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THE EVOLUTION OF APPALACHIAN FLUVIOKARST: COMPETITION BETWEEN STREAM EROSION, CAVE DEVELOPMENT, SURFACE DENUDATION, AND TECTONIC UPLIFT

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Abstract: The long and complex depositional and tectonic history of the Appalachians has produced a substrate of folded and faulted sandstones, shales, and carbonate rocks (leaving aside the metamorphic and igneous core). The Appalachian fluviokarst is an evolving landscape developed on the carbonate rocks. The erosion of surface streams competes with dissolutional processes in the carbonate rocks, and both compete with tectonic uplift of the eastern margin of the North American plate. The Appalachians have undergone erosion since the Jurassic and 5 to 15 km of sediment have been removed. Many karst landscapes have come and gone during this time period. The earliest cosmogenic-isotope dates place the oldest Appalachian caves in the early Pliocene. Various interpretations and back-calculations extend the recognizable topography to the mid to late Miocene. Much of the present-day karst landscape was created during the Pleistocene. There have been many measurements and estimates of the rate of denudation of karst surfaces by dissolution of the carbonate bedrock and many estimates of the rate of downcutting of surface streams. Curiously, both of these estimates give similar values (in the range of 30 mm ka^{-1}), in spite of the differences in the erosional processes. These rates are somewhat higher than present-day rates of tectonic uplift, leaving the contemporary landscape the result of a balance between competing processes. Introduction of tectonic forces into the interpretation of karst landscapes requires consideration of the long-term uplift rates. In the Davisian point of view, uplift was episodic, with short periods of rapid uplift followed by long static periods that allowed the development of peneplains. In the Hackian point of view, uplift has occurred at a more or less constant rate, so that present topography is mainly the result of differential erosion rates. Attempts to back-calculate the development of karst landscapes requires a conceptual model somewhere between these rather extreme points of view.

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Introduction

The Appalachian Mountains are a belt of folded and faulted Paleozoic rocks that extend southwestward roughly 3000 km from the Canadian Maritimes to central Alabama, where they are covered with young Coastal Plain sediments. The overall width of the belt ranges from 300 to 500 km. The Appalachian karst is composed of a loosely connected set of karst drainage basins that occur in the exposures of carbonate rock, mainly in the folded Appalachians and around the margins of the Appalachian plateaus. The karst regions of concern in this paper span an extensive area from the Mohawk Valley of New York to central Alabama and from the western foot of the Blue Ridge Mountains of Virginia and Tennessee to the western margin of the Cumberland Plateau in Tennessee and Kentucky. Taken as a whole, the Appalachians are one of the world's great karst areas.

The objective of the present paper is to interpret the evolution of the Appalachian karst by comparing the rates of the various processes responsible for its development. Most of the Appalachian karst is fluviokarst, and as a result, there are competing rate processes that together produce the observed landscape. Weathering of non-carbonate rocks, valley deepening by fluvial processes, and chemical denudation of exposed carbonate rocks combine to sculpt the landscape. Regional uplift serves to keep the erosive processes activated. Caves that have developed in response to local base levels have often been taken as markers for pauses in the downcutting of valleys. However, caves drift upward, riding the regional uplift, so they do not form fixed markers for absolute elevations.

This paper builds on early work on the Appalachian karst. Studies have been made of stream profiles (White and White, 1974; White and White, 1983), drainage-basin properties (White and White, 1979), and rates of carbonate-rock denudation (White, 1984). An earlier discussion of the evolution of the Appalachian karst attempted to relate karst surfaces to the classic erosion surfaces long identified in the Appalachians (White and White, 1991). A more recent and broader discussion of the evolution of karst landscapes draws heavily on the Appalachians for examples (White, 2007). The present paper takes up the evolutionary theme again, this time with a better recognition of the role of tectonic uplift in driving karst processes.

The Appalachian Karst: The Long View

The rocks of the Appalachians record a long history of basin filling, plate collisions, mountain building, and erosion, extending back at least to Grenville time, 1.2 Ga. The very complex geology that has resulted is summarized for the north-central Appalachians by Faill (1997a, 1997b, 1998). The sequence of orogenies and depositional basins provides the three main groups of carbonate rocks that support the Appalachian karst: the Cambro-Ordovician limestones and dolomites, the Silurian/Devonian limestones, and the Mississippian limestones. For detail concerning Appalachian tectonics and geologic history, see Hatcher et al. (1989). Overviews of Appalachian geomorphology are given by Fenneman (1938), Thornbury (1965), and Hack (1989).

