Windy Mouth Cave

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Abstract

Windy Mouth Cave is a mostly abandoned paleospring conduit that drained water from the Big Levels surface northward to the Greenbrier River. The formation of the cave was controlled by a combination of structural and hydrologic factors. Geologic structure provided a pre-solutional network of faults, joints, and bedding planes in the bedrock that was later exploited by groundwater flux. The cave is situated on the western limb of the Sinks Grove Anticline. Beds dip gently to the northwest and strike generally N40–50°E in the cave. Conduits are primarily oriented along strike, while a smaller component is oriented sub-parallel to dip. In plan view, Windy Mouth Cave appears as a branchwork system with a minor anastomotic morphological element overprinted on the dominant dendritic pattern. There are three levels in the cave. Upper levels are phreatic tubes that are connected to small vadose canyons at their origin, and contain some active water. The middle level comprises mainly large phreatic passages, but with substantial clastic fills. The lower levels are well-developed canyon passages that run down dip and crosscut and incise below the main level of the cave. Conduit cross-section morphology is complicated by interbedded chert and shale layers in the Hillsdale Limestone host rock. The impermeable layers form resistant ledges that split individual conduits into multiple levels. Fluvial sediment deposits that are suitable for paleomagnetic analyses were not found in the upper levels, although the position and hydrologic genesis of the system suggest that the upper levels were formed first and are thus the oldest portion of the cave. A magnetically reversed sample was found near the base of one section that was presumably deposited during the reversal of the geomagnetic field which ended at 788 ka. This sets the minimum age of the cave. The modern-day hydrology is markedly different from the past. The drainage basin area is much smaller ($\sim$2 km^2), and the resident streams have considerably less discharge. Much of the drainage has been pirated to the Scott Hollow drainage basin located south and west of Windy Mouth Cave.

15.1 Introduction

Windy Mouth Cave is one of three large cave systems (along with Organ and Scott Hollow Caves) known from the portion of the Big Levels limestone plateau lying south of the Greenbrier River in Monroe and Greenbrier Counties. The cave's reported length and depth are 29 km (18 miles) and 61 m (200 ft), respectively (Gulden 2017), ranking it as 39th on the US long cave list. Although it has a history of exploration going back over 60 years (see Chap. 5), difficulties in accessing the entrance and traversing the cave have

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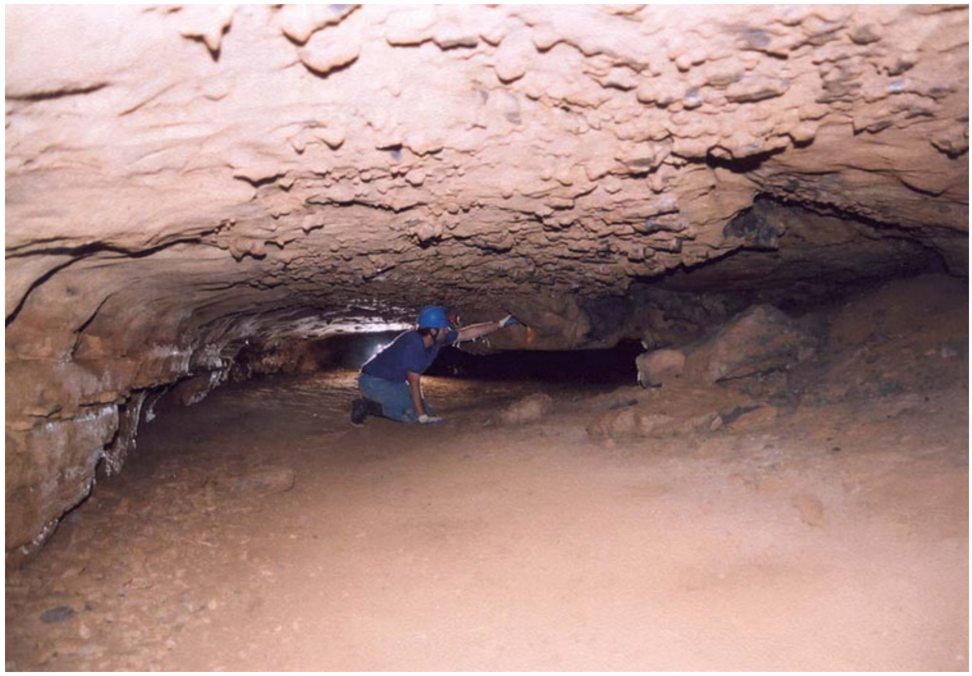

Fig. 15.1 Entrance passage crawl. Photograph by I.D. Sasowsky

precluded the completion of a comprehensive map for the system, or even a delineation of its full extent and length. The cave is usually accessed by traversing along the south bank of the Greenbrier River, and when water levels are high, or weather cold, this is challenging. A caver died by drowning in the river in 1998 after exiting the cave. Additionally, the front sections of the cave involve very long (Fig. 15.1), and frequently low, crawls. When we first considered working in the cave, we spoke with Jim Hixson who had surveyed in the cave earlier. His advice was "Wear double kneepads," which we interpreted as a joke. Our subsequent initial trip into the cave convinced us that he was correct, and on later trips we wore double kneepads, and even affixed padding into the palms of our gloves. Nevertheless, the cave has its appeal (Fig. 15.2) and many walking passages beyond the entrance series (Fig. 15.3).

Brief descriptions of the cave, some with associated maps (discussed below), have appeared over the years (Davies 1958, p. 132; Peters and Davis 1960; Davies 1965, pp. 26–27; Whittemore 1971; Dore 1995; Dasher 2002). The most

Fig. 15.2 Speleothems in trunk passage south of the waterfall room. Photograph by I.D. Sasowsky

Fig. 15.3 Walking passage beyond entrance crawls. Photograph by E. McCarthy. Used with permission

complete written description, running just over two single-spaced typewritten pages (Davis and Peters 1960), is unpublished as far as we know and was shared with us from the personal files of Jim Hixson. The present chapter makes use of these early works (including maps discussed below), our personal experiences in the cave, and the scientific studies of Shank (2002) and Curry (2002), to discuss the geologic and hydrologic conditions and history of this major system.

15.2 Setting

The area near the cave is within the transition zone, referred to as the "Folded Plateau," adjacent to the boundary between the Valley and Ridge and the Appalachian Plateaus physiographic provinces. Specifically, this area is situated between the Allegheny Structural Front to the west and the Intraplateau Structural Front to the east (Kulander and Dean 1986). The region is characterized by gently dipping northeast trending folds in Middle-Late Paleozoic sedimentary rocks (Heller 1980; Ogden 1976). Scott Hollow Cave (Chap. 16) lies directly south of Windy Mouth Cave. This position, along with the general alignment of the trunk passages in the two caves, has led to the hypothesis that they may consist of one more extensive system, as yet unconnected by explorers.

15.2.1 Stratigraphy and Structure

The Greenbrier Group carbonates and siliciclastics within which the cave is formed are exposed in a northeast trending belt that outcrops along the eastern margin of West Virginia. Locally, the outcrop belt forms a broad sinkhole plain that ranges in elevation between 560 and 690 m (1820–2250 ft) and is referred to as the "Big Levels." Hills that surround the sinkhole plain are capped by clastic rocks of the Mississippian Mauch Chunk Group that conformably overly the Greenbrier Group (Heller 1980). In the study area, the sinkhole plain is deeply dissected by the Greenbrier River, a major tributary to the New River in the Ohio River drainage basin. Numerous karst features such as blind valleys, sinkholes, and disappearing streams dominate the scenic landscape of the plain. There is also a notable lack of surface drainage on the Big Levels. Groundwater enters the system on the karst upland and discharges through springs and seeps at river level, 150 m (490 ft) below.

The Greenbrier Group is approximately 240 m (900 ft) thick (Fig. 15.4) in southern Greenbrier County (Wells 1950) and is bounded at its upper and lower contacts by Mississippian Shales (Ogden 1976). The upper contact is made with The Lillydale Shale of the Mauch Chunk Group (Bluefield Formation). The Lillydale is only found at the highest elevations in the study area. The Maccrady Shale bounds the lowest unit of the Greenbrier Group and plays a major role in the hydrogeology and karst development in the area (Palmer 1974). The cave is confined to the Hillsdale Limestone (Fig. 15.5) with one possible exception, in the First Creek dome, where it may extend vertically into the Sinks Grove Limestone. In an overview of the stratigraphy in nearby Organ Cave, Deike (1988) mentions that the contact may be observed in a large room that extends high into the overlying strata. Organ and Windy Mouth Caves are similar in that they are both confined to the lower Greenbrier Group strata, as are many other caves in the region.

Several minor folds, mapped and named by Heller (1980), exist between major structures in the study area (Fig. 15.6). These include the Fort Spring Anticline and Syncline as well and another unnamed fold pair that lies just west of the study area. An additional unnamed thrust fault and fold pair lies just to the east. Heller (1980) attributes these minor structures to splay faulting through the relatively competent Greenbrier Group carbonate sequence from underlying Lower Paleozoic strata.

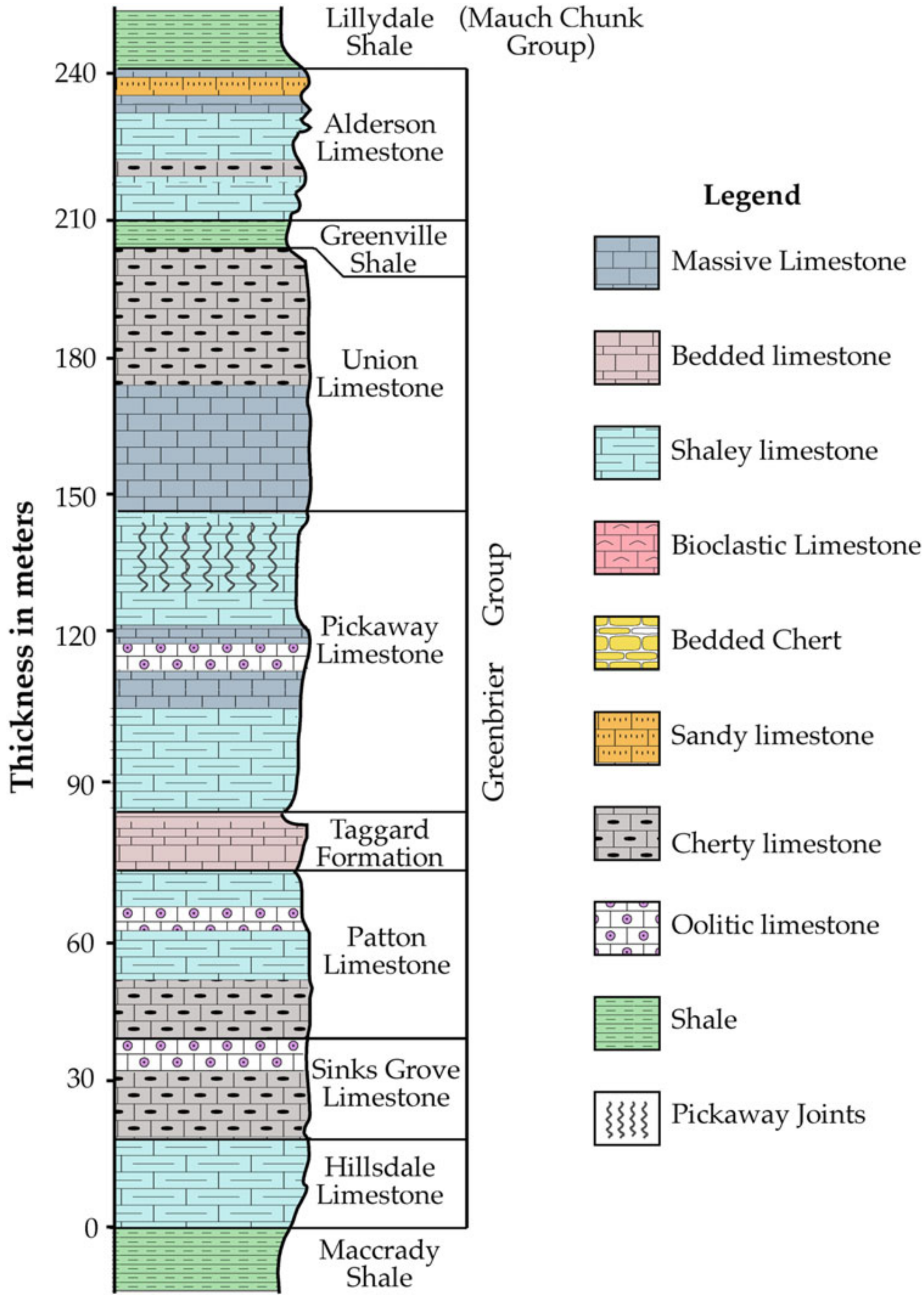

Fig. 15.4 Generalized stratigraphic column of the Greenbrier Group carbonates in southern Greenbrier County. *Source* Shank (2002), after Heller (1980)

15.2.2 Hydrology

The cave is considered to lie within the Scott Hollow groundwater basin, although no dye tracing has confirmed this. The Scott Hollow drainage basin is bounded to the west and south by two topographic highs: Flat Top Mountain and Swoopes Knobs (Fig. 15.7). These form the highest points within the study area and are capped by clastic rocks of the Mauch Chunk Group (Fig. 15.4; Heller 1980). The Greenbrier River and Second Creek form the northern and eastern boundaries. The Greenbrier River serves as regional base level.

