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# DOLINE GROWTH PATTERNS ON THE WESTERN HIGHLAND RIM: INITIATION TO STEADY-STATE CONDITIONS

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## ABSTRACT

The first documented case of doline initiation and enlargement on the Western Highland Rim is examined on the basis of axial and areal growth and subsidence rates from initiation to steady-state conditions. Three-dimensional doline geometry is controlled by interaction of vertical solution, lateral erosion, evacuation of solutes and clasts, and clastic fill rates. Growth rates are sigmoidal and conform closely to a genetic model proposed earlier.

## INTRODUCTION

Work in karst morphometry recently has focused on spatial distribution (La Valle, 1967, 1968; Williams, 1972), probability models (McConnell and Horn, 1972), and depression geometry (Jennings, 1975). Studies of doline (sinkhole) geometry have revealed size-related differences between depressions in the same area and through time (Kemmerly and Towe, 1978). Any viable model of doline genesis requires data on depression initiation and short-term growth.

The purpose of this paper is to provide morphometric data on doline initiation and short-term enlargement on the Western Highland Rim. Rates of axial growth and subsidence are evaluated in terms of the independent variables responsible for initiation and enlargement and in terms of the relative influence of structural versus gravitational effects on three-dimensional geometry.

## SITE GEOLOGY

On February 13, 1975, field work, in the southeastern portion of the Clarksville Quadrangle (Tennessee Coordinates: 670,000, N., 1,510,000 E., 87°15′25″ W. Longitude, 36°30′58″ N. Latitude), indicated a small swallet (solution chimney) on a 2-degree west-facing hillslope at an elevation of approximately 540 ft (165 m).

Site geology consisted almost entirely of cherty, clayey residuum derived from the chemical weathering of the St. Louis Limestone. Regionally, three systematic joint sets (N. 70-80°E., N. 20-40°E., and N. 20-30°W.) occur in the St. Louis Limestone. No bedrock cropped-out at the site. Silty colluvium occurred on the hillslope both higher and lower than the swallet. Colluvium originates from down-slope mixing (by sheet wash and channelized flow) of Peoria loess (25,000-50,000 yrs b.p.) with the cherty, clayey residuum. Detailed discussions of surficial geology on the Highland Rim are found elsewhere (Kemmerly, 1975; Kemmerly and Towe, 1978).

The swallet occurred within 300 ft of a large uvala (coalesced, compound doline). The uvala drains a second-order (Strahler nomenclature) intermittent drainage network. A first-order intermittent drainage network ends in another doline 180 ft southwest of the swallet.

Geomorphic competition between the uvala and doline is significant. Competition describes the interaction of dolines for catchment area and runoff. Vigorous headward slope erosion in the catchment areas of two or more adjacent dolines commonly triggers uvala development. Less commonly, vertical downwasting occurs with little shifting of sub-basin (doline) divides. Competition is a function of many variables including (1) spatial distribution of the dolines prior to uvala development (i.e., regular or clustered as opposed to random), (2) depression density, (3) detailed terrain slope configuration, (4) lithologic variations (both bedrock and unconsolidated), (5) systematic joint spacing, and (6) bedrock and regolith permeability. First-order drainage segment (gulleys) geometry, rill development, and the areal extent of exposed regolith indicate that the second-order sub-basin will eventually capture the first-order sub-basin.

## METHOD

The length, mean width, and depth (subsidence) of the developing doline containing the swallet were measured periodically for 1500 days until each parameter reached steady-state conditions. Steady-state conditions mean here that the product of the two ratios of the rate of vertical solution (of bedrock)/rate of lateral erosion (of the regolith) and the ratio of the rate of evacuation of the solutes and clasts (through the swallet)/rate of clastic fill (in the depression) equals 1.0. Aubert (1966) developed these ratios to describe geomorphic controls on doline morphometry. A ratio product equal to 1.0 indicates process adjustment to local surficial geology, bedrock geology, and hydrology. Steady-state conditions exist when doline length, mean width, and subsidence values are constant with time. Changes in geologic and hydrologic conditions invariably disrupt steady-state conditions (Graf, 1977). Disruption triggers either a new growth episode or clastic filling of the doline.

## RESULTS AND DISCUSSION

Doline long axis (L) and mean width (W, normal to L) enlarged in distinct and congruent growth phases (Fig. 1). Doline long-axis measurements show at least three significant growth phases based on changes in