The development of the Appalachian karst depends on erosion of overlying clastic rocks and consequent exposure of older carbonate rocks to denudation and cave development. The earliest event of interest to karst development was the last of the major Appalachian tectonic events, the Alleghany Orogeny in Permian time. This major plate collision produced the broad-scale structures that guide the development of contemporary karst features. The succeeding Mesozoic period was one of plate rifting, with extensional faults and infilling of graben structures by rapidly eroded material represented by the Triassic red beds and fanglomerates in Pennsylvania. Only with the opening of the Atlantic Ocean in Cretaceous time could the ancestral versions of the present drainage systems begin to take shape.

Calculations based on mass balance suggest that the Appalachian Mountains at the beginning of the Mesozoic were an Andes-like chain with a maximum relief on the order of 3500 to 4500 meters (Slingerland and Furlong, 1989). According to the time scale of Gradstein et al. (2004), the Mesozoic extended from 251.0 to 65.5 Ma ago. During that 185.5 Ma interval, except for some basin-filling with mainly Triassic sediments, the Appalachians were subject to erosion. How much material has been eroded away, and when, is conjectural, since few records remain. MacLachlan (1999) claimed that approximately 15 km of sediment were removed from southeastern Pennsylvania during the Mesozoic. Judson (1975) proposed 6 km of removal from the Valley and Ridge, but only one km or less from the Allegheny Plateau. Most investigators are of the opinion that 90% or more of the erosion took place during the Mesozoic, so that the Appalachian topography was close to its present form by the beginning of the Cenozoic.

The interpretation of Appalachian landscapes taking on roughly their present form by the end of the Mesozoic poses a significant problem for the interpretation of karst development. The entire 65.5 Ma of the Cenozoic is available for further erosion, carbonate denudation, and cave development. Somewhere, in this span of time, there evolved an erosion surface, generally called the Schooley Peneplain, which is represented by the quartzite ridge-tops of the folded Appalachians and the uppermost elevations of the Appalachian Plateaus. Consistent with the notion that erosion of the high Appalachians was largely complete by the end of the Cretaceous, a late Cretaceous or early Tertiary age is often given to the Schooley surface. Also evolved during the Cenozoic is an intermediate level, the Harrisburg Peneplain, which is widely represented by karst surfaces on limestone valley floors. Various estimates place the age of the Harrisburg Surface as mid-Tertiary. If this traditional view is accepted, the karst features and secondary valleys that cut below the Harrisburg surface have roughly 30 million years available for their development. As will be shown below, there is about a ten-fold discrepancy between the rates of karst processes and the traditional view.

The Appalachian Karst: The Geographic View

The Appalachians were subdivided into provinces and sub-provinces by early geomorphologists (Fig. 1). The Appalachian karst is mainly concentrated in the folded Appalachians—the Great Valley and Valley and Ridge Provinces—and on the margins of the Appalachian Plateaus—the Allegheny Plateau on the north and the Cumberland Plateau on the south. The karst of the folded Appalachians is mainly developed in the Cambrian/Ordovician limestones and dolomites and the Silurian/Devonian limestones. The karst of the plateaus in mainly developed in the Mississippian limestones. Because the Mississippian limestones thin to the north, karst development is much more extensive in the Cumberland Plateau than in the northern Allegheny Plateau.

An overview description of the Appalachian karst (White and White, 2009) and many detailed descriptions of individual areas are in preparation (Palmer and Palmer, 2009).

Processes of Landscape Sculpturing

The sculpturing of any sort of landscape is accomplished by processes of mass transfer: solid rock and its surficial weathering products are transported by flowing water, wind, ice and, in the special case of karst landscapes, by the chemical dissolution of the carbonate rocks. Each of the landscape-sculpturing processes proceeds at a certain rate dictated by the process itself and by relevant environmental parameters such as temperature, precipitation, and, for karst processes, by available carbon dioxide.

