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DETECTION OF SINKHOLES DEVELOPED ON SHALY ORDOVICIAN LIMESTONES, HAMILTON COUNTY, OHIO, USING DIGITAL TOPOGRAPHIC DATA: DEPENDENCE OF TOPOGRAPHIC EXPRESSION OF SINKHOLES ON SCALE, CONTOUR INTERVAL, AND SLOPE

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The Ohio Geological Survey has recently published a map showing the locations of known and probable karst in Ohio. The map shows some areas of karst developed on the extremely shaly Ordovician limestone of Hamilton County, in the southwestern corner of the state. Detailed mapping of these sinkholes in Mt. Airy Forest, a municipal park near Cincinnati, shows that they occur only where the lower 10 m of the Corryville Member of the Grant Lake Formation is the surface bedrock. Of the many sinkholes in the study area, only one is evident on the 1:24,000 USGS topographic map. The expression of sinkholes on contour maps is dependent on the size of the sinkhole, as well as the scale of the map, the contour interval at which the topography is sampled, and the slope of the ground surface around the sinkhole. It is possible to determine the minimum size of sinkhole which will consistently be expressed on a given part of a contour map. Conversely, it is also possible to determine the scale and contour interval which will be necessary to consistently indicate the presence of sinkholes of a given minimum size.

The Ohio Geological Survey has recently published a map at a scale of 1:500,000 showing the locations of known and probable karst areas in Ohio (Pavey *et al.* 1999). Most of the karst areas in the state are underlain by relatively pure Silurian and Devonian carbonates; the units most prone to karstification are the Silurian Peebles Dolomite and the Devonian Columbus Limestone (Pavey *et al*. 1999). However, the map also shows a number of karst features developed on the interbedded shales and limestones of Upper Ordovician age in southwestern Ohio. In particular, the karst areas of Hamilton County, which are developed on some extremely shaly limestones, have never been described or mapped at any larger scale. This paper provides the results of some detailed mapping of sinkholes in a small area near Cincinnati.

The results of this mapping exercise have implications for the practice of locating sinkholes on US Geological Survey (USGS) 1:24,000 topographic maps. A qualitative comparison of the mapped locations of the sinkholes with 2 topographic data sets show that contours from the USGS quadrangle maps do not predict the presence of sinkholes as well as contours plotted at a scale of 1:100. Even this higher-resolution data set (from the Cincinnati Area Geographic Information System) does not give a true picture of the number, density, nor size of sinkholes in the field area.

STUDY AREA

The Ohio Geological Survey's karst map identifies 3 general areas of known karst in Hamilton County (Fig. 1). These areas occur at the western end of Winton Lake (Greenhills 7.5-min. quadrangle), north of Taylor Creek (Addyston quad), and near West Fork Creek in Mt. Airy Forest (Cincinnati West quad).

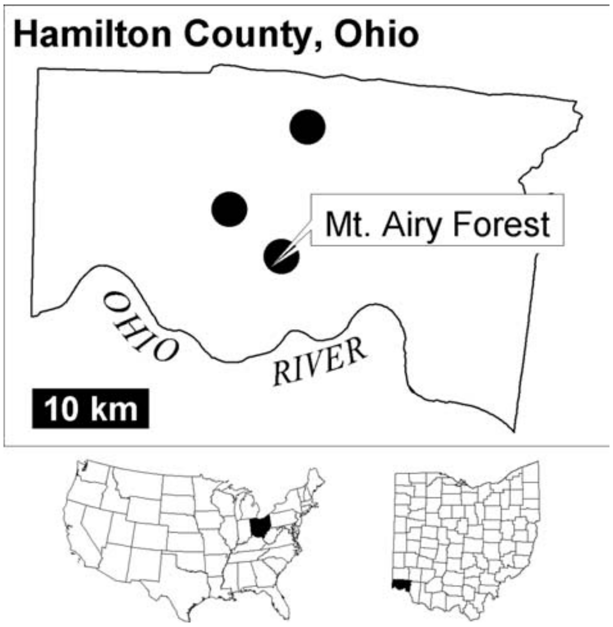

Figure 1. Map of Hamilton County, Ohio, showing the general locations of areas of known karst (black dots; simplified from Pavey *et al.* 1999). Sources: ESRI (US map) and Wells (2000; county outlines).

