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KARST LANDFORMS AND DRAINAGE BASIN EVOLUTION IN THE OBEY RIVER BASIN, NORTH-CENTRAL TENNESSEE, U.S.A.

ELIZABETH L.WHITE and WILLIAM B. WHITE

Department of Civil Engineering, Materials Research Laboratory, The Pennsylvania State University, University Park, PA 16802 (U.S.A.)
Department of Geosciences, Materials Research Laboratory, The Pennsylvania State University, University Park, PA 16802 (U.S.A.)

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ABSTRACT

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An extensive karst landscape is developed on the Mississippian limestones of the dissected western margin of the Cumberland Plateau. Surface streams rising on the clastic rocks of the Cumberland Plateau flow down the escarpment and sink along its slopes at the upper contact of the Bangor Limestone. Some surface channels are continuous across the karst of the lower slopes while others terminate in blind valleys as swallow holes. At the base of the escarpment is an upland surface of doline karst developed in the Monteagle and St. Louis limestones at an elevation of 300—330 m. It consists of 1—5 km^2 shallow blind valleys and uvala-like closed depressions along with many smaller dolines. The internal drainage from the dolines and from the sinking streams is perched on the impermeable Warsaw Formation and emerges as contact springs on the inner gorges of the rivers which have cut deep narrow valleys below the level of the upland surface.

Tributary streams to the Wolf, Obey and Roaring rivers (tributaries of the Cumberland River in north-central Tennessee) were analysed by fitting their longitudinal profiles to exponential and logarithmic functions. Linear segments of semilogarithmic plots permitted extrapolating both active streams and underdrained stream channels through the doline karst. The presently active streams extrapolated through the karst emerge at grade with the present-day base-level streams. Underdrained segments of the tributary valleys extrapolate to the upland surface and suggest that dry karst valleys can be interpreted much like river terraces. The development of interior drainage appears to be a much faster process than is the adjustment of the surface drainage.

INTRODUCTION

The dissected margin of the Cumberland Plateau in Tennessee, northern Alabama and eastern Kentucky is a region of well-developed fluvio-karst. The underground water circulation system is shallow and well-integrated with surface drainage. Surface streams rise on the clastic caprock of the Cumberland Plateau, flow down the steep slopes of the plateau margins, and

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TABLE I

Characteristics of the four study basins

	Basin area (km^2)	Karst area (km^2)	Doline input* (km^2)	Sinking stream input* (km^2)
Wolf R.	274	117	6.0	3.8
East Fork, Obey R.	523	34	7.1	15.2
West Fork, Obey R.	298	79	18.6	74.6
Roaring R.	204	134	57.5	19.4

*Doline input and sinking stream inputs are the total areas of catchment that drain internally through sinking streams or as internal runoff through dolines.

frequently sink at the upper contact of the limestone. The water re-emerges from springs at base level or at the contact with insoluble rocks that underlie the limestone. In some drainage basins, dry valleys extend across the karst and in others all traces of the surface drainage have been obliterated.

The plateau margin karst of the Cumberlands is an attractive place to study the inter-relationships between surface and sub-surface drainage and between the characteristic profiles of normal fluvial valleys and those that have been disrupted by karstic processes. The karstic portion of the drainage basins occurs mostly in the downstream reaches but at higher elevation than the perennial surface master streams. Thus, there is a choice of many tributaries that cross the karst either as surface streams or as sub-surface drainage, and comparisons can be made.

This study will report results from four drainage basins located in Overton and Fentress counties in north-central Tennessee. These are the Wolf River to the north, the East and West Forks of the Obey River in the central part of the area, and Roaring River to the southwest (Fig. 1). All four basins are tributaries of the Cumberland River. The runoff characteristics of these basins were studied previously as part of an investigation of flood-flow (White, 1976) and low-flow (White, 1977) characteristics of karstic Appalachian drainage basins. Some of the basin characteristics are summarized in Table I.

This paper is part of a continuing study of the Appalachian karst (White and White, 1979). It addresses first the description and hydrogeologic setting of the plateau margin karst. Then follows an analysis of stream profiles. We conclude that drainage systems maintain their profiles through the karst and that the development of sub-surface drainage routes is a more rapid process than is the development of longitudinal stream profiles.