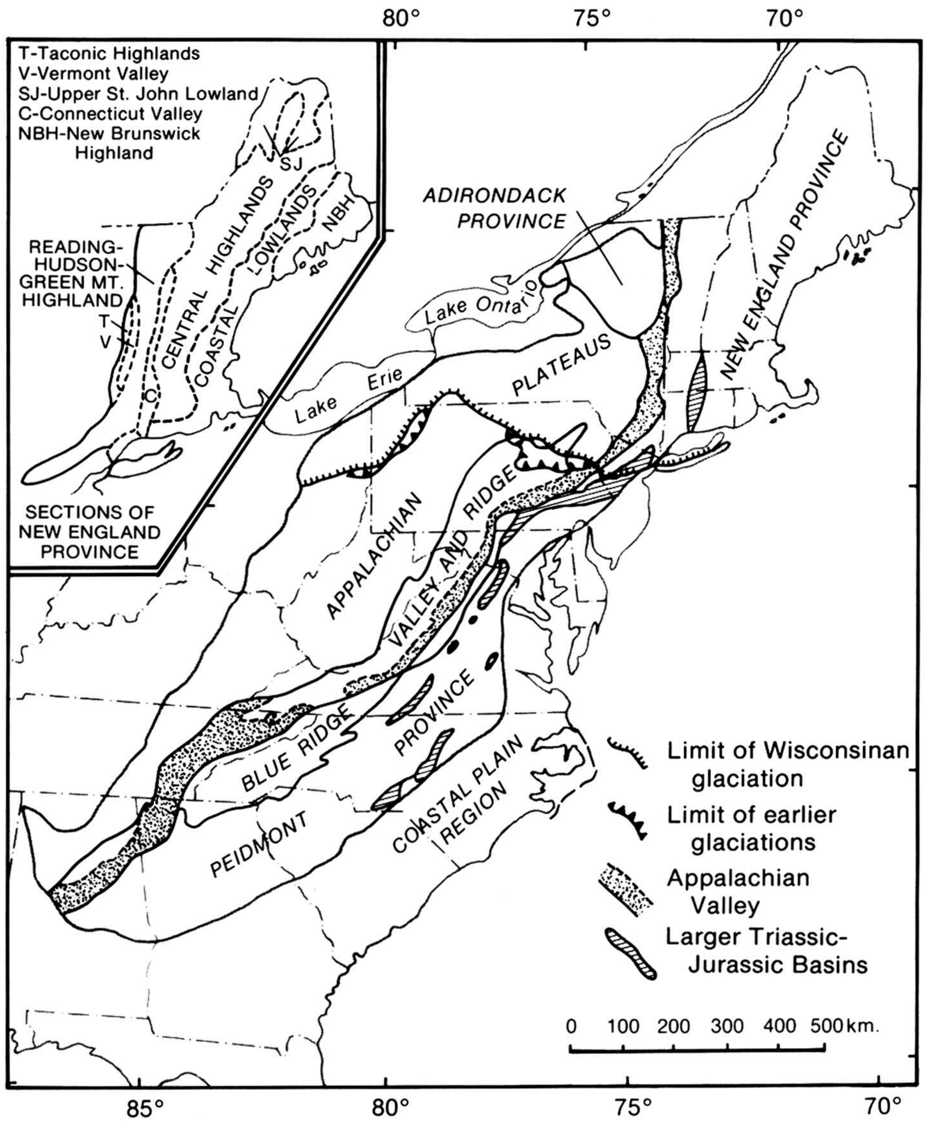


Figure 1. The Appalachian provinces. From Hack (1989).

Karst Denudation

In well-developed karst surfaces such as much of the Great Valley, the lower Greenbrier Valley, and the carbonate-floored valleys of the Valley and Ridge, there is often little surface runoff. Rainfall seeps through the soil, picks up an excess of CO_2 from the upper organic-rich horizons, and then reaches the underlying carbonate rock in the epikarst. The highly undersaturated water attacks the carbonates, often taking Ca^{2+} and HCO_3^{2-} into solution to the saturation limit defined by the soil-CO_2 partial pressure. This carbonate-laden water then migrates downward through the vadose zone along fractures and shafts. The bedrock surface is gradually lowered without dissection, thus retaining the appearance of an erosion surface.

The rate of carbonate dissolution is sufficiently fast that it can be measured directly by micrometer on exposed rock surfaces. Rates are also determined by burying rock tablets in selected locations, then digging them up after specific time periods and determining dissolution rate by weight loss. A more regional estimate can be made by measuring discharge and dissolved carbonate content of water leaving the drainage basin. For descriptions of the methods and for comparisons of measurements, see White (2000). The measured rate of carbonate-rock removal can be recalculated as an average surface-lowering rate, the rate of karst denudation.

Karst denudation has been of interest to karst geomorphologists for a long time, and many measurements have been made (for summaries see Smith and Atkinson, 1976; White, 2000; White, 2007). Rates vary from 5 to 50 mm ka^{-1}, depending on soil characteristics, climate, and precipitation. For soil-covered, temperate karst such as most of the Appalachians, a value of 30 mm ka^{-1} is representative.

Table 1. Rates of River Down-Cutting in the Appalachians.

