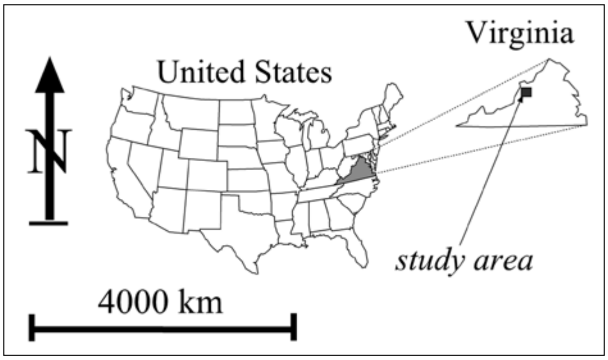


Fig. 1: Location map for Burnsville Cove, Virginia, USA.

The Butler Cave - Sinking Creek System is located in Burnsville Cove, Bath and Highland Counties, in west-central Virginia within the Appalachian Mountains (Fig. 1). The valley of Burnsville Cove is oriented northeast-southwest following the general trend of the folded Appalachians. The master stream in the valley, usually dry, is Sinking Creek which drains northeast as a tributary to the Bullpasture River. The Bullpasture River is a headwater tributary of the James River, part of the Atlantic slope drainage. Burnsville Cove is bounded on the southeast by Tower Hill Mountain and on the northwest by Jack Mountain, both underlain by Silurian shales and sandstones. The major structures in Burnsville Cove consist of two synclines with an intermediate anticline that forms the secondary topographic high known as Chestnut Ridge. In detail, the structure is much more complex. The valley itself is underlain by upper Silurian and lower Devonian carbonate rocks which support an extensive surface karst as well as a series of significant caves. The Butler

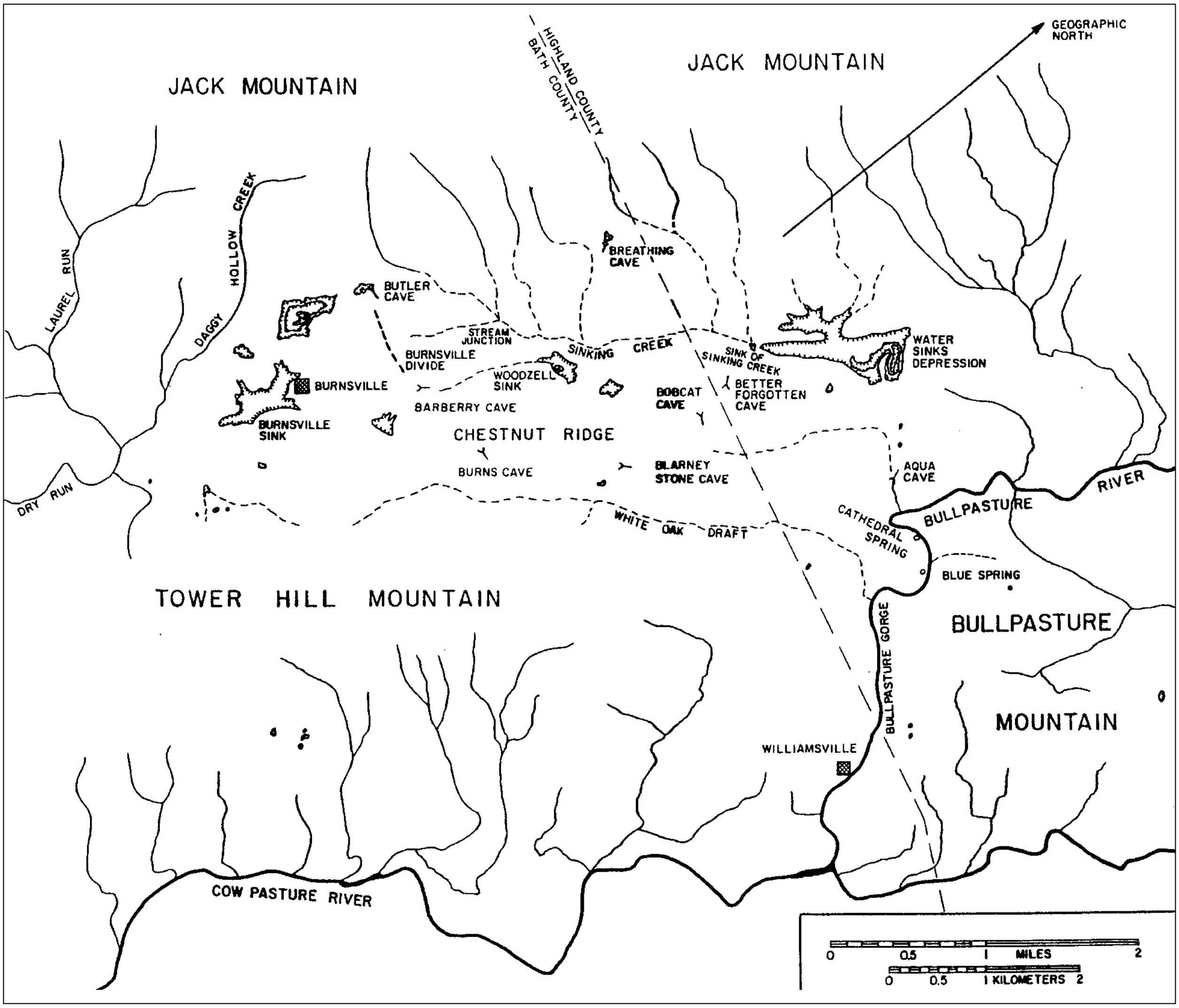


Fig. 2: Map of Burnsville Cove derived from U.S. Geological Survey Staunton 1:100,000 topographic map.

Cave - Sinking Creek System, located mainly below and to the west of the Sinking Creek Valley, and the Chestnut Ridge Cave System beneath Chestnut Ridge, are the largest at 25.8 and 31.0 km respectively. There are many other caves in the Cove, some in the length range of a few km. The structure axes plunge to the northeast, carrying the carbonate rocks beneath the overlying clastics before the Cove opens into the valley of the Bullpasture River.

The topography of Burnsville Cove is shown on U.S. Geological Survey Burnsville and Williamsville 7.5 minute quadrangles. The general layout of the topography and the cave entrances are shown in Fig. 2. There is a geologic map for the Williamsville 15 minute quadrangle (Bick 1962) that shows the broad outline of the geology but with little detail. The carbonate rocks that underlie Burnsville Cove belong to a Silurian-Devonian sequence that extends hundreds of kilometers to the northeast. The carbonate units change in detail and there are clastic interbeds in some localities. Fig. 3 presents a stratigraphic column with some of the commonly used nomenclature. Previous studies of the caves of Burnsville Cove include the exploration (Wefer & Nicholson 1982), geology (Deike 1960; White & Hess 1982), hydrology (Davis & Hess 1982) and more recently an interpretation of the geologic evolution of the caves (Schwartz & Doctor 2009).

It has been argued (White & Hess 1982; White & White 1991; Schwartz & Doctor 2009) that the Burnsville Cove caves are very old and contain the imprints of the many climatic changes and drainage rearrangements that have taken place since the Pliocene. One of these imprints is the complex suite of clastic sediments that occur in the cave systems. The objective of the present paper is to describe the cave sediments, specifically of Butler Cave, in some detail and to interpret, as far as possible, the circumstances of their emplacement.