THE PLATEAU MARGIN KARST

Hydrogeologic setting

Fig. 2 gives the general stratigraphic and structural situation. The youngest rock exposed is the Pennsylvanian sandstones which form the caprock

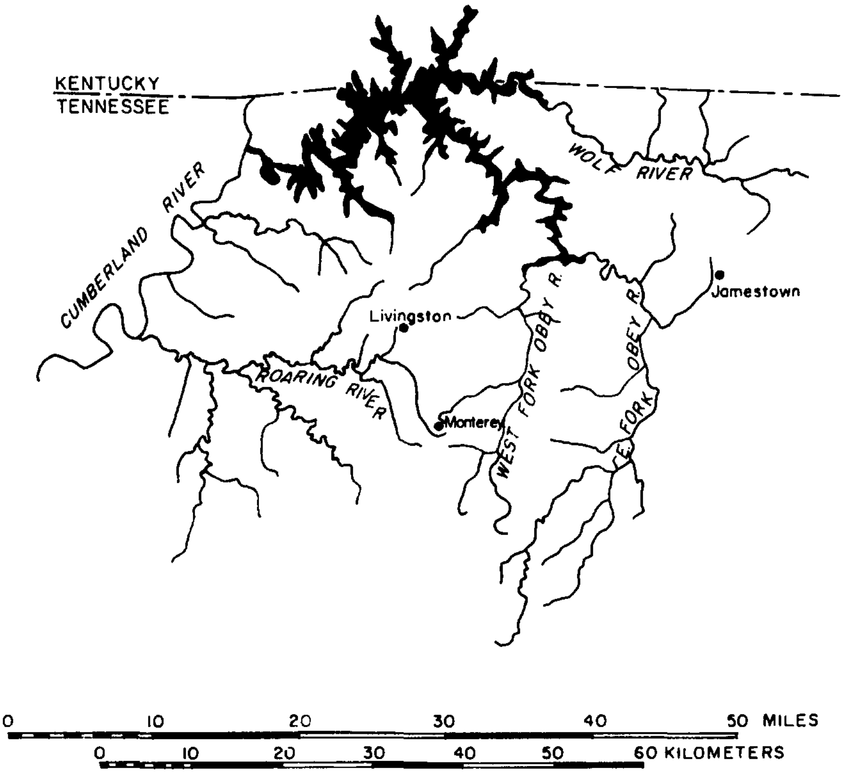


Fig. 1. Location map showing the tributaries of the Cumberland River in north-central Tennessee.

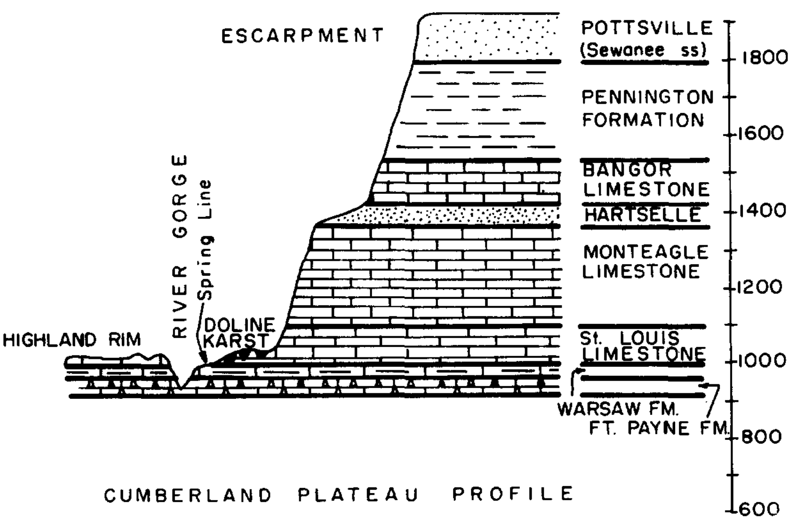


Fig. 2. Geologic cross-section through the Cumberland Escarpment.

supporting the Cumberland Plateau and are responsible for the very sharp break in slope between the top of the plateau and the base of the escarpment. Beneath the sandstone lies the Pennington Formation, a mixed sequence of limestone units one to a few meters thick, and shale and siltstone units. The Pennington is not karstic although some caves and springs are known within the limestone units. On the escarpment slope below the Pennington is located the Mississippian Bangor Limestone. This is a massive thick-bedded crystalline low-magnesium limestone, well-suited for the development of solution weathering. The Bangor is separated from the underlying Monteagle Limestone by the Hartselle Sandstone which in this portion of Tennessee ranges from 10 to 15 m in thickness. The Hartselle is generally resistant and results in a pronounced topographic bench on the side of the escarpment and is responsible for a series of flat-topped foothills.