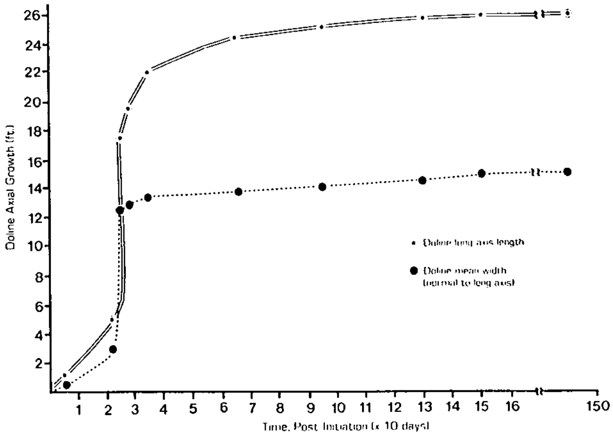

FIG. 1. *Doline axial growth rates during 1500-day period from initiation to steady-state conditions.*

slope and dL/dt (Table 1). Previous work (Williams, 1972; Kemmerly, 1978) showed dL/dt to be the best estimate of structural influence on doline morphometry. Regionally, three systematic joint sets (N. 70-80°E., N. 20-40°E., and N. 20-30°W.) occur in the St. Louis Limestone. Structural influence is greatest in dolines with long-axis orientations parallel to the solution-enlarged N.70°-80°E. joint set. Increased bedrock permeability promotes accelerated sediment evacuation primarily through solution-enlarged joints parallel to doline long axes. Although slope processes operate on all depression slopes, these processes are subordinate to the structural component parallel to joint orientations.

Doline short-axis measurements ($\overline{W}$) also show at least three growth phases based on changes in slope (Fig. 1) and dW/dt (Table 1). Both axial growth profiles have transitional phases (L: $25 \leq t \leq 65$ days; $\overline{W}$: $25 \leq t \leq 35$ days) during which geomorphic processes (variables in equation 1) interact to re-establish steady-state conditions. Phase congruency refers to the parallel trends of both axial growth profiles.

TABLE 1. *Axial growth phases*

| Time*<br>(Post-Initiation) | $\frac{dL}{dt}$ | $\frac{dW}{dt}$ |
|---|---|---|
| 1- 22 days | 0.2 ft/day | 0.1 ft/day |
| 22- 25 | 4.2 | 3.2 |
| 25- 30 | 0.9 | 0.1 |
| 30- 60 | 0.1 | 0.01 |
| 60- 130 | 0.02 | 0.01 |
| 130-1500 | 0.002 | 0.001 |

*Keyed to slope changes in Figure 1.

Slope processes, termed gravitational factors by Williams (1972), reflect surficial geology in terms of the factors that control shear strength of the unconsolidated deposits in karst depressions. Previous work (Kemmerly and Towe, 1978) indicated that dW/dt characterized the relative influence of slope processes on depression enlargement. Although the relative influence of the structural component on depression geometry cannot be isolated from depression geometry, its effect is minimized in the short-axis direction. Given the same surficial geology (Kemmerly and Towe, 1978), slope angles did not change significantly with depression enlargement.

Aubert (1966), in characterizing solution dolines (British equivalent of subsidence doline) as a landform, indicated that doline geometry is a function of the interaction product of two ratios

$$G = f[(V_S/L_E) \times (E_R/C_F)] \qquad (1)$$

where doline three-dimensional geometry (G) is a function of the rates of vertical solution ($V_S$), lateral erosion ($L_E$), evacuation of solutes and clasts ($E_R$), and clastic fill ($C_F$). Aubert's argument has important implications for this study. Axial growth occurs when $(E_R)(V_S)>(L_E)(C_F)$. An intrinsic geomorphic threshold is reached when $(E_R)(V_S)=(L_E)(C_F)$. At this point, doline geometry is stable ($dG/dt = 0$). Credibility increased for both the threshold argument and for $dG/dt = 0$ when maximum depth (subsidence, S) (Fig. 2) stabilized in the same time frame as the axial growth rates. The $dS/dt \neq 0$ if $(E_R)(V_S)>(C_F)(L_E)$ or if the reverse existed, i.e., $(V_S)(E_R)<(L_E)(C_F)$. Subsidence increases where $(V_S)(E_R)>(C_F)(L_E)$. Sediment filling of the doline occurs where $(V_S)(E_R)<(L_E)(C_F)$. One explanation of the sediment-filled dolines in the relict karst of New Mexico may be a long-term shift toward clastic filling of dolines, $(V_S)(E_R)<(L_E)(C_F)$. Certainly, a shift from humid conditions in the Pleistocene to arid conditions would tend to disrupt geomorphic processes described by the two ratios, probably in the direction of (clastic) filling depressions.

