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# LANDSCAPE DEVELOPMENT AS INDICATED BY BASIN MORPHOLOGY AND THE MAGNETIC POLARITY OF CAVE SEDIMENTS, CRAWFORD UPLAND, SOUTH-CENTRAL INDIANA

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**ABSTRACT. Paleomagnetic dates of sediment deposits in the Marengo Cave system and four caves in Wyandotte Ridge have been combined with the morphometric analysis of surface drainage basins in their vicinity to elucidate the timing and significance of geomorphic events affecting karst landscape development in the southern portion of the Crawford Upland in Crawford County, Indiana. Wyandotte Cave exhibits two distinct levels separated by a 24 m vertical gap. It is located near the Ohio River, which acts as the local and regional control on base level. The magnetostratigraphy suggests that the upper level of Wyandotte Cave was abandoned in the early to middle Pleistocene, following a drop in the regional base level that occurred no later than 0.78 Ma ago and accompanied the expansion of the Ohio River drainage system. Commensurate with the time taken for the effects of a drop in base level to propagate up-basin, it is likely the upper level in Marengo Cave was abandoned after the upper level in Wyandotte Cave was vacated (that is, ≤0.78 Ma ago). The smaller (7 m) separation between the upper and lower levels in Marengo Cave reflects the diminished influence that a drop in base level commonly has in locales relatively far removed from a basin outlet. Greater stability of the landscape in the vicinity of Marengo Cave implies that there the subsurface and surface landforms are more mature than caves and drainage basins in close proximity to the Ohio River. Stability also facilitates the development of an extensive, integrated drainage system in basins buffered by distance from the full impact of base level lowering. In these basins, a further drop in base level will likely be absorbed by the subsurface portion of the drainage network. Therefore, in the Crawford Upland, evolution toward a karst plain will progress more rapidly in tributary drainage basins that are relatively far removed from the Ohio River.**

## INTRODUCTION

The elevation of a surface river exerts considerable influence on conduit-based groundwater flow paths, and many cave systems in southern Indiana developed after surface drainage routes were diverted underground following the Pleistocene entrenchment of the Ohio River and its tributaries (Malott, 1952; Gray and Powell, 1965; Des Marais, 1981; Johnson and Gomez, 1994). Attempts have been made to link cave development in the Crawford Upland and Mitchell Plain of Southern Indiana to the geomorphic history of the river valleys to which they drain (Powell, 1970; Palmer, 1987; Pease and others, 1994). The role of base level in the development of the Mitchell Plain was emphasized by Powell (1964) and Palmer and Palmer

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(1975), whereas Miller and others (1990) sought to describe the evolution of the Crawford Upland in terms of the morphometric response of tributary drainage basins to base-level lowering. It is recognized that the morphology of cave passages and the surface landscape varies with distance from the entrenched river valley that acts as the control on base level (Miller and others, 1991; Johnson and Gomez, 1994). However, despite acceptance that the evolution of surface and subsurface karst are intimately related (Malott, 1944; Palmer and Palmer, 1975; Miller and others, 1990) and recognition that the hydrologic function of many cave systems is to act as subsurface conduits for surface rivers (Brune, 1949; Bassett, 1976; Johnson and Gomez, 1994), there have been few integrated studies of the erosional history of caves and surface landforms in southern Indiana (Malott, 1952; Des Marais, 1981). In this paper we contemplate the development of both cave systems and the surface landscape of the Crawford Upland. Paleomagnetism is used to determine the age and developmental history of cave systems in the Blue River drainage, and morphometric analysis is used to characterize the manner in which the surface landscape has evolved. Wyandotte Cave and adjacent drainage basins exemplify landscape development near the regional base-level control (that is, the Ohio River). Marengo Cave and low-order drainages in the vicinity are representative of a landscape system that is relatively far removed from the basin outlet.

## STUDY AREA

The Crawford Upland, Indiana, is the northern extension of the Chester Upland, Kentucky. It lies along the eastern (up-dip) edge of the Illinois Basin, where the regional dip is 4 to 6 m/km to the southwest (Droste and Carpenter, 1990), and represents an incipient karst plain which is being incorporated into the Mitchell Plain that borders it to the east (Miller and others, 1990). Upper Mississippian (Chesterian) siliciclastic and carbonate rocks of the Buffalo Wallow, Stephensport, and West Baden Groups and middle Mississippian (Valmeyeran) carbonates (the Paoli, Ste. Genevieve, and St. Louis limestones) of the Blue River Group underlie the Crawford Upland.

*River valleys.*–The Blue River is a southward-flowing tributary of the Ohio River which acts as the base-level control for the Crawford Upland in the study area (fig. 1). Its downstream reaches are entrenched as much as 120 m below the sub-accordant ridge tops that delimit the Lexington Peneplain (Gray and Powell, 1965; Powell, 1968). Two bedrock terraces are evident along the Blue River valley. The upper, more significant is the Blue River Strath (fig. 2). A lower terrace is poorly preserved as abandoned meander bends in downstream reaches of the valley (Powell, 1968).

