Stratigraphic and Structural Controls On Landform Development in the Central Kentucky Karst

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ABSTRACT

The number of sinks and hilltops on Meramec and lowest Chester rocks in central Kentucky was found to be closely controlled by several factors, among which the stratigraphic horizon upon which they are developed and the local and regional structure are most important. Several persistent sink-forming stratigraphic units were found in the basal Ste. Genevieve and upper St. Louis formations which crop out as low-relief "sink escarpments." These stratigraphic units are tentatively identified with bedded chert sequences.

The form of the Big Clifty (Dripping Springs) escarpment is closely controlled by the stratigraphic dip; low dip is associated with an irregular escarpment front of linear ridges and numerous outliers, with solutional valleys below the escarpment. In contrast, the escarpment front is nearly parallel to the structural contours in areas of high dip and there exist few reentrants or solutional valleys.

Little evidence was found within the present topography for any past periods of baseleveling within the karst area. However, striking changes of landforms through time are occasioned by the vertical succession of stratigraphy and the local and regional structure. Clear evidence is lacking within the topography for historical changes in landforms resultant from climatic change or fluctuation of local baselevel. However, evidence for such environmental change might be read from alluvial, surficial, and cavern deposits and cavern levels.

INTRODUCTION

Most of the central Kentucky karst area is now covered by 7½ minute Geologic Quadrangle Maps (table 1 and plate 1). These provide an excellent basis for studies into the nature and degree of stratigraphic and structural controls upon landforms in this classic karst area. The investigations reported below are largely based upon an analysis of these maps together with some literature research and field investigation.

The central Kentucky karst area is part of a fairly continuous karst belt developed on Meramec and lowest Chester strata (Mississippian) which extends from southern Indiana through northern Alabama. The limits of the area considered within the present study are shown in plate 1 along with quadrangle locations, major towns, and main streams and rivers.

The stratigraphic sequence is summarized in figure 1. Estimates of the thickness of the stratigraphic units vary greatly with the source of the estimate. Certainly this is partly due to variations in thickness of the units. However, part of the difference in estimates of thickness is probably due to differences in interpretation of the location of the breaks between formations within the stratigraphic column. Additional variation may have been caused by the poor exposure of the units within the karst area, which necessitates indirect estimates of stratigraphic thickness based

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upon structural contours. This last source of variation is perhaps the most important of the three for the St. Louis limestone.

The limited exposure of bedrock within the karst area has also precluded precise definition and lateral tracing of sub-units within the formations, especially within the St. Louis and Ste. Genevieve formations. Part of the purpose of this study was to determine whether it is possible to recognize stratigraphic subunits on the basis of their topographic expression.

For the purpose of this study I have defined six landform "units" within the karst area, which are mapped in plate 1. Landform unit 1 includes those land areas underlain by Big Clifty sandstone or overlying formations. Unit 2 consists of landforms on the Girken formation and upper part of the Ste. Genevieve limestone. This includes steep slopes directly fronting the Big Clifty escarpment, solutional valleys and sink complexes in these formations, and knobs in these strata lying in front of the Big Clifty escarpment and rising above the level of the surrounding sink plains. Units 1 and 2 are not distinguished north of the Green River, but are lumped together under unit 6 because of the predominance of surface drainage. Unit 3 consists of those areas irrespective of underlying bedrock which have low relief coupled with sparse, shallow, and broad sinks and occasional surface drainage ("low" sink plain). Unit 4 similarly includes those areas of low relief having numerous, deep, and steep sinks and no surface drainage ("high" sink plain). Unit 5 includes all areas having surface drainage where the drainage eventually sinks underground. Unit 6 is composed of areas having almost complete surface drainage.

Thus landform units 3, 4, 5, and 6 are defined on the basis of general topographic expression without reference to the stratigraphic horizons upon which they are developed. The escarpment in the northern part of the karst area, which is commonly called

Table 1

Geologic Quadrangle Maps Covering the Central Kentucky Karst Area

Quadrange Name	Map No.	Author	Publication Date
Allen Springs	GQ-285	Moore, Sampel L.	1963
Bowling Green North	GQ-234	Shawe, Fred R.	1963
Bowling Green South	GQ-235	Shawe, Fred R.	1963
Bristow	GQ-216	Gildersleeve, Benjamin	1963
Brownsville	GQ-411	Gildersleeve, Benjamin	1965
Drake	GQ-277	Moore, Samuel L.	1963
Glasgow North	GQ-339	Haynes, Donald D.	1964
Glasgow South	GQ-416	Moore, Samuel L., and Miller, Robert C.	1965
Hiseville	GQ-401	Haynes, Donald D.	1965
Horse Cave	GQ-401	Haynes, Donald D.	1966
Lucas	GQ-251	Haynes, Donald D.	1963
Mammoth Cave	GQ-351	Haynes, Donald D.	1964
Meador	GQ-288	Nelson, Willis H.	1963
Park City	GQ-183	Haynes, Donald D.	1962
Polkville	GQ-194	Gildersleeve, Benjamin	1962
Rhoda	GQ-219	Klemic, Harry	1963
Smiths Grove	CQ-357	Richards, Paul W.	1964
Temple Hill	GQ-402	Moore, Samuel L., and Miller, Robert C.	1965

System	Series	Formation or Group		Thickness (in feet)	Lithology	Characteristic Landforms
Mississippian	Chester	Hardinsburg Sandstone		10-60	Sandstone, fine- to medium grained; with minor shale. Sandstones mostly friable to locally indurated.	Underlies broad uplands above Big Clifty escarpment.
		Golconda Formation	Honey Limestone	10-55	Limestone, fine- to coarsely-crystalline, locally argillaceous.	Underlies uplands above Big Clifty escarpment. Poorly exposed, often solutionally removed in zone of outcrop. Minor sink horizon.
			Big Clifty Sandstone	40-120	Sandstone, fine-grained, thin-bedded to massive, well indurated. Variable amounts of shale, especially near top and base.	Most of formation exposed at escarpment face. Upper beds underlie marginal parts of upland escarpment. Blocks of sandstone solutionally lowered at escarpment front.
		Girken		60-200	Limestone, dense to crystalline, locally argillaceous or oolitic, massive- to thin-bedded. Contains sparse chert. Contains a few feet of sandstone and shale locally at top.	Exposed on steep slopes fronting the Big Clifty escarpment and in knobs where Big Clifty cap unit is absent. Solutional valleys and deep sinks developed in these beds where stratigraphic dip is low.
	Meramec	Ste. Genevieve Limestone		135-215	Limestone, predominantly oolitic, medium- to massive-bedded. Some argillaceous interbeds present. Contains beds and stringers of chert, especially near base. Persistent bedded chert unit recognized at base of formation.	Underlies low-relief plains with sparse, shallow, broad sinks and minor surface drainage.
		St. Louis Limestone		230-350	Limestone, fine- to coarsely-crystalline, thin- to medium-bedded. Contains some argillaceous and silty beds, especially near base. Minor dolomitic beds present locally. Chert nodules and beds are abundant throughout formation. Lower contact is transitional.	Underlies low-relief plains with numerous, deep, steep sinks and no surface drainage. Underlies low-relief, dip-slope plain with surface drainage which disappears beneath sink plains.
		Warsaw-Salem		40-170	Limestone, thick-bedded, variable chert nodules. Also siltstone and dolomitic limestone, thin- to thick-bedded.	Supports surface drainage with moderate relief.
	Osage	Fort Payne		230+	Dolomitic limestone, thick bedded, very cherty. Also clastic limestone, thick-bedded, and dolomitic siltstone.	
Devonian		Chattanooga Shale			Not Exposed.	