The Bangor and the Monteagle limestones together make up the lower half of the escarpment slope. The St. Louis Limestone crops out near the base of the escarpment and underlies most of the upland surface that parallels the river valleys and underlies many of the flat-floored coves that are incised into the Cumberland Plateau.

Below the cavernous limestone sequence is the Warsaw Formation which is exposed in the downstream reaches of the drainage basins where it crops out along the sides of the river gorges. Finally, near the gages on the four rivers, the Fort Payne Formation is exposed. The St. Louis Limestone is a somewhat cherty but generally massive and karstic limestone whereas the Warsaw Formation although it contains carbonate units is very shaley and cherty and generally acts as an aquiclude or karst basis limiting the downward percolation of the water that drains through the carbonate section. The Fort Payne is mainly shale and chert, and acts as a final seal.

The rocks as shown in Fig. 2 are nearly flat-lying and dip gently into the plateau. The rocks are well-jointed. The plateau itself slopes gently to the northeast toward the center of the structural trough that makes up the Pittsburgh— Huntington Basin.

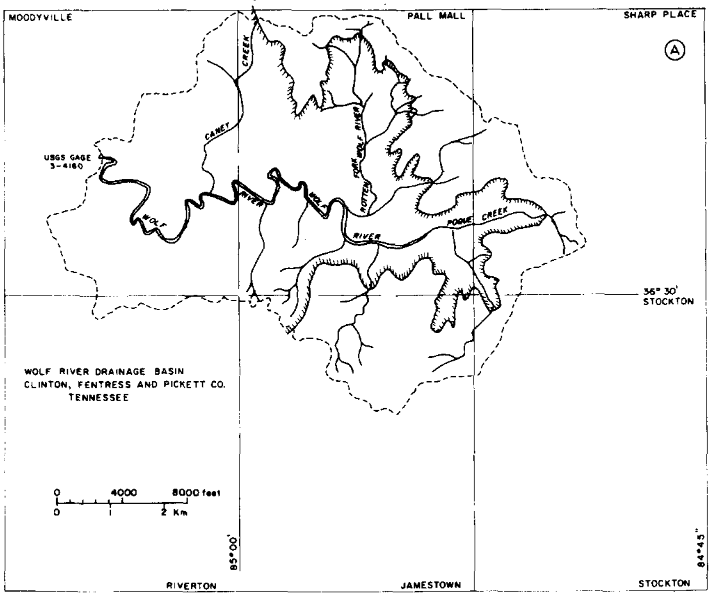
Fig. 3 shows the outlines of the Wolf River and Obey River basins. The drainage divide is sketched. Wolf River has its catchment around the margins of the prominently developed escarpment. Various tributaries such as Poque Creek (the longest collector) head on the escarpment, flow over the steep escarpment down very steep river valleys and onto a rather prominent and well-developed flood plain and thence westward to the gage. The East Fork of the Obey lies on the Cumberland Escarpment and the Obey River valley is a steep-walled gorge which cuts down from the plateau surface and emerges onto the Highland Rim surface. The river more or less parallels the edge of the escarpment. The deep cove formed by the East Fork of the Obey is underlain by the limestones and there is developed a karst surface into which the river has cut still further. The West Fork of the Obey lies almost parallel with the edge of the escarpment and so the topography of the West Fork valley is really quite different. The plateau is almost completely dissected. Remnants occur as isolated mesa-like ridges. The basin of the West Fork has extremely rugged topography, underlain by limestone with extensive doline karst development. The West Fork has also developed a narrow flood plain at 275 m (900 ft.) somewhat below the Highland Rim surface.

Physiographic Setting

The plateau margin karst lies on the boundary between two physiographic provinces: the Cumberland Plateau and the Highland Rim. The Cumberland Plateau in north-central Tennessee is a structural surface supported by the Pottsville sandstones at an elevation of 500—600 m. The Highland Rim is a rolling upland at an elevation of ~ 300 m that can be traced around the Nashville Dome in central Tennessee. The floors of the coves that extend into the Cumberland Plateau are generally at the same elevation as the Highland Rim. The Cumberland River and its tributaries have cut ~ 100 m into the Highland Rim surface. Fig. 4 shows the elevations of these major surfaces. The Wolf River flood plain is ~ 50 m lower than the average elevation of the Highland Rim and the doline karst that bounds the rivers seems to slope from this elevation in the northeast up to the Highland Rim, which is best displayed in the two southwestern basins.