The Mt. Airy Forest karst area lies almost completely within a large municipal park of the same name. The sinkholes there are well developed and accessible. The field observations

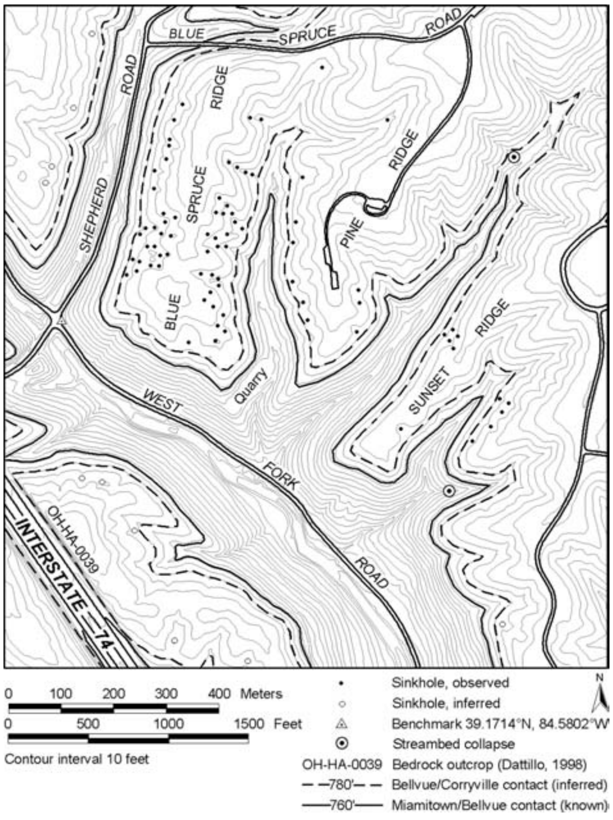

Figure 2. Mt. Airy Forest study area (Blue Spruce, Pine, and Sunset Ridges) and immediate surroundings; contour interval 10 ft. Topography from Cincinnati Area Geographic Information System (CAGIS).

for this paper were made in Mt. Airy Forest on Blue Spruce Ridge, Pine Ridge, and Sunset Ridge (Fig. 2).

Geologic maps of the Cincinnati West quadrangle (Ford 1974; Swinford & Ford 1996) show that the bedrock units listed in Table 1 are exposed in the study area. It is important to note that none of the units exposed in the study area are pure carbonates. Most are interbedded with considerable amounts of shale. The individual beds of limestone are thickest in the Fairview Formation, and even there they are rarely more than 0.3 m thick.

METHODS

All of the sinkholes in the Mt. Airy Forest study area (Fig. 2) were plotted by hand on a topographic base map prepared from the 10-ft contour interval topographic layer of the Cincinnati Area Geographic Information System (CAGIS). The contours in the CAGIS topographic layer were traced using a stereo plotter at a scale of 1:100, rather than the 1:24,000 scale used for USGS 7.5-min. maps (John Coulter, pers. comm., 2002).

For the purposes of this mapping, a sinkhole was considered to be any closed, localized depression in the ground surface. Where small depressions occurred within larger ones, the smaller depressions were mapped.

The elevation of the Bellvue/Miamitown contact was confirmed in the field. The Corryville/Bellvue contact is covered in the study area, but the thickness of the Bellvue was measured by Dattillo (1998) at a roadcut along Interstate 74 just outside of the field area (OH-HA-0039 on Fig. 2). Adding the 6.5-m thickness of the Bellvue at that roadcut to the 760-ft elevation of the Bellvue/Miamitown contact gives an elevation of about 780 ft for the Corryville/Bellvue contact.

RESULTS

All of the sinkholes in the Mt. Airy Forest study area plot between the 780- and 810-ft contours on the map, within the lower 10 m (30 feet) of the Corryville Member (Fig. 2). Field sheets from the Ohio Geological Survey show that the sinkholes in the other known karst areas in Hamilton County also occur in this stratigraphic interval (Dennis Hull, pers. comm., 2002).

In Mt. Airy Forest, the sinkholes tend to be <25 m across and 3 m deep. The single largest sinkhole observed in the study area is near the southern end of Blue Spruce Ridge, and is ~63 m across and 4 m deep.