Figure 1.

Columnar section of rocks exposed in the Central Kentucky Karst. Data on rock types summarized from the geologic quadrangle maps listed in table 1. Characteristic landforms summarized from discussion in text. Thickness figures are maximum and minimum thicknesses reported in the geologic quadrangle map texts.

the Dripping Springs escarpment, is universally associated with a caprock of Big Clifty sandstone. Because of the obvious stratigraphic control of the escarpment, the break between physiographic units 1 and 2 is defined as the contact between the Big Clifty sandstone and the underlying Girken formation. As will be discussed later, however, *all* of the physiographic units have consistent association with stratigraphic units.

Structural contours taken from those shown on the new 7½ minute Geologic Quadrangle Maps are given in plate 1, with a contour interval of 100 feet. The datum for contours south of the Big Clifty escarpment (solid lines) is the top of the Chattanooga shale, while the base of the Big Clifty is the datum for areas to the north of the escarpment front (dashed lines).

The contours show the structure of the karst region in the area of the present study to be gentle flexures superimposed upon a farily uniform dip to the northwest. The flexures are primarily either local monoclinal steepenings of the dip or small, shallow anticlines and synclines.

The first part of the paper will be concerned with the nature and extent of stratigraphic and structural controls in the Kentucky karst landforms. The second part of the paper will present speculation on the historical evolution of the karst landforms insofar as evidence for landform changes through time may be found in the topography, geology, and structure. Particular attention will be paid to evidence relating to the contrasting hypotheses of baseleveling (peneplanation or pediplanation) and "dynamic equilibrium".

STRUCTURAL AND STRATIGRAPHIC CONTROLS UPON THE KARST LANDFORMS

The existence of controls by underlying bedrock upon the landforms developed thereon is fairly obvious in the case of the Drippings Springs escarpment. The Big Clifty sandstone acts as a cap rock unit over the Girken and Ste. Genevieve formations. Solutional valleys, domepits, and marginal sinks are associated with the escarpment front. These features have been discussed at length by Pohl (1955) and Quinlan and Pohl (1966), and will not be emphasized in this paper.

On the other hand, the nature or existence of geologic controls upon landforms developed on the lower Ste. Genevieve, St. Louis, and Warsaw-Salem formations is not obvious. Regional patterns of landforms in the karst area correlate broadly with the outcrop patterns of underlying formations, so some degree of stratigraphic control seems reasonable. The outcrop pattern of the lower part of the Ste. Genevieve generally may be correlated with zones of "low" sink plain and to a lesser extent with "high" sink plain, as these terms are used in plate 1. The upper part of the St. Louis formation generally underlies broad "high" sink plains. The lower strata of the St. Louis generally support surface drainage which may disappear into the sink plains developed on the upper part of the St. Louis. The lowest part of the St. Louis limestone and the Warsaw-Salem and underlying formations are generally characterized by surface drainage with minor, local sink zones.

However, these general correlations do not define the precise nature of the stratigraphic controls. Relief on the sink plains is so low that any stratigraphic controls are only subtly expressed in the topography. More powerful criteria for stratigraphic and structural controls were sought to demonstrate conclusively their nature and existence.

Preliminary investigations were directed toward the delineation of stratigraphic controls on sinks. If such controls exist, they should be manifested primarily in the density and distribution of sinks with respect to the stratigraphic horizon upon which they have developed. Stratigraphic controls presumably affect other properties of sinks, such as depth, area, and elongation. These morphological factors have been studied and indirectly related to stratigraphic controls by LaValle (1965). The present study will be primarily concerned with stratigraphic controls upon density and distribution of sinks.

The number of sink bottoms and sink rims (or lips) developed upon each ten-foot interval of exposed stratigraphic column was selected for study as an informative, objective, and easily-measured quality of sinks. A parallel study measured frequency of hill summits along the stratigraphic column.

Sampling was conducted along strips one-quarter-quadrangle in width running north-south across the width of the karst belt. The sample strips were terminated to the south by the last exposures of the St. Louis limestone and to the north by: 1, the Green River; 2, unbroken expanse of Chester upland (unit 1 in plate 1); or 3, inavailability of geologic quadrangles. In all but one case the entire belt of sink landforms was sampled. Location of the sample strips is shown in plate 1.

Along each sample strip the altitude of the lowest enclosed contour of each sink was noted, together with the structural elevation at that point as read from the structural contours. Both altitude and structural elevation were read to the nearest 10 feet (except on a few maps where the topographic contour interval was 20 feet). In addition, for each sink noted above the number of enclosed contours composing the sink were noted. Where the sinks were compound (sinks within sinks), only the altitude and depth of individual component sinks were used; that is, the compound sink was not treated as an entity. Along the same sample strips the altitude and structural elevation of each hilltop was noted.

The stratigraphic elevation of each hilltop and sink bottom relative to the reference bed used in the structural contours was computed by subtracting the structural elevation from the altitude for each hilltop or sink. Additionally, the stratigraphic elevation of each sink rim was computed by adding the number of enclosed contours to the stratigraphic elevation of the sink bottom.

Plots were made of the frequency of hilltops and sinks versus altitude and stratigraphic elevation. In figure 2 the stratigraphic elevation of each sink bottom was plotted for each sample transect to give the resultant frequency distribution. Figure 3 shows the frequency of hilltops versus stratigraphic elevation. In figure 4 the difference between the number of sink rims and the number of

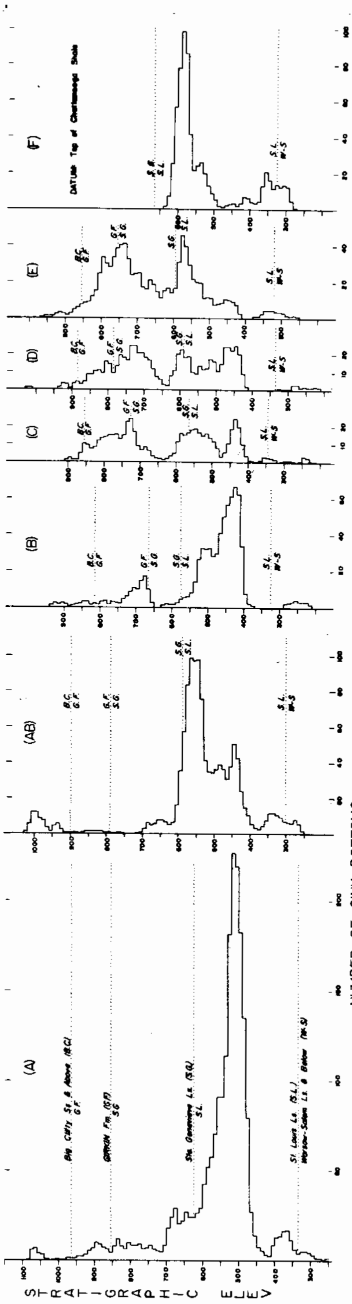

Figure 2.