It is likely that drainage through the cave currently serves as direct flow to the Greenbrier River. Groundwater flow in most of the mature karst of southeast West Virginia is predominantly through large diameter solution conduits (Jones

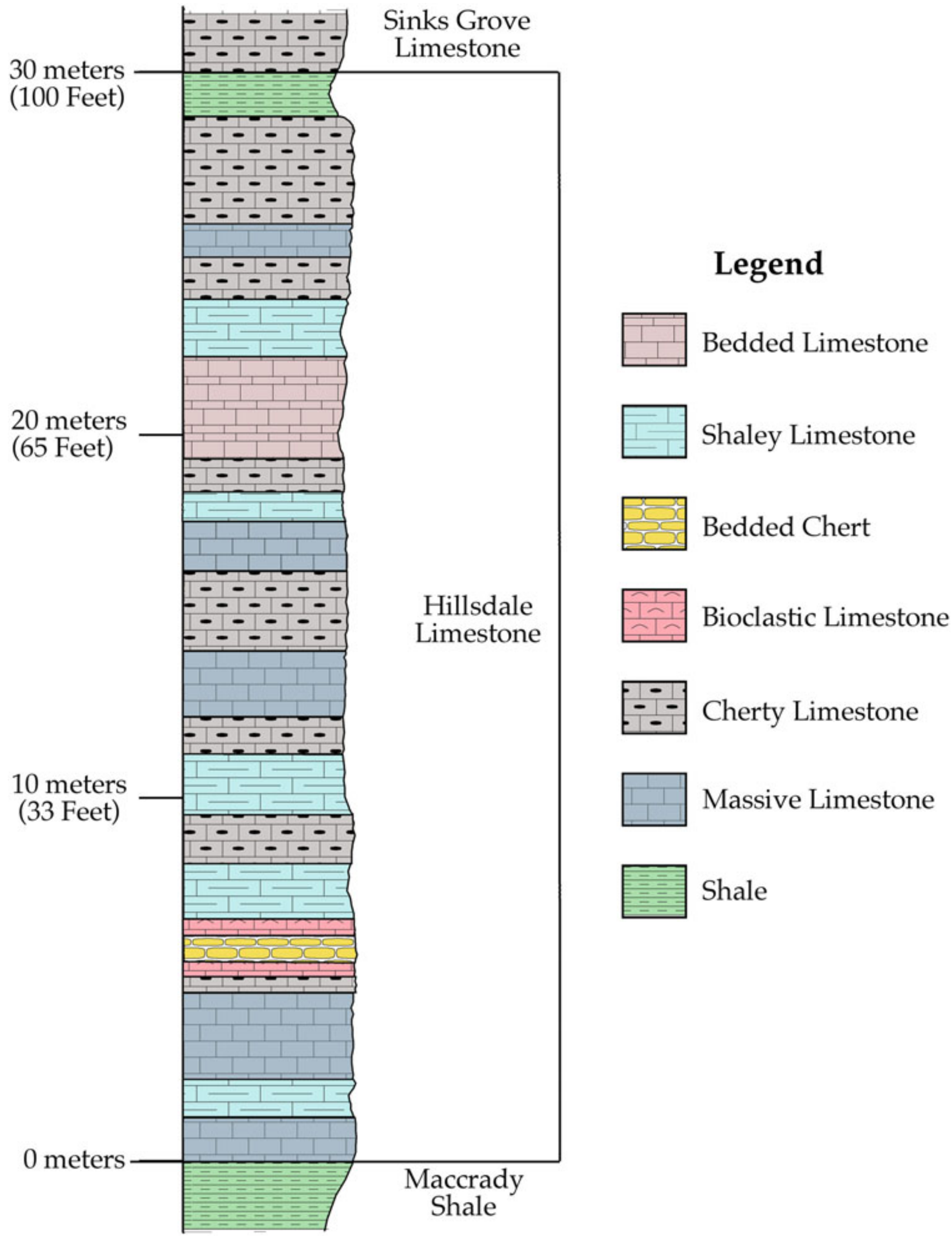

Fig. 15.5 Stratigraphic column of the Hillsdale Limestone of the Greenbrier Group in Organ Cave. *Source* Shank (2002), after Deike (1988)

1997). Surface streams are commonly short-circuited through insurgences on the Big Levels. Subsurface stream piracy complicates the delineation of drainage basin boundaries. Dye trace tests reported by Jones (1997) determined that the Scott Hollow drainage basin covers approximately 47 km^2 (18 mi^2), 90% of which is carbonate outcrop.

It is known that water in Scott Hollow Cave currently enters that cave system on the karst upland surface as far south as the town of Sinks Grove (see Chap. 16). It flows into several smaller subsurface tributaries to the Mystic River in Scott Hollow Cave. That north-flowing water eventually resurges at several points along the Greenbrier River, downstream of the entrance to Windy Mouth Cave. These waters are underneath Windy Mouth Cave, which contains limited higher-level vadose flow at the present time. It appears the waters currently flowing in Windy Mouth Cave originate in closed depressions further north, closer to the river.

Average annual runoff for the Kanawha/New River basin, of which the Greenbrier is a tributary, is reported by Jones (1997) to be 43.2 cm (17 in.). The stream gradient for the Greenbrier River in the area of Windy Mouth Cave is 0.0014 (~7 ft/mile). Annual mean discharge for the Greenbrier River over the decade 1991–2001 was 58 m^3/s (2050 ft^3/s; USGS 2001). The present-day entrance to Windy Mouth Cave is at the apex of a meander in the southern wall of the Greenbrier River Gorge, and it appears to be an abandoned

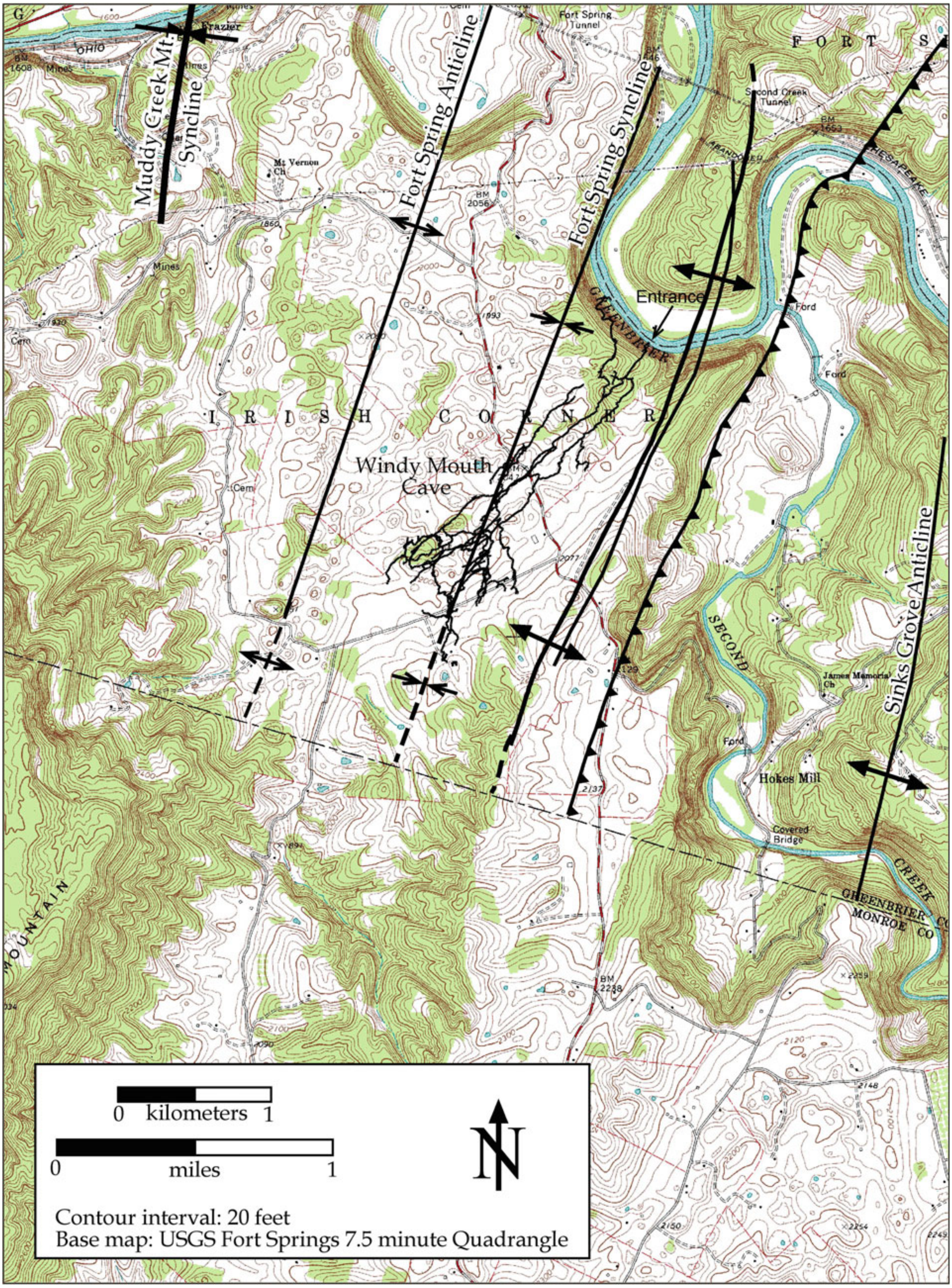

Fig. 15.6 Structural map of southern Greenbrier County with Windy Mouth Cave and first-order folds. After Heller (1980)