The present drainage patterns were not established until the middle to late Pleistocene. Prior to the Pleistocene the Ohio River was a relatively small stream with its headwaters in southeastern Indiana. At this time the Teays River flowed across north-central Indiana and joined the proto-Mississippi upstream from the present confluence with the Ohio River (Thornbury, 1950; Wayne, 1952; Bleuer, 1991; Gray 1991). An ice advance impounded

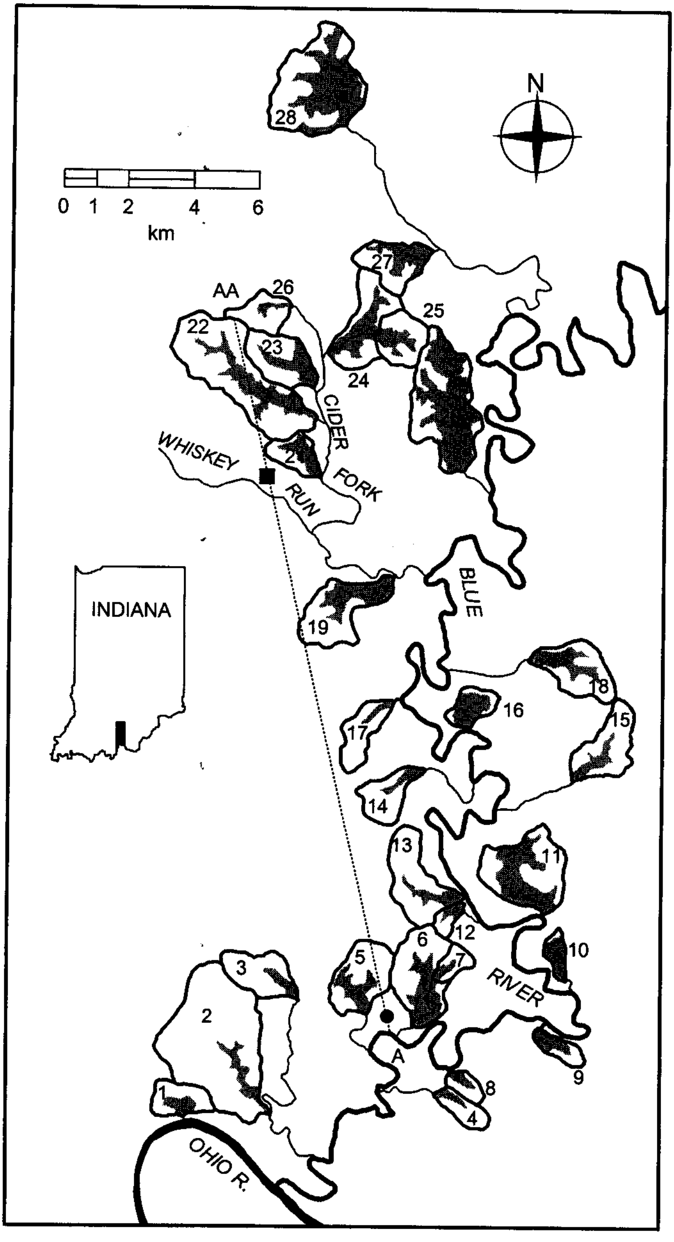

Fig. 1. Caves and drainage basins used for morphometric analysis in the study area. The locations of Wyandotte and Marengo caves are indicated by the dot and squares, respectively. The portion of each drainage basin in which the Blue River Group carbonates crop out is denoted by the stippled tone and is indicative of the extent to which valley heads have encroached into drainage divides. The basin numbers correspond with the numbered data points in figures 5. The dashed line (AA-A) indicates the location of the cross section in figure 2. The location of the study area is indicated by the shaded rectangle on the inset map.

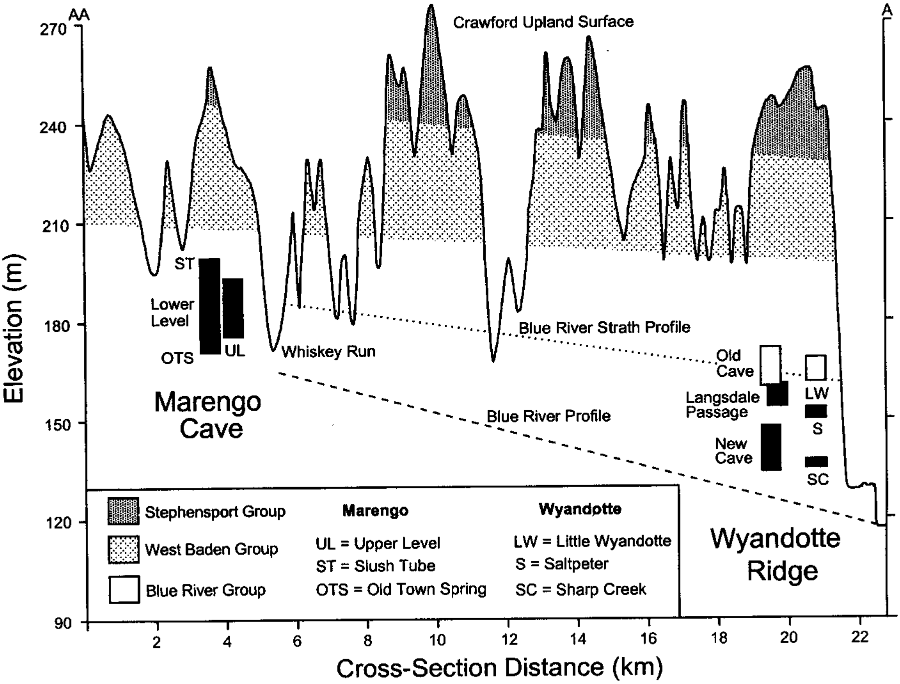

Fig. 2. Cross section of the Crawford Upland and diagrammatic relation of passage levels in Marengo and Wyandotte caves (vertical exaggeration is 115 times; see fig. 1 for location). Solid rectangles indicate cave passages possessing sediment fill characterized by a normal polarity, whereas open rectangles indicate a reversed polarity. The distance averaged elevation of the Blue River and Blue River Strath is shown by the dashed and dotted lines.