Landforms

In common with most of the Appalachian karst, there are three main categories of landforms in the study area: closed-depression features, under-



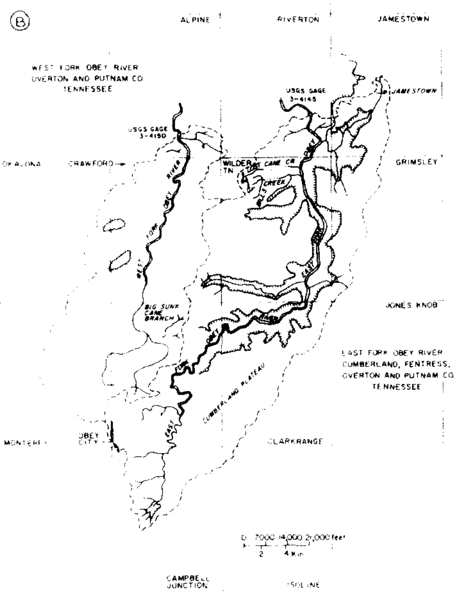


Fig. 3. Wolf River drainage basin (A) and Obey River drainage basin (B). Rectangles identify U.S.G.S. 7.5′ quadrangles.

drained valleys, and caves.

The closed depressions form two main groups. The upland surface where the rivers flow out of the coves of the Cumberland Escarpment has developed extensive but a shallow doline karst on the St. Louis limestone. Most of the dolines range from 10 to 30 m in diameter and 50 to 20 m in depth. These dolines appear to drain through localized and shallow systems to springs that can be observed at the St. Louis—Warsaw contact along the incised valleys of the rivers. In the western basins, the West Fork of the Obey and Roaring rivers, are much larger dolines and related closed-depression features. The largest of these is Big Sunk Cane (Fig. 5). It is more than 1 km in diameter but rather shallow. Feeding into it are several tributary streams including Sunk Cane Branch to be discussed later.

The cave systems of the area were not investigated during the present study. A number of smaller ones are listed by Barr (1961) and Matthews (1971). Several very large cave systems have been discovered in the past decade. Wolf River Cave has at this time a reported length of 12.7 km. In the gorge of the East Fork Obey are found the 11.3-km Zarathustra'a Cave (Deane, 1977) and the Xanadu—Alph—Zoroaster cave system (Clark et al., 1981) where there is an accumulated length of more than 15 km. The Xanadu system occurs along the flanks of Lint's Cove, a tributary to the Obey about halfway along the gorge and immediately below the Hartselle Sandstone.

The undergound drainage systems in this area follow rather well the model put forth by Crawford (1980). Streams which rise on the sandstone-capped

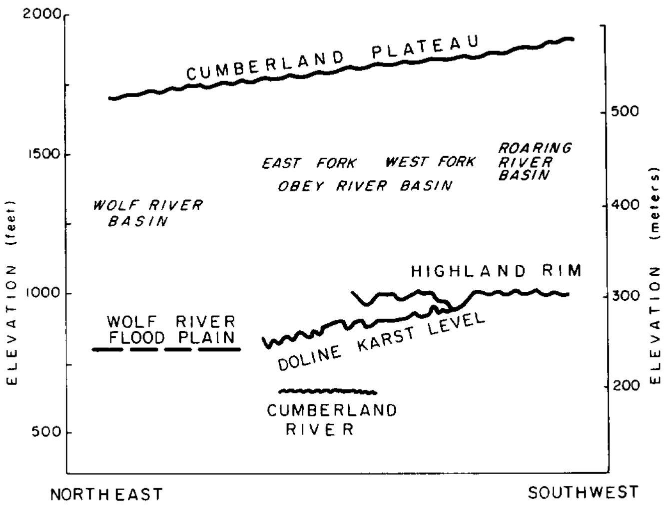


Fig. 4. The principal erosion surfaces in north-central Tennessee.

plateau flow down the slope and often go undergound and remerge over very short distances in the limestone units of the Pennington Formation. They commonly sink completely at the contact with the Bangor Limestone. Instead of a gradual slope, the underground drainage takes on a stair-step pattern in which the vertical parts are vertical shafts and the horizontal sections are often perched on impermeable beds, especially the Hartselle Formation. Often tributary streams will emerge as springs above the Hartselle, cross it as surface streams, in some places as waterfalls over the Hartselle ledge, and then sink again into the Monteagle Limestone below.

Vertical shafts are often developed directly below the Hartselle and these penetrate the Monteagle Limestone. The small dolines that occur along the Hartselle topographic bench appear to be feeders for lines of vertical shafts.