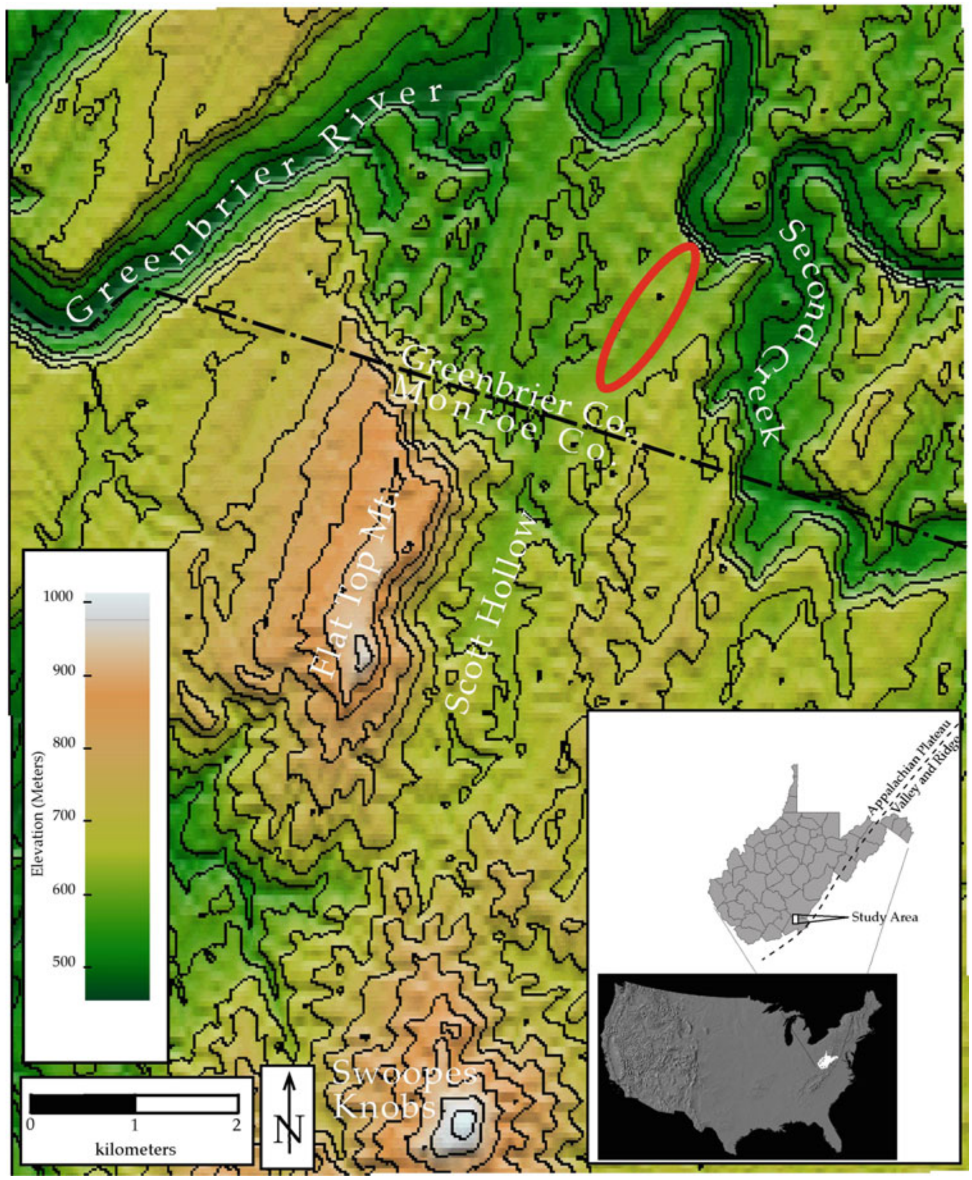

Fig. 15.7 Shaded topography of the study area showing major surface features and general extent of Windy Mouth Cave (*red ellipse*). Base created from USGS Fort Springs digital elevation (DEM) data

spring mouth that once conveyed water from the Big Levels to the Greenbrier River. The initially reported entrance elevation (Davies 1958) is 1750 ft amsl. Our own calculations place it at circa 100 ft. above river level, or 1710 ft, (521 m) amsl. The cave trends southward from the entrance, underneath the karstified limestone upland surface.

15.3 Maps

There are four known versions of maps existing for the cave, and another version is currently being prepared during ongoing survey (see Chap. 5). The earliest known map ("Version 1," Fig. 15.8) is a hand-drawn outline on an 8.5 × 11-in. sheet, dated March 5, 1960, and labeled "Rough sketch, not to scale." It is annotated with many useful descriptions, and it presents estimated distances between major junctions. The next map, Version 2 (Fig. 15.9), is a cleaner page-sized version of that map, published in a caving club newsletter. The third map (Version 3) is a 4 × 6-in. outline map ("sketch survey") and it appears in the supplement to the compendium *Caverns of West Virginia*, attributed to the West Virginia Association for Cave Studies (Fig. 15.10). The final existing map, Version 4 (electronic map M-15.1), is a line plot prepared by Shank (2002) using the software *Compass* (Fountainware, Denver, Colorado) with survey data collected by Jim Hixson and colleagues. Each of these maps contains useful information on the position, length, navigability, and hydrology of the cave.

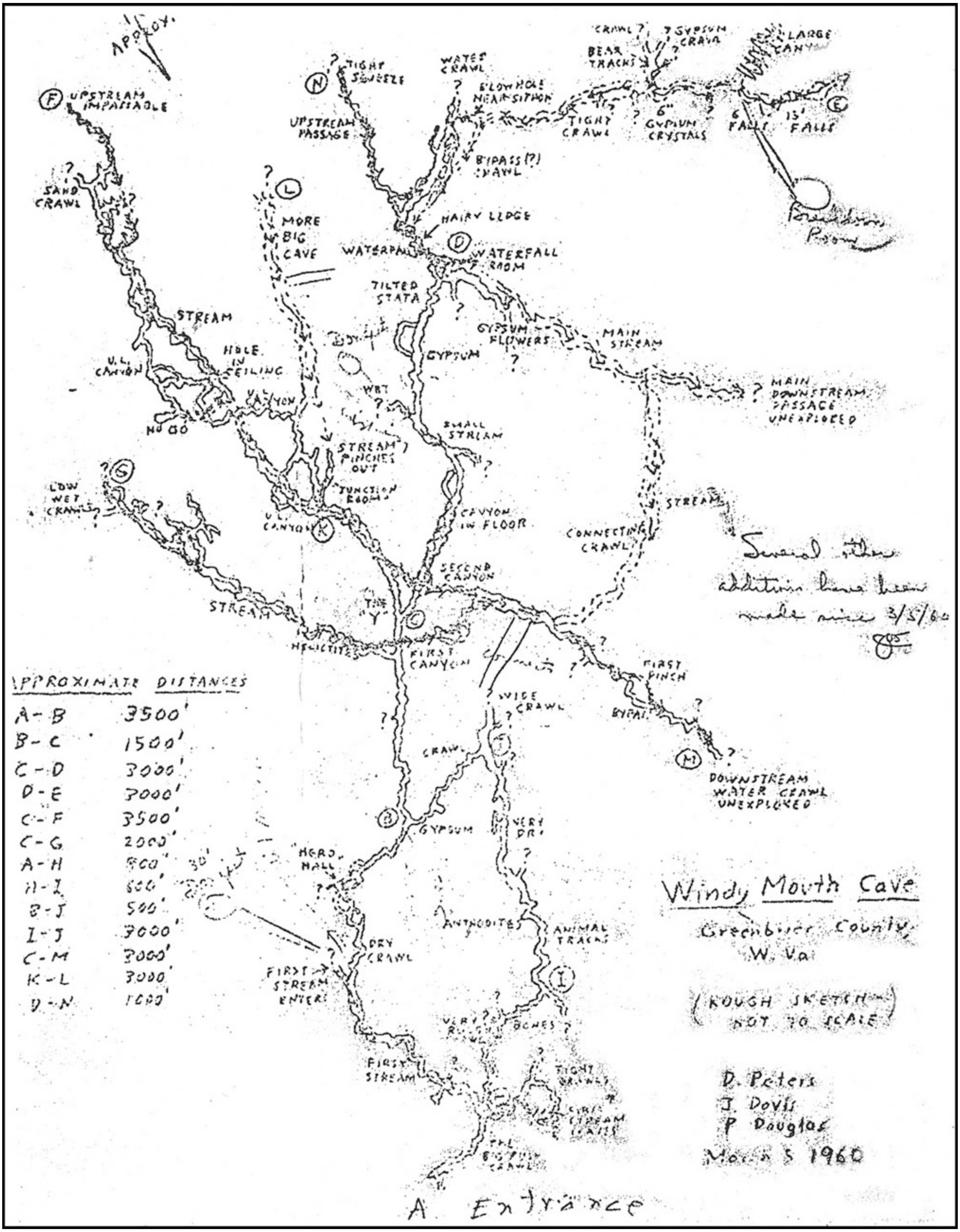

Fig. 15.8 Windy Mouth Cave map version 1. This is a reproduction of the March 5, 1960 map by D. Peters, J. Davis, and P. Douglas, which was further annotated by Jim Hixson. Not to scale, but see approximate distances indicted in table at *bottom left*

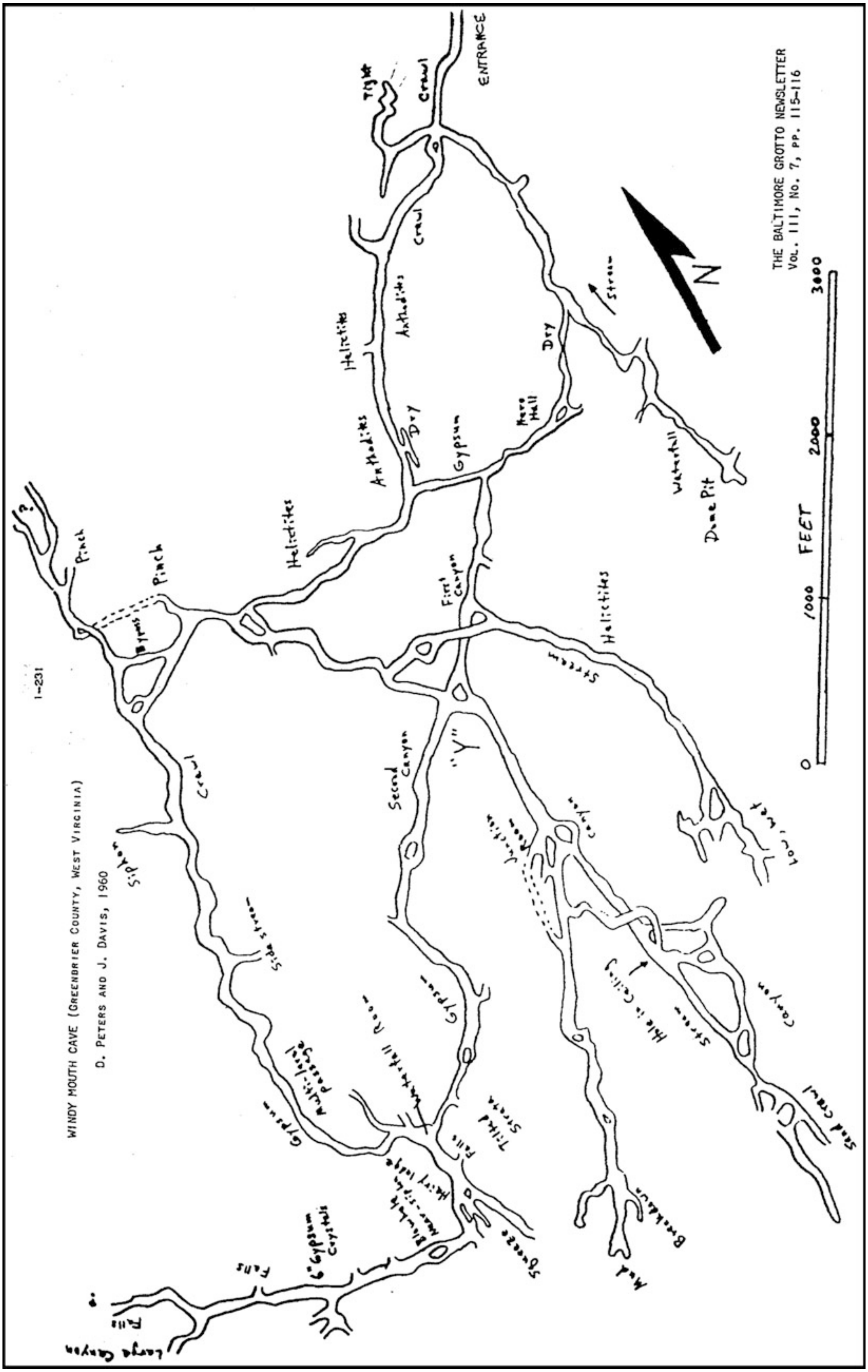

Fig. 15.9 Windy Mouth Cave map version 2 (Peters and Davis 1960)