the Teays in the early to middle Pleistocene (Jacobson and others, 1988; Bonnet and others, 1991). This event was associated with flow reversal in some tributary drainages and extensive lacustrine deposition (Wayne, 1952; Bonnet and others, 1991; Teller and Goldthwait, 1991). Paleomagnetic dating of the lacustrine sediments (the Minford Silt) places them within the Matuyama Epoch (0.78-2.6 Ma), and Bonnet and others (1991) suggested they were deposited between 0.78 and 1.757 Ma. The headwaters of the Teays River were diverted into what is now the Ohio River between 0.78 and 0.984 Ma (Bonnet and others, 1991). This caused the Ohio River and its tributaries (for example, the Blue River) to entrench rapidly below their Teays-age valley floors (Walker, 1957; Teller and Goldthwait, 1991). The Blue River Strath surface was abandoned at this time (Wayne, 1952). The major phase of valley entrenchment appears to have been completed prior to the Illinoian glaciation (that is, prior to 0.302 Ma) (Bowen and others, 1986; Fullerton, 1986; Teller and Goldthwait, 1991).

*Caves.*–Four caves in the Wyandotte Ridge area and three caves that are part of the Marengo Cave system are considered in this study. The caves in Wyandotte Ridge (Wyandotte, Little Wyandotte, Saltpeter, and Sharp Creek caves) are located about 7 km upriver from the confluence of the Blue and Ohio rivers (fig. 1). Wyandotte Cave itself is a multi-level, branchwork cave developed in the Ste. Genevieve Limestone. It consists of over 9 km of surveyed and an estimated 5 km of unsurveyed passages. There are three traversable levels (fig. 2); two upper levels (Old Cave and Langsdale Passage) and a lower level (New Cave and its tributary passages). The ceilings of the upper and lower levels are separated by approx 24 m. The Old Cave (upper level) passage exhibits a tubular cross section (where its morphology is not obscured by collapse and a fine-grained, laminated alluvial fill). Langsdale Passage (intermediate level) lies at a slightly lower elevation. It is a narrow, sinuous, entrenched passage that deepens in the down-cave direction. Sediment lines the upper keyhole portion of the passage, but the lower canyon is nearly devoid of fill. New Cave (lower level) is a 7 km long tubular passage floored by alluvium, which in some areas has been estimated to be as much as 15 m in depth (Powell, 1968). No stream presently flows through Wyandotte Cave nor any of the three smaller caves in Wyandotte Ridge referred to in this study. There is no obvious lithologic control on passage development in Wyandotte Cave; chert beds outcrop only in ceilings that have been exposed through post-solution collapse.

Little Wyandotte and Saltpeter caves are coincident in elevation with passages in Wyandotte Cave (fig. 2). Little Wyandotte Cave is probably a downstream portion of Old Cave (upper level), severed by surface valley development. Saltpeter Cave is likely a severed branch of New Cave (lower level). Sharp Creek Cave is developed in the St. Louis Limestone. It lies below Wyandotte Cave and is graded to the lowest terrace in the Blue River valley. Further details about the caves in Wyandotte Ridge are provided by Powell (1968) and Pease (1994).

The Marengo Cave system is composed of three formerly connected caves. These include Marengo, Slush Tube, and Old Town Spring caves. Marengo Cave is located 72 km upriver from the confluence of the Blue and Ohio rivers (fig. 1). The cave system has two levels (fig. 2) and consists of more than 3 km of surveyed and an estimated 2 km of unsurveyed passages developed in the Ste. Genevieve Limestone. The upper level is a 1 km long anastomosing passage, floored with entrenched alluvium. The average ceiling elevation is 184 m. Passage heights range from 1.5 to 7.5 m and passage widths from 3 to 25 m. Side passages containing a thick, non-eroded sediment fill are suspended about 4 m above the floor of the main cave. The lower level lies up-dip, at a higher (actual and stratigraphic) elevation, from the lowest level in Wyandotte Cave (fig. 2). The upper level overlies a short section of the down-stream end of the lower level passage. In the area of overlap, the ceiling of the down-stream section of the lower level lies about 7 m below the ceiling of the upper level. The gradient and greater length of the lower level means that, for some of its length, its elevation is greater than that of the upper level. The sinuous up-cave segment of the lower level is as much as 30 m wide and 12 m high. It is floored by a thin gravel deposit, and thick alluvium lines the passage walls. The lower level is separated from Slush Tube Cave by an estimated 500 m of collapse. A stream flowing through

Slush Tube Cave provides the connection to the lower level of Marengo Cave. Connections between the lower level in Marengo Cave and both Slush Tube and Old Town Spring caves have been substantiated by dye and air tracing (Komisarcik, 1979; G. Roberson, personal communication). The stream in Slush Tube Cave pirates water from the Cider Fork drainage, diverting it into Whiskey Run Creek at a point 10 km upstream from the confluence with the Blue River. Its surface catchment is a 7.36 km$^2$ karst valley that lies north of the cave (fig. 1). A thin chert bed crops out in the down-cave portion of the lower level of Marengo Cave. Although it has now been breached, the chert bed may have influenced the recent development of this part of the cave. However, the relatively small adjustment made by the stream following its breaching of the chert ($<1$ m) and the elevation of the lower level relative to Whiskey Run Creek lead us to believe the chert bed has not exerted a significant influence on the overall development of the cave system. Pease (1994) provides further details about Marengo Cave.