Frequency of sink bottoms versus stratigraphic elevation relative to the top of the Chattanooga shale. Letters in brackets refer to sample transects keyed in Plate 1.

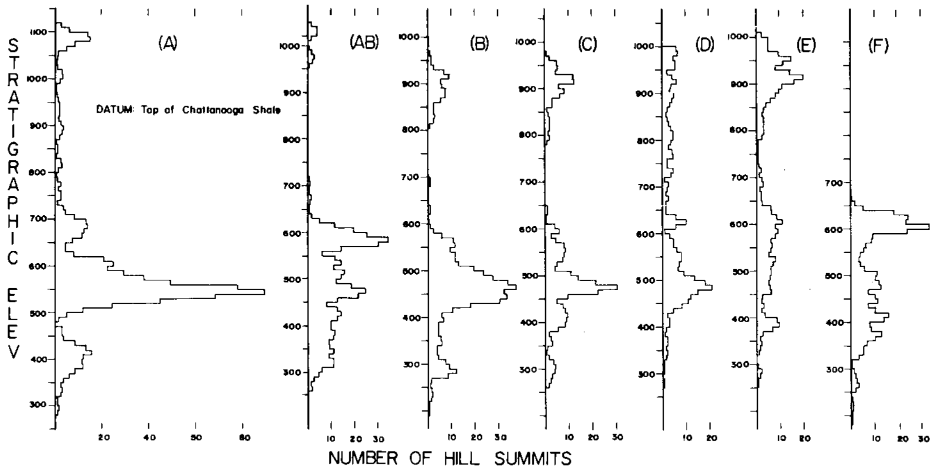

Figure 3.

Frequency of hilltops versus stratigraphic elevation relative to the top of the Chattanooga shale.

sink bottoms is given for each 10-foot interval of relative stratigraphic elevation. A plot of the frequency of sink rims versus structural elevation is not given, because this data is inherent in figures 3 and 5. In figure 5 the frequency of sink bottoms (solid line) and hilltops (dashed line) are shown versus altitude above sea level.

On most of the geologic quadrangles the contour interval was 10 feet; on a few it was 20 feet. This produced relative peaks at 20 foot intervals on some frequency distributions upon raw plotting. In addition, the error in the structural and topographic contours as drawn on the quadrangle maps must be of the order of 10 feet or more. Therefore, in order to reduce the possibility of over-interpretation of the data, the raw frequency plots were smoothed by a traveling average of 20 feet before drawing figures 2-5.

Stratigraphic elevations in figures 2-4 are in feet above the top of the Chattanooga shale. Most of the structural contours on the geologic maps were drawn with respect to this horizon. However, in areas where the Big Clifty sandstone is exposed, the base of this unit was used as a datum for structural contours on the geologic quadrangles. Contours on the Big Clifty sandstone were converted to contours relative to the Chattanooga shale by matching the structural elevations of the two systems of contours at their junction on the map. Where the two systems had a discordant juncture (theoretically indicating variations in thickness of the strata between the two reference horizons), the average value of the junction equivalence over the width of the sample strip was used.

Frequencies of sink rims, sink bottoms, and hilltops derived from these transects are directly comparable only if the structural dip remains constant over all the sample strips. This was, in general, not true for any of the sample strips, so the graphs of figures 2-4 should be used only to make rough comparisons of *relative frequencies*. *Positions* of relative peaks and valleys in the distributions within the stratigraphic columns are regarded as being much more significant than absolute values of the peaks and valleys.

The use of structural contours to define stratigraphic position within the geologic column rests upon several assumptions:

1. That the overburden (regolith) over the bedrock is of constant thickness over the areas sampled. It was assumed that variations in regolith thickness would either be random or would be systematically associated with

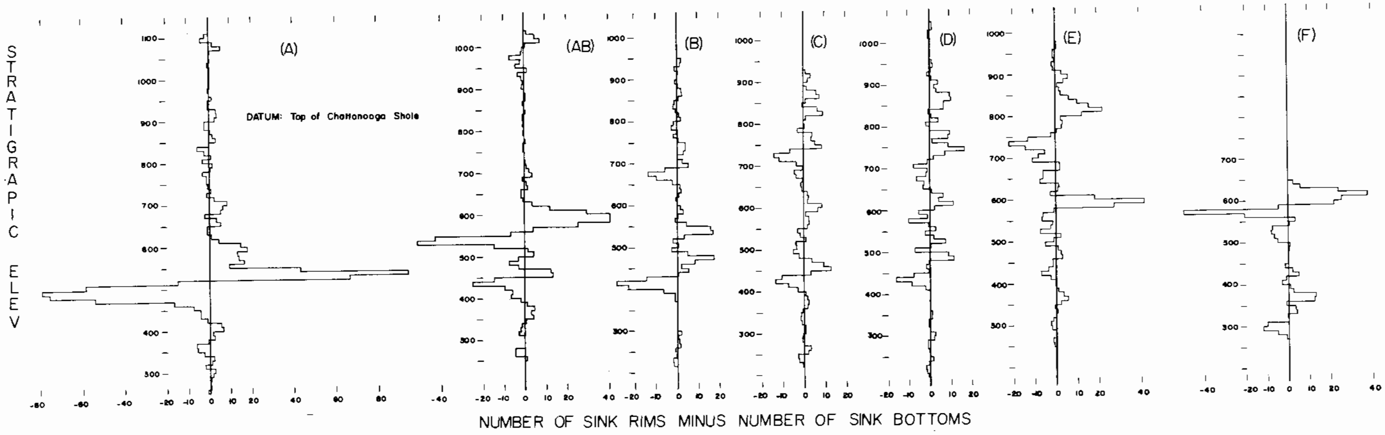

Figure 4.

Difference between frequency of sink rims and sink bottoms versus stratigraphic elevation relative to the top of the Chattanooga shale. Positive values indicate a greater number of sink rims than sink bottoms, while negative values indicate a relative preponderance of sink bottoms.