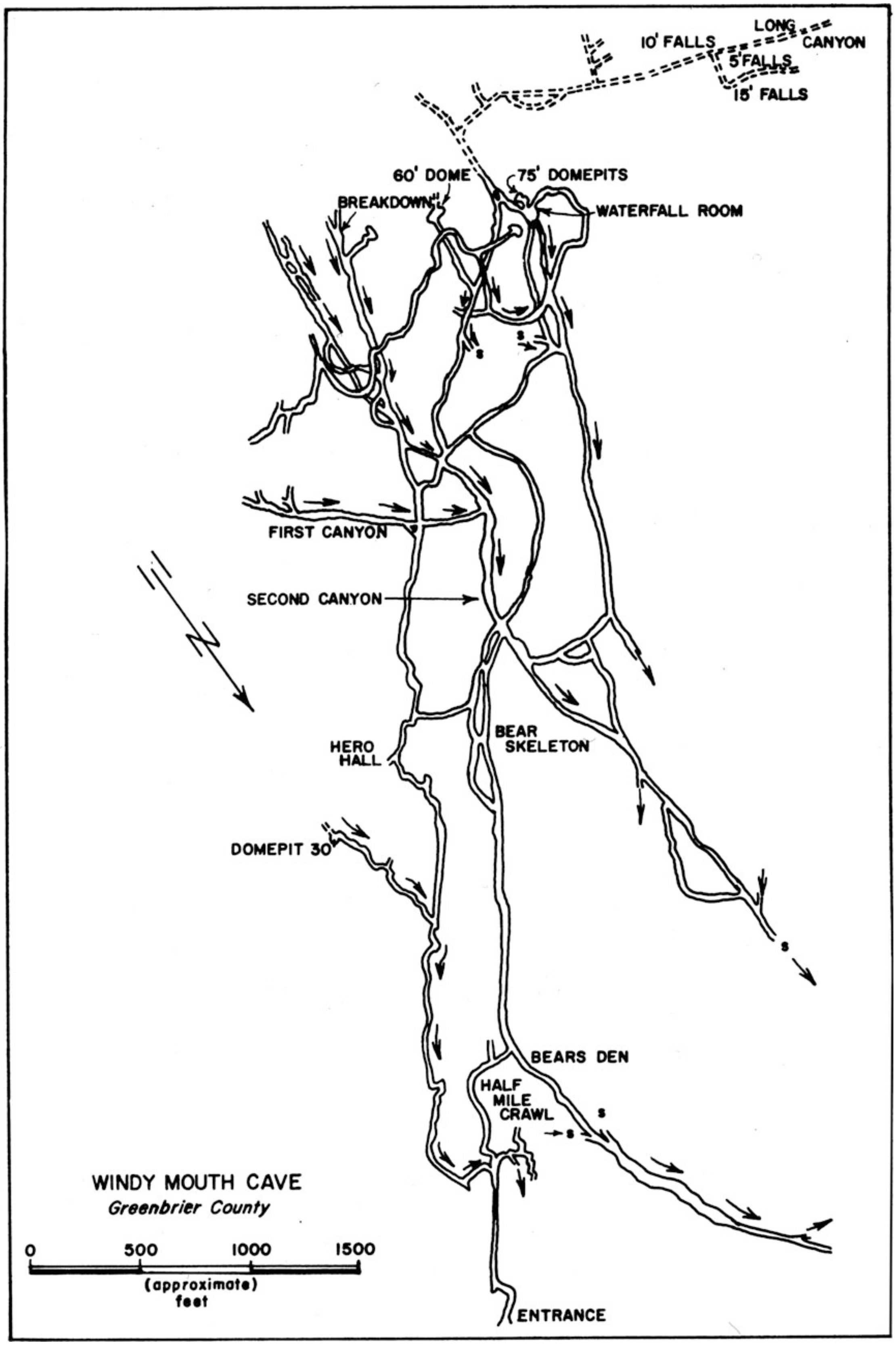

Fig. 15.10 Windy Mouth Cave map version 3, from Davies (1965). Attributed to West Virginia Association for Cave Studies

15.4 General Form and Structural Influences

Cave passages in this region have been interpreted to originate under phreatic conditions in the Hillsdale Limestone and to gradually become vadose as they mechanically incise into the relatively insoluble Maccrady Shale (Palmer 1974). Incision into the Maccrady Shale is usually localized within conduit systems where active streams form canyons. The situation with Windy Mouth Cave is complex due to its length and polygenetic nature as will be described below.

15.4.1 General Form and Position

Examination of the cave map in relation to the landscape clearly shows that at least some portions represent a paleospring conduit that drained to the Greenbrier River (Fig. 15.11). A lower passage to the west currently carries water which is interpreted to feed some active spring on the Greenbrier River (local base level), but this has not been traced. The cave generally trends southward from the entrance. The southernmost part of the cave aligns with the northernmost portion of Scott Hollow Cave, suggesting that the caves might be part of the same conduit system. This may be possible, but exploration to date (see Chap. 5) has not revealed a connection. Furthermore, although the caves are only separated by about 600 horizontal meters (2000 ft), the southern portions of Windy Mouth are likely circa 30 m (100 ft) higher than the nearest reaches of those in Scott Hollow Cave. This suggests that Scott Hollow Cave evolved at a later phase than Windy Mouth Cave, and may be isolated from that drainage.

The overall plan view morphology of Windy Mouth Cave fits the general classification by Palmer (1991) of a "branchwork cave," where several lower-order conduits converge into fewer higher-order conduits in a dendritic pattern (Fig. 15.10). The cave also exhibits some characteristics of an anastomotic pattern. The hybrid morphology is the result of a combination of recharge types. The dominant branchwork pattern results from numerous sinkhole inputs, whereas the anastomotic element originates from the influence of a single, relatively high discharge, sinking stream input. The cave is remarkably flat in profile, with vertical relief primarily coming from a few steep gradient infeeders and domes.

15.4.2 Structural Controls

Windy Mouth Cave is developed in gently dipping (5–7°) limestone strata on the western limb of the Sinks Grove Anticline. Trunk passages have formed just off bedding, oriented N30°E–N65°E (Fig. 15.12). Structural measurements taken at the surface near the study area show that the dominant strike direction of bedding is between N40°E–N50°E (Ogden 1976) and N20°E–N30°E (Heller 1980). Ogden (1976) found that the dominant joint set in the area is oriented N31°E–N41°E. Many passages observed in the cave display at least some degree of joint control. There are several sets of joints that were observed and measured in the cave, although they are not the predominant control on conduit formation.

First and Second Canyons are two major canyon passages whose general orientation is different from that of the rest of the cave. They are deep, narrow fissures that display drawdown passage morphology in cross section. Both canyon passages contain active streams that flow almost directly north–south, oblique to northwest dip, and the main northeast orientation of the cave. Canyon passages are incised 3–4 m (10–12 ft) below the floor of the trunk passage where they intersect. Canyon development is evidence of recent hydrologic activity that contrasts the paleohydrology of the cave.

Some passages in the cave terminate at faults associated with large rooms or domes and active streams. Other Greenbrier County caves such as Taylor Falls and Culverson Creek Caves also contain major passages that abruptly terminate in similar fault structures (Heller 1980). Faulting and active streams are associated with some of the large dome rooms that were observed in Windy Mouth Cave.

There are at least three "significant" faults in Windy Mouth Cave that have influenced the formation of conduits and/or the (paleo) hydrology of the cave. Two significant thrust faults and two minor reverse faults were observed in the southwest section of the cave, in and around the Waterfall Room (Fig. 15.13). A third thrust fault is located approximately 200 m southeast of the Waterfall Room faults.

The Waterfall Room fault is the main fault in a fault zone that occupies the southwest section of the cave. The main fault is a thrust, oriented N41°E 27°SE, with at least 2 m (7 ft) of displacement. Drag associated with the movement of the fault complicates the displacement estimate. Small-scale anticline and syncline folds are observed immediately adjacent to the fault plane.

Three large domes, the first of which lies just 3 m to the south of the Waterfall Room, contain abundant evidence of a fault zone associated with the Waterfall Room fault. Overturned beds, slickensides (on breakdown blocks), and brecciated zones can be observed in these domes.

In summary, the morphology of Windy Mouth Cave is dictated largely by structural factors that have been exploited by groundwater flux. The cave has developed primarily along strike of gently dipping bedrock in the lower Hillsdale Limestone. The resulting "branchwork" pattern of the cave is analogous to a dendritic drainage basin on the surface. Minor anastomoses formed from recharge through a single,

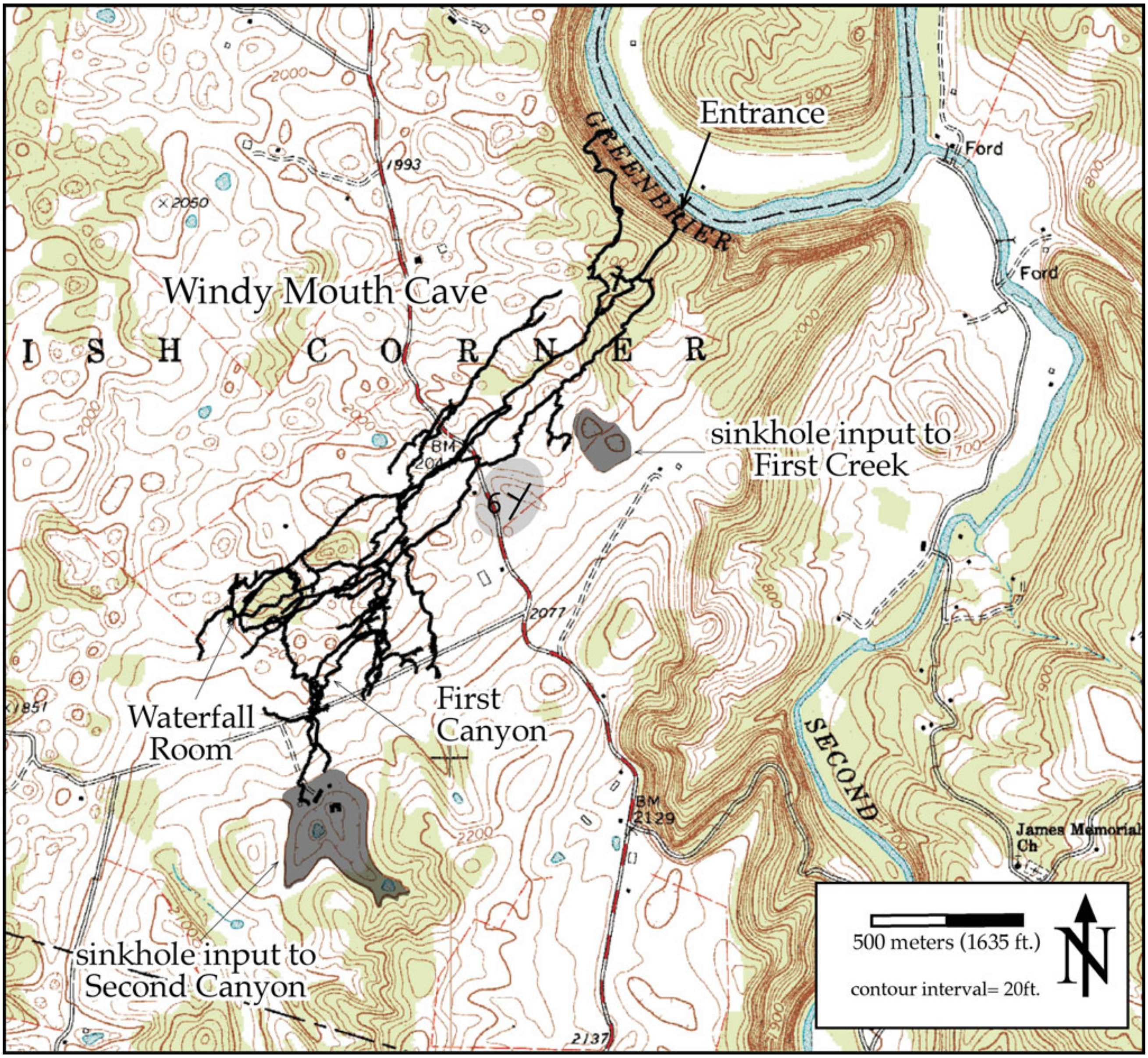

Fig. 15.11 Topographic map showing sinkhole insurgences into Windy Mouth Cave. Base USGS Fort Springs 7.5-min topographic quadrangle

large input point (sinking stream) in the cave have been overprinted by the more dominant and numerous recharge-type sinkholes.

Bedding planes provided the most important pre-solutional openings for conduit development. Conduits that have developed along the long axis of the cave are primarily strike-oriented along bedding planes. Closed loops and angulate passage elements are generally formed along joints. One major dome at the end of First Creek Passage is also formed as a result of jointing. Faults physically and hydrologically connect the upper and main levels of the cave in the Waterfall Room. The three large dome rooms in that area are also formed as a result of faulting associated with a fault zone.