DISCUSSION

Since the Corryville Member is mostly shale (65% on average; Swinford *et al*. 2001), it is surprising that the sinkholes are found only where it is the surface bedrock. Its high shale content suggests that it is probably not being removed solutionally. Instead, there may be a water table perched on the

Table 1. Descriptions of bedrock units exposed in the study area. The thickness of the Fairview Formation is estimated from Ford (1974) and Swinford and Ford (1996). The thicknesses of the Miamitown Shale and the Bellvue Member were measured by Dattillo (1998) at outcrop OH-HA-0039 (Fig. 2). Other values are from Swinford *et al*. (2001).

Formation	Member	Thickness	% Limestone	Description
Grant Lake	Corryville	19 m (60 ft)	35	Interbedded limestone and shale; poorly exposed in study area
	Bellvue	6.5 m (21 ft)	65	Wavy-bedded, nodular, shelly limestone, interbedded with minor amounts of shale
Miamitown Shale	2.7 m (9 ft)	10		Shale
Fairview	undivided	15 m (100 ft)	50	Limestone interbedded with shale; lower portion is less limestone-rich than upper portion
Kope	undivided	60 m (200 ft)	25	Interbedded limestone and shale; only about 9 m (30 ft) exposed in study area

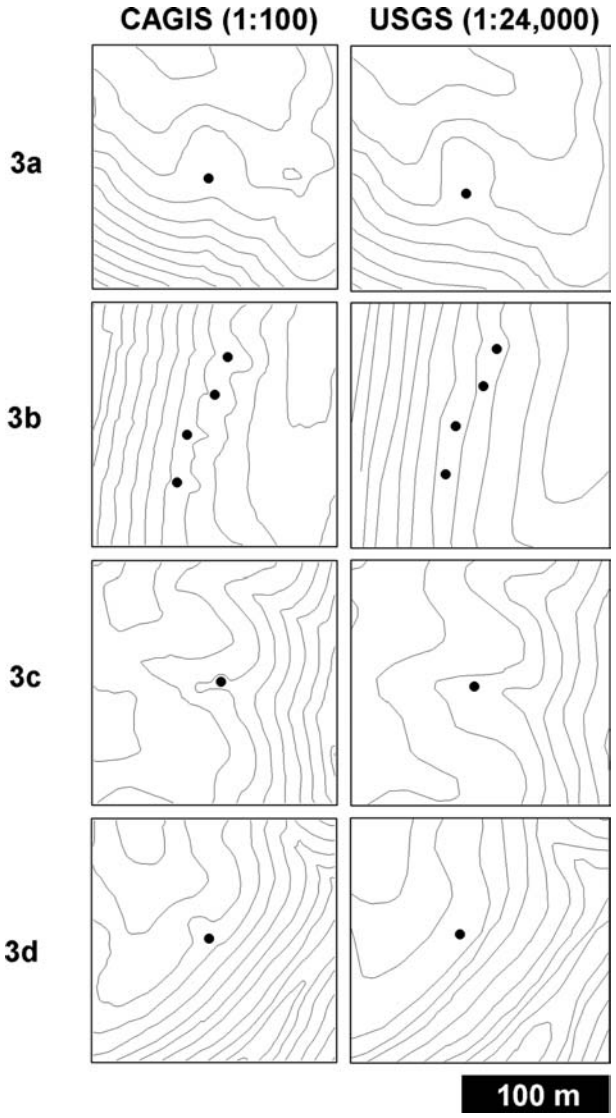

Figure 3. This figure shows the contour crenulations produced by selected sinkholes in the study area. Of all the sinkholes in the study area, only that in 3a is evident from the USGS contours. The contour interval is 10 ft for all eight maps.

Miamitown Shale that is dissolving the Bellvue Member, while the Corryville is collapsing into the cavities. It has historically been observed (Fenneman 1916) that the Bellvue Member is particularly resistant to erosion, and tends to mark a break in slope between itself and the overlying strata. It may be that no sinkholes appear where the Bellvue itself is the surface bedrock because the slopes it forms are too steep.

Most of the sinkholes in the study area do not hold water, even after heavy rains (though there are exceptions; one sinkhole on Blue Spruce Ridge is a seasonal pond). After prolonged periods of rain, many of the sinkholes show collapses at their bottoms, indicating that they have some way of passing sediment through themselves as well as water. The proximity of some of these sinkholes to gullies, and the presence in some of these gullies of collapses (Fig. 2), suggest that the gullies may be the surface expressions of conduits that drain the sinkholes. Without further study, however, this hypothesis must remain tentative.