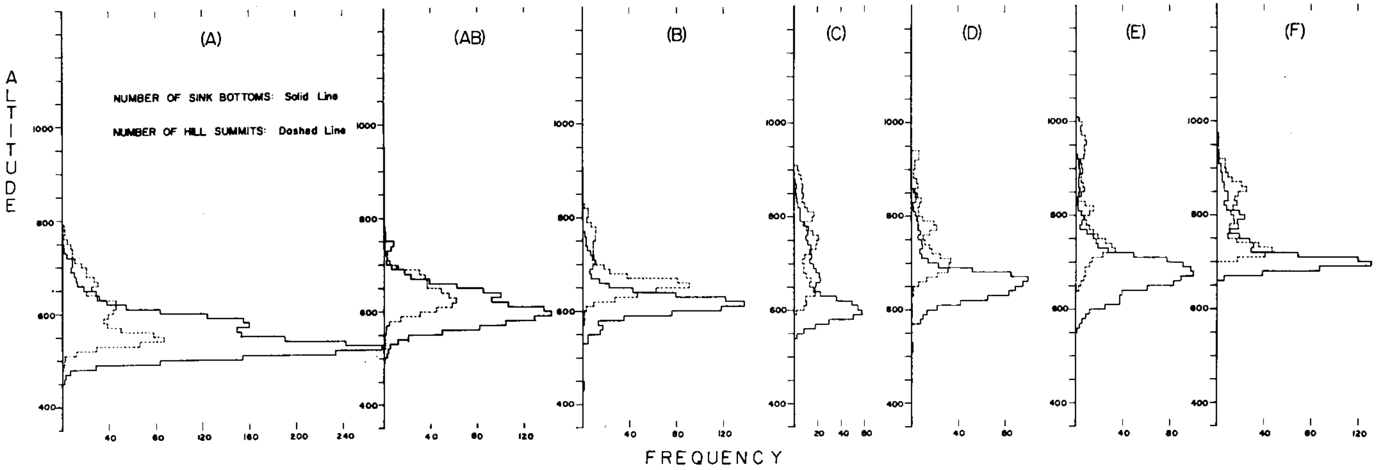

Figure 5.

Frequency of sink bottoms (solid line) and hilltops (dashed line) versus altitude above sea level.

stratigraphic controls. The thick regolith in the Kentucky karst area probably tends to obscure slightly the stratigraphic controls on the bedrock configuration. On the other hand, many sinks are largely features of the overburden, and are perhaps not reflected in the bedrock beneath as depressions of comparable size.

2. That the structural contours are accurate. Structural contours with a datum of the top of the Chattanooga shale were based on subsurface data, largely from oil wells. These holes were not uniformly or densely distributed, so the structural contours in many areas of the sink plains are only approximate. No measure of the amount of error is possible at present. Small-scale, ramdom errors in the structural contours would be represented in the sink and hilltop frequency analyses by a smoothing of relative peaks and valleys. Larger-scale or systematic errors in structural contours would be reflected in the histograms as apparent changes in thickness of the units overlying the datum. This would result in a shifting or distortion of peaks and valleys in the distribution.

3. That the thickness of the stratigraphic column between the reference horizon and the unit measured remains constant. The discordance between structural contours based upon the Chattanooga shale and the Big Clifty sandstone, respectively, affords an indication that this assumption is not exactly met.

4. That the dips are not great enough to cause errors due to neglect of the cosine of the dip in the direct subtraction method used to calculate stratigraphic elevation. Relative to the other errors, and because of the shallowness of the dip in almost all areas, this error is thought to be negligible.

5. That the topographic maps are accurate. This is not thought to be a significant source of error, and any errors should be random. There may, however, be a slight systematic underestimation of the depth of sinks due to dense vegetation common to deeper sinks.

6. That lateral changes of rock type within the sampled formations is either negligible or gradual. If stratigraphic controls exist, but the stratigraphic units which influence sink development are of only very local extent, then no pronounced peaks and valleys should be expected in the frequency histograms, or if present, they should not correlate between sample strips.

An indication of the reasonableness of the above assumptions lies in the degree of consistency of the resultant frequency distributions in figures 2-4. The following paragraphs will concern the consistency of the results.

Stratigraphic positions of the contacts between the geologic formations, as mapped on the Geologic Quadrangle Maps, are indicated in figure 2. This figure shows pronounced zones of high sink frequencies developed on the upper two-thirds of the St. Louis formation, and sink-poor zones in the lower part of the St. Louis and middle of the Ste. Genevieve formations. Some transects encountered and a high density of sinks in the Girken formation and the upper part of the Ste. Genevieve limestone, and minor sink zones in the lowest St. Louis and Warsaw-Salem formations. These observations confirm the general relationships between sink distribution and underlying bedrock suggested by the landform classification of plate 1.

Beyond this point the interpretation of the frequency distributions becomes more subjective, but I will advance three general observations about the distributions:

1. Two zones of high sink frequency are found within the St. Louis and lowest Ste. Genevieve limestones. One of these is near the St. Louis-Ste. Genevieve contact, and the other is near the middle of the St. Louis. Transects (AB), (C), (D), and (E) show both of these zones, while the other transects show only one of the two zones clearly. One or more stratigraphic zones with moderate sink frequency may be present between these two. The two zones of high sink frequency are also reflected in the frequency distribution of the difference between the number of sink rims and number of sink bottoms (figure 4). In this figure the zones of high sink frequency are at about the same structural elevation as transitions downward

from a stratigraphic zone supporting a relative surplus of sink rims to an underlying zone of relative deficiency of sink rims as compared to sink bottoms.

2. Stratigraphic zones of relatively high frequency of hill summits usually overlie by 20 to 40 feet zones of high frequency of sinks within the Warsaw-Salem, St. Louis, and lower part of the Ste. Genevieve formations. Sink zones in the Girken and upper part of the Ste. Genevieve formations, on the other hand, are associated with almost no hill summits, but summits are common about 150 feet above the sink bottoms on the Big Clifty and overlying formations.

3. The total number of sinks or hilltops developed on a given stratigraphic horizon is greater the more gentle is the stratigraphic dip. Profiles (A), (AB), (B), and (F) are in areas of predominantly low stratigraphic dip, while the other profiles are in areas of steeper dip. This is expressed also in the general width of the sink plains in the areas of sampling (see plate 1). The absence of a discernable peak of sink frequency in the middle part of the St. Louis formation in transect (F) is probably due to the local steepening of dip which is present at the zone of outcrop of that part of the formation. The relative lowness of the sink peak associated with the St. Louis-Ste. Genevieve contact in transect (A) may also be due to a steepening of the dip.

In figure 2 a lateral correlation of the histograms was attempted. The frequency histograms of each transect were shifted vertically so that the sink frequency maximum in the middle part of the St. Louis formation, where present, was positioned along a line of constant value of the vertical ordinate. The peak in the upper part of the St. Louis formation in transect (F) was equated with the upper peak in transect (E). These correlations were carried through figures 3 and 4.