## MAGNETOSTRATIGRAPHY AND CAVE DEVELOPMENT

Sediment samples for paleomagnetic analysis were obtained from all accessible levels in the caves. The sampling methodology and laboratory procedures used in this study are described in detail in Schmidt (1982) and Pease and others (1994). All samples consisted of moist, fine grain silt and clay sized material collected from laminated deposits. Sample locations included sediment mantling ledges, deposits along passage walls, and the sides of trenches cut in sediment deposits covering passage floors. Sediments that had undergone slumping or bioturbation were not sampled. Oriented sediment samples were collected in 8 cm$^3$ plastic boxes. Strike, dip, dip direction, and tilt measurements were taken with a Brunton pocket transit before the samples were removed from their setting. Duplicate samples were obtained at all sampling locations. All the samples were analyzed in a cryogenic magnetometer at the University of Pittsburgh Rock Magnetism Laboratory.

Samples were obtained from 14 sites in Wyandotte Cave and single sites in Sharp Creek, Little Wyandotte, and Saltpeter caves. Sample sites from these caves range from 137 m (near the current base level) to 171 m above sealevel (asl). Sample site locations were identified using a vertical survey map (Indiana Geological Survey, 1966) and confirmed with altimeter measurements. In the Marengo Cave system samples were collected from 20 sites. Multiple altimeter readings made at each sample site were related to the elevation of a point in the upper level which was established by transit survey from a nearby USGS benchmark. Eight sample sites in the lower level of Marengo Cave and three sites in Slush Tube Cave were located between 170 and 195 m asl, 1 to 8 m above the bed of the stream flowing through the cave. The elevations of the seven sample sites in the dry, inactive upper level of Marengo Cave were between 178 to 194 m asl. The two sample sites in Old Town Spring Cave were located at 171 and 172 m asl, 1 to 2 m above the stream bed. Sample polarity was established from Zijderveld (1967) vector endpoint diagrams, and the magnetic timescale we employ is that of Cande and Kent (1992).

*Wyandotte magnetostratigraphy.*–A detailed discussion on the magnetostratigraphy of the caves in Wyandotte Ridge can be found in Pease and others (1994). The data are summarized in figure 3. Sediment from New Cave (lower level) and Langsdale Passage (intermediate level) in Wyandotte Cave and Sharp Creek and Saltpeter caves (located between elevations of 137-162 m asl) exhibited a normal polarity and were assigned to the Brunhes Epoch (0-0.78 Ma). The Matuyama Epoch (0.78-2.6 Ma) was presumed to be represented by sediment with a reversed polarity in Old Cave (upper level) and Little Wyandotte Cave (located between 168-171 m asl).

*Marengo magnetostratigraphy.*–All samples obtained from the Marengo system exhibit a normal polarity (fig. 3). Given the continuous stability of the magnetic polarity in fill above the current base level, sediment throughout the lower level of Marengo Cave is assumed to be young and is assigned to the Brunhes Epoch (0-0.78 Ma). On the basis of polarity and elevation, there

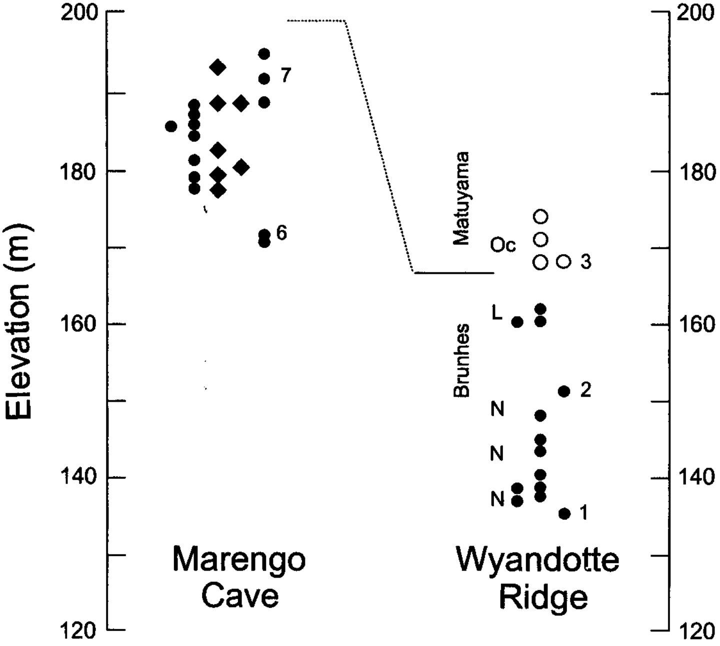

Fig. 3. Magnetic polarities of sediment samples from Marengo Cave arranged by elevation and correlated with samples from caves in Wyandotte Ridge (after Pease and others, 1994). Solid dots and diamonds indicate normal polarity, and open circles indicate reversed polarity (compare fig. 2, solid and open rectangles). The chronology of the polarity for sediments in Marengo cave is as inferred in the text. Wyandotte Cave: Oc = Old Cave; L = Langsdale Passage; N = New Cave. Wyandotte Ridge: 1 = Sharp Creek Cave; 2 = Saltpeter Cave; 3 = Little Wyandotte Cave. Marengo Cave: diamonds distinguish upper level from lower level sample sites; 6 = Old Town Spring Cave; 7 = Slush Tube Cave.