The larger stream valleys of the Cumberland Escarpment maintain their surface channels and carry water at least during periods of high flow. Most of these streams including the main tributaries of the Obey are underdrained and may not carry water during periods of low flow. Many of the smaller streams occur in karst valleys, the floors of which are interrupted by sinkhole development. The stream channels are discontinuous and terminate in swallow holes in these sinks. All drainage is sub-surface even during flood runoff. Sunk Cane Branch, Lost Cane Creek and Bills Creek, discussed in the next section are of this type.

SURFACE DRAINAGE ACROSS AND THROUGH THE KARST

An analysis was made of the longitudinal profiles of the surface streams that flow down the Cumberland Escarpment and through or across the karst

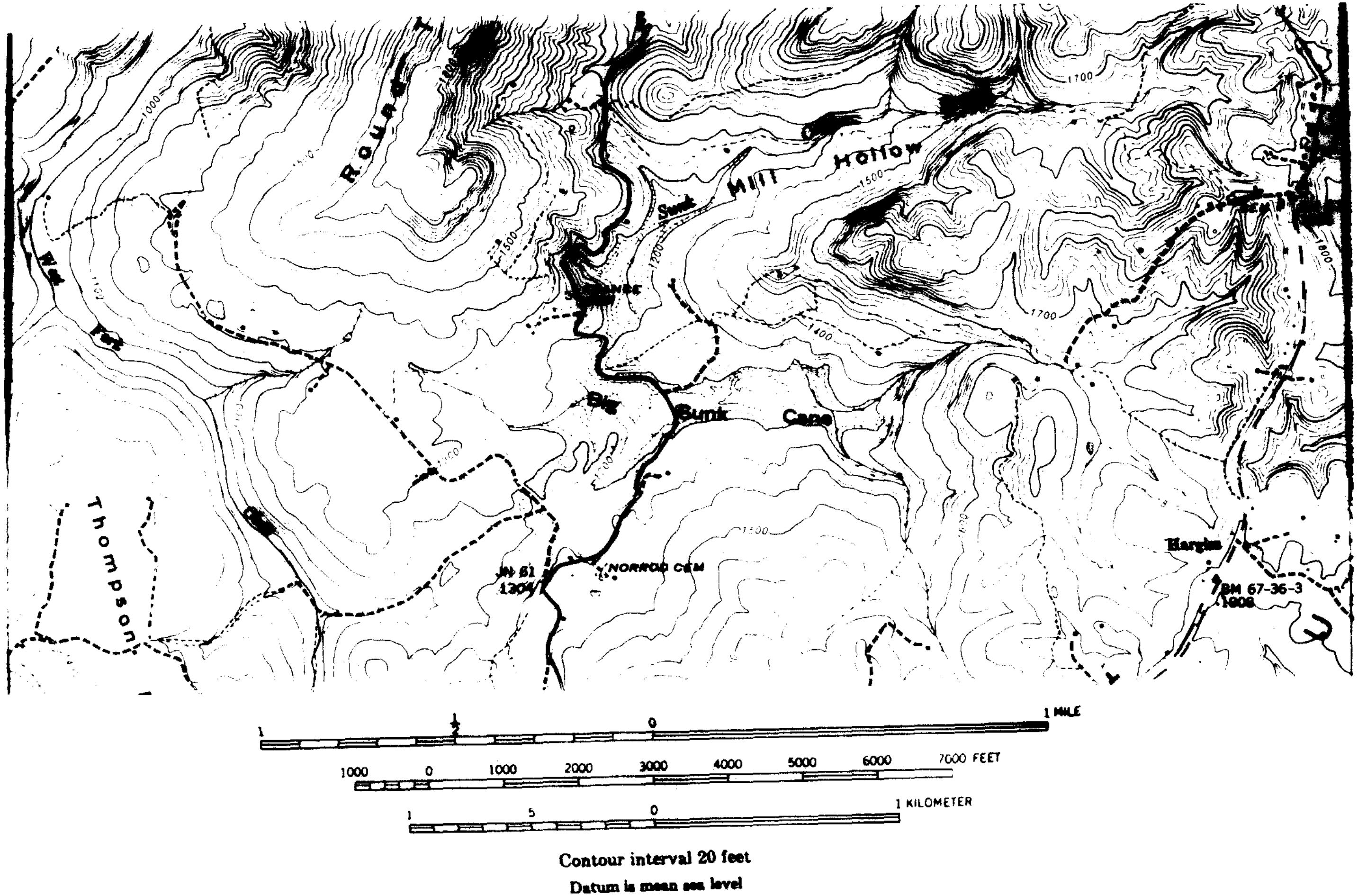


Fig. 5. Big Sunk Cane, an uvala in the doline karst of the West Fork of the Obey River. Taken from U.S. Geological Survey Obey City 7.5′ quadrangle.