Name	Rate, mm ka^{-1}	Method	Reference
Cheat River, W.Va.	56–63	Magnetic Reversal	Springer et al. (2004)
East Fork, Obey River, Tenn.	30	Cosmogenic Isotopes	Anthony and Granger (2004)
Juniata River, Newport, Pa.	27	Sediment Load	Sevon (1989)
New River, Pearisburg, Va.	27	Cosmogenic Isotopes	Granger et al. (1997)
South River, Grottoes, Va.	23–41	Magnetic Reversal	Kastning (1995)

EROSION OF RESISTANT ROCKS

The resistant rocks that support the high ridges and plateaus of the Appalachians are sandstones, quartzites, and conglomerates, all of which consist mainly of quartz. Quartz rocks are resistant to erosional forces. Quartz has a chemical solubility of about 10 mg L^{-1}, but the kinetics of the dissolution reaction are so slow that runoff from quartzite ridges contains much less silica than the solubility limit.

Quantitative measurements of denudation rates on quartzite are sparse. Sevon's (1989) compilation of erosion rates for the eastern United States gave only values of 2.5, 2, and 5 mm ka^{-1} as erosion rates on Quartzitic rocks. Anthony and Granger (2004) estimated the denudation rate for the quartzite conglomerate on the Cumberland Plateau as 3 to 5 mm ka^{-1}. The available values fall into the same range within a factor of two, and are smaller than carbonate denudation rates by about an order of magnitude.

RIVER DOWNCUTTING

There is an important distinction between fluvial landscape sculpting and karstic landscape sculpting. Surface streams downcut their valleys by transport of clastic sediment. Such transport is episodic and occurs mainly during flood flows. Low-gradient streams may have the sediment in their channels balanced, such that input of fresh sediment equals the sediment discharge and there is little net deepening of the channel. Fresh sediment is injected from valley walls by solifluction, by landslides, and by other down-slope movement of weathered material from the underlying bedrock. In well-developed karst areas, drainage is internal through the conduit system. Lowering of the land surface is by dissolution of the carbonate bedrock, with most of the transport in solution along with a certain fraction of clastic load. As a result, karst surfaces tend to have low relief, except for the development of sinkholes. This contrast can be seen in many Appalachian valleys, where those valleys underlain by carbonate rock have a relatively low relief, while those underlain by shales are usually strongly dissected by surface streams.

The rate of down-cutting for streams on bedrock channels can be estimated from measured sediment loads or from the elevation difference between stream channel and dated terraces or caves on the valley walls. The latter should give more accurate values, because sediment load is more dependent on weathering in the entire basin, including all of the tributaries. Rate data for five Appalachian rivers are given in Table 1.

The downcutting rate of surface streams is very similar to the denudation rate for the limestone uplands. If the denudation rates were significantly faster than surface-stream down-cutting, all of the limestone uplands would be planated to local base levels. If down-cutting rates were significantly faster, the limestone uplands would be cut by deep canyons. In most of the Appalachians, neither is the case. Groundwater systems in areas such as the Great Valley and the limestone valleys of the Valley and Ridge are mostly shallow systems. Only when karstic drainage travels beneath sandstone-protected ridges do we find deep flow paths.

REGIONAL UPLIFT

The east coast of the United States is considered to be a passive margin. The extension and rifting of the Mesozoic have become quiescent. Epeirogenic mechanisms still function, however. There is evidence that at least the Piedmont and Great Valley continue to rise as sediment is eroded from the interior, carried to the coast by rivers, and deposited off the continental shelf. Because of the shift in mass, the crustal plate is bent slightly, with a hinge line near the Fall Line at the eastern edge of the Piedmont. Superimposed on the regional uplift is isostatic rebound from retreating glaciers in the northern part of the region, as well as the effects of rising and falling sea levels during the Pleistocene. Terraces in the Susquehanna River Basin were dated by tracing them downstream to the coastal plain and correlating them with Cenozoic sediments (Pazzaglia and Gardner, 1994). The highest terrace, dated as mid-Miocene, indicates an uplift of 130 m in the Great Valley, giving an uplift rate, if constant, of 9 mm ka^{-1}. Other terraces confirmed uplift rates as high as 10 mm ka^{-1} (Pazzaglia and Gardner, 1993).

What is not well known is the uplift in the Valley and Ridge and in the Appalachian Plateaus. There was less unloading of Paleozoic sediment on the plateaus, but some uplift is expected.

CONCEPTUAL SCHEMES

If the Appalachians (or any other contemporary landscape) have been subject to erosion since the early Mesozoic, any reasonable continuous denudation rate would have planed the land surface down to sea level. There must have been uplift to provide fresh rock for attack by the erosive processes. The key question, and a question that has not been satisfactorily answered, is what is the time-dependence of the uplift. There are two points of view that define the opposite ends of the uplift scale. These may be called the Davisian model and the Hackian model.