15.5 Paleohydrology and Geomorphology

Windy Mouth Cave is a multi-level cavern system that contains abundant sediment deposits. These, along with other paleohydrologic evidence from the shape and distribution of conduits in the system as a whole and individually,

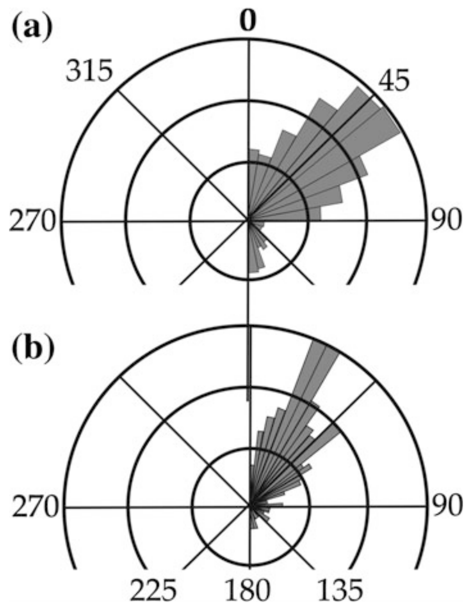

Fig. 15.12 Rose diagrams comparing cave passage orientation to stratigraphic strike (Shank 2002)

allow interpretation of the former hydrologic function of the cave, as well as its age. The cave has three distinct levels. Each level consists of a network of interconnected, hydrologically related conduits that are at similar stratigraphic elevations and share characteristics of morphology and general trend of orientation. The three levels are referred to as the upper levels, main or "trunk" level, and the canyons, with the canyons forming the lowest levels in the cave.

15.5.1 Passage Characteristics

The morphology of Windy Mouth Cave in plan view is characterized by several low-order conduits converging into higher-order conduits that flow into the main trunk passage in a dendritic stream pattern. The plan view pattern emulates that of Palmer's (1991) "branchwork"-type cave. In terms of conduit orientation, there are two distinct trends. The dominant orientation trend follows the northeast strike of the beds. A minor trend exists sub-parallel to dip, roughly north–south.

Primary development of trunk passages in Windy Mouth Cave is almost exclusively phreatic. Tubular conduits are oriented along the northeast strike of the beds. Their cross sections are generally elliptical and show smooth, rounded ceilings that roughly parallel bedding. Some joint control on conduit formation is present although such passages account for only a small fraction of total conduit length. Bedding planes provided the most important pre-solutional pathways for phreatic tubes with vertical joints playing a less dominant role (Fig. 15.14). North–south conduits have formed sub-parallel to local dip. These passages are primarily vadose canyons and shafts that show more pronounced vertical cross-section morphology.

Variation in conduit orientation between the vadose canyons and the phreatic trunk is attributed to the hydrologic differences in their origin. Gravity-driven flow, through vertical fractures or down dip in the vadose zone, formed vertical conduits (dome pits) and north–south oriented canyons. During the active development stage of the cave, these conduits collected recharge from discrete surface inputs (i.e., sinkholes and/or sinking streams) and transmitted water to the trunk conduits along solutional openings that originated along bedding planes or joints. Canyon passage formation resulted from vadose flow incision of the floor that occurred after the initial solutional opening enlarged enough to permit turbulent flow. A marked change in conduit orientation occurs where vadose conduits intersect the strike-oriented phreatic trunk passages.

Trunk passages are phreatic and developed along strike in response to groundwater flow near the water table. The strong correlation between trunk passage orientation and strike resulted from flow through the phreatic zone along bedding planes, toward the spring at base level. The extensive development of conduits at the main level suggests that base level remained static at this elevation for extended periods of time.

Upper levels are present in the southern portion of the cave. The upper-level conduits are comparatively shorter in length and less extensively developed as the other levels. Small active streams are present where the upper levels are connected to the main level at the southern end of the system near the Waterfall Room.

The upper levels of the cave are the most complex in terms of orientation and cross-section morphology. Smaller vadose canyons that are located upstream feed a less extensively developed phreatic conduit system that formed prior to the development of the main level below. Upper-level canyons run immediately above and parallel to the lower-level canyons, separated by only a few meters of bedrock between them. The vertical distribution and morphological similarities of the upper and lower levels in the upstream reaches of the cave suggest that the upper levels formed under similar hydrologic conditions and just prior to the lower levels.

Although minor streams are present in the upper level, the initial hydrologic activity that formed these passages while they were in the phreatic zone has ceased. The spatial distribution of the upper levels with respect to the remainder of the cave is interpreted to indicate that they were the first conduits to be hydrologically abandoned during the initial phase of base-level drop.

Trunk passages in the main level are largest in cross section and the longest in length of all cave elements. They are generally phreatic and contain numerous sediment

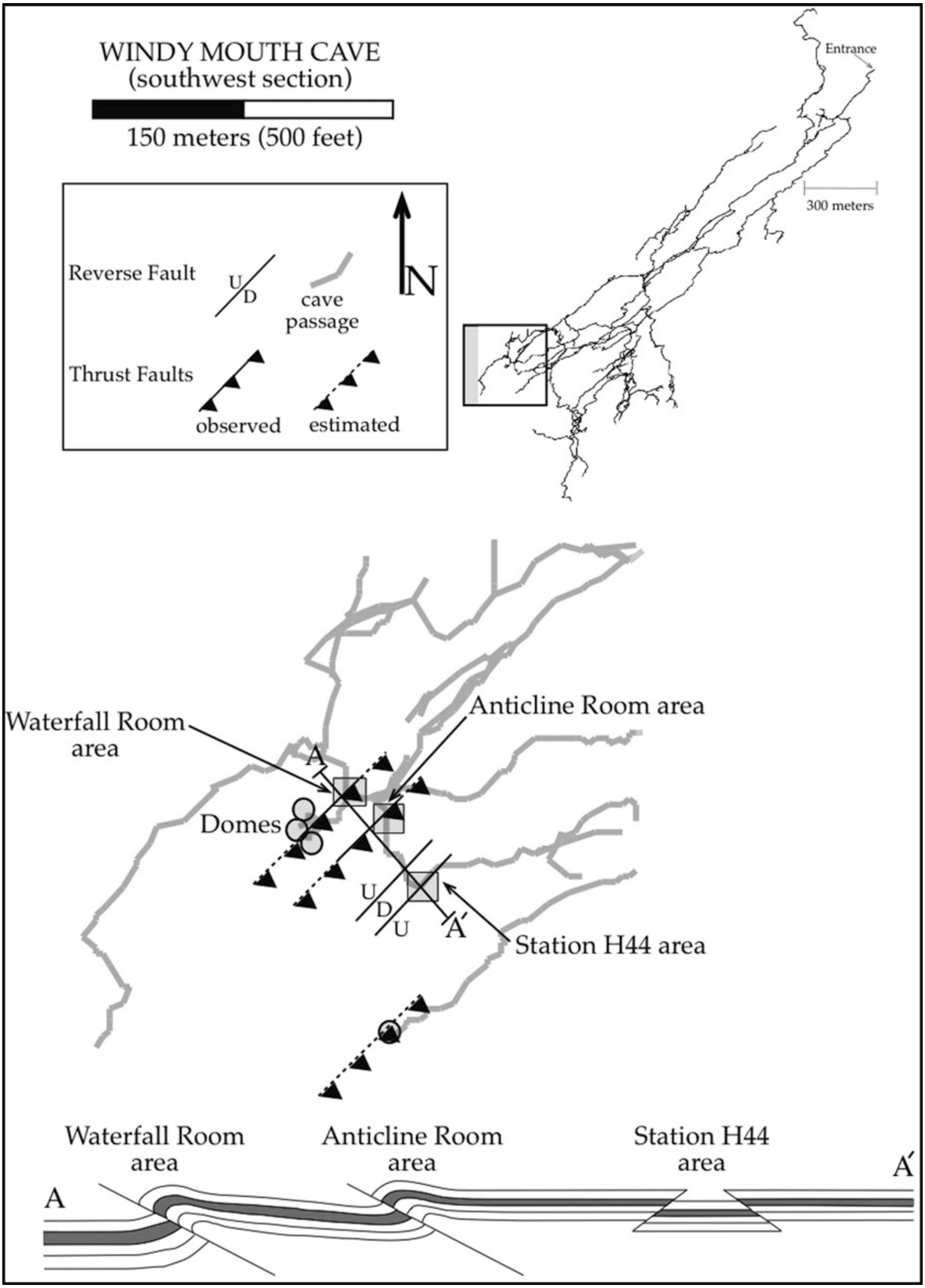

Fig. 15.13 Structural map and cross section illustrative of the southwest section of Windy Mouth Cave (Shank 2002)

Fig. 15.14 Tube/canyon formed with shaley limestone in lower portion. Photograph by E. McCarthy. Used with permission

deposits in a wide variety of forms including imbricated gravel bars and fine-grained, laminated sections. The main level is developed along local strike and is directly connected to the paleospring mouth (entrance) of the cave.

The main level of the cave consists primarily of a well-developed trunk passage. The trunk passage in Windy Mouth Cave received paleoinput from smaller feeder conduits that were located up dip and the trunk transmitted the input to the spring mouth. The base level must have remained relatively stationary at the elevation of the main level for an extended period of time to produce the well-defined trunk passage. The large cross section and extensive gravel deposits are interpreted to indicate that the main level of the cave was hydrologically active during a period where base level fluctuated around the elevation of the trunk passage.

The lowest elevations in the cave are vadose canyons. These conduits are relatively large, well-developed canyon passages that run down dip, crosscut, and are incised below the main level of the cave. They are long sinuous passages that are many times deeper than they are wide. Maximum height reaches approximately 12 m (40 ft), while width varies from little more than 3 m (10 ft) to less than a half of a meter (1 foot). The canyons contain active streams that run oblique to the general orientation of the cave, sub-parallel to local dip. Canyons are typically only navigable upstream from the junction with the trunk passage. The lower-level canyons originate in large deposits of breakdown at southern most, upstream, reaches of the passages.

The canyons contain modern streams and are thus still being developed. The north–south orientation of these lower conduits reflects the different hydrologic factors that governed their evolution in comparison with the overlying levels. Canyon passages are decoupled from the trunk passage where they intersect and incise beneath it and continue down dip. As base level dropped below the elevation of the trunk passage, conditions became vadose and subsequently, water flow was shifted down dip.

15.5.2 Clastic Sediments

As with most caves in the Appalachian Highlands, Windy Mouth Cave contains passages with evidence of being nearly completely blocked by clastic sediments in the past, which have been subsequently re-excavated. Numerous sediment deposits are located throughout the main level of Windy Mouth Cave. They record several stages of hydrologic activity including aggradation and subsequent excavation that occurred periodically throughout the active history of the cave. Sediment deposits range in character from well-sorted clays to unsorted gravels, sands, and silts, which show distinct grouping in a ternary plot (Fig. 15.15). Distinct marker beds are traceable throughout the main level of

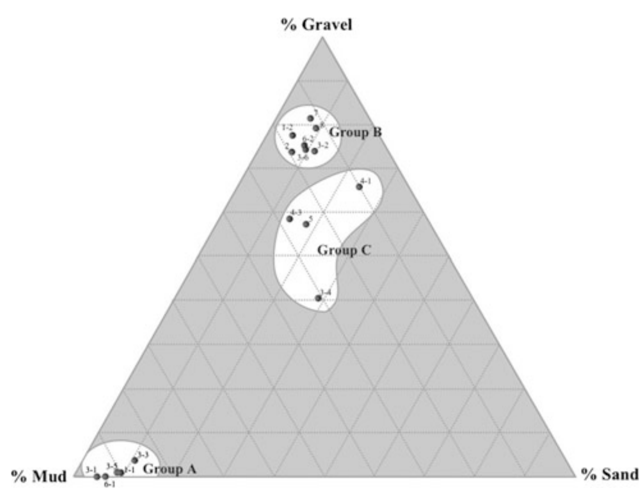

Fig. 15.15 Ternary plot of cave clastic sediment size (Curry 2002)

the cave. Sediments deposited from flooding of the Greenbrier River subsequent to hydrologic abandonment are also found in the floor of the entrance passage. Sediment samples for paleomagnetic analyses were collected from five locations in the cave (see Shank 2002 for details).

A key marker bed in the cave sediments is a fine-grained, approximately 0.5-m (1.5 ft)-thick, laminated clay layer that is found at or near the ceiling of the trunk passage. The clay unit is underlain by a ~1-m (3 ft)-thick, unsorted, gravel/sand/silt layer. Both layers can be traced almost continuously throughout the main level. A sharp, well-defined boundary exists between the two distinct units.