It becomes immediately apparent in comparing relative stratigraphic elevations and formation contacts laterally between the transects that the assumptions made during the sampling of the transects are only partially met. The difference in relative stratigraphic elevation of the lower sink zone in the St. Louis formation should presumably represent changes in thickness of the strata between the sink zone and the Chattanooga shale (errors in assumption 2, above) or less likely, systematic errors over wide areas in structural contours (assumption 3). Similar errors are indicated by the variation in the position of the Big Clifty-Girken contact with respect to both stratigraphic elevation and the lateral correlation. Variations in the position of the St. Louis-Ste. Genevieve and St. Louis-Warsaw-Salem contacts are regarded as being less significant because of the poor exposure of these units, and in the latter case because of a transitional zone between the formations. The position of the minor, sporadic sink zone(s) near the contact between the St. Louis and Warsaw-Salem formations varies both with respect to stratigraphic elevation and the lateral correlation. However, in this case the stratigraphic zones supporting sink development may be truly local, and not correlative over long distances.

Because of both the partial failure of the assumptions used in constructing the frequency traverses and the limited information inherent in characterization of the karst area landforms solely in terms of sink frequency, sink depth, and hill summit altitude, additional techniques were sought to delineate more precisely the nature of the stratigraphic controls. The traverses had indicated two strong sink zones developed on the upper and middle parts of the St. Louis formation, respectively; the outcrop belts of these zones were examined in order to determine whether a characteristic suite of landforms is associated with these zones of high sink frequency.

In areas of low dip the upper and lower sink maxima on the St. Louis appeared to be associated with low, irregular escarpments. Relatively deep sinks are common immediately behind the escarpments. The escarpment relative relief averages perhaps 30 feet. If these escarpments indeed have objective reality, they should be mappable.

Such an attempt at mapping was made to the southeast of the town of Smiths Grove, through which transect (AB) passes. This area was chosen because the high, narrow peaks of transect (AB) gave promise that the structural contours in this area give a relatively accurate measure of stratigraphic position within the St. Louis formation. The method of mapping was to define the escarpment by two criteria:

1. The lips of deep, steep sinks. This was defined as the uppermost enclosed contour which *closely* rings any deep, steep sink.

2. The break in slope at the escarpment front separating flattish upland from steep slopes fronting the escarpment.

It was assumed that the escarpments are developed on a "resistant" layer of some sort, and that the outcrop of such a layer would be at approximately that topographic position defined by the two criteria given above.

The criteria were applied in a statistical sense, in that the average stratigraphic elevation of sink rims and segments of escarpment front over a small area was used to define the stratigraphic elevation of the escarpment within that area. The stratigraphic elevation was determined by subtraction of structural elevation from topographic elevation as was done in the transects. This procedure was employed over the outcrop zones of both the upper and lower sink zones to find the estimated stratigraphic elevation of the two "resistant layers" over the width of the sink plain to be mapped. Note that in this method continuity of the escarpment rather than a constant association of rock layers with a particular stratigraphic elevation is assumed.

The estimated stratigraphic elevations of both resistant layers were found to vary through approximately 30 feet over the width of the mapped sink belt. The estimated stratigraphic elevations of the two hypothetical resistant layers were used together with the structural contours to draw the map given as plate 2, together with a cross-section through the mapped area approximately parallel to the dip. The assumed outcrop pattern of the upper resistant layer is drawn with solid lines, and that of the lower layer with dashed lines. The presence of an additional escarpment intermediate between the upper and lower escarpments discussed above became apparent during the mapping, and was subsequently added as dotted lines.

The resultant map and cross-section form an extremely subjective interpretation of the geomorphology of the sink plain. One positive indication of the "reality" of the interpretation is the close coincidence between the average stratigraphic elevation of the "resistant layers" and the maxima in the sink frequency distribution of sink bottoms in transect (AB) (figure 2), especially for the upper and lower sink zones. The average stratigraphic elevation of the hypothetical resistant layers is, however, slightly above the maxima of sinks in the transect, as would be expected between data based on sink rims on the map and sink bottoms in the transect. Similar positive correlations hold between the mapped horizons and hilltop maxima (figure 3, transect (AB) and inflections in the graph of the difference between frequency of sink rims and sink bottoms (figure 4, transect (AB)).

A series of escarpments associated with approximately the same portions of the St. Louis and Ste. Genevieve limestones were identified and traced to the southeast of Bowling Green, but were not mapped in detail. Their existence, however, forms another partial confirmation of the map units.

Despite the self-consistency of the interpretation of the geomorphology of the sink plains offered in plate 2, the interpretation must be regarded as hypothetical until detailed mapping either confirms or rejects the presence of natural rock units which can be identified with the "resistant layers." A strong possibility exists that the resistant layers may be identified with cherty horizons in the limestone sequence. Malott (1922) recognized the strong influence of cherty layers in the development of the sink plains of southern Indiana. Several of the Geologic Quadrangle Maps (GQ 227, 234, 235, 401, and 558) identify massive or bedded chert units within the limestone near the contact of the St. Louis and Ste. Genevieve formations. Quinlan and Pohl (1966) have identified a persistent bedded chert unit at the base of the Ste. Genevieve formation averaging several feet in thickness, which they feel acts as an impermeable and resistant layer supporting sink topography. This unit may, therefore, approximately correspond in outcrop pattern with the uppermost resistant unit (solid line) in plate 2. Unfortunately, to my knowledge, no persistent rock units have been identified within the St. Louis formation to correspond with the lower two sink maxima, although all quadrangle maps indicate an abundance of beds and stringers of chert throughout the upper and middle part of the St. Louis formation.

The relationship between sinks and escarpments mapped in plate 2 suggests that there may exist at least two basic types of sinks on the St. Louis sink plain. Near the margin of the escarpments occur a large number of deep, steep sinks which breach the supposed resistant layer. Less-steep, shallower sinks which do not penetrate the resistant layer are common above and behind the escarpments.

The portion of plate 2 which is south of the sink plains and north of the Barren River drainage network is dominated by surface drainage which closely follows the dip of the stata and which drains northward into the sink plain, disappearing underground at its margin. This zone of dip-slope drainage on lower St. Louis beds is a conspicuous feature of the central Kentucky karst, as is demonstrated by plate 1. Presumably the dip-slope drainage is developed on top of one or more resistant and/or impermeable beds in the lower portion of the St. Louis formation which therefore cap a southward-facing cuesta. Although the low escarpments of the sink plains appear to be determined by thin resistant beds whose outcrops are adequately represented by thin lines in plate 2, the cuesta escarpment is developed on 30-50 feet of lower St. Louis strata which apparently contain more than one resistant horizon. An arbitrary marker horizon which is associated with a minor sink zone in the lower-right-hand corner of plate 2 has been selected to demonstrate the close approximation of the slope of the dip-slope cuesta to the regional dip (dash-dot lines in plate 2).