In his famous interpretation of the rivers and valleys of Pennsylvania in 1889, William Morris Davis proposed that regional uplift was episodic (Davis, 1889). There were periods of rapid uplift interspersed with long periods of, at most, minor uplift. The landscape was planated during the quiescent periods. These planated surfaces were then dissected by rapidly down-cutting streams during the succeeding episodes of rapid uplift. In the Appalachians, one product was the Schooley Peneplain, the remnants of which are the (roughly) accordant summits of the ridges of the Valley and Ridge. Another product was the Harrisburg Peneplain, which seems coincident with many of the limestone valley floors.

The opposite concept is that the rate of regional uplift is essentially constant. Therefore, denudation is also essentially constant, except that the rate of denudation varies widely with rock type. The landscape, therefore, is simply the product of differential erosion. Sandstones and quartzites, being highly resistant, form the ridge tops, while limestones and shales, being less resistant, form the valleys. This is the concept of dynamic equilibrium. Erosion is balanced against uplift, and the form of the landscape does not dramatically change. The concept goes back at least to G.K. Gilbert, but the name most commonly credited with fleshing out the idea is that of John T. Hack (Hack, 1960). The concepts are illustrated schematically in Figure 2. As end-members, both have their problems. Their application to karst topography introduces some additional problems.

The Evolution and Development of the Appalachian Karst

Most attempts to interpret the evolution of Appalachian landscapes have been top-down. Terraces, terrace gravels, filled sinkholes, and related features are given estimated dates and then fitted into the scheme of landscape evolution. The interpretation offered here is bottom-up. We begin with the existing landscape, and then, using the established rates of the various processes, work backward to see how parts of the landscape fit together. There are some horrendous assumptions, the most important being that rates operating today are adequate to evaluate what has happened in the past. Some important features are ignored, such as the wildly fluctuating climate during the Pleistocene and the corresponding dramatic changes in sea level. These are what might be called back-of-the-envelope calculations, but some of the derived conclusions are remarkably consistent. They are also in disagreement with some previous interpretations by an order of magnitude or more.

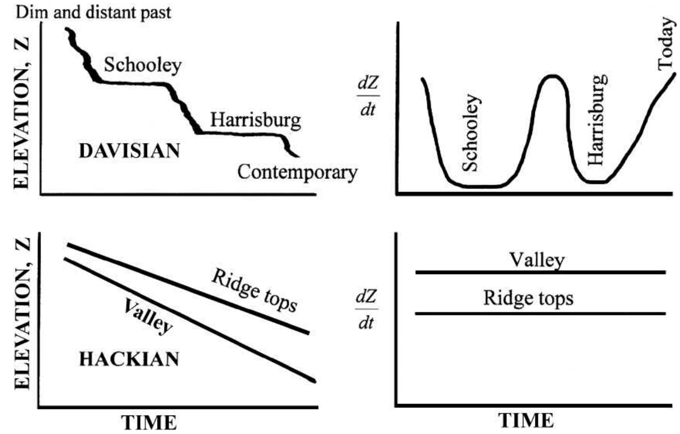


Figure 2. Sketch comparing the classic Davisian concept of landform development with the Hackian concept.

Anchor Points

Much of the previous interpretation of Appalachian topography, particularly the erosion surfaces, has been based on evidence derived from residual deposits and from river terraces. These are important pieces of the puzzle that must be fitted into their proper places, but the chronology of such features is imprecise. Age-dating of caves has become an important way of interpreting landscape evolution (Atkinson and Rowe, 1992). A much more precise chronology is provided by the recently introduced techniques of cosmogenic isotope dating, especially as applied to clastic sediments in caves.

There has been a dramatic reversal in the role of caves in geomorphic interpretation. The Bretz-Davis view was that caves are deep-seated, random objects, re-excavated by recent streams after the dissection of peneplains, and with no relationship to contemporary topography. Next came the realization that caves, for the most part, are formed as part of contemporary drainage systems and that large, dry passages relate to terrace levels in nearby river valleys. If so, the age of the cave can be estimated from the age of the terrace. With the introduction of cosmogenic isotope dating (Granger and Muzikar, 2001), the caves can be used to provide high-precision dates for the terraces. Infilling of cave passages with clastic sediments is one of the last events in cave development. The burial date of quartz sand and pebbles from these sediments can be determined, a date that is assumed to be the age of the cave and the time at which the cave discharged into a surface stream at base level.