The extensive gravel deposits throughout the trunk passage indicate that high-velocity, turbulent flow conditions must have existed in the cave during this phase. Sedimentation must have occurred while substantial recharge was entering the system, perhaps via a sinking stream from the surface. Large sinkholes on the surface may have been the source of surface drainage. Imbrications within gravel bars indicate paleoflow direction toward the spring mouth in the main level. The bulk of gravel is chert (Figs. 15.16 and 15.17).

The fine-grained laminated clays located near the ceiling were perhaps deposited after the conduit was completely filled with water and sediment. Stream flow velocity would decrease dramatically if the space allowed for flow to occur becomes restricted and choked with aggrading sediments. The abrupt transition from turbulent to quiet water conditions is expressed in the sharp contact between the gravel and clay units.

The most extensive stratigraphic section of fluvial deposits in the cave is located in the Waterfall Room (Fig. 15.18). The 2-m section comprises alternating beds of laminated clay/silt units with unsorted, coarse-grained gravel, sand, and silt (Fig. 15.19). Abrupt and periodic facies changes are indicated in the section by sharp contacts between coarse and fine-grained units.

Upper-level sediment deposits are sparse. Where they are found, the deposits are discontinuous and untraceable. Most sediment deposits in the upper levels are autochthonous and occur as breakdown from the ceiling. Sediments that are suitable for paleomagnetic analyses were not found in the upper levels of the cave.

The lower levels contain active streams in canyons. Flow direction in the canyons is directly evident. The streams are currently downcutting, sub-parallel to dip. Sediments that were suitable for paleomagnetic sampling were found where the canyons intersect the trunk passage. The sediments are lodged into the upper portion of the canyon ceiling and the floor of the trunk passage. These deposits appear to be representative of when the canyon became decoupled from the trunk, hydrologically abandoning the trunk conduit.

Deposits from flooding of the Greenbrier River after the main phase of river incision are found in the 260-m (850 ft) entrance passage. An active stream that flows into the floor

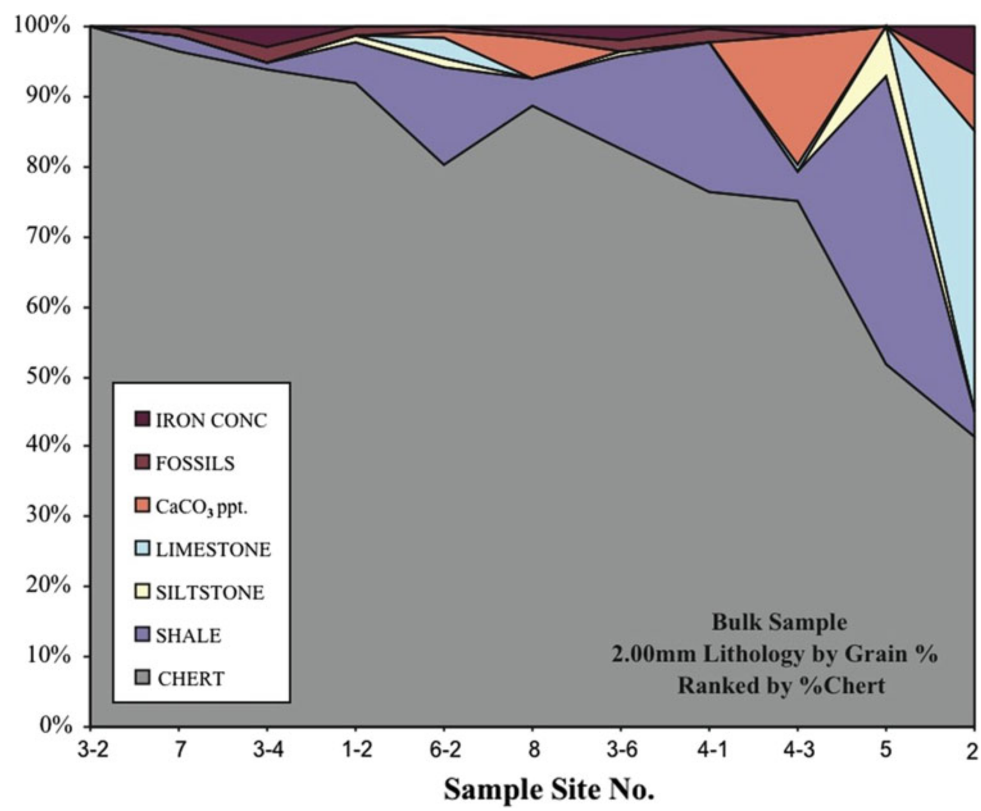

Fig. 15.16 Graph of coarse fragment lithology of cave sediments (Curry 2002)

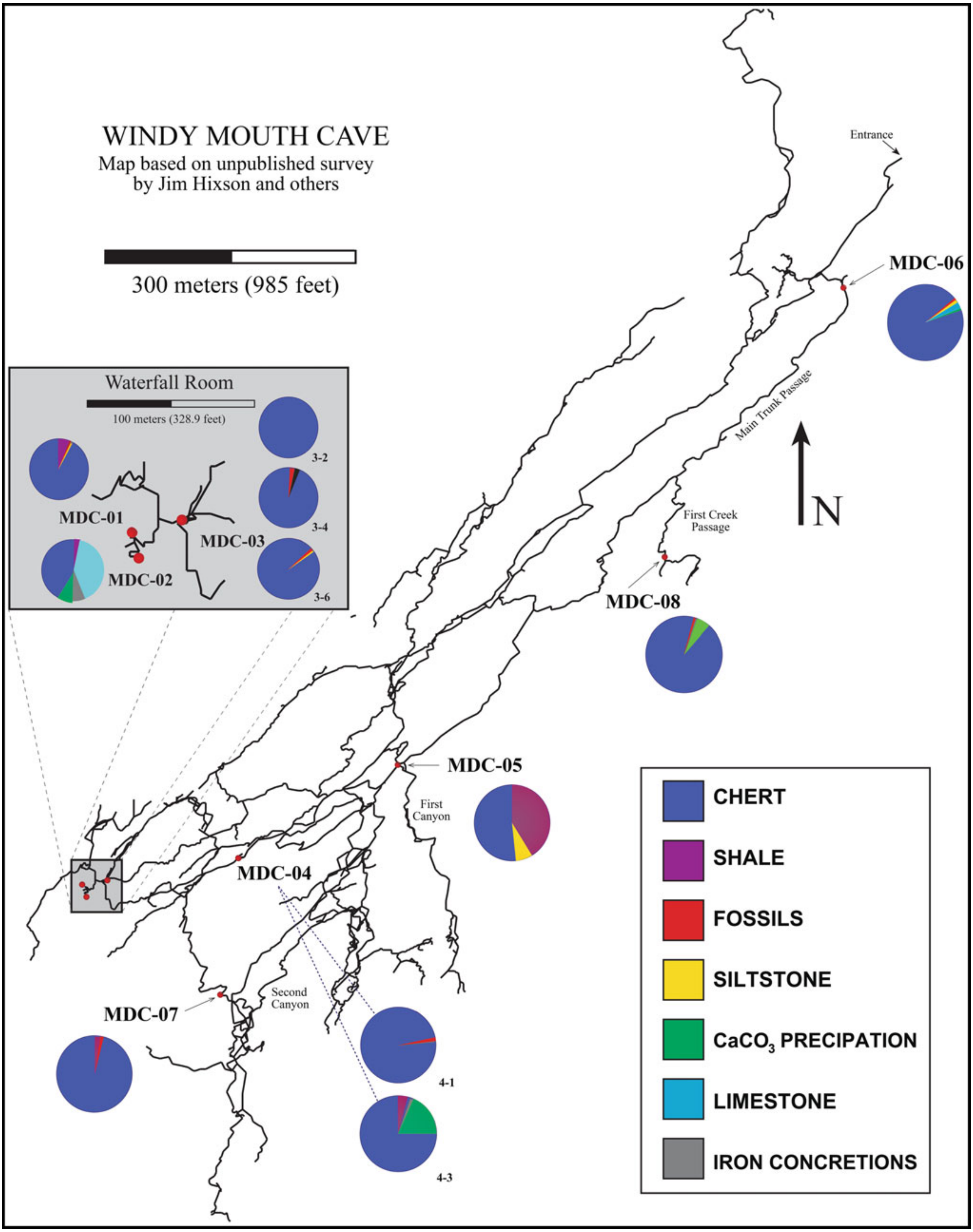

Fig. 15.17 Map showing distribution of coarse fragment lithologies throughout the cave (Curry 2002)

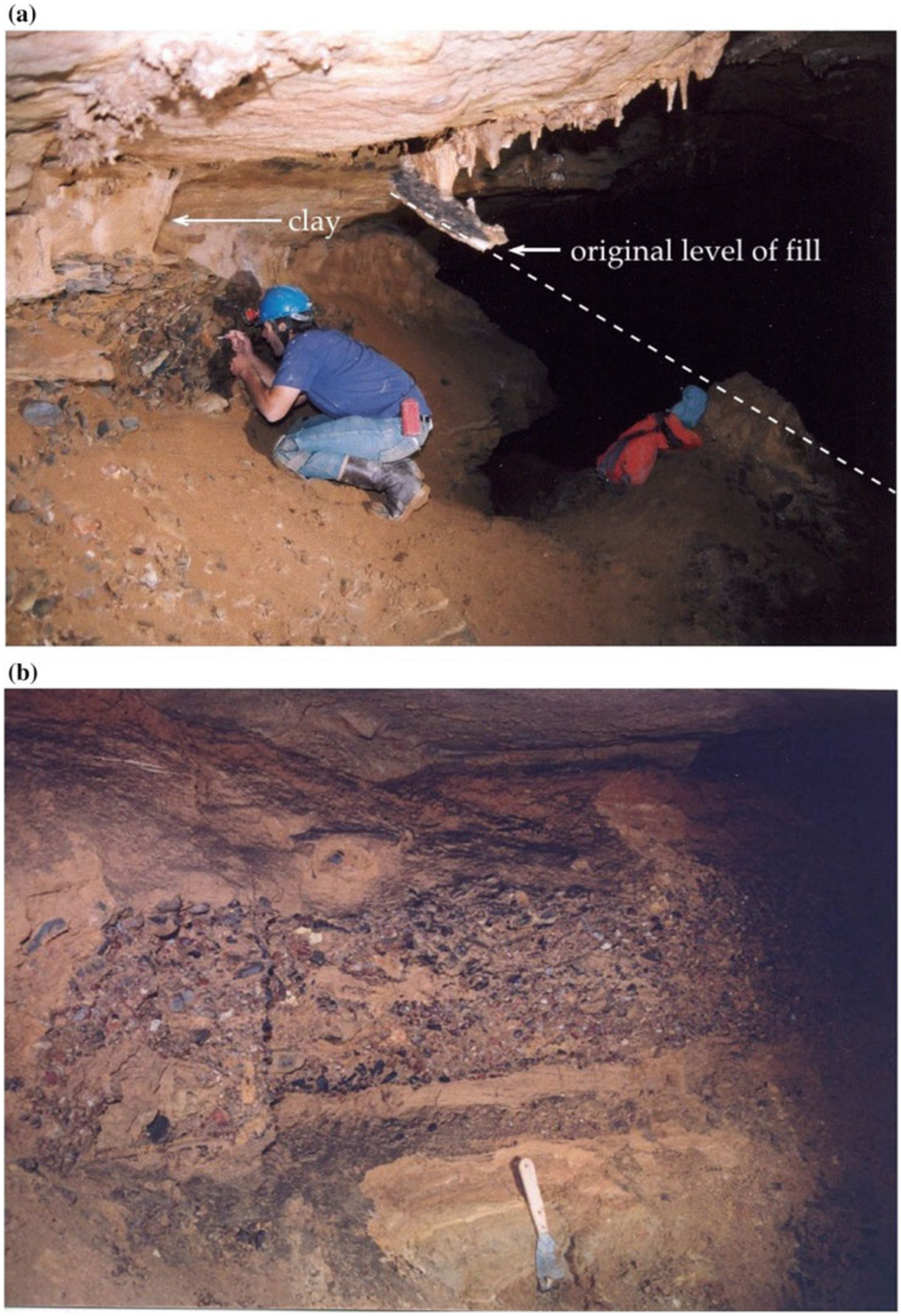

Fig. 15.18 Photographs of coarse sediment deposits in Windy Mouth Cave. **a** Sediment deposits in the trunk passage; note that erosion of the material has left a flowstone/column suspended above cave floor. **b** Gravel/clay deposits in the Waterfall Room. Photographs by I.D. Sasowsky

of the cave where the entrance passage ends has effectively removed flood sediments beyond the entrance passage. This implies that the absence of flood deposits in the remainder of the cave may represent postcave formation hydrologic activity and thus would not represent the period of active cave formation.