The stratigraphic units within the lower Ste. Genevieve, St. Louis, and upper Warsaw-Salem formations postulated in the preceding discussion are summarized in figure 6, along with their most common topographic associations. The lateral persistence of these units (assuming their objective existence) is unknown.

Quinlan and Pohl (1966) also distinguish a chert horizon high in the Ste. Genevieve limestone which they recognize as a sink- and bench-forming horizon. This layer probably correlates with the zone of high sink frequency at the top of the Ste. Genevieve formation and the base of the Girken formation (figure 2).

Regional and local rock structure influences landforms both directly and indirectly. Structural features controlling landforms may include faults, joints, local and regional strike and dip, and folds.

Joints are of undoubted importance in controlling the development of landforms. This is especially true in karst landforms, for much of the subsurface drainage is along solutionally-enlarged fractures. Linear sinks and lines of sinks on the sink plains are most likely developed along strong joints. However, this study is primarily concerned with the larger-scale structural controls on landforms which are subject to analysis on the basis of topographic and geologic maps.

The effects of stratigraphic dip upon landforms is most strikingly displayed by the Big Clifty escarpment. Where the local dip is relatively steep, as it is immediately north of Smiths Grove (plate 1), the Big Clifty escarpment closely parallels the structural contours. In such a case the front of the escarpment is nearly linear, and the few re-entrant valleys in the escarpment are shallow. Solutional valleys behind the escarpment are conspicuously absent. Also, the pro-escarpment ramparts in the Girken and Ste. Genevieve formations (unit 2 in plate 1) are narrow, and correspondingly steep. Escarpment outliers are rare or absent.

On the other hand, where the dip is low, as in the Mammoth Cave, Horse Cave, and Park quadrangles to the east, and in the Bowling Green North quadrangle to the west, the escarpment front is quite irregular, or at the extreme it is broken up into separate ridges and outliers. Solutional valleys and

Formation	Conjectured Subdivisions and Lithology	Thickness in Feet	Mapping Symbols on Plate 1	Associated Landforms (explained in text)
Ste. Genevieve Limestone	Predominantly oolitic limestone			"Low" sink plain grading upwards to escarpment front and knobs
	chert beds		solid line	
St. Louis Limestone	Predominantly limestone	40		Sink escarpment
	chert beds?		dotted line	Sink escarpment
	Predominantly limestone	50		
	chert beds?		dashed line	Sink escarpment Dip-slope surface drainage disappearing beneath sink plain
	Predominantly limestone	80		
	Limestone and Siltstone, variable chert.	marker horizon	dash-dot line	Surface drainage with local, minor sink zones
		Approx. 40	Contact is approx., not shown on Plate 1.	
Warsow-Salem				

Figure 6.

Conjectured lithologic subdivisions within the lower Ste. Genevieve and St. Louis formations. The outcrops of these units are mapped in Plate 2.

sink complexes on the Girken and upper Ste. Genevieve formations are common.

To a certain extent the position of escarpment outliers and escarpment reentrants is related to local anticlines or synclines. Solutional valleys tend to be developed in anticlinal flexures, whereas outliers are common in synclines.

Control by dip is less obvious on the sink plains, although the width of the plain is inversely proportional to the steepness of the dip. In areas of steep dip the topographic expression of the sink plain escarpments appears to be less pronounced than where the dip is low.

The degree of development of underground drainage on the sink plains may be a more indirect effect of rock dip. In limestone terrain the stability of subterranean drainage should be related to several factors, including length of underground flow, the physiographic relief, rock dip, and rock types and stratigraphic sequence. These last two factors act together as the major determinant of the degree of sink drainage. A well-developed subterranean drainage is presumably correlative with a high density of sinks and with deep, steep sinks (LaValle, 1965).

The St. Louis and lower Ste. Genevieve formations are composed of a diversity of rock types, in which limestones of varying texture and purity predominate. Chert stringers and beds are the most common secondary rock type, with minor argillaceous and dolomitic zones. Because of the heterogeneity of the limestones, some portions of the stratigraphic column are more soluble than others. This should result in an anisotropy in the "effective permeability" of the limestone to groundwater flow. Groundwater flowing parallel to the bedding can evenly dissolve the limestone along the more soluble layers. In contrast, when the groundwater is constrained to cross the bedding, the flow should be impeded by the less-soluble layers. Therefore, when the stratigraphic dip is approximately parallel to the slope of the water table, the development of subterranean drainage should be most favored. Thus heterogeneous limestone having a moderate dip toward a major stream should have dense sink drainage developed on it, while areas of higher or lower dip, or dip away from major surface drainage, should have fewer and shallower sinks, all other factors being equal.

The area to the southeast of Bowling Green along Drakes Creek may exhibit the above relationships. To the south of Bowling Green and west of Drakes Creek lies a broad area of "low" sink plain where the stratigraphic dip is away from the river (plate 1). Contrasting with this is the "high" sink plain directly opposite on the east side of Drakes Creek, where the dip is moderate and toward the river. A narrow strip immediately west of Drakes Creek also has "high" sink plain, presumably because of the high relative relief near the river. However, the above relationships may not be as exact an example of the effects of dip as the discussion indicates; much of the area to the south of Bowling Green is underlain by the middle part of the Ste. Genevieve formation, which supports a few sinks over the karst belt as a whole, while the lowest Ste. Genevieve and St. Louis formations exposed along and to the east of Drakes Creek are generally associated with "high" sink plain. Both rock type and rock dip may therefore be partial determinants of the contrast of landforms across Drakes Creek.

The drainage network is less obviously controlled by structural dip and fold patterns than are uplands and slopes. The Green River, the Barren River, and major tributaries to these rivers are not obviously controlled by local or regional structure. These rivers discordantly cross bedrock flexures and are not significantly aligned along either the dip or the strike. Low-order streams are more closely controlled by the structure (although they are naturally absent in sink areas). The small streams located south of the sink plains and draining into them are primarily dip-slope streams (see plate 1), although the largest of these disappearing streams are less directly controlled by the local dip.

The conclusion appears inescapable that a high degree of control of landforms by stratigraphic and structural controls is present in the Kentucky karst area. The significance of these controls to hypotheses of landscape evolution through time is discussed in the following section.

DISCUSSION

Inferences about the evolution of landforms through time may be possible from studies of the present relationships of landforms if appropriate assumptions are made. In the past 70 years the most common assumption has been that the geometrical relationships of hillslopes, summits, and drainage are determined in a simple, direct manner by the historical changes in the factors controlling erosion. Workers subscribing to this assumption have usually emphasized the delineation of upland flats and straths, whose origins were attributed to periods of complete or partial baseleveling. Their evidence has usually been drawn from map studies, with occasional stratigraphic evidence. The usual criterion applied to landforms to delineate erosional levels has been the presence of broad uplands or "remnants" of former upland surfaces which are sub-horizontal and discordant to structure. Particular attention was paid in the present study to testing for the presence of such topographically-accordant levels in the karst area.