to the major rivers. The idea was to describe these profiles by mathematical functions that would permit extrapolation of particular reaches of the stream out to the position of the surface river and to extrapolate the sinking streams across the karst to the rivers. The surface stream bed is interrupted and deranged in the karst but what happens to the subsurface drainage?

The choice of fitting functions offered some difficulty. Most workers have agreed that longitudinal profiles of streams are an exponential function of some sort. Shulits (1941) derived an exponential form for rivers from the Sternberg abrasion law. His slope equation,

$$S = S_0 \exp(ax)$$

has been used as the basis for most later discussions of river profiles (e.g., Yatsu, 1955; Leopold et al., 1964). Hack (1957, 1973) used a logarithmic form for the profile equation:

$$H = C - \ln L$$

which, although exponential in form, is the inverse of the Shulits exponential profile equation.

Most investigations of river profiles have concerned major rivers (e.g., Carlston, 1969). The problem of the present paper is that we are concerned with relatively small tributary systems and questions of reference elevations, origins, and the continuity of slopes at stream junctions must be considered. As a result of these uncertainties, streams were fitted to both equations and although neither gave exactly the desired results, it was possible to carry out the desired extrapolations. Overall, it appears that Hack's logarithmic equation produces better straight-line fits and further, since the origin for the coordinate system is set at the drainage divide, and the other variable is the fall of the river, the equation is more suitable for extrapolation.

The sorts of stream profiles found where karst processes have not disrupted the surface channel are illustrated in Fig. 6 for three streams in the Wolf River basin. The profile of Williams Creek shows the plateau and the edge of the escarpment as a pronounced break in slope. The profile of Williams Creek down the escarpment and out onto the Wolf River flood plain, however, is a smooth concave curve. Poque Creek, which is actually the longest collector of Wolf River has a concave slope throughout its reach. The profile of Poque Creek plots as a single straight line with a small offset at the Hartselle Sandstone when fitted with Hack's logarithmic equation. Bear Branch, in constrast, has a more complex profile with a convex slope in its upper reaches and a concave profile in the lower reaches. No further investigation of this type of profile was made in the present study. All of the tributary streams could be fitted into one of the three reference profiles described above.

The behavior of streams that drain into the karst are illustrated by Bills Creek, Lost Cane Creek and Sunk Cane Branch. In each of these streams there is an actively flowing upper reach near the top of the escarpment, a lower