The few cosmogenic isotope dates for Appalachian caves are from the work of Darryl Granger and his colleagues (Granger et al., 1997; Anthony and Granger, 2004, 2006). These dates agree well with the results of back-calculations from denudation and river down-cutting rates and they also serve to anchor those calculations.

THE HARRISBURG SURFACE

Much of an earlier paper (White and White, 1991) was focused on the Harrisburg Peneplain. There does indeed appear to be a well-developed surface that can be traced throughout the Appalachians. Near Harrisburg, Pennsylvania, the type locality, the Harrisburg Surface is the upland level of the Great Valley at 150 meters, now somewhat dissected by surface streams. Along the Juniata River northwest of Harrisburg, the surface is represented by accordant hill summits at 200 meters, mostly on shale, that truncate the local geologic structure. Still farther northwest, the surface appears in the broad interfluve area of the Nittany Valley as a rolling limestone upland at an elevation of 360 meters. The valley uplands of the Shenandoah Valley are at an elevation of 150 meters where the Shenandoah Valley merges into the Potomac Valley, but rise to the southwest, reaching 450 meters at the drainage divide. In Burnsville Cove, west-central Virginia, the Harrisburg Surface is represented by a highly karstic drainage divide and corresponding ridge tops at 760 meters. The surface appears as accordant hill tops in the Swago Creek Basin in the upper Greenbrier Valley (750 m). The Little Levels (730 m) and the Great Savannah (700 m), both sinkhole plains, in the lower Greenbrier Valley, West Virginia, also correspond to the Harrisburg Surface. The Highland Rim of the western Cumberland Plateau is usually considered equivalent to the Harrisburg Surface.

The Harrisburg Surface is clearly not a peneplain in the Davisian sense of the word. It is a surface representing development of wide valleys during a period of stable base level. The surface slopes toward major surface drainages of the Susquehanna, the Potomac, the James, the New, and the Cumberland Rivers.

Using an argument based on residual soils and carbonate denudation in the Nittany Valley of Pennsylvania, Parizek and White (1985) deduced that the dissection of the Harrisburg surface began about 3 Ma ago. A much better anchor point was provided by Anthony and Granger (2004). According to cosmogenic isotope ages of sediments in Big Bone Cave on the Cumberland Plateau, the cave was at grade with the Highland Rim surface at 5.7 Ma. Dissection of the Highland Rim began 3.5 Ma ago, suggesting that the earlier estimate based on denudation rates is not out of line. The secondary valleys, stream networks, and caves below the Harrisburg Surface have developed in the last 3 to 5 million years. Many Appalachian caves, therefore, have ages ranging from mid-Pliocene to relatively recent.

The age of the Harrisburg Surface is a different question. The data cited above show that the dissection of the surface began 3 to 5 Ma ago. The argument has been that the surface could have been in existence as a low-relief, wide valley bottom for much longer. In 5 Ma, chemical denudation would have lowered the Harrisburg Surface by 150 meters. In the Great Valley, the uplift was estimated to be 40 to 50 meters (130 meters in 15 Ma according to Pazzaglia and Gardner, 1994). The net change in elevation of the Harrisburg Surface in the Great Valley is about 100 meters since dissection began.

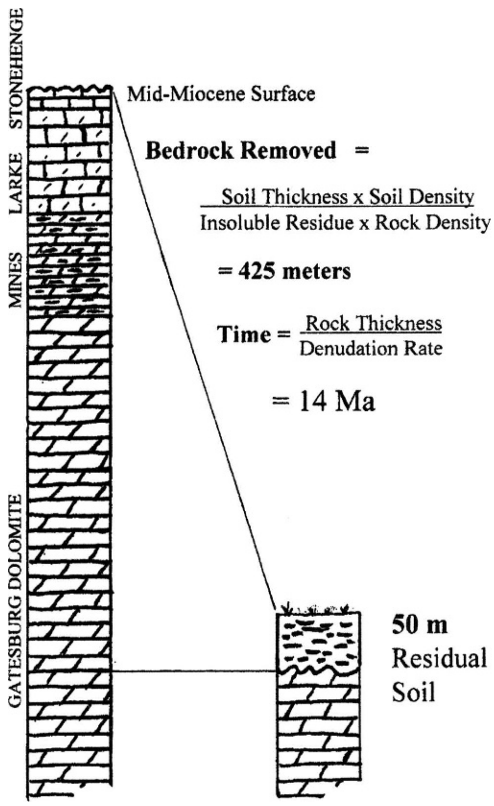
The classic interpretation of erosion surfaces is that there is a pause in uplift rates. Stream gradients decrease and valleys widen until there is achieved a low-relief valley floor containing a meandering stream of little erosive power. Such a topography could remain stable for long periods of time until uplift was renewed and gradients restored. However, most of the expressions of the Harrisburg surface are karst surfaces. Chemical denudation depends on precipitation, on soil CO_2 (in turn dependent on vegetative cover), and weakly on temperature. Chemical denudation does not depend on gradient as long as the base of the epikarst is above the water table. Although there might be a pause in stream erosion because of decreased gradients, chemical denudation would continue. The low-relief karst surfaces continue to lower, but without dissection.