The fluvial history of Windy Mouth Cave is complex. The interbedded coarse and fine-grained deposits in the cave suggest episodic aggradation, flooding, and excavation. Aggradation of sediments indicates a net rise in base level or an increased sediment supply from the surface. When conduits became filled with sediment, flow was restricted, and

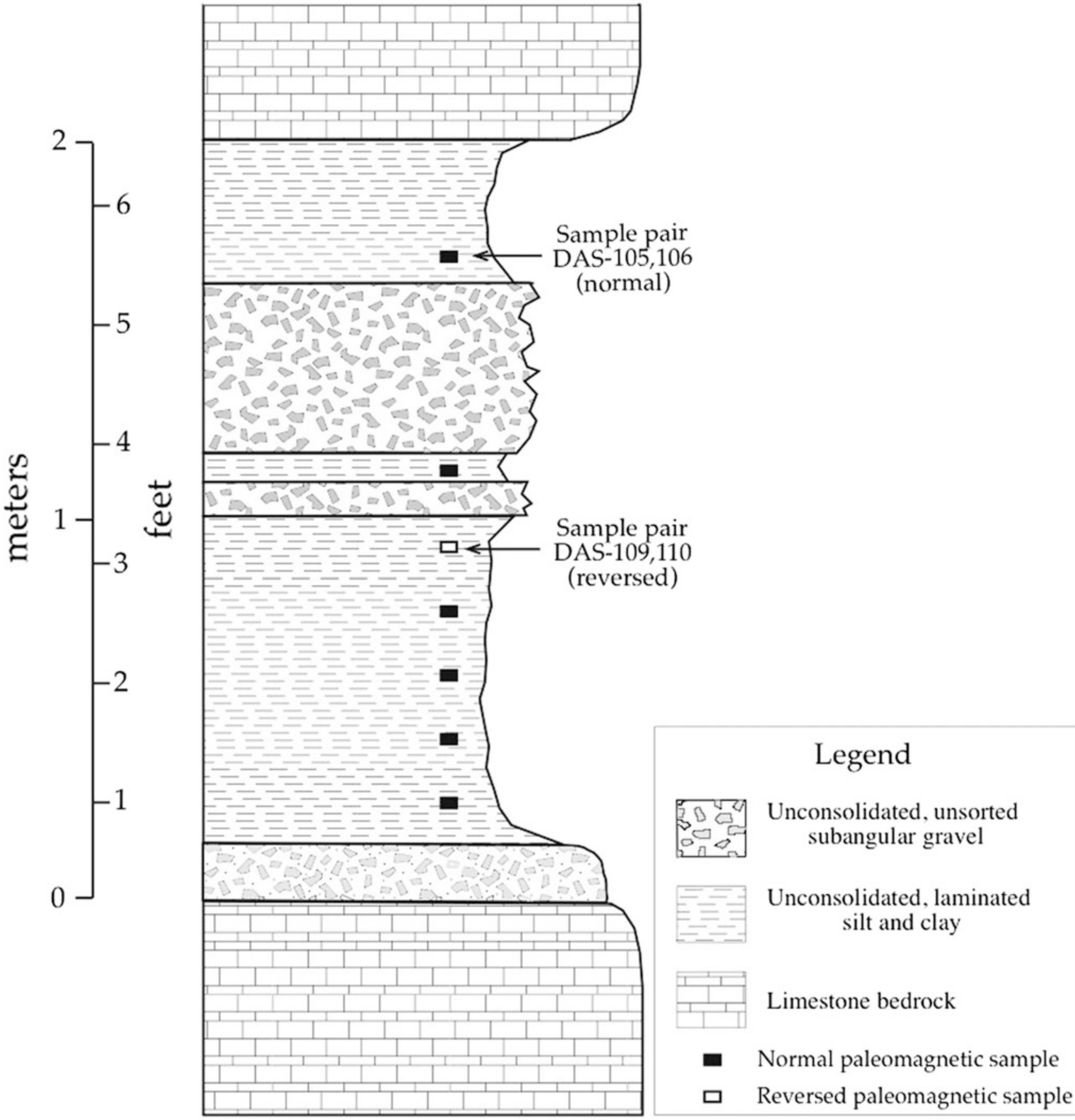

Fig. 15.19 Stratigraphic column of fluvial deposits in the Waterfall Room (Shank 2002)

fine-grained clasts settled out near the ceiling of the conduit. Subsequent lowering of base level, and thus an increase in hydraulic gradient through the conduits, generated high-velocity flow and excavation of aggraded deposits. Paleoflow indicators such as imbrications on gravel deposits are interpreted to show that flow direction was unidirectional, toward the spring mouth.

15.5.3 Paleomagnetism of Clastic Sediments

Paleomagnetic samples of fine-grained clastic cave sediments samples were taken from various locations throughout Windy Mouth Cave where the following criteria could be met: (1) sediments were relatively undisturbed or "in situ," (2) sediments were fluvial/clastic in nature (i.e., they were deposited by very low-velocity streams and do not represent insoluble residue weathered from the host limestone), and (3) they should be fine-grained (silts and clays) and preferably thinly bedded or laminated.

Twenty sample pairs (40 samples) were collected in spatially oriented plastic cubes according to methods described in Sasowsky et al. (1995). Stratigraphically equivalent pairs were taken to insure accuracy of analytical results. Details are found in Shank (2002), and results are discussed below.

The samples all provided paleomagnetic signals of high fidelity (Fig. 15.20). Best-line fitting shows good clustering of normal directions and consistency in the reversed sample directions (Fig. 15.21). The results support the idea that most of the cave was developed since the last major reversal of the earth's geomagnetic field since most samples are of normal polarity. A lone pair of magnetically reversed sediments (Fig. 15.19) was found near the bottom of the most extensive deposit of clastic sediments in the cave.

15.5.4 Landscape Evolution

The observed magnetic reversal implies that trunk passages in Windy Mouth Cave were active prior to 788 ka, thus close to the base level as it existed at that time. This would place the Greenbrier River 30 m (100 ft) above its present average river bed elevation of 490 m (1610 ft). Therefore, the river has incised 30 m (100 ft) below the present elevation of the spring mouth over the past 788,000 years. The average incision rate is then 39 mm/ka (39 M/Ma). This rate is comparable to others calculated for other similar karst terrains in the New River, Virginia, 27 mm/ka (Granger et al. 1997), the Obey River of Tennessee, 30 mm/ka (Anthony and Granger 2004), the Cheat River, West Virginia, 56–62 nm/ka (Springer et al. 1997), and the Green River, Kentucky, 30 mm/ka (Granger et al. 2001).

The river incision rate is based on two assumptions: (1) Windy Mouth Cave is a water table-type cave that was formed when base level (Greenbrier River) was at the same elevation as the cave entrance (spring mouth); (2) the paleomagnetic reversal located in the Waterfall Room sediments resulted from deposition of the clay unit during the Matuyama Reversed Chron, near the boundary with the Brunhes Normal Chron.

15.6 Present Hydrology and Hydrochemistry

The modern-day hydrology of Windy Mouth Cave contrasts sharply with that of the past. There is no indication that coarse clastic materials are currently being carried into the cave. Modern stream flows, although minor in comparison to paleostreams, continue to flow along pathways that began to form during the earlier stages of cave development.

Water samples were taken from the two most accessible streams in the cave. Sample locations were First Creek (sample# 200) and the Waterfall Room (sample# WR1). These samples were collected during the near-drought conditions in 2001 that created unusually low flow conditions in the cave streams. Active streams in the cave are typically found at First Creek, First Canyon, Second Canyon, and the Waterfall Room. The conditions that existed during this study reduced flow in the canyons to almost zero. Details on field and lab methods are given in Shank (2002).

Although the cave system is largely abandoned hydrologically, active streams that persist in the cave contain water that is drained from the Big Levels surface and therefore the cave system represents the nature of water in the drainage basin. Delineation of flow paths from the surface and through the cave is important to establish the physical boundaries of the drainage basin and potential contaminant transport pathways through the system.

Within the cave, First Creek is a relatively small stream, <30 L/s (<8 gallon/s) that can be traced upstream to a large dome room where it flows into the cave from the eastern side of the ceiling, >11 m (35 ft) above the floor. The existence of the dome is attributed to the stream flowing along a near vertical joint that strikes N45°E.

The dome was formed as dissolutionally aggressive water entered the groundwater system from the sinkhole located almost directly above the dome room (Fig. 15.11). A shaley, dolomitic unit forms the base of the cascade and provides a resistant bed along which the water flows into the main trunk passage. The stream flows north along First Creek Passage, the access passage to the dome room, until the passage terminates at a junction with the main trunk passage. First Creek then turns northeast and flows down the main trunk passage. The stream disappears into a non-navigable opening in the floor, just a few meters from the water sampling location.

Chemical analyses of the water in First Creek (Table 15.1) indicate a relatively short residence time and minimal natural filtration. The water is undersaturated with respect to calcite and dolomite. Given the low flow conditions that existed at the time of sampling, one would expect that these saturation values to be at their maximum. With increased flow, residence time would decrease and thus water would be even less saturated with calcite and dolomite. Negative saturation indices (SI values) are indicative of a short residence time and/or direct recharge for groundwater (White 1988).

Elevated levels of nitrate in First Creek are compared with those higher nitrate levels found in the study area by Ogden (1976), Heller (1980) and Davis (1999). High nitrate levels are indicative of the lack of natural filtration of animal waste and fertilizers from the agricultural land on the

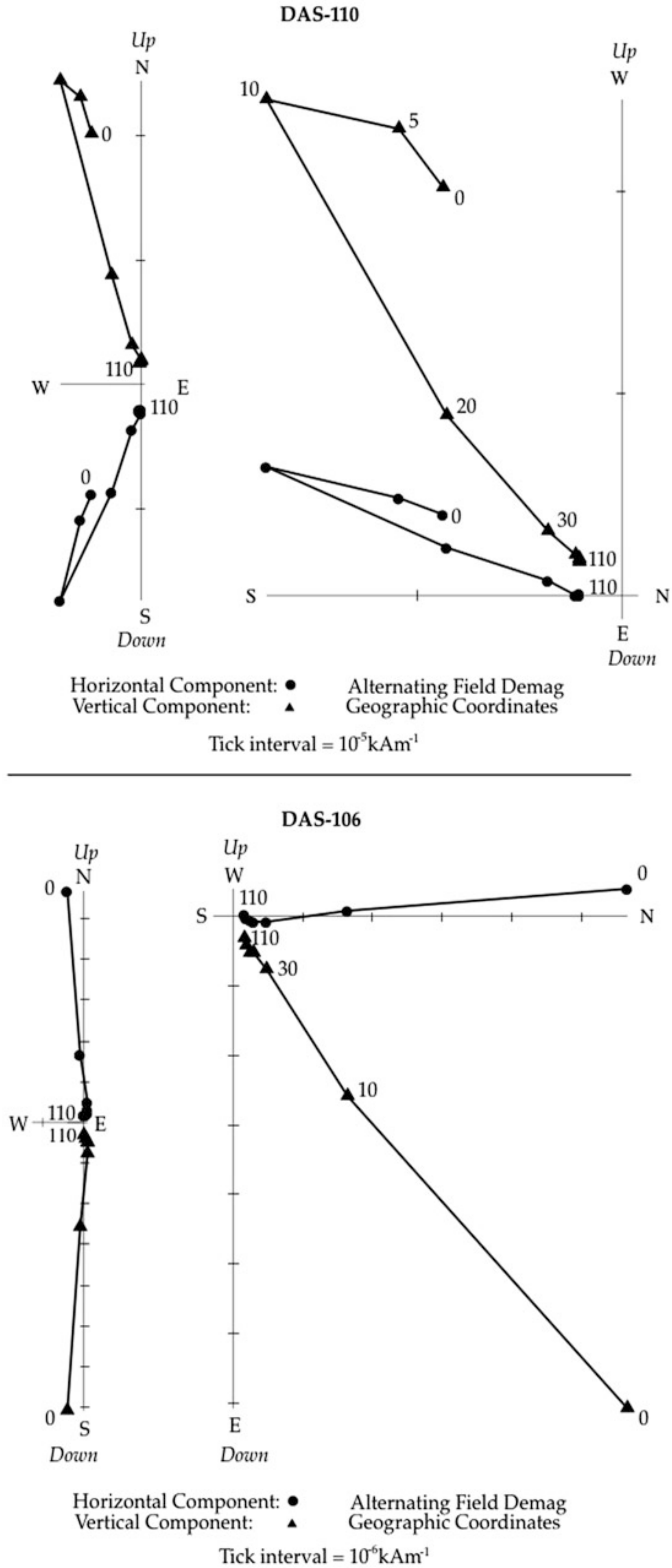

Fig. 15.20 Zijderveld diagrams showing typical reverse (*top*) and normal (*bottom*) polarity samples