Convincing evidence for sub-horizontal controls of uplands is lacking for both the Big Clifty escarpment and the zone of dip-slope drainage on the lower St. Louis formation. On both of these geomorphic units the general upland level closely follows the same geologic units downdip, with the highest topographic elevations corresponding to the furtherest updip extension of the capping strata.

On the other hand, most of the St. Louis-Ste. Genevieve sink plains are broad uplands of rather low relief which are inclined with the stratigraphic dip, but which are not inclined as steeply as the dip. On the average, the sink plains incline at about one-half to one-quarter of the stratigraphic dip. Thus the general pattern of the sink plains does not conclusively prove or disprove the presence of erosional levels, inasmuch as some structural control is present, but it is not the sole determinant of the general level of the sink plain.

"Cyclical" theories of karst development generally postulate the close association of sinks with erosional surfaces. Under this assumption, an unbiased test for any erosional levels associated with sink development would be the distribution of sinks with respect to the altitude of their occurrence. Therefore the frequency of sink bottom with respect to altitude was calculated for each traverse made across the karst belt (solid-line histograms in figure 5). Some of these traverses included sinks associated with the Big Clifty escarpment, but because erosional surfaces are supposedly structure-cutting, this should not compromise the results. The histograms have basically the same single-peaked form which is asymmetric toward higher elevations. A vertical zone of about 100 feet must be constructed for each traverse in order to include a sizable majority of sinks. This is a rather high relief for a postulated erosional surface supporting a karst cycle.

Accordance of hill summits is another criterion commonly used to distinguish erosion levels. The altitude-frequency histograms for hill summit elevations along the sample traverses is given in figure 5 as dashed lines. The hill summits follow the same type of distribution as the sinks, but with an even greater scatter of hill heights. The hill summits, as would be expected, have frequency peaks higher in elevation than those of the sink bottoms. This gives an even greater relief to a postulated erosional surface.

Even more damaging to the erosional-level hypothesis is the systematic increase in elevation of the histogram peaks from west to east across the karst belt from traverse (A) to traverse (F). It might be argued that this is resultant from tilting of an original erosional surface, but this represents a very high tilt for an area on stable shield basement.

A much less *ad hoc* explanation for the increase of the average sink and hill altitude to the east makes use of the progressively greater separation toward the east of the majority of the upland from major rivers (see plate 1). In the western parts of the study area both the Green River and the Barren River pass close to or through the sink belt. In the eastern part of the area, on the other hand, most of the land area covered by the traverses lies far from the Green River, the Barren River, or major tributaries to these.

It is perhaps a trite observation that in drainage basins of all sizes both the average elevation of the land surface and the height of divides increases the more remote the area from the master drainage stream or river. This is apparently resultant from an automatic adjustment within any drainage basin toward providing approximately equal relief throughout the drainage basin with the corresponding result that the average rate of erosion is made approximately equal throughout the drainage basin, lithologic and structural factors being equal.

More subtle techniques have been used in attempts to define erosion levels in present-day topography (*e.g.,* Clarke, 1966). Among these might be mentioned altitude-areas histograms and shoulder or col altitude-frequency histograms. While I have not applied these techniques to the central Kentucky karst area, I believe that these refinements would show little support for sub-horizontal erosional surfaces in view of the negative results of the above tests.

The absence of topographic evidence for the classic type of ersional surfaces in the karst belt does not preclude the existence of former episodes of baseleveling in this area, nor does it preclude the possibility that stratigraphic evidence for such periods might be found. It does, however, indicate that the inheritance of topographic forms from any such baseleveling has been negligible.

If the presence of inherited erosional surfaces of large scale within the karst belt thus seems doubtful, what are the alternative ways to look at landform evolution within the karst belt? One attractive alternative which has gained recent popularity proposes that erosion may have been relatively continuous over a geologically-long period of time under approximately constant climatic conditions, with the result that rates of downwasting of divides, slopes, and valleys would be approximately equal (subject to stratigraphic controls). The term "dynamic equilibrium" is generally associated with this thesis, and its main proponent is Hack (1960, 1965, 1966). The excellent correlation between landforms and structural and stratigraphic controls in the Kentucky karst area strongly support the idea of long-continued erosion leading to apparently complete adjustment between landforms and underlying geology.

The configuration of the Big Clifty escarpment most clearly shows the close control by geology which suggests extensive erosion under conditions approximating those of the present. In order to interpret historically the Big Clifty escarpment the only major assumption that need be made is that, as the escarpment retreats, approximately the same landforms are developed on the same geologic units. The present perfect correlation of the escarpment front with outcrops of the Big Clifty sandstone supports the hypothesis of continuous landform correlation with underlying geology.

Additional indirect evidence that this correlation between landscape elements of the escarpment and stratigraphy and structure has been maintained through a considerable period of erosion is afforded by the numerous rounded hills, or knobs, in the Girken and upper Ste. Genevieve formations which generally are positioned updip from the last outliers of the present Big Clifty escarpment, and which are especially numerous where the dip is low. These are designated in plate 1 as isolated areas of geomorphic unit 2. The Girken and upper Ste. Genevieve formations are usually exposed only in a narrow belt in front of the Big Clifty escarpment, suggesting that this limestone sequence is relatively easily eroded, and hence is rapidly stripped off once the protective cap of the Big Clifty sandstone is removed.

By analogy, it is postulated that these outlying knobs indicate the former presence of a caprock of Big Clifty sandstone. Many of these knobs lie up to tens of miles beyond the present outliers of the Big Clifty escarpment; these indicate that escarpment retreat with attendant landforms similar to the present ones has occurred over a considerable period of geologic time and during the removal of a considerable volume of rock.

Residual knobs are present at a greater distance from the escarpment front in areas of low stratigraphic dip than in areas of high dip. Assuming a sub-equal rate of removal of residual knobs upon stripping of the Big Clifty caprock, then it follows that: 1, the rate of horizontal retreat of the Big Clifty escarpment is more rapid the more shallow the dip; 2, escarpment retreat occurs in a direction approximately normal to the structural contours; and 3, reentrant valleys and solutional valleys tend to form first in anticlinal flexures, while outliers tend to persist in synclinal flexures. These relationships are apparent in plate 1.

Similar generalizations can probably be applied to the more muted escarpments on the Ste. Genevieve-St. Louis sink plains and to the dip-slope cuesta with surface drainage to the south of the sink plain, but these relationships were not investigated in detail.