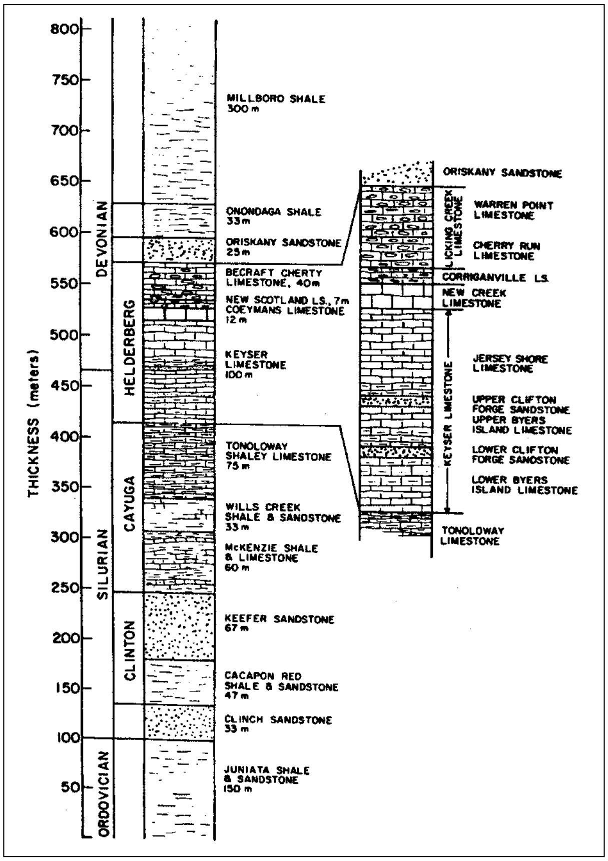


Fig. 3: Stratigraphic column for the Silurian and Devonian rocks of Burnsville Cove. There are some differences in the names of subdivisions of the rock units between various investigators. Column from White and Hess (1982).

THE BUTLER CAVE - SINKING CREEK SYSTEM

The exploration and physical description of the Butler Cave – Sinking Creek System has been presented by Wefer and Nicholson (1982). A line map for the entire system is shown in Fig. 4. The main axis of the cave is a trunk passage that more or less follows the axis of the Sinking Creek Syncline. The upstream (southwest) end of the trunk splays into a network of infeeders that lie close to a large catchment basin on the surface known as the Burnsville Depression. To the northwest of the trunk passage are a series of side caves. These are mainly network mazes oriented along joint sets on the flank of the syncline. All of them slope toward the trunk passage at about the angle of the dip which locally is 8–10°. In order, moving in the down stream direction, these are known as Huntley's Cave, the Pennsylvania Section, Butler Cave proper, the Moon Room Section, and Pat's Section. Butler Cave connects with the trunk passage at Sand Canyon, an important junction for discussion of the cave sediments. Because Butler Cave is the main focus for the present study, a detailed map is given in Fig. 5. Further downstream, near the mid-reaches of the trunk passage, there are no side passages. However, in the downstream section, the cave again develops into a network maze pattern. Breathing Cave, an independent large network maze cave, also lies on the northwest flank of the syncline (Deike 1960). Hydrologically, Breathing Cave is appar-

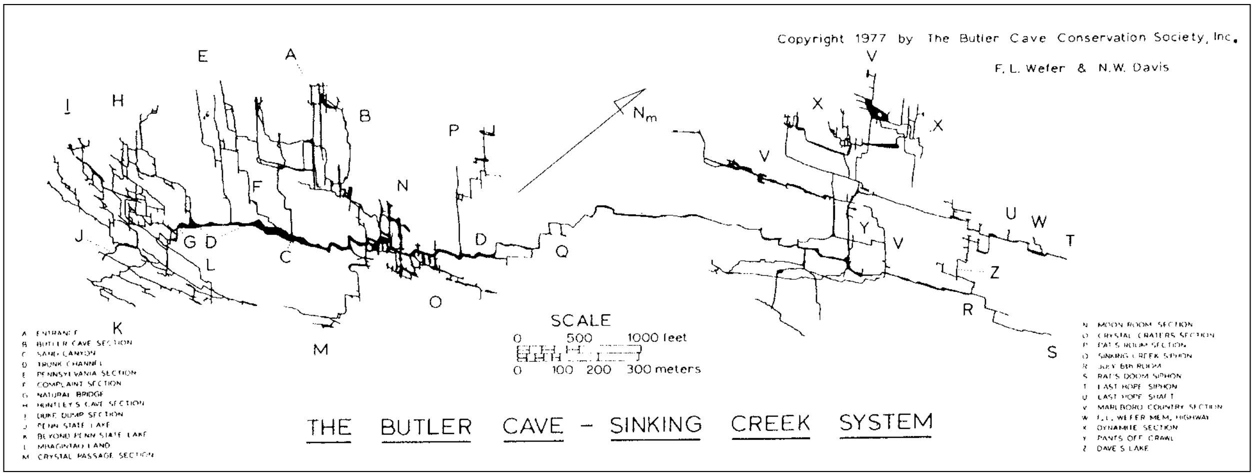


Fig. 4: Line map of the entire Butler Cave - Sinking Creek System. Map courtesy of the Butler Cave Conservation Society.

ently another side cave which drains into the main trunk somewhere downstream from the terminal sumps. The down-dip ends of its many dip passages are blocked by sediment plugs.

All of the side caves receive recharge from the flanks of Jack Mountain on their up-dip sides. Some of these infeeders are observable in the cave as, for example, Rotten Rocks Creek in Butler Cave, and the Huntley's Cave stream. None, however, currently has a humanly enterable surface opening. As such, most flow into the cave is somewhat restricted at present. The drainage in the trunk passage is disjointed. The upstream portion has a well developed channel which carries flood flow but which is dry during low flow periods. The tributary infeeders connect to the trunk drain through unobserved and/or flooded passages that have developed below the master trunk. Sinking Creek enters the trunk passage near the Crystal Passage (Fig. 6) and flows along the main trunk for about 500 meters until it is lost at the Sinking Creek Sump. Another 500 meters downstream, Sneaky Creek enters through the roof of the trunk passage. Slippery Creek is a third stream which enters from a series of infeeders in the downstream section. Sneaky Creek is lost at the Rats Doom sump and Slippery Creek at the Lost Hope sump. All streams in the cave reappear at Lockridge Aqua Cave near the Bullpasture Gorge, four km to the northeast of the terminal sumps. Exploration by divers reveals that the springs are fed from deep phreatic conduits that extend at least 50 meters below present day base level.

The hydrology of the cave is further complicated by the presence of two tongues of the Clifton Forge Sandstone which separate the limestones into three distinct units (Fig. 3). Butler Cave and the section of trunk passage at Sand Canyon lie below the lower sandstone. The maze passages at the upstream end of the trunk also lie below the lower sandstone. However, above the upstream trunk there is a tier of cave, known as Mbagintao Land, that lies between the sandstones. The trunk pas-

Fig. 6: The active stream of Sinking Creek where it enters the much larger master trunk passage. Note manganese oxide-coated cobbles that make up the stream bed (Photo: W. B. White).