THE SCHOOLEY SURFACE

An interesting and enigmatic case is that of the mountain/plateau surface that may or may not represent the Schooley Peneplain. While many of the remnants of the Harrisburg surface are karst plains, the remnants of the Schooley surface are resistant quartzites (Valley and Ridge ridges) and conglomerates (Cumberland Plateau). Erosion rates are in the range of 3 to 5 mm ka^{-1}, so that the denudation of the ridge tops is much smaller. During the 3 to 5 million years since the onset of dissection of the Harrisburg Surface, the lowering of the ridge tops would have been no more than 15 to 25 meters.

If the missing carbonate rocks from the carbonate valleys of the Valley and Ridge are back-calculated, the more rapid denudation rate of the carbonates compared with the quartzites of the ridge tops means that the valleys will fill. On the Cumberland plateau, the limestones are relatively thin, so that back-calculating the missing carbonates will intersect the clastic rocks that cap the plateau.

Calculations based on 50 m of residual soil on the Cambrian Gatesburg Dolomite on the crest of the Nittany Anticlinorium in central Pennsylvania concluded that 425 meters of carbonate rock had been removed in order to produce the soil (Parizek and White, 1985). Using the reference denudation rate of 30 mm ka^{-1}, the denudation of the valley center extends back at least 14 million years, to the mid-Miocene. If this column of dissolved limestone is placed in the context of the present Nittany Valley with its bounding Appalachian ridges, the column extends well above the ridge tops (Fig. 3). The valley floor, the Harrisburg surface, is at an elevation of 360 m. The carbonate surface at the beginning of recorded denudation would have been at 785 m. The quartzite crests of the present ridges are at 690 m. Scaling of the elevations would



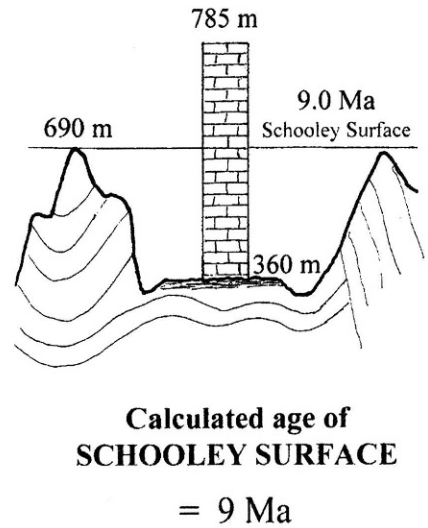


Figure 3. Carbonate rock denudation in the Nittany Valley, Pennsylvania. Estimation of thickness of removed carbonate rock from residual soil taken from Parizek and White (1985).

give a calculated age for the Schooley surface of 9 Ma. Allowing for some denudation of the quartzite would add 30 to 50 meters to the elevation of the ridge tops and thus extend the age to about 10 Ma. Not taken into account is the unknown rate of uplift of the Valley and Ridge.

Another estimate comes from the East Fork of the Obey River on the western margin of the Cumberland Plateau in north-central Tennessee (Fig. 4). The anchor point here is the cosmogenic isotope date for sediments in the upper levels of Xanadu Cave (Anthony and Granger, 2004). This date, 1.64 Ma, and the elevation of the cave above the river give a downcutting rate of 30 mm ka^{-1}. Assuming that this rate has remained constant, on average and extrapolating to the top of the Cumberland Plateau, gives a date of 9.35 Ma for the time that the capping conglomerate was breached at this point in the Obey River Gorge.

The Obey River Gorge has cut about 100 meters below the present-day Highland Rim, which is at an elevation of about 300 m. Using the Big Bone Cave date, the ancestral highland rim would be at an elevation of 450 m, which is the top of the limestone if the karst denudation rate has been maintained. Extrapolating farther back would give the age of the breaching of the plateau as 9.5 Ma.