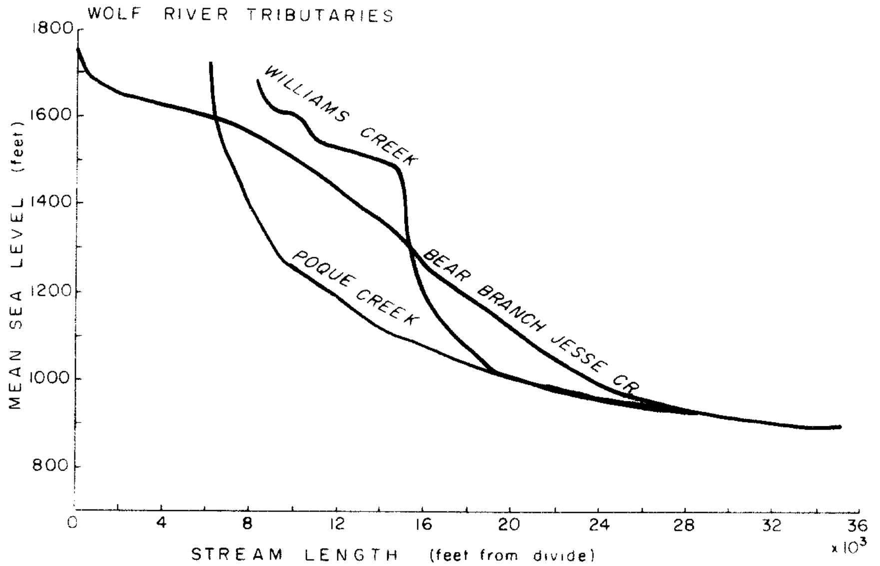


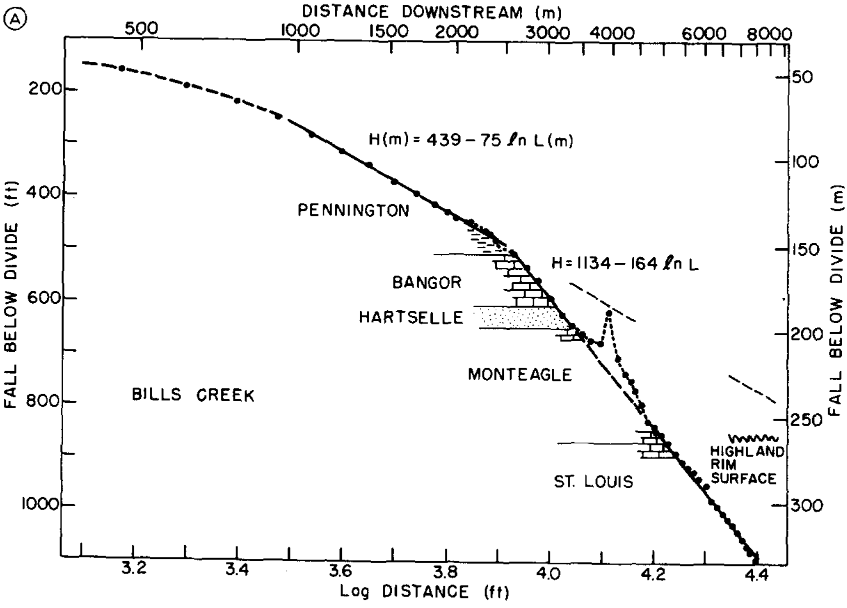
Fig. 6. **Profiles taken along the channel of three tributary streams in the Wolf River basin, scaled directly from topographic maps.**

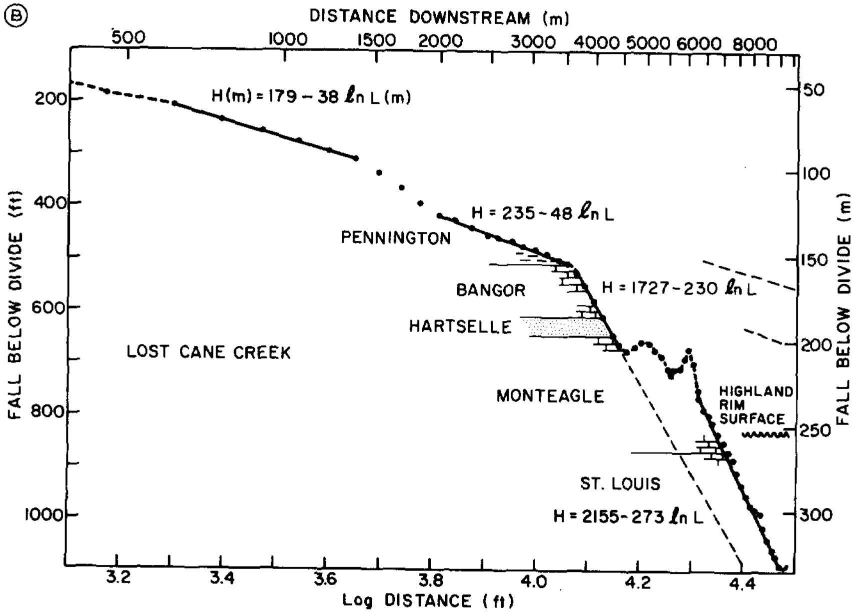
reach that is underdrained or dry, and each terminates in swallow holes in the doline karst so that each may be regarded as flowing in a blind valley.

Fig. 7A shows the logarithmic profile of Bills Creek. The upland reach on the Pennington Formation plots as a straight line down to the Bangor contact where there is an abrupt steepening of the slope. The reach of the stream from the Pennington—Bangor contact to its confluence with the East Fork of the Obey River can be fitted to a single straight line. This logarithmic profile passes under the karst with no offset and no change in slope. Curiously, the crest of the saddle blocking the blind surface valley lies very close to the extension of the upper reach profile. The upper reach profile extends to the Obey River at an elevation of 335 m (~ 1100 ft.) just above the Highland Rim surface. The dolines that disrupt the Bills Creek valley occur directly below the Hartselle Sandstone but there is no apparent break in the drainage profile where the stream bed is extrapolated across the contact and into the karst.