are two ways to interpret the fill in the upper level of Marengo Cave: (1) if the sediment is assigned to the Brunhes Epoch or to the Jaramillo Normal Events (0.984-1.049 Ma; Matuyama Epoch) it is relatively young; (2) if it is assigned to the Olduvai (1.759-1.983 Ma) or Réunion normal (2.12-2.27 Ma) events (Matuyama Epoch) or to the Gauss Epoch (2.6-3.553 Ma), the fill is a minimum of 1.757 Ma old and perhaps ≥2.6 Ma in age. Given the small vertical separation between the upper and lower levels in Marengo Cave (7 m) it does not seem likely that the time represented by the Matuyama Reversed Epoch (1.82 Ma) would be unrepresented in the cave (by sediment with a reversed polarity). Furthermore, the Olduvai, Réunion, and Gauss ages imply a very slow time-averaged rate of downcutting. Even if the sediment is assigned to the Olduvai event, the 7 m separation between the two levels encompasses a time period of about 1.0 Ma. Thus, we argue that the fill in the upper level of Marengo Cave is either ≤0.78 Ma (Brunhes Epoch) or 0.984 to 1.049 Ma (Jaramillo Event) (cf. Schmidt, 1982; Pease and others, 1994). We favor the more recent (≤0.78 Ma) date for the reasons outlined below.

*Cave development.*–Significant cave development in the study area began during the Pleistocene when extensive subsurface flow through the Blue River Group carbonates was initiated (Powell, 1968). The upper level passages in Wyandotte and Marengo caves probably were among the first large caves to develop. The size and tubular form of these passages suggest that their formation was associated with a quasi-stable water table (Palmer, 1987, 1989, 1991; Quinlan and Ewers, 1989). These passages are likely subsurface manifestations of the lengthy period of base-level stability which is associated with the formation of the Blue River Strath (Powell, 1968; Pease and others, 1994).

The upper level passages in Wyandotte Cave were probably abandoned in the early to middle Pleistocene as a result of the entrenchment of the Ohio River following the Teays diversion, which occurred between 0.78 and 0.984 Ma (Bonnet and others, 1991). Based on the difference in elevation between the polarity transition and the current river elevation (49 m), the magnetostratigraphic age of the upper level of Wyandotte Cave implies that the maximum time-averaged incision rate of the lower reaches of the Blue River was 0.06 m/Ka. The Langsdale Passage level lies at a slightly lower elevation than Old Cave (upper level). Although its relation to the upper level is obscured by collapse, its canyon-like form, coupled with the normal polarity of the fill, suggests it represents the entrenchment phase. The lower (New Cave) level in Wyandotte Cave then developed during another period of stability. A subsequent, minor phase of entrenchment isolated this passage and created the lowest terrace in the Blue River valley.

Although the upper levels in Marengo and Wyandotte caves likely were initiated at about the same time, we argue that the upper level in Marengo Cave was abandoned later (≤0.78 Ma ago) than its counterpart in Wyandotte Cave. The later date for abandonment reflects the additional time required for the effects of a drop in base level at the basin outlet to propagate up-basin (Slingerland and Snow, 1988). Previous studies have shown that the impact of a drop in base level is commonly diminished as it propagates up-basin (Schumm, 1993; Leopold and Bull, 1979). This effect is manifested in the Crawford Upland by the degree of separation between the Blue River Strath and the Blue River, evident at different locations within the study area. In the vicinity of Wyandotte Cave the separation is 41 m. Further up-basin, near the confluence of Whiskey Run with the Blue River, it is 24 m. There is no clearly defined strath in evidence along Whiskey Run, but along downstream reaches small karst valleys and benches provide tentative evidence for an erosion surface that lies 17 to 23 m above the main valley floor.

We contend that the drop in base level experienced in the Whiskey Run drainage was of insufficient magnitude to motivate abandonment of an entire level in Marengo Cave. Instead, minor stream entrenchment within the cave, coupled with flow diversion following a ceiling collapse, divided a single passage into two levels. Flow was diverted from the downstream portion of the formerly unified cave system into a new passage. The new route evolved into the present 100 m long downstream section of the lower level. As the stream, flowing along its newly established route, underwent minor entrenchment, the two sections of the formerly connected passage were further isolated. In short, the upper and lower levels in Marengo Cave represent inactive and active sections of the same passage.

## BASIN ANALYSIS

Twenty-eight low-order drainage basins (fig. 1) were selected for morphometric analysis on the basis of similarities in lithology and stream order (Coates, 1958). The basins are divided into three groups to facilitate comparisons between the Wyandotte and Marengo areas. A sub-set of ten basins in the vicinity of each cave system is used to exemplify the surface basin characteristics of that area. The ten basins in the vicinity of Wyandotte Cave typify drainages located near the local base level control; basin area ranges from 0.54 to 10.22 km$^2$, and basin relief ranges from 80 to 130 m. The ten basins most closely situated in the vicinity of Marengo Cave represent drainages farther removed from the Ohio River; basin area ranges from 1.39 to 7.36 km$^2$, and basin relief ranges from 45 to 100 m. The remaining eight basins lie in the intervening region of the Blue River catchment. In general, siliciclastic rocks of the West Baden Group underlie valley-side slopes and drainage divides in undissected portions of the basins, whereas valley floors are developed in the Blue River Group carbonates (fig. 2). Topographic data were extracted from USGS 7.5 minute maps. The hypsometric integral (the relation of horizontal cross-sectional basin area to elevation) the ruggedness number (the product of basin relief and drainage density) and the area of undissected upland (the area of a basin above the break in slope that delimits the transition between the valley-side and the upland surface) were determined for each basin using methodologies outlined by Strahler (1952) and Coates (1958). Drainage basins in the vicinity of the caves in Wyandotte Ridge exhibit values for the hypsometric integral of between 0.55 and 0.66, the ruggedness number ranges from 0.10 to 0.21, and undissected upland accounts for between 7.7 and 30.1 percent of total basin area. Values for the hypsometric integral in basins in the vicinity of Marengo Cave are between 0.41 and 0.57, the ruggedness number ranges from 0.01 to 0.12, and undissected upland accounts for between 1.4 and 25.6 percent of total basin area. Composite (mean) hypsometric curves (Strahler, 1952) for basins in the vicinity of Wyandotte and Marengo caves and the intermediate basins are presented in figure 4. Although there are variations among basins in any given area (Miller and others, 1990), a t-test shows that the group means for basins in the vicinity of the two cave systems are significantly different at the 0.95 confidence level.

## LANDSCAPE DEVELOPMENT

We believe that there is a systematic decrease in the magnitude of the drop in base level in the Blue River catchment with increasing distance upstream from the Ohio River. Evidence of the varying effect that a drop in base level has on different portions of a drainage basin is manifested both in the morphometric properties of the low-order surface drainage basins and the morphology of cave systems in the Crawford Upland. The implication is that

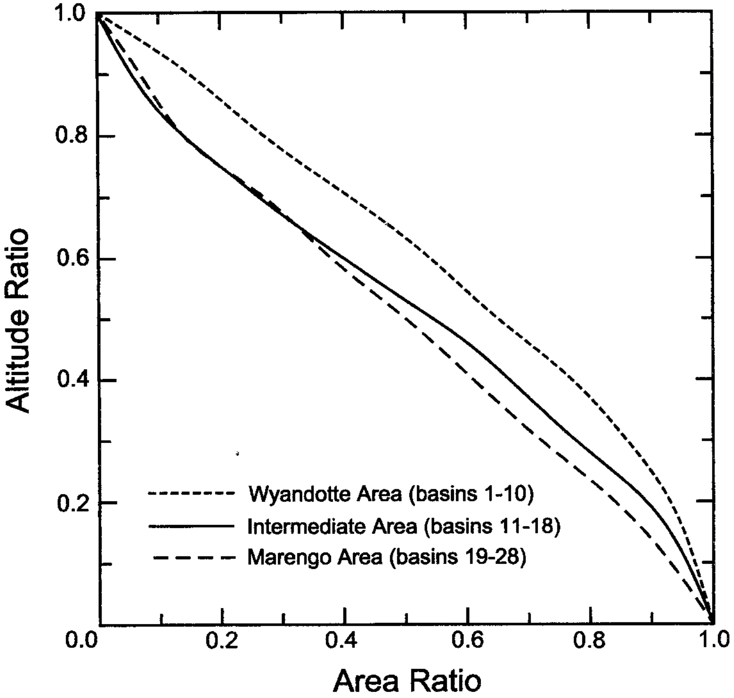

Fig. 4. Average hypsometric curves for ten representative drainage basins in the vicinity of Wyandotte (basins 1-10) and Marengo (basins 19-28) caves, respectively, and eight intermediate basins along the Blue River catchment (basins 11-18). The locations of the individual basins are shown in figure 1.

headwater basins, which are farther removed from the regional base level control, are better adjusted to their local base level and, thus, more mature. This maturity allowed extensive sub-surface drainage networks to develop in the upstream basins in the Blue River catchment. These well-developed conduits were able to absorb much of the surface flow as the landscape in the upstream portion of the Blue River catchment slowly adjusted.

Figure 5 shows there is a relation between the "maturity" of basins in the Blue River catchment and their proximity to the Ohio River. However, there does not appear to be a significant relation between the area of a basin underlain by Blue River Group carbonates and the hypsometric integral area of undissected upland or ruggedness number (fig. 6). This suggests that variations in basin morphology are influenced more by hydrological than lithological parameters. A multiple linear regression of the measured indicators of "maturity" versus distance from the Ohio River lends support to this proposition. A three parameters model yielded an R-square value of 0.7 with all parameters contributing significantly (0.95 confidence level) to its performance. Regression lines, which define the relation for each of the parameters, are shown in figure 5.

The decrease in the value of the hypsometric integral with increasing distance from the Ohio River implies that drainage basins in the vicinity of Marengo Cave are better adjusted to their local hydrologic setting. Hypsometric curves for drainage basins in the vicinity of Wyandotte Cave have a convex-up form (fig. 4), and hypsometric integrals are relatively high. Drainage basins in the vicinity of Marengo Cave, which are relatively far removed from the local base level control, are characterized by lower hypsometric integrals and hypsometric curves with a straight to convex-down form (fig. 4). We believe this is because they have experienced a longer period of denudation under conditions where base level was stable and therefore are relatively more mature than basins in the Wyandotte area. This is supported by the position of the composite curve for basins in intermidiate locations: the maturity of these basins is transitional between the basins in the vicinity of the two cave systems. Lower ruggedness numbers also serve to emphasize the more subdued relief and relatively greater maturity of drainage basins in the vicinity of Marengo Cave (fig. 4). Greater maturity additionally is implied by the smaller amount of undissected upland preserved in basins in the vicinity of Marengo Cave. This indicates that the valley heads have encroached further into drainage divides (compare figs. 1 and 4). Lengthy periods of comparative base-level stability also encourage integration of the surface and subsurface drainage networks. Thus, the surface flow has been pirated from the downstream portions of stream channels in many basins in the area adjacent to Marengo Cave. This helps to explain why surface karst is more prominent in the area around Marengo Cave than it is in the vicinity of Wyandotte Cave, even though the limestone was presumably exposed at about the same time in both areas (Malott, 1952). It may also compel further rejuvenation to be absorbed by the subsurface drainage network.

Miller and others (1990) argued that there is no systematic variation in erosional history with increasing distance from the Ohio River in low-order

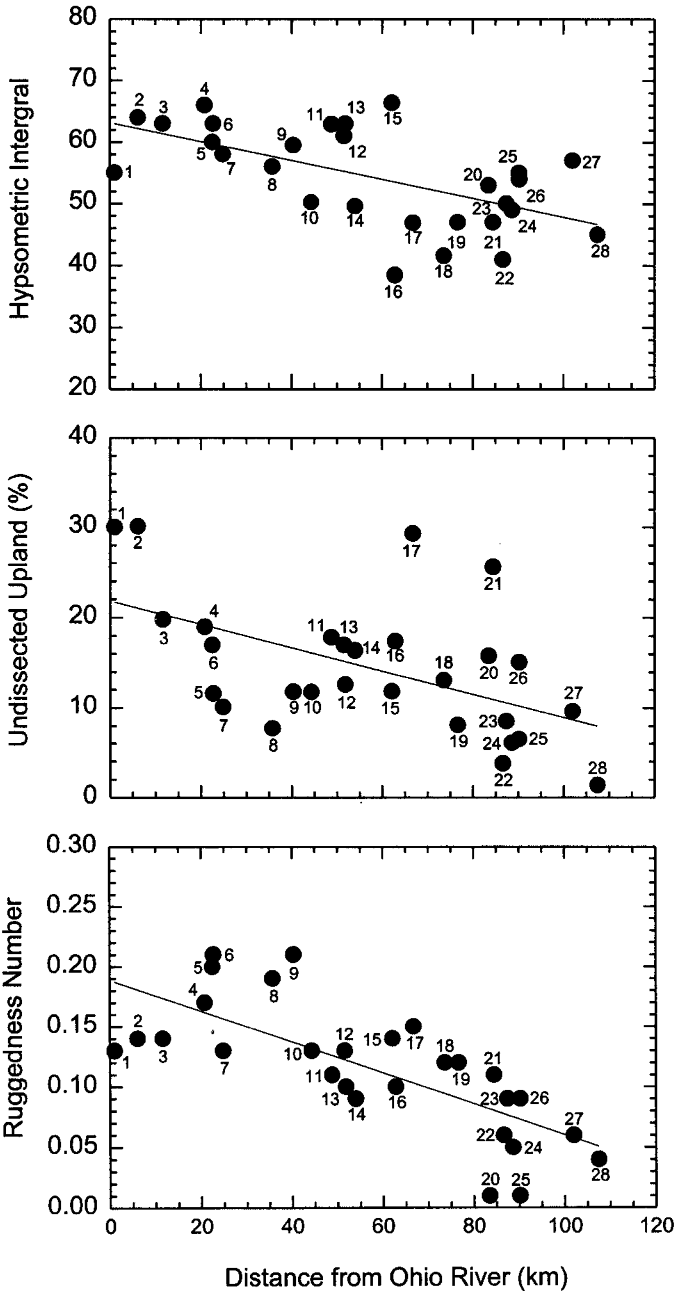

Fig. 5. Variation of hypsometric integral, area of undissected upland, and ruggedness number with distance from the confluence with the Ohio River for 28 low order basins in the Blue River catchment. The regression lines are shown to emphasize the trend. Numbers correspond with basins in figure 1.

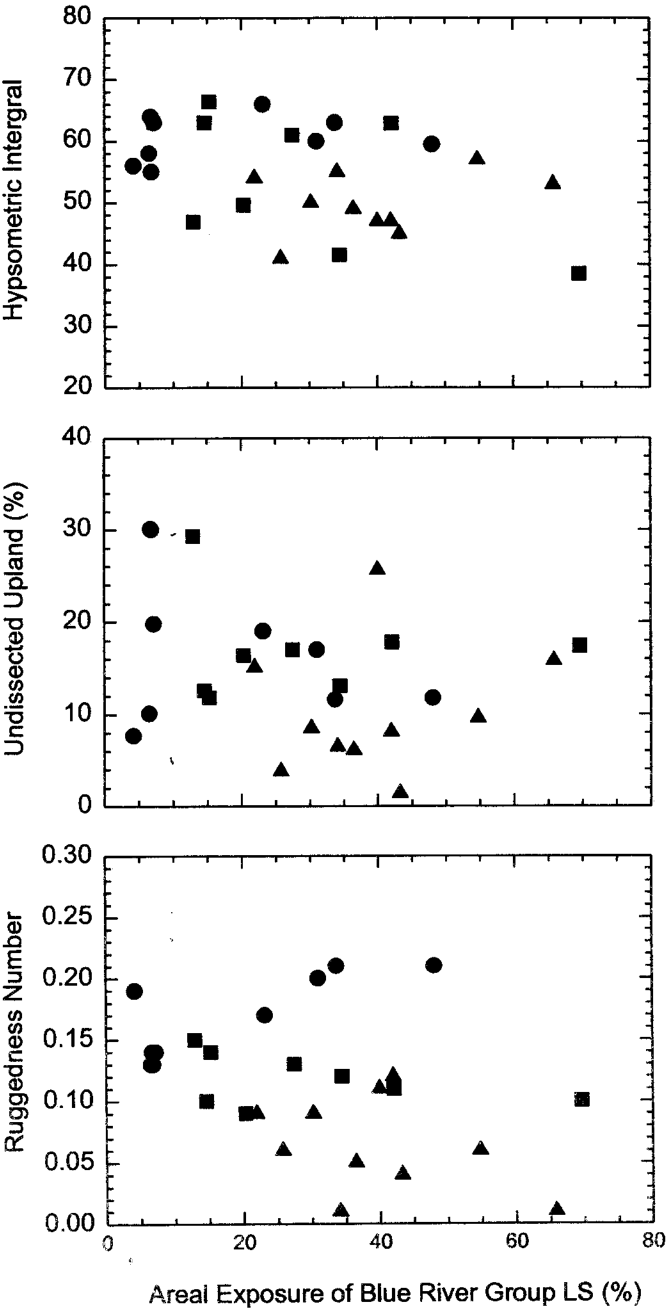

Fig. 6. Plots of hypsometric integral, area of undissected upland and ruggedness number against areal exposure of Blue River Group limestone in 28 low order basins in the Blue River drainage. Dots represent basins 1–10, squares represent basins 11–18, and triangles represent basins 19–28.

basins predominantly underlain by carbonate rocks. They believed variations in basin morphology result from lithologic controls in the form of resistant siliceous strata and nickpoint development. As figure 5 demonstrates, their contention is not borne out by our analysis nor by the results of previous work (Coates, 1958). Thin units of resistant strata (primarily discontinuous chert beds) have caused the development of small nickpoints in the area, which do affect localized hydraulic conditions as suggested by Miller and others (1990). However, the influence of resistant strata and nickpoint migration is manifested only as irregularities in individual curves (Miller, 1991) not in the overall curve form. Lithology may exert some influence on the hypsometric distribution (Moglen and Bras, 1995), but there is no evidence to suggest that it influences the overall morphology of low order drainage basins in the study area. Also, drainage basins in our study and in the study undertaken by Coates (1958) generally were of a higher order than the basins Miller and others (1990) examined. The significant erosion processes are spatially variable (Willgoose, 1994). Thus, the contrasting results may reflect the dominance of (diffusive) hillslope erosion and transport mechanisms in the small basins over (advective) channel erosion and transport mechanisms. The latter likely dominates in larger basins.

A smaller mass of the landscape (indicated by hypsometric intergrals, basin ruggedness, and percent undissected upland area) remains above the basin outlet in drainages buffered by distance from the full effects of the drop in base level that was precipitated by reconstruction of the Ohio River drainage system. This leads us to suggest that low-order basins in the Crawford Upland that are relatively far removed from regional base-level control will be incorporated into the adjacent Mitchell Plain, through westward migration of the Chester Escarpment, more rapidly than basins nearer to the Ohio River. This conclusion concurs with arguments by Powell (1964) and Palmer and Palmer (1975) for base-level stripping of the Mitchell Plain which calls for erosional planning of the landscape resulting from stable river (and ground water) levels and, thus, a lack of rejuvenation. Our argument for the existence of an integrated surface and subsurface drainage system concurs with that of Howe (1982) who suggested that shallow caves in the Mitchell Plain developed along piezometric surfaces controlled by river levels. Our conclusions conflict with the detail but not the essence of the model presented by Miller and others (1990) who argued that the Crawford Upland is progressing toward a karst plain through isolation of low-order basins from the effects of rapid drops in base level that encourage surface stream piracy.

## CONCLUSION

Multiple levels in many cave systems develop in response to base-level lowering, and it is possible to correlate passages in widely separated locales (Pease and others, 1994). However, our investigation of cave systems in the southern portion of the Crawford Upland, in Crawford County, Indiana, suggests that correlations between cave levels in different drainage basins may not always be sustained by the association between cave systems in the same drainage basin.

The magnetostratigraphy of sediments from Wyandotte and Marengo caves and the morphometry of surface drainage basins in the Blue River drainage indicate that the response of the landscape of the Crawford Upland to base-level lowering varies with distance from the Ohio River (the regional control on base level). Drainage basins in the vicinity of Wyandotte Cave, near to the Ohio River, responded rapidly to the middle Pleistocene (≥0.78 and ≤0.984 Ma) drop in base level precipitated by reorganization of the Ohio River drainage system. Surface streams are deeply entrenched, and Wyandotte Cave exhibits two distinct levels separated by a pronounced (24 m) gap.

We argue that (what is now) the upper level in Marengo Cave was abandoned later (≤0.78 Ma) than its counterpart in Wyandotte Cave. The vertical separation between the upper and lower levels in Marengo Cave is only 7 m. The later date for abandonment and smaller vertical separation between levels are indicative of the delayed and diminished effects that base-level lowering may have in the upstream portions of a drainage basin.

Morphometric indices suggest that surface basins in the vicinity of Marengo Cave are more mature than basins near caves in Wyandotte Ridge. The caves and surface landscape in areas buffered by distance from the full impact of base-level lowering have spent more time under conditions where base level was stable and thus are more mature than portions of the Blue River catchment that are nearer to the outlet and were directly influenced by changes in base level. Lengthy periods of base-level stability also encouraged the development of an integrated surface and subsurface drainage system in the Marengo Cave area. This is evidenced by a lack of sustained surface flow in the area. The integrated drainage system has absorbed much of the down-basin portion of the drainage network in the tributary basins, causing (advective) channel processes to decline in intensity while the pace at which (diffusive) hillslope processes operate remains largely unaltered. The local topography thus becomes more subdued as hillslopes degrade and valleys aggrade. The development of an integrated drainage network likely will also reduce the impact of future base-level adjustments in the headwater basins. In sum, the implication is that headwater basins will be incorporated into the Mitchell Plain more rapidly than will basins in other parts of the Crawford Upland.

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