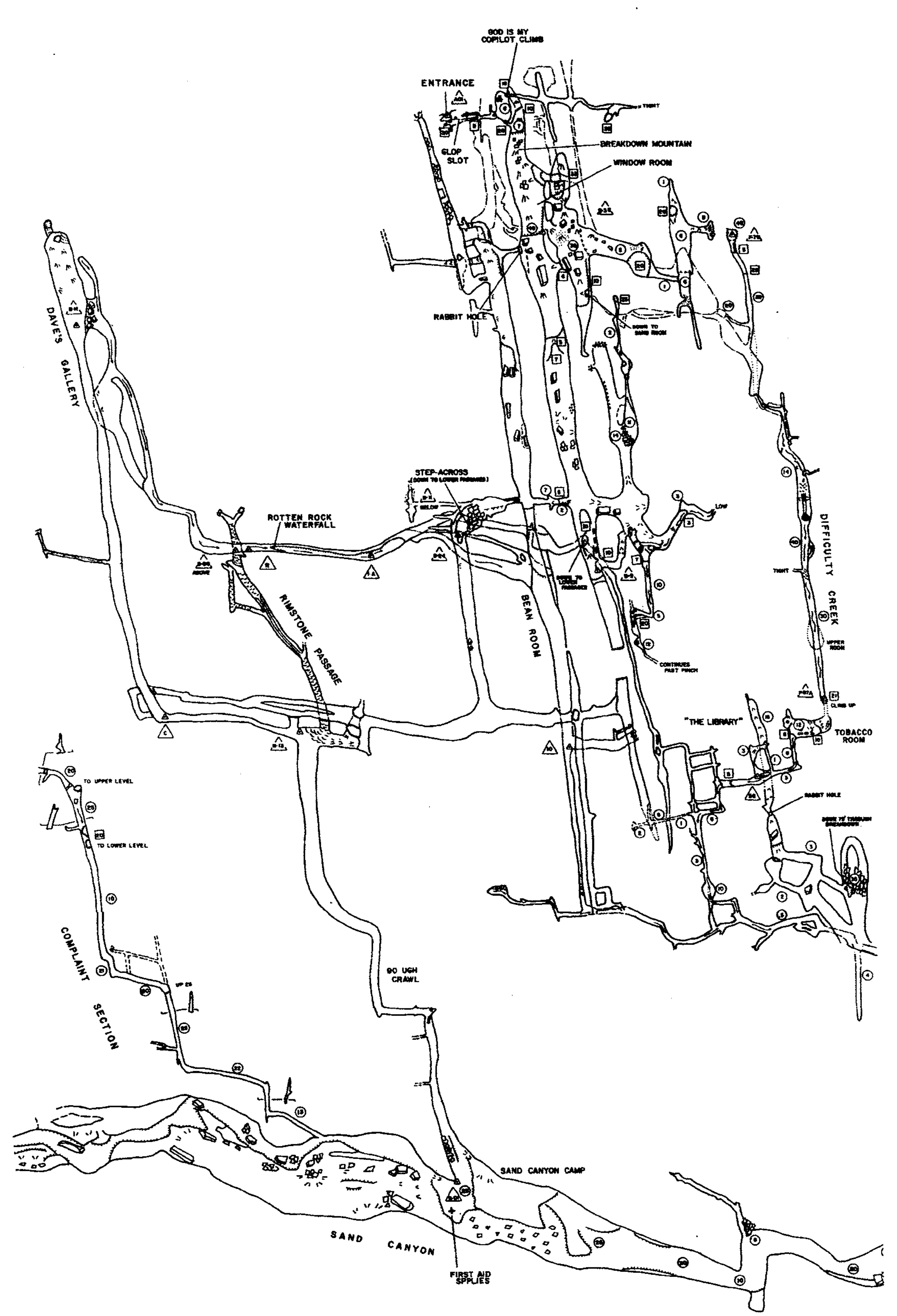


Fig. 5: Detailed map of the Butler Cave portion of the system. Map courtesy of the Butler Cave Conservation Society.

sage breaches the lower sandstone at the Dry Sumps so that the downstream section of the trunk is developed between the sandstones, the same stratigraphic horizon as Breathing Cave. The Rats Doom and Last Hope sumps are both perched on the lower sandstone. Below the lower sandstone in the downstream section is Marlboro County, and extensive section of cave with its own streams and sumps.

PHYSICAL PROPERTIES OF THE CAVE SEDIMENTS

DESCRIPTION OF CAVE DEPOSITS

In broad terms, the Butler sediments consist of breakdown, calcite and gypsum speleothems, and fluvial sequences of various kinds. A description of the speleothems was given by White (1982). In the present investigation we are interested only in the fluvial component. The water-transported sediments consist mostly of silt, sand, pebbles and cobbles with a wide range of particle sizes and degrees of sorting. The fine-grained fraction consists almost entirely of quartz while there is a mix of sandstone and limestone fragments in the large-grained fraction. Discussion of transported detrital sediments in caves in terms of their individual strata has not proved to be useful. The facies concept is more helpful. There is no generally agreed-upon nomenclature for clastic sediment facies although various investigators (e.g., Gillieson 1986; Springer & Kite 1997) have proposed useful terms. The classification used here is based on grain size and sorting (Fig. 7).

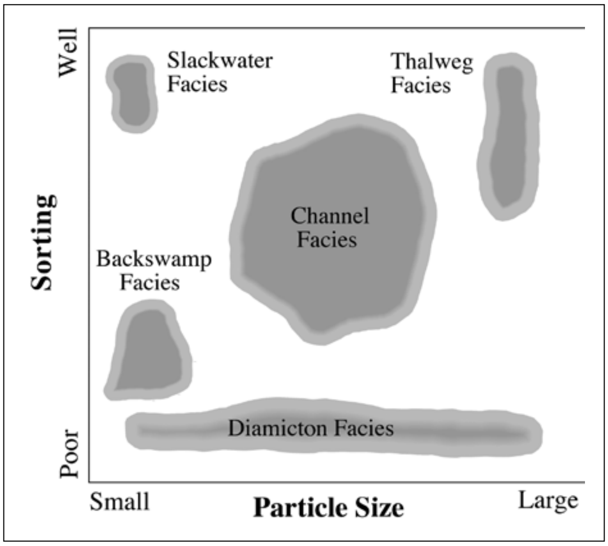


Fig. 7: Sketch showing cave sediment facies as a function of grain size and degree of sorting. In reality, these fields overlap and do not have sharp boundaries. Adapted from Bosch and White (2004).

Definitions for the facies sketched in cartoon fashion in Fig. 7 are:

(i) Slackwater facies: Fine-grained clays and silts that have settled out of muddy flood waters. Often these show a fine layering or varving. Usually they occur at the top of sediment piles.

(ii) Channel or Bank facies: Interbedded sands, silts, possibly with pebbles. Some stratification with substantial sorting between layers. These are most clearly stream deposits that, although stratified, show rapid changes in statification over short horizontal distances.

(iii) Thalweg facies: Well-winnowed gravel, cobbles and sometimes boulders with most fine-grained material removed. These are stream bed deposits not particularly different from similar deposits in surface streams.

(iv) Diamicton facies: Chaotic, unsorted mélange of silt, sand, pebbles and cobbles. Little or no stratification. Diamicton facies are the remnants of debris flows. They were originally described for high gradient caves in New Guinea (Gillieson 1986).

(v) Backswamp facies: Uncommon in Butler Cave, these are usually fine-grained, poorly stratified muds and silts that accumulate as the insoluble fraction of the limestone. This facies shows little evidence of transport and the caves in which they are found usually have little evidence of stream action. Backswamp facies differ from slackwater facies in that they are bulk deposits with little or no layering.

Sediments of the thalweg facies are found in the normally dry stream channel from Penn State Lake down to the Sinking Creek Sump. The channel bed is floored with a well-winnowed assortment of cobbles (Fig. 8). Some "grains" are in the boulder size range. Both limestone and sandstone boulders occur (Fig. 9). The sandstone can be recognized by its coating of black manganese oxides. The Trunk Channel in this reach is a spillover route used only by floods of sufficient magnitude to exceed the carrying capacity of the lower (but unidentified) route of Sinking Creek. The source of the sandstone must be Jack Mountain. Flood flows must have sufficient energy to move these boulders down into the cave and then transport them along the relatively low-gradient trunk passage for distances on the order of 1,000 meters. The most extreme example of boulder transport in the system was an accumulation of sandstone boulders almost two meters in diameter that had apparently been forced up the lift tube at the drainage outlet in Lockridge Aqua Cave (Fig. 13 in Palmer & Palmer 2005).

Fig. 8: Thalweg facies. Typical well-winnowed cobble fill in channel of trunk stream (Photo: W. B. White).

Fig. 9: Thalweg facies. Mixed sandstone and limestone boulders in the normally dry stream channel near Sand Canyon (Photo: W. B. White).

Fig. 10: Channel facies exposed by stream down-cutting in the master trunk during the excavation phase (Photo: W. B. White).

Fig. 11: Close-up of channel facies shown in Fig. 9: Bedded sand overlying unsorted and unstratified cobble deposit (Photo: W. B. White).

Fig. 12: Residual column of cobble fill on a breakdown block in the main trunk channel downstream from Sand Canyon (Photo: W. B. White).

Fig. 13: Diamicton facies. unsorted and unstratified chaotic mix of sandstone material of all grain sizes plastered into a wall pocket in Dave's Galley (Photo: W. B. White).

Channel facies occur in many places in the cave but are best displayed 100 meters downstream from Sand Canyon. A deep sediment infilling has been cut by later stream action exposing interbedded sand and gravel

(Figs. 10, 11). Evidence that the channel was filled with sediment that was later excavated is provided by a column of sediment remaining on top of a large breakdown block (Fig. 12). There is a large range in particle size but substantial sorting and stratification.

Most remarkable of the Butler sediments are the diamicton facies. These are unsorted and unstratified mixtures of sand, pebbles, and cobbles. These seem to have infilled all of the side caves on the western side of the system. Masses of this sediment occur in pockets along Dave's Gallery (Fig. 13). Similar fills have been described in Breathing Cave (Deike 1960). Diamicton facies implies a debris flow and recent work in other caves has documented that these materials can be rapidly transported and emplaced (Van Gundy & White 2009). It is not obvious whether the sediment-filled pockets were left behind as the debris swept past or whether they are remnants of a passage infilling that was later excavated. The debris flow sediments are observed mainly in the high gradient dip passages.

Slackwater facies are found in many parts of the cave but occur only as a thin layer of clay and silt overlying much coarser clastic material. In the side caves, the slackwater facies sediments are coated with an extremely thin layer of black material thought to be manganese oxides. The absence of substantial slackwater facies development may be evidence that, in spite of extensive floodwater action, ponded, muddy floodwater is relatively uncommon. The caves appear to have drained rapidly during and following flood events with little evidence of ponding.

PARTICLE SIZE DISTRIBUTIONS

Thirty two samples of cave sediments were collected from various locations throughout the southern (upstream) and mid-sections of the cave. Sample locations chosen were from the major passages within the cave and in some cases several sediment samples were taken from the same passage. It was intended that these samples would represent the different sediment facies and perhaps different ages of deposition. The discriminating factor used in sample selection was "low and wet" versus "high and dry" locations. The sources included areas lower in the cave known to be the recent depositional environments as expressed by active streams and seeps and higher, drier areas which should be older and removed from present day stream action.

Particle size distributions were determined by sieve analysis for a selection of upper and base level sediments (Fig. 14A, B). The base level materials are much more variable than the high level material. A few base level sediments appear to be well sorted, while several show a bimodal distribution.

HEAVY MINERALS

The bulk of the fluvial sediment is made up of quartz in the form of silt, sand, and sandstone rock fragments, clay minerals, some feldspar, and, of course, calcite from limestone rock fragments although these tend to be removed by dissolution. However, in addition to these relatively low density materials, most sediments also contain a suite of minerals of relatively high density, usually in minor amounts. These are the "heavy minerals" which can be extracted by heavy liquid separation.

The heavy liquid of choice was tetrabromoethane, which has a density of 2.96 g cm^{-3}. Quartz, clays, and other silicate minerals will float in it while the heavy minerals will sink. Approximately 500 grams of cave sediment were air-dried and then mixed with tetrabromoethane in a separatory flask. The heavier material settled and was drawn off the bottom, washed with acetone, air dried, and inspected under 25X magnification in a polarized light microscope. Minerals were identified by their optical characteristics.

The results are given in Tab. 1. The relative abundances of the heavy minerals were determined semiquantitatively. The suites of heavy minerals are similar for both upper level and lower level materials. All samples contained a larger fraction of opaque minerals than transparent minerals. The base level samples showed a substantial increase in tourmaline, rutile, and zircon. These minerals are very stable and highly resistant to abrasion and weathering. There are nearly twice as many heavy minerals in the base level sediments than in the upper level sediments.

DIFFUSE REFLECTANCE SPECTRA

Clastic sediments in caves are usually colored various shades of yellow to brown due to hydrated iron oxides and also to humic substances derived from overlying soils. Although the colors can be expressed semiquantitatively on the Munsell color scale, it is difficult to relate these values to other measurements or to the pigmenting minerals within the sediment. An alternative approach is to measure the optical absorption spectra of the sediments by diffuse reflectance spectroscopy, a technique that can be applied to particulate specimens such as the unconsolidated cave sediments (White 1977). This technique has the further advantage that it can be extended into the near-infrared region of the spectrum where additional information may be found.

Samples were collected in 250 mL polyethylene bottles and dried to laboratory ambient conditions. Five to ten grams of each sample were reduced to single grain-size powders in an agate mortar. Care was taken to just separate the agglomerated clumps and not to crush the separated mineral particles. The samples were packed

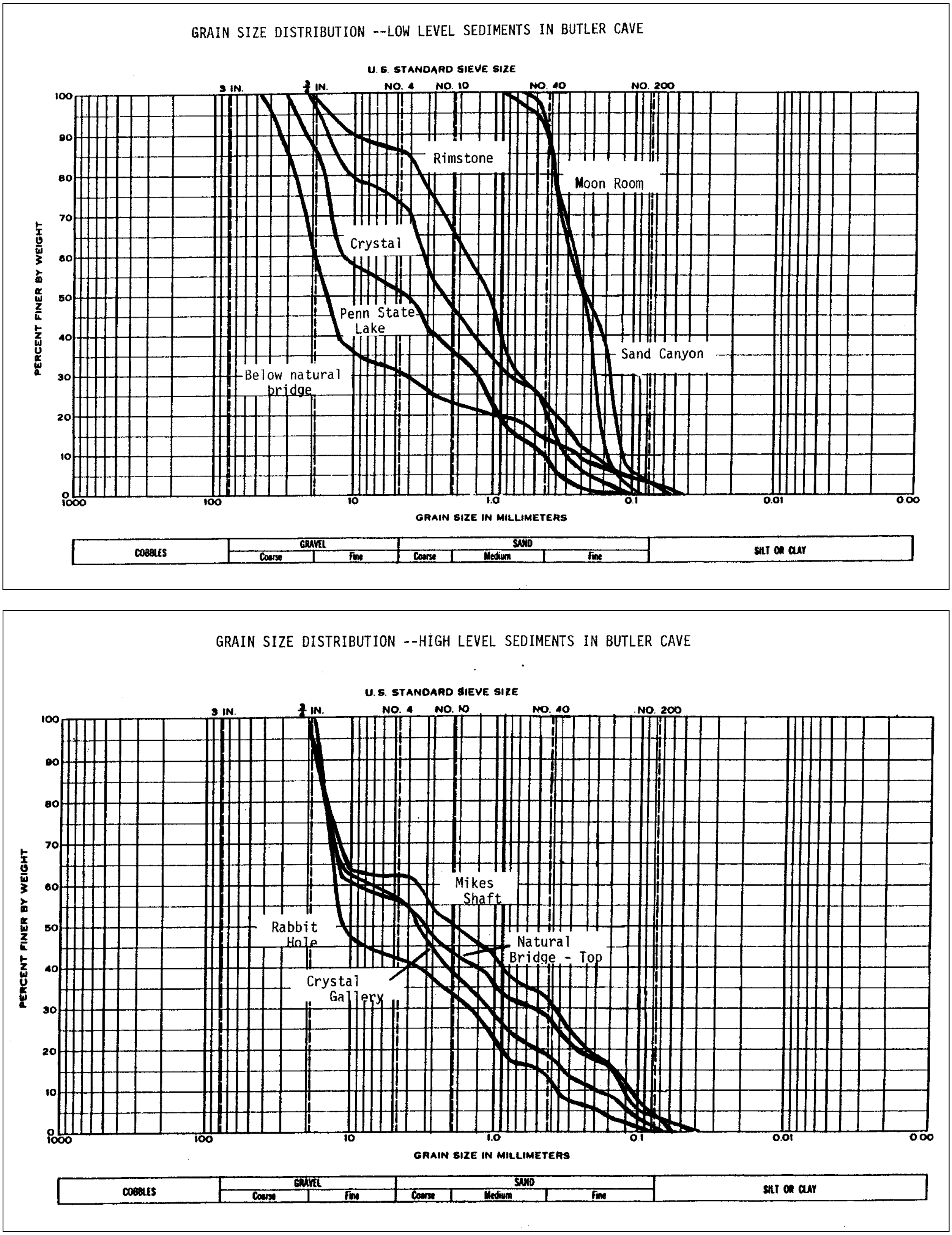


Fig. 14: Grain size distributions for various Butler Cave sediments. Sample locations are labeled on the curves. (A) Lower level sediments. (B) Upper level sediments.

Tab. 1: Heavy mineral assemblages from sediments in Butler Cave.

Location	*Goethite*	*Leucoxene**	*Chromite*	*Zircon*	*Tourmaline*	*Rutile*	*Brookite*	*Anatase*	*Garnet*	*% Heavy*
Upper Cave										
Top Natural Bridge	4	2	1	1	1	1	1	-	1	0.88
Rabbit Hole	5	2	1	1	1	1	1	-	-	4.08
Mike's Shaft	5	1	1	1	1	1	1	-	-	0.25
Lower Cave										
Penn State Lake	4	2	1	1	-	1	1	1	-	3.30
Moon Room	5	2	1	2	2	1	1	-	-	0.90
Sand Canyon	3	1	1	3	1	2	1	1	1	1.10
Crystal Passage	4	2	1	1	-	1	1	-	1	8.90
Below Sand Canyon	4	1	1	2	2	2	1	-	-	2.70
Below Natural Bridge	5	1	1	2	1	1	1	1	-	5.19

** Name applied to an alteration product of illite.*

5: more than 80% of the heavy fraction
4: 50-80%
3: 20-50%
2: 5-20%
1: less than 5%

into a 2-cm diameter, 0.3 cm-deep aluminum plaques. The loose powder samples were wetted with carbon tetrachloride and flattened with a stainless steel spatula to produce a flat matte surface for reflectance measurement. The wetting agent was allowed to evaporate before measurements were made.

All spectra were obtained using a Beckman model DK-2A spectrophotometer with an integrating sphere diffuse reflectance attachment. Kodak $BaSO_4$ optical paint was used as a white reference standard. Spectra were measured from 2,500 to 500 nm using a PbS solid state detector and through the region from 700–350 nm using a photomultiplier detector. In all cases the instrument scale was adjusted to 100% reflectance when the $BaSO_4$ reference material was in both beams.

Typical spectra are shown in Fig. 15. The characteristic features are a broad band at 900 nm and three relatively sharp bands at 1,400, 1,900, and 2,300 nm. The 900 nm band is an electronic transition of Fe^{3+} in the crystallographic host of goethite, FeOOH, or ferrihydrite, $Fe(OH)_3$ and thus is a measure of the concentration of iron stains on the sediment grains. The three

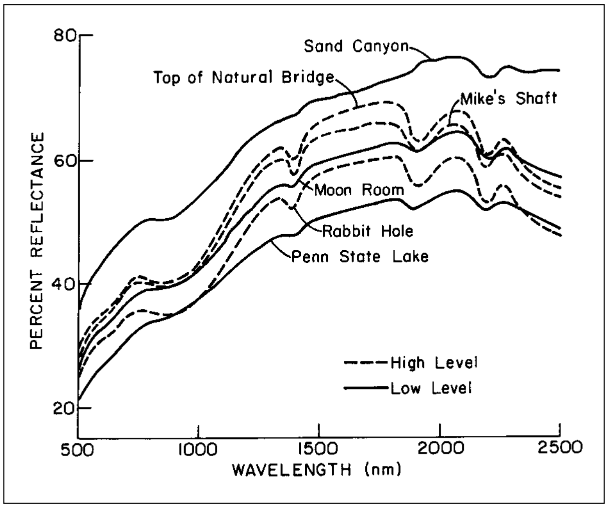


Fig. 15: Visible-near infrared spectra of a selection of Butler Cave sediments.

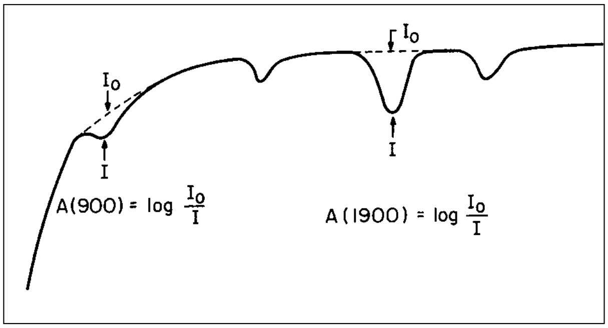


Fig. 16: Sketch showing extraction of absorbance of iron and water bands from diffuse reflectance spectra.

sharp bands are vibrational overtones of water or hydroxyl groups. Of these, the 1,900 nm band is the most intense and can be used as a measure of the concentration of hydrated phases in the sediments. Concentration is proportional to absorbance, not reflectance, so that band absorbance must be extracted from the reflectance curves by taking account of the overall background, as indicated in Fig. 16.

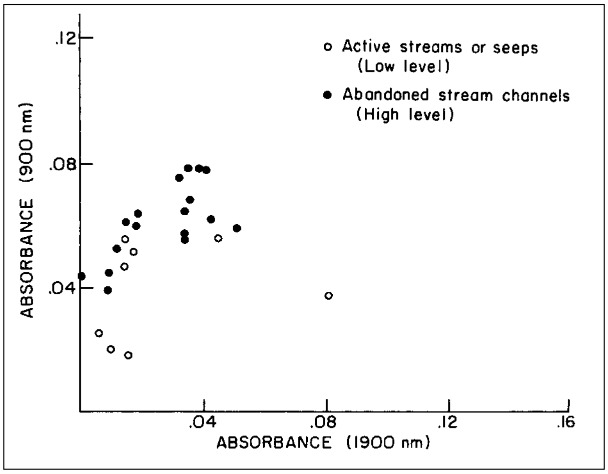


Fig. 17: Plot of absorbance of the 900 nm band, a measure of iron concentration, with absorbance of the 1900 band, a measure of the concentration of hydrated phases.

The 900 nm absorbance was plotted against the 1,900 nm absorbance for each sample (Fig. 17). The values for the lower level sediments clustered near the bottom of the plot while the higher level sediments clustered higher. Four samples labeled on the graph are of interest. The Huntley's Cave sample is 20–30% gypsum and as a result, plots in the high hydroxyl area. The cave entrance sample is exposed directly to surface atmospheric influence and cannot be considered to have the same ambient environment as the remainder of the cave samples. The Dave's Galley sample was taken from a seep in the cave that is directly linked to a sinkhole drain and surface soils can be considered a direct source for this sample. Penn State Lake also has a direct surface water link and can be considered derived from surface soil.

The color brown is represented spectroscopically as an absorption edge in the visible region of the spectrum (Fig. 18). The human eye is very sensitive to subtle changes in color so that shades of brown easily visible to the eye appear in the spectra only as small shifts in the shape and overall slope of the absorption edge. The absorption edge is due to intense electronic transitions in ferric iron but the variation is caused by details in the degree of hydration of the iron oxides and by details of their structure. One way to display the variations in the shape of the absorption edge, in contrast to its absolute intensity, is to compare absorbance in the blue $(A4_{50})$/absorbance in the red (A_{600}) to absorbance in the green (A_{525})/absorbance in the red (A_{600}). The results are shown

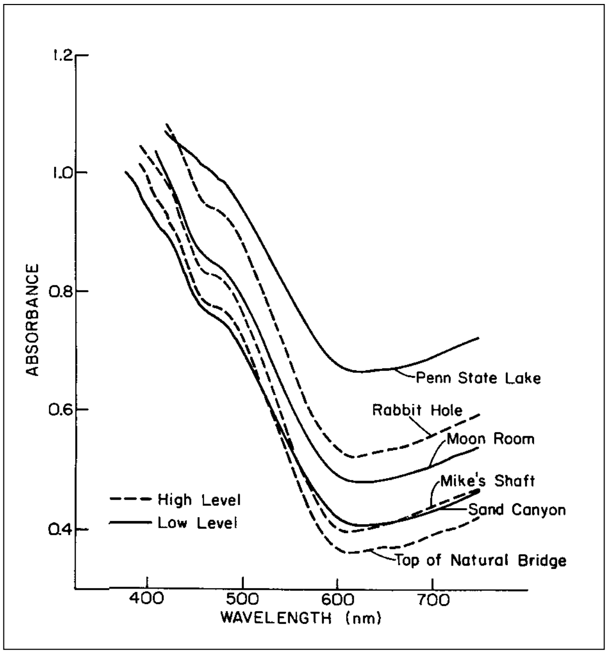


Fig. 18: Absorption edge for cave samples.

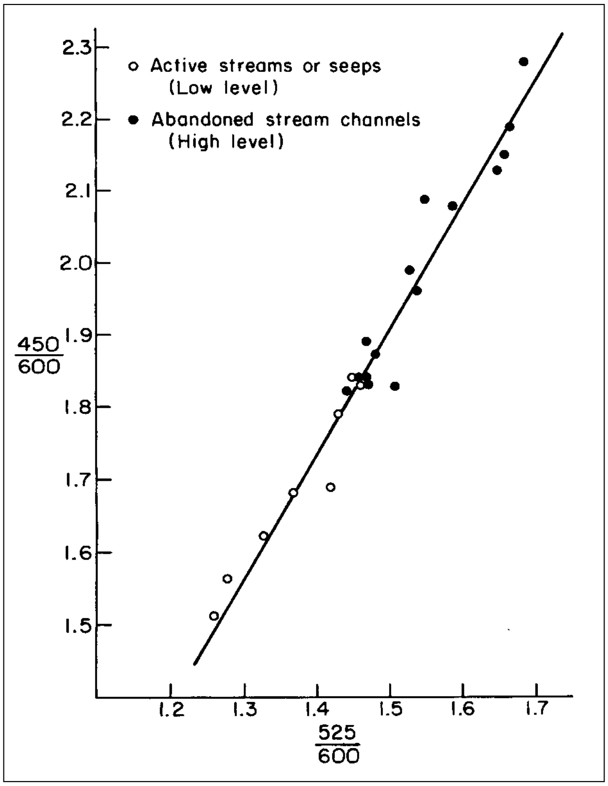
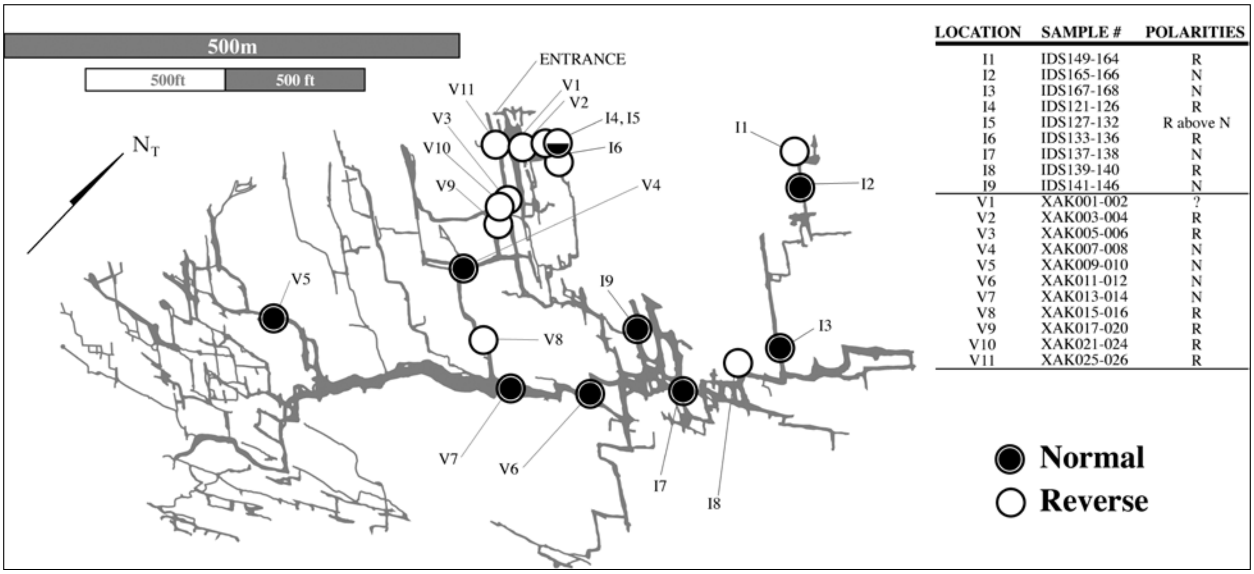


Fig. 19: Color ratios for cave samples.

in Fig. 19. The observation that the color ratios for all samples plot on the same straight line is an indication that all sediments, regardless of age or location in the cave, come from essentially the same source.

SEDIMENT EMPLACEMENT

The massive cobble fills occupy most of the dip passages on the western side of the trunk passage. Indeed, many of the dip passages both in Butler Cave and in Breathing Cave are completely choked by this material at their downstream termini. There are clastic fills in the few dip passages that extend up the eastern side of the syncline into Chestnut Ridge, but these are mainly sand and silt such as might have been derived from the Oriskany Sandstone. Most of the recent history of the cave has been one of excavation so that the best exposure of the older fills is in the channels cut by later excavation. Likewise, the boulders and cobbles of the thalweg facies found in the active stream channels is likely derived from reworking and winnowing of the older fills.



LOCATION	SAMPLE #	POLARITIES
I1	IDS149-164	R
I2	IDS165-166	N
I3	IDS167-168	N
I4	IDS121-126	R
I5	IDS127-132	R above N
I6	IDS133-136	R
I7	IDS137-138	N
I8	IDS139-140	R
I9	IDS141-146	N
V1	XAK001-002	?
V2	XAK003-004	R
V3	XAK005-006	R
V4	XAK007-008	N
V5	XAK009-010	N
V6	XAK011-012	N
V7	XAK013-014	N
V8	XAK015-016	R
V9	XAK017-020	R
V10	XAK021-024	R
V11	XAK025-026	R

● Normal
○ Reverse

Fig. 20: Map of a portion of the Butler Cave – Sinking Creek System showing paleomagnetic sampling locations and results (modified from Butler Cave Conservation Society).

The first phase in the development of the trunk channel was a phreatic tube, remnants of which can be seen near Sand Canyon. However, the tube has been greatly modified by the incision of a wide canyon (Fig. 5) cut 6-10 meters into the bedrock below the tube. A remnant of the floor of the original tube survives as the natural bridge located 200 meters upstream from Sand Canyon. The edges the passage remnants are packed with cobble fills, clearly showing that these materials were emplaced before the incision of the canyon.

The left-most of the dip passages shown in Fig. 5 slopes gently downward for about half the distance shown on the map where, abruptly, the passage ends in an overhang dropping into the Bean Room, 40 meters below. The overhang is formed on cobble fills with remnants of other deposits in the walls. The entire depth of the Bean Room has been excavated since the cobble fills were deposited. This implies 40 meters of downcutting, through bedrock, after the major deposition event.

Nearby, a presently active stream, Rotten Rocks Creek has cut a canyon, including a waterfall, into fresh limestone with little evidence of extensive sediment transport. The surface stream sinks just outside the artificial entrance of the cave and reappears just inside the entrance as a canyon to one side and 5 meters lower than Dave's Gallery but it has a high gradient and emerges into the Bean Room at the floor level.

PALEOMAGNETIC INVESTIGATION

A paleomagnetic investigation identified at least one magnetic field reversal. These reversals are abrupt (on a geologic time scale) and the chronologies of the reversals have been well established (Cande & Kent 1995). The disadvantage of paleomagnetic dating is that the method provides only a few fixed points on the time scale rather than actual dates. Even when reversals can be identified in a cave sediment pile, there is the serious problem of determining the specific reversal that has been observed.

Samples were collected on 3 occasions, with the purpose of characterizing the timing and modes of deposition in the cave. Locations were chosen based upon position in the cave and suitability of the deposit (Fig. 20). Sediments in this cave system consist mainly of sand, gravel and cobbles, which can be problematic for paleomagnetic analysis. Nevertheless, robust samples spanning the front half of the cave were successfully collected and analyzed.

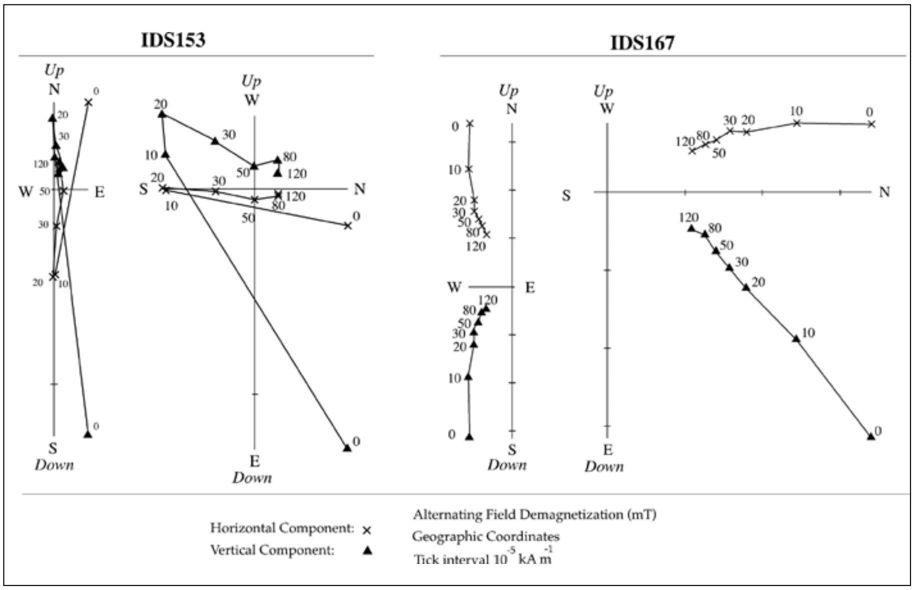


Fig. 21: Representative demagnetization diagrams from paleomagnetic study. Sample IDS153 shows classical reverse polarity with a normal viscous overprint. Sample IDS167 displays normal polarity.

The first group of samples included in the present study were collected by V. A. Schmidt. Eleven sites (V1 through V11) comprising 26 samples (XAK001-XAK026) were obtained. The original field notes and the data plots for these samples are used, but the raw data are no longer available. I. D. Sasowsky collected 46 samples (IDS121-IDS146 and IDS149-IDS168) from 9 sites (I1 through I9). Therefore, a total of 72 samples were considered in our evaluation.

Collection methods described in Sasowsky *et al.* (1995) were employed, whereby a 2-cm plastic box was used to contain the sample. The box was carefully oriented and cut off flush with the face of the sedimentary deposit. The box was capped and taken to the University of Pittsburgh rock magnetism laboratory for measurement. Corrections were made for local variation of the magnetic field based on the date of collection. Samples were subjected to stepwise alternating field demagnetization to isolate the vectors of interest. Application of a 20 mT field usually removed any viscous remnant magnetization, although such was not always present. Samples were collected in pairs, and good agreement was seen in almost all cases. Fig. 21 shows representative normal and reversed polarity samples. Summary results are displayed in Fig. 20, and paleodirections for the IDS sample series are given in Fig. 22.

The overall results are unusual, in our experience, for caves in the Appalachian Highlands. In particular, of the 20 localities sampled, 11 showed reversed polarity. This is a much greater proportion than we have seen in any other cave in the Appalachians, and likely means that sediments have been sequestered in this cave longer than typical for the region.

The distribution of paleomagnetic orientations within the cave is consistent with expected patterns of sediment emplacement. Discontinuity of the deposits, however, does not permit placing each sample location in rigorous stratigraphic context. Reversed polarities were found far up-dip in all the western tributaries sampled (Fig. 20, locations V1, 2, 3, 9, 10, 11; I1, 4, 5) and within 10 meters elevation of the main trunk stream at Sand Canyon (V8), and at the Air Dig (I8, close to the main stream, but several meters above). Other reversed samples have been found in the upper levels of nearby Breathing Cave. Nor-

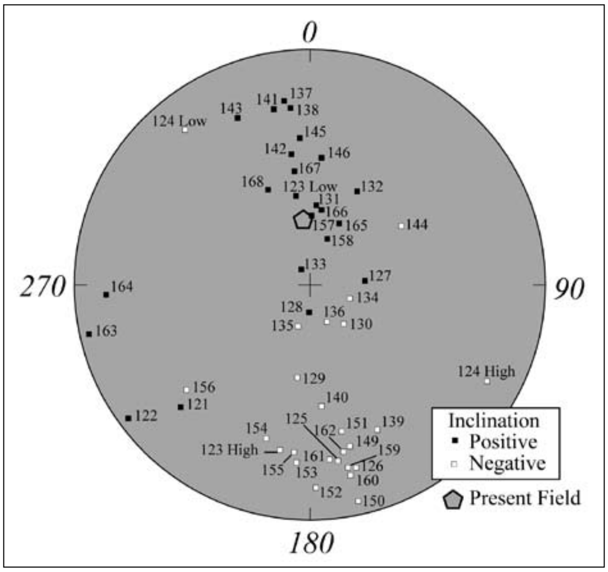


Fig. 22: Lambert equal-area stereoplot of magnetic sample directions. Present day field (PDF) is shown as a polygon. Sample numbers are all in the IDS-prefix series.

mal polarity samples were found throughout the remainder of the cave, particularly along the main cave stream (locations V6, V7, I7, I8), and in the currently dry Pat's Section tributary (I2, I3). At only one location (I5), were sediments of different polarity found in stratigraphic context. This deposit is a laminated orange-brown clay capped by gravel. Three layers of the clay were sampled, and the upper 2 layers (IDS127-130) were magnetically reversed while the lower layer was normal. We interpret this to be, at a minimum, the end of the Jaramillo reversal (Chron C1r.1n), 990 ka (Cande & Kent 1995). They could easily be older.

DISCUSSION AND CONCLUSIONS

The extensive clastic fills in the Butler Cave – Sinking Creek System consist mainly of quartz with particle sizes ranging from fine silt to sandstone boulders. Reworked breakdown in the form of rounded limestone pebbles to boulders occurs as part of the coarse fraction. Clay minerals make up only a small fraction of the material. Physical properties and the physical location of the cave within the drainage basin support the hypothesis of a single provenance for the sediments, namely the flank of Jack Mountain. The sediments are transported and reworked Silurian sandstones and siltstones. Authigenic gypsum occurs in some of the sediment samples. There is some material that probably represents insoluble residue from the limestone but this appears to be volumetrically a minor component.

The cave system is located in the headwaters of the James River at elevations ranging from 600 to 750 meters as well as being far south of the glacial margins. Direct influence of sea level fluctuations during the Pleistocene and the rearrangement of river systems in response to ice blockage and sedimentation from glacial outwash are likely to be very small.

Butler Cave, and indeed all of the caves of Burnsville Cove have a long and complex history. These stages may be outlined as follows:

(i) A possible pre-history of hypogenic speleogenesis has been proposed by Schwartz and Doctor (2009). Deep-seated fluids would be possible for the initial openings of joints and bedding plane partings at great depth before Burnsville Cove. Schwartz and Doctor note the presence of euhedral quartz in the Keyser Limestone and suggest that initial speleogenesis could be as early as the Eocene igneous activity that occurred in the area immediately to the north.

(ii) Excavation of most of the network maze by phreatic movement of groundwater well below base level.

(iii) Lowering of the valley floors and development of an extensive karst surface at 750 meters elevation. Initiation of large closed depressions. This surface is considered to be a headwater extension of the Harrisburg Peneplain, the dissection of which began in the Pliocene about 3–5 million years ago (White 2009). At this time the trunk passage would be more than 100 meters below the land surface but the upper extensions of the side caves would be close to the surface.

(iv) Truncation of the up-dip passage by the lowering land surface with the possible formation for multiple entrances along the flank of Jack Mountain.

(v) Infilling of cobble-fill deposits associated with intense flood events.

(vi) Invasion of the cave by surface recharge and conversion to a shallow karst drainage system, albeit with a phreatic part at the downstream end. Deepening of canyon passages and removal of much of the cobble fill.

The massive boulder fills with magnetically reversed sediments likely were deposited during the early to mid-Pleistocene. It was a time when many of the up-dip passages may have been open cave entrances on the flank of Jack Mountain. It was a time of sparse vegetation and cold and very wet climate such as might have occurred during one of the major ice sheet advances in the North. Much of this sediment entered the cave as debris flows, a suspended mass of rock and water moving at high velocity. Some remnants of the event are seen in the diamicton facies sediment plastered in recesses in the walls of Dave's Gallery and in other parts of the cave.

The age of the massive fill event (or events) cannot be given with certainty with the available dating information. Certainly the event preceded the Jaramillo reversal 990,000 years ago. It may be older. It was not possible to construct a sequence of normals and reversals such as Schmidt (1982) found in Mammoth Cave. Unlike the tiered caves of the south-central Kentucky karst and of the Cumberland Plateau, the Butler Cave – Sinking Creek System does not contain "levels". The central trunk passage and the side caves have been guided by the dip and plunge of the syncline and by the influence of the inter-fingering tongues of the Clifton Forge Sandstone. Sediment transport throughout the cave's history has been through essentially the same sequence of passages which themselves are older than any of the sedimentation events. An examination of the magnetostratigraphy of cave sediments in the Obey River Gorge in the western margin of the Cumberland Plateau of Tennessee revealed only a single zone of reversed sediment in the highest cave levels (Sasowsky *et al.* 1995). It was therefore assigned to the younger end of the Jaramillo event and given an age of 0.91 Ma. An alternative would have been the younger end of the Olduvai reversed period at 1.66 Ma. Later cosmogenic isotope dating of these sediments (Anthony & Granger 2004) placed the age of these sediments at 1.66 Ma. The expected Jaramillo reversal was not found in any of the cave sediments examined. Cosmogenic isotope dating of sediments in Mammoth Cave (Granger *et al.* 2001) and of the cave sediments of the Cumberland Plateau (Anthony & Granger 2004) show a period of massive sedimentation about 850,000 years ago. Since this event was pervasive in the caves of Kentucky and Tennessee, it seems not too much of a stretch to propose that the event is also recorded in Butler Cave by the extensive cobble fills.

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