There is a general conclusion here. When active streams from border lands sink into the karst, the profile of the active stream system is maintained through the subsurface. This represents an average profile, of course. In detail, underground streams pass through cave systems by means of open streamways, waterfalls, and sometimes through flooded passages. Stratigraphic and structural barriers control the detail, but on a scale of the entire drainage basin, it appears that hydraulic demands of a uniform profile are met.

The profile of Lost Cane Creek (Fig. 7B) is similar but somewhat more complex. The upstream reach on the Pennington Formation plots as two line segments of similar slope with a small offset between them. Again there is an abrupt steepening of slope at the contact with the Bangor Limestone. Downstream from the contact there is a short steep segment across the Bangor and the Hartselle formations until the stream terminates in a large closed depression. Below the depression, the surface channel continues in a steep-walled valley, the slope of which is parallel to the slope immediately above





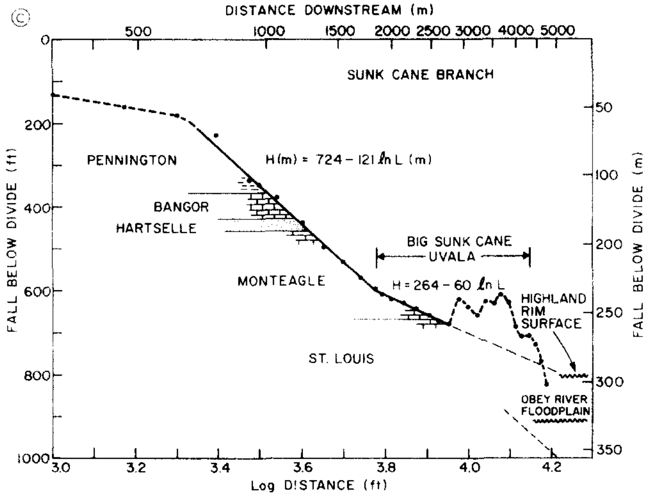


Fig. 7. Profiles of: (A) Bills Creek; (B) Lost Cane Creek; and (C) Sunk Cane Branch, fitted to Hack's logarithmic equation.

the karst but offset from it. The lower reach of the Lost Cane Creek Valley is completely underdrained because of the closed depressions upstream at the Hartselle contact. It appears that the stream bed across the Bangor Limestone is maintaining the same profile that it had earlier when it was continuous with the downstream reach. Although four segments were identified by fitting Hack's logarithmic functions, the two on the Pennington have very similar slopes and the two downstream segments have similar slopes.

Sunk Cane Branch drains from the margin of the plateau into the large closed depression of Big Sunk Cane. The main portion of the channel (Fig. 7C) is linear from the head of the stream to the edge of the closed depression. This stream segment can be described by a single logarithmic function and there are no breaks in slope at any of the bedrock contacts. There is a break in slope at the edge of Big Sunk Cane and the channel continues with a much gentler slope. Three kilometers acrosss the floor of Big Sunk Cane it terminates in a deep sinkhole. The stream segment in the closed depression can also be fitted to a logarithmic function which extrapolates across the depression and reaches the Obey River at an elevation of 310 m (1020 ft.) just about the level of the Highland Rim surface. The extrapolation of the segment of stream above the depression would reach the river at 250 m (820 ft.) considerably deeper than the present-day river channel this far upstream.

CONCLUSIONS

Three tentative conclusions are offered from this examination of stream profiles in fluvio-karst terrain.

(1) Active stream systems maintain, on the average, the profiles and gradients that they would have had if they had been flowing in normal surface channels. Although the details of the subsurface drainage are likely to be controlled by details of the structural and stratigraphic setting, the overall pattern is retained and streams emerge from the karst at elevations appropriate to the hydraulic characteristics of the drainage basin that feed the system.

This conclusion reinforces the view that highly localized conduit drainage in karst should be regarded as a "surface stream with a roof" rather than as some sort of groundwater.

(2) The dry underdrained channels in fluvio-karst can be related to river terraces and erosion surfaces in the same way that dry upper-level cave passages can be so related. The tributary stream channels examined here relate the Highland Rim surface, the band of doline karst that borders the Cumberland Escarpment, and the flood plains of the principal rivers.

(3) The maintenance of the hydraulic profile of the tributary streams through their underdrained reaches suggests that the development of sub-surface drainage and the excavation of conduits by dissolution of the limestone is a more rapid process than is the adjustment of the surface channels. The sub-surface conduit systems seem to keep pace with the surface channel without difficulty.

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