It would be mistaken to conclude that the evidence for fairly continuous erosion in the study area precludes changes in landforms through time. Some changes may be required in adjustment to differences in stratigraphy and structure as erosion continues. Likewise, changes of climate and fluctuations of local baselevel may have required past adjustments of landforms on a limited scale.

Landform changes of the first type are dictated by the horizontal migration of landform belts with maintenance of structural and stratigraphic controls as erosion continues. Any point in space may be associated with landforms which are in turn: upland above the Big Clifty sandstone; escarpment front on the Girken and Ste. Genevieve formations; sink plain on the lower Ste. Genevieve and St. Louis formations; dip slope surface drainage on lower St. Louis limestone, etc.

The rate of vertical downwasting at any one point is not uniform, but changes with the stratigraphic unit at the surface. The geometry of an escarpment dictates that the upland behind the escarpment front is lowering more slowly than is the pro-escarpment rampart. "Resistant" beds tend to act as a local base level to the less-resistant strata above them, producing low-relief landforms on top of the escarpment. In complementary fashion the weaker units below the escarpment cap are held high above the general land level by the caprock. Thus when the retreating cap unit exposes the underlying weaker units, the weak units develop steep slopes and are eroded rapidly toward the general level of the surrounding land. Such non-uniform rates of erosion are presumably characteristic of the Big Clifty escarpment, the sink-plain escarpments, and the dip-slope cuesta on lower St. Louis beds.

In addition to these "local" fluctuations in rates of vertical downwasting, stratigraphic and structural controls may introduce larger-scale historical changes in landform evolution. For example, the breaching of a resistant layer along a river might lead to intrenchment upstream. With the Kentucky karst area the only such geologically-controlled landform change of regional extent which has been identified resulted from changes in patterns of flow of subterranean drainage.

In the area lying approximately between Smiths Grove on the west and to beyond Horse Cave on the east the drainage from the dip-slope on the lower St. Louis formation, from the St. Louis-Ste. Genevieve sink plains, and from parts of the Big Clifty escarpment complex presently flows as subterranean drainage to the north and west beneath the sink plain and Big Clifty escarpment to exit into the Green River (Cushman, 1966). The present drainage divide between the Green and Barren drainage networks lies asymmetrically close to the Barren River. This pattern of groundwater flow could not have been present before the Green River had cut below the sandstones and shales of the Big Clifty and overlying formations. Until such a time, groundwater flow north to the Green River would have been impeded by the shaly beds. Subsequent to the incision of the Green River into the Girken formation, a strong, unimpeded groundwater gradient through the underlying limestones was established, and subterranean drainage to the north was initiated.

This mechanism is similar to the tapping of static groundwater proposed by Gardner (1935). According to the mechanism proposed here, the degree of subterranean drainage development should be directly related to the gradient of the flow through soluble layers and the absence of barriers to flow. A suitable measure of the degree of subterranean drainage is probably the density of sinks (other stratigraphic factors being equal).

Within the area discussed above, the establishment of subterranean drainage north to the Green River was probably, therefore, accompanied by the development of an increased number of sinks, and probably, on the average, of steeper and deeper sinks. The initiation of northward-flowing subterranean drainage to the Green River presumably occured earlier in the eastern part of this area than to the west because of the slight tilt of the beds to the west. Northwest-trending subterranean drainage may be in the process of establishment or enlargement in the area to the northeast of Bowling Green.

The outcrop pattern of the lower sink-supporting horizon in the St. Louis formation (dashed lines, plate 2) offers possible indirect support for this proposed sequence of events. Apparently this unit both underlies the sink plain to the northwest and caps some of the cuesta ridges to the southeast. Further to the east of plate 2 this unit caps even larger tracts of surface-drained areas while supporting a sink plain further to the north. This situation could not have arisen if erosion through time had produced only a continuous dipward migration of landform belts where each geologic unit constrantly supported a characteristic landform. Presumably, before initiation of subterranean drainage to the northwest, landforms over the outcrop belt of the St. Louis and lower Ste. Genevieve formations within the area described above were either surface drainage or "low" sink plain. Upon initiation of a strong water table gradient to the northwest, intense sink drainage probably developed in the area immediately adjacent to the Big Clifty escarpment, while further away from the Green River on the dip slope of the St. Louis cuesta surface drainage became or remained the stable hydrologic regime. The lowest sink plain unit on the St. Louis formation presumably underlay parts of both of these zones. Stratigraphic dip, distance from the Green River, original drainage patterns, and types of geologic units exposed at the surface are major factors which determined the difference in drainage patterns between the present sink plain and the dip-slope cuesta.

The concept of "dynamic equilibrium" in its most extreme formulation includes the postulate that landforms are so completely adjusted to the present climate and to the local base level that the landscape contains few, if any influences from or indications of past changes of climate or base level. This is probably too strong a restriction. Although the landforms of the central Kentucky karst area do not seem to contain a record of past episodes of baseleveling, and a long-continued erosional history seems indicated, it should not be ruled out *a priori* that the area has not been subjected to fluctuations of local base level and/or climatic changes which have left their imprint on present-day landforms.

The topographic expression of landforms is a notably poor indicator of past changes of environment. Much more information about changes of erosional processes is present in soils, alluvial deposits, caves, and cave fills than is present in topographic forms. For example, Ruhe (1966), working with soils and alluvial deposits, has demonstrated a striking sequence of gullying, alluviation and stability in Iowa due presumably to Pleistocene and Recent climatic changes which are belied by the simplicity and regularity of the topography. Such changes are not clearly expressed in the topography both

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*Quinlan and Pohl (1966) have detailed what they they feel to be an ancestral surface drainage network generally flowing to the northwest within this area on the basis of the present topographic relationships of ridges and lowlands. Therefore this would presumably represent the drainage conditions prior to initiation of subterranean drainage to the Green River.

because landform modifications occasioned by moderate changes of climate or local base level take place without changes in the position of drainage divides or drainage basins, and because changes of landforms in response to changes in environmental factors tend to obliterate the topographic forms characteristic of the former conditions either by burial or erosion.

Caves and their deposits, by viture of their protected position and sensitivity to changes of base level and climate are excellent potential indicators of detailed erosional history. Many caves form in a restricted vertical zone surrounding the basal water table. This basal water table is often closely controlled by the regional base level. Levels of stability of the basal water table should then be reflected in a high frequency of cavern levels (*e.g.,* studies by Sweeting (1950), Davies (1957), White (1960), and Wolfe (1964).

In summary, the central Kentucky karst area has landforms which are closely controlled by stratigraphy and structure. The karst area has undergone a long period of fairly continuous erosion in which the broad patterns of landform evolution have been determined by geologic factors. Presumably superimposed upon the general history of erosion are periods of fluctuation and stability of local base level and climate. These details of erosional history must be studied through examinations of soils, alluvial deposits, caves, and cave deposits, because they have not left a simple record in the present topography.

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