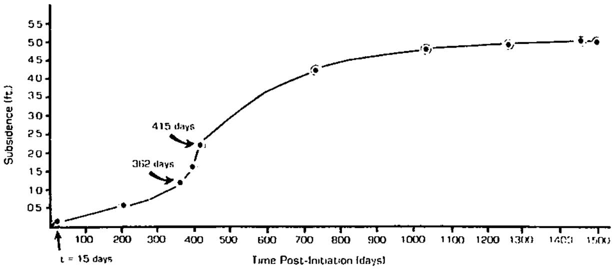

FIG. 2. *Maximum subsidence from initiation to steady-state conditions.*

Subsidence appears most sensitive to the ratio $E_R/C_F$. A rate of solute and clast evacuation that exceeds the rate of clastic fill requires settlement of the depression floor in the swallet area. Drainage networks developed in the catchment area of the doline are adjusted to the mean elevation of the depression floor. Subsidence alters the drainage network by locally increasing stream gradient. This has the effect of increasing slope erosion. Catchment and slope erosion will continue until the gradient prior to subsidence is re-established. Increased slope stability results as clastic fill, derived by erosion of depression slopes, accumulates at the toe of these slopes. This process insures growth of both L and $\overline{W}$ axes. Where the ratio is less than 1.0, $dS/dt < 0$ and clastic fill is deposited in the depression bottom more rapidly than solutes and clasts are removed. Figure 2 shows the interaction of the four processes (equation 1) on subsidence, particularly the effects of the $E_R/C_F$ ratio on cross-sectional geometry. The subsidence rate ($dS/dt$) reached a maximum value from $1 \leq t \leq 15$ days where the ratio $(V_S)(E_R)>(L_E)(C_F)$. Rapid subsidence occurred during the period of maximum evacuation of the solutes and clasts (through the swallet, regolith, solution-enlarged joints, and voids in the carbonate bedrock beneath the doline). During the time period $15 \leq t \leq 360$ days, the ratio $(V_S)(E_R)/(L_E)(C_F)$ approached unity. This transitional subsidence rate represents a near-equilibrium condition as the rates of clastic fill and lateral erosion nearly equaled the rates of vertical solution and evacuation of solutes and clasts. Subsurface conduits transporting the regolith, through the void in the bedrock, were constricted temporarily due to the volume of sediment entering the swallet channels below ground level. A second subsidence phase, from $360 \leq t \leq 415$ days, marked the next time that the threshold (product ratio $= 1.0$)

greatly exceeded unity. Equilibrium conditions were reestablished from $415 \leq t \leq 1500$ days as subsidence rates decreased markedly.

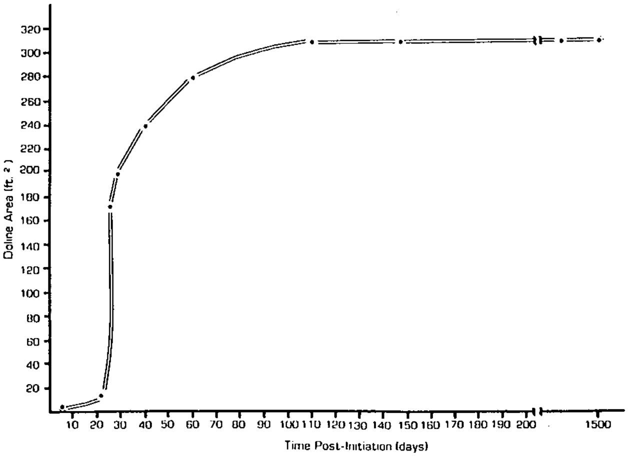

FIG. 3. *Doline planar area during 1500-day period from initiation to steady-state conditions.*

Morphometric data (Fig. 1) were utilized to estimate doline planar area. Field measurements confirmed the basic ellipticity of dolines and therefore

$$A = \pi(L/2)(\overline{W}/2) \qquad (2)$$

where L and $\overline{W}$ are the length of the doline long axis and mean width, respectively. Doline planar area (Fig. 3) exhibits much the same sigmoidal character as the axial growth profiles. Variation in doline areal growth rates reflected differences in slope stability and regolith permeability.

Previous work (Kemmerly, 1980; Kemmerly and Towe, 1978) suggested a particular model for doline initiation and areal enlargement. Doline initiation in mantled karst terrains first becomes apparent when subsidence is observed along shear-failure scarplets. Subsidence follows the evacuation (via diffuse and tubular flow) of solutes and fine sediment through surficial deposits and solution-enlarged joints. The original topographic profile is altered and unstable slopes of varying length, percent grade, and vegetational stability are exposed to slumping, sheet wash, rilling, and channeling. During this initial phase, clastic fill rate is typically less than the evacuation rate of solutes and suspended sediments. Subsequent subsidence generally parallels solution-enlarged joints. The second phase of doline enlargement involves the erosion (via sheet wash and channelized flow) and redeposition of silty colluvium in the doline. This phase contributes to, or initiates, two geomorphic reactions. First, a reduction in secondary premeability along solution-enlarged joints commonly reduces the structural growth rate (dL/dt); second, when the clastic fill rate exceeds the evacuation rate, some filling of the doline occurs, accompanied by an increase in dW/dt. Later, the dW/dt diminishes as the side-slope angle decreases to a stable slope. This entire process reoccurs as a function of continued redevelopment of adequate permeability in the unconsolidated deposits.

Once the doline area exceeds some threshold area ($A_C$), areal growth rates (dA/dt) accelerate as greater runoff volumes are diverted through the swallet system. Several factors can slow this stage of doline growth: (1) secondary permeability may be reduced substantially; (2) the rate of clastic fill can exceed the rate of sediment evacuation; (3) competition may interrupt areal growth.

## CONCLUSIONS

A 1500-day study of doline initiation and short-term enlargement on the Western Highland Rim demonstrated that depression long- and short-axes growth rates followed a sigmoidal growth profile predicted by the theoretical model proposed by Kemmerly and Towe (1978). Subsidence rates also increased sigmoidally. Three-dimensional doline geometry largely is controlled by interaction between the rates of vertical solution, lateral erosion, evacuation of solutes and clasts, and clastic fill.

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