Cave Mountain Cave, Pendleton County, West Virginia (Dasher, 2001) has the appearance of an old spring mouth. It is located on the crest of the Cave Mountain Anticline, 275 meters above the North Fork River. The crest of Cave Mountain, just above the cave, would also correspond to a remnant of the Schooley surface. Taking a downcutting rate for the North Fork similar to those shown in Table 1, extrapolating to the top of the Smoke Hole Gorge would give an age for Cave Mountain Cave of 9.2 Ma. This would make Cave Mountain Cave one of the oldest caves in the Appalachians, but to the writer's knowledge, no dates have been obtained. Cave Mountain Cave should have functioned as a spring on the bank of the ancestral North Fork when it was just beginning to dissect the Schooley surface. The actual breaching of the surface would have been a bit earlier, perhaps 10 Ma.

Three independent locations give the same 9 to 10 Ma age for the breaching of the Schooley surface. They do not give the age of the surface itself. If, indeed, one can speak of a Schooley surface, it, like the Harrisburg surface, sloped upward toward the drainage divides. Elevations in the Allegheny Mountains of West Virginia are much higher, as are the ridges of the Valley and Ridge, than the corresponding features in Pennsylvania. It appears that the dissection dated to 9 to 10 Ma marks the beginning of present-day topography, rather than the rapid uplift of a low-lying Schooley Peneplain.

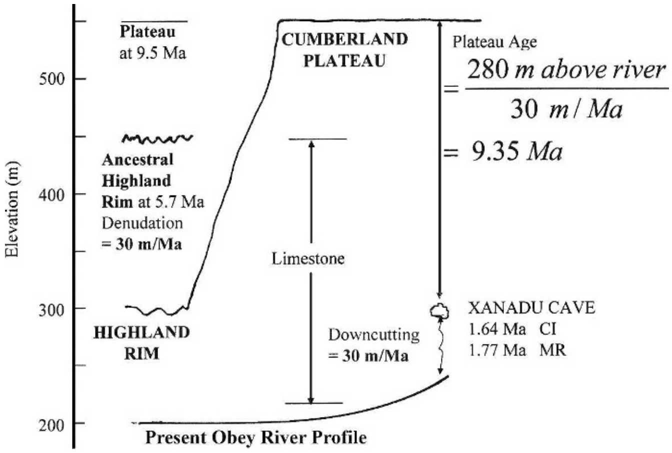


Figure 4. Sketch of Cumberland Plateau showing two estimates of the time of breaching of the caprock.

Development of The Appalachian Karst: Late Miocene to Present

The hypothesis that Appalachian topography had evolved close to its present form by the early Cenozoic is not consistent with observations of present denudation rates unless long intervals of greatly reduced denudation are inserted. The oldest topographic features that can be linked to present-day topography are the plateau surfaces, especially of the Cumberland Plateau, and the ridge tops of the Valley and Ridge. Although these ridge tops and plateau surfaces have been labeled as the Schooley surface, there is no certainty that it is the Schooley Peneplain as visualized by the early geomorphologists. The dissection of the Schooley surface can be traced back to the Mid-Miocene. Certain features, such as Spruce Knob in West Virginia, with an elevation of 1480 m, and the Cumberland and Crab Orchard Mountains in Tennessee and southwestern Virginia may be remnants from a still earlier time.

During the 5-Ma interval following the initial dissection of the Schooley Surface, there must have been sufficient erosion and denudation to form the Harrisburg surface. The karst denudation data place a severe constraint on the Harrisburg/Highland Rim surface. Because the best development of the Harrisburg surface is represented by carbonate rocks, these will have undergone continuous chemical denudation. It is not appropriate to consider the Harrisburg surface as representing a fixed elevation.

Downcutting of surface streams below the Harrisburg level provided the gradients for the development of large cave systems, particularly in the Greenbrier Valley and along the deep coves of the dissected Cumberland Plateau. Most presently accessible caves range in age from Pliocene to Recent. Most pre-Harrisburg caves have been eroded away with some exceptions of caves in the high ridges, such as Cave Mountain Cave in West Virginia.

The existence of karst surfaces combined with the existence of large master trunk conduits is evidence for a neo-Davisian concept for Appalachian geomorphology. Neither uplift nor downcutting rates appear to have been constant. However, the karst surfaces are lowering continuously, and in this sense, differ from the original peneplain concept.

To end on a note of warning: The foregoing discussion and interpretation should be taken for what it is, back-of-the-envelope number juggling. The hard data are sparse. More cave-sediment dates and more detailed denudation and river down-cutting measurements would certainly help. Other assumptions, such as equating the age of the clastic sediments to the age of the caves and their associated base levels, need more checking. At present, however, the conclusion remains. Present-day Appalachian topography, and certainly the karst topography, can be traced back only to the mid to late Miocene. The shape of the topography at the end of the Cretaceous and its evolution to the mid-Miocene remains lost in the shadows of time.

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