Figure 3 shows the contour crenulations that represent selected field-verified sinkholes from the Mt. Airy Forest study area. Except in Figure 3a, which shows the largest sinkhole in the study area, the crenulations seen in the CAGIS contours are absent in the USGS contours. However, even the more detailed CAGIS data does not show all of the sinkholes (Fig. 2).

There are three factors that influence whether or not a sinkhole of a given size will be expressed on a contour map: 1) the scale at which the data is prepared; 2) the contour interval at which the topography is sampled; 3) the slope of the ground surface around the sinkhole.

We can assume that a circular topographic feature must be at least 2 mm across at the scale of the final map in order to be represented on that map. Therefore, the minimum sinkhole width that may be expressed on a USGS 7.5-minute quadrangle map is

$$2 \text{ map mm} \cdot \frac{24{,}000 \text{ ground mm}}{1 \text{ map mm}} \cdot \frac{1 \text{ m}}{1000 \text{ mm}} = 48 \text{ ground m}$$

In contrast, the minimum sinkhole width which may be expressed by the CAGIS contours, which were prepared at a scale of 1:100, is

$$2 \text{ map mm} \cdot \frac{100 \text{ ground mm}}{1 \text{ map mm}} \cdot \frac{1 \text{ m}}{1000 \text{ mm}} = 0.2 \text{ ground m}$$

The 1:100 scale is probably larger than necessary for sinkhole mapping, since a depression only 20 cm across would not be mapped as a sinkhole.

Sinkholes can be expressed on topographic maps as either contour crenulations, like those seen in figure 3, or as sets of closed, hachured contours. The style of expression of a particular sinkhole is dependent on the slope of the ground around it. On a steep slope, where the contours are close together, one or more of the contours may intersect the sinkhole, producing contour crenulations. Where the ground is flat and horizontal, however, the contours will be much further apart than the width of any sinkhole. In that case, the sinkholes will be expressed as hachured contours.

Figure 4 illustrates the importance of contour interval in the expression on contour maps of sinkholes developed on flat ground. Sinkholes that have a depth of twice the contour interval will always contain at least one hachured contour, and will usually contain two. By extension, the minimum sinkhole depth, D, which will consistently contain a given number of contours, n, on a flat surface is

$$D = nC$$

where C is the contour interval.

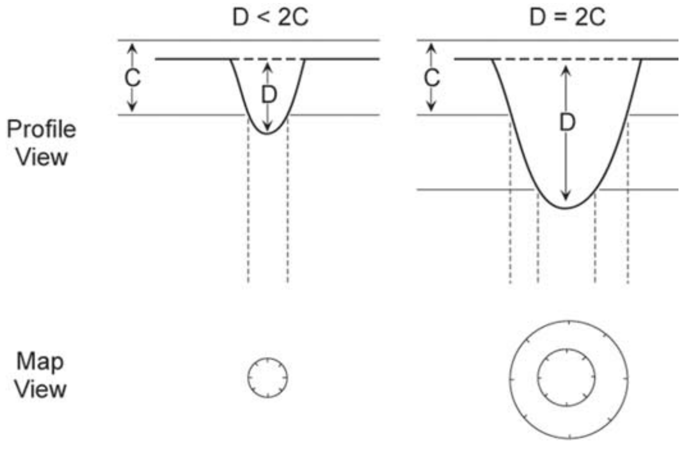

Figure 4. This figure shows the importance of sinkhole depth in the expression of that sinkhole on a contour map. The sinkhole on the right, which has a depth, D, equal to twice the contour interval, is better represented by the contours than the sinkhole on the left, which is much less deep. Contour interval, C, is held constant between the 2 drawings.

On a slope, however, the width of a sinkhole, rather than its depth, determines whether or not it will be expressed on a contour map (Fig. 5). Sinkholes that are twice as wide as the horizontal distance between contours will always be represented on a contour map by at least one crenulated contour, and will usually include two. The minimum sinkhole width, W, that will consistently be represented on a topographic map by a given number of crenulated contours, n, on a slope is

$$W = \frac{nC}{\tan \alpha}$$

where C is the contour interval and α is the angle that the slope forms with the horizontal.

Both these situations are present in the study area (Fig. 2). The shoulders of the ridges are relatively steep, and the sinkholes there tend