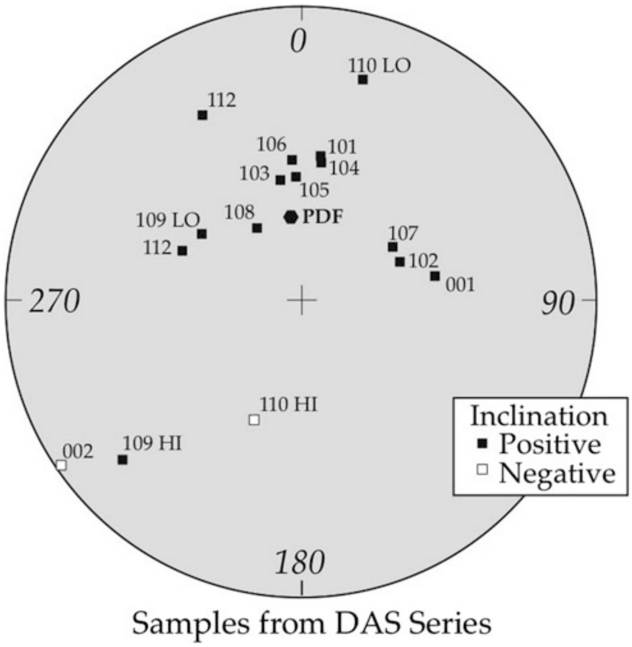

Fig. 15.21 Pole plot of paleomagnetic directions

surface. There also may be a concentrating effect in the waters due to the low flow conditions that existed during sampling.

The Waterfall Room stream is chemically very similar to First Creek. It had a slightly higher discharge during the time of sampling. Negative SI values and elevated nitrate levels in the Waterfall Stream also indicate short residence time and lack of natural filtration of waters (Table 15.1).

The falls are formed as the stream cascades over steeply dipping beds associated with the thrust fault in the Waterfall Room. Massive breakdown piles obscure the downstream reaches of the stream, but it appears to flow beneath the established main level of the cave. There are multiple sources to the stream, but the majority of flow comes from a stream in the upper levels of the cave that cannot be traced to its origin. However, there are several sinkholes located on the surface above the southern reaches of the cave where the stream appears to originate from (Fig. 15.11).

The stream in Second Canyon was not active during this investigation and therefore could not be sampled; however, it is known to flow when precipitation levels are considered normal. The source of Second Canyon stream is a large asymmetrical sinkhole located at the terminus of the passage on the surface (Fig. 15.11). The upstream passage terminates underground at a large impassable pile of breakdown. The Second Canyon stream flows north, sub-parallel to dip, but cannot be traced beyond the surveyed portion of the cave. It is inferred from that the stream continues to flow north, incising below the known levels of the cave, toward base level.

Drainage through Windy Mouth Cave is classified as a part of the Scott Hollow drainage basin (Jones 1997). However, the fact that it contains an active stream network with drainage from the surface suggests that Windy Mouth Cave is its own autonomous drainage basin. Calculations

Table 15.1 Aqueous geochemical results. Elemental and TDS values are in mg/L

	Waterfall room	First creek
HCO_3^-	208	202
pH	6.99	6.98
Temp (°C)	12.1	11.2
Cond. (µS)	403	420
Sat. index	−0.469	−0.550
Cl^{-1}	4.05	4.67
SO_4^{-2}	2.95	3.02
NO_3^-	22.62	16.25
PO_4^{-2}	0.197	0.126
Al^{+3}	0	0.01
Ca^{+2}	70.82	63.63
Fe^{+2}	0.01	0
Mg^{+2}	6.82	8.31
Mn^{+2}	0	0
SiO_2	9.14	9.25
K^+	1.25	1.34
Na^+	2.60	3.80
TDS	319.31	303.16
CBE (%)	+0.26	−0.05

yield a drainage basin area for Windy Mouth Cave of 1.95 km^2 (0.75 $mile^2$).

Water chemistry data reinforce the inferences of short residence time and minimal filtration. The stream in Windy Mouth Cave is undersaturated with respect to calcite and dolomite, indicating minimal exposure time to limestone and/or dolostone and continued cave development at lower levels in the bedrock. Elevated levels of nitrate indicate a lack of natural filtration that results from direct input of water into the cave.

Windy Mouth Cave is an extensive cave system that developed when the Scott Hollow drainage basin was different than it is today. Paleoinput and drainage basin size of the cave was substantially greater during its development as evidenced by the size and extent of conduits. Drainage was pirated from Windy Mouth Cave when the Greenbrier River incised beneath the current level of its entrance. Drainage was diverted to the west, into Scott Hollow and other caves that are located on the western limb of the Sinks Grove Anticline, as a result of base-level lowering. Modern discharge from the Scott Hollow drainage basin is from river level springs on the Greenbrier River downstream and west of Windy Mouth Cave.

15.7 Summary

The formation of Windy Mouth Cave was controlled by a combination of structural and hydrologic factors. Stratigraphy also had a role in cave development, albeit to a lesser extent. The cave system is almost completely abandoned hydrologically; however, extensive fluvial sediment deposits in conduits indicate that it was an important route for groundwater from the Scott Hollow drainage basin in the past.

Geologic structure provided a pre-solutional network of faults, joints, and bedding planes in the bedrock that was later exploited by groundwater flux. The cave is situated on the western limb of the Sinks Grove Anticline. Beds dip gently to the northwest and strike generally N40–50°E in the cave. Conduits are primarily oriented along strike, while a smaller component is oriented sub-parallel to dip. Bedding planes provided the most important pre-dissolutional fissures, although closed loops are formed along joints.

Faults are locally important to cave system hydrology. A fault zone located in the southern reaches of Windy Mouth Cave connects the upper and main levels (Fig. 15.13). The fault plane breaches an impermeable layer of bedded chert, allowing water to descend through the Waterfall Room and into breakdown on the floor. The faulting and related fracturing extend upward an estimated 30 m (100 ft) into the overlying strata, creating an opening for water to enter the system from the surface. At least three such domes exist in the cave in the Waterfall Room, First Creek, and an unnamed dome in the upper levels.

In plan view, Windy Mouth Cave appears as a branchwork system similar to that described by Palmer (1991). A minor anastomotic morphological element is overprinted on the dominant dendritic pattern. The pattern is suggestive of primary recharge originating from discrete input points such as sinkholes, while in the past focused recharge may have entered the cave from a sinking stream. Imbricated gravel bars in the trunk passage of the cave support the interpretation that considerable direct recharge was received via a sinking stream.

Trunk conduits originated as phreatic tubes that directly connected to the spring mouth (entrance). Tributary conduits were vadose canyons that ran down dip until they reached the phreatic trunk where they altered course and ran along strike.

There are three levels in the cave (Fig. 15.22). Upper levels are phreatic tubes that are connected to small vadose canyons at their origin. Conduit cross-section morphology is complicated by interbedded chert and shale layers in the Hillsdale Limestone host rock. The impermeable layers form resistant ledges that split individual conduits into multiple levels. Fluvial sediment deposits that are suitable for paleomagnetic analyses were not found in the upper levels, although the position and hydrologic genesis of the system suggest that the upper levels were formed first and are thus the oldest portion of the cave.

The main levels (trunk conduits) are the most extensively developed and comprise the majority of conduits in the cave. They are primarily phreatic tubes that have been reshaped by a transition to vadose conditions that resulted from base-level lowering.

Lower-order infeeders are connected to the higher-order trunks to form a dendritic drainage pattern in the main levels. The infeeders are well-developed vadose canyons that intersect and are incised below the trunk conduits. The junctions between First and Second Canyons with the trunk are important because they illustrate the hydrologic decoupling between the trunk conduit and vadose canyons. Originally, the vadose canyons originating in the south acted as infeeder streams that descended down dip into the phreatic zone where they intersected the trunk conduit. As base level lowered, the vadose conduits incised below the trunk and consequently became hydrologically decoupled by diverting drainage into the newly forming conduits beneath. Currently, the canyons are occupied by small streams that discharge through springs at river level.

Fluvial sediment deposits in the main levels consist of gravel, sand, and clay. Coarse deposits are generally unsorted and occasionally imbricated. They represent high discharge flow regimes that probably originated from a sinking stream input source. Fine-grained deposits are

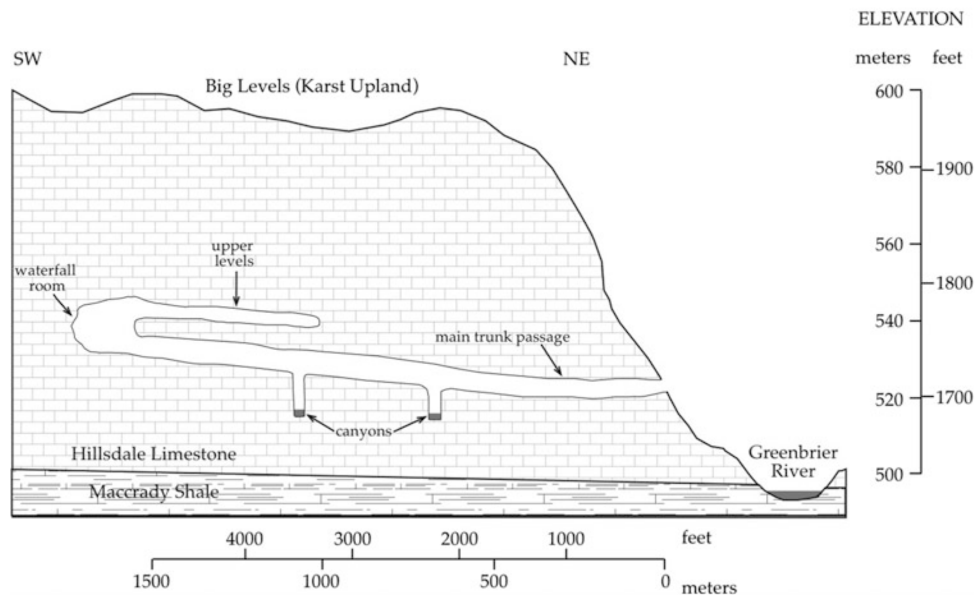

Fig. 15.22 Simplified longitudinal cross section of Windy Mouth Cave that illustrates the distribution of different levels within the cave and relation to Greenbrier River (Shank 2002)

typically found at or near the ceiling, which indicates sediment aggradation until the conduits were choked with sediment, restricting the flow to quiet water conditions. The final stage of cave sediment evolution was a high discharge stream that excavated most of the sediments. This probably resulted from a high hydraulic gradient caused by base-level lowering that excavated most of the deposits.

A magnetically reversed sample found near the base one section was presumably deposited during the reversal of the geomagnetic field which ended at 788 ka. This sets the minimum age of the cave. Because Windy Mouth Cave is a water table cave, formed when local base level was near the trunk conduits, the assumption is made that the reversed sediments were deposited when the river bed was 30 m (100 ft) above its current elevation. Conversely, the river has incised 30 m (100 ft) since those reversed sediments were deposited. This yields an average incision rate for the Greenbrier River of 0.04 m/ka (1.6 in./ka).

The modern-day hydrology is markedly different than in the past. The drainage basin area is much smaller (~ 2 km^2), and the resident streams have considerably less discharge. Much of the drainage has been pirated to the Scott Hollow drainage basin located south and west of Windy Mouth Cave. Current stream sources are sinkholes located on the surface above the origins of active cave streams (Fig. 15.11). Chemical analyses of cave water indicate a short residence time and minimal filtration evidenced by negative SI (calcite) and slightly elevated levels of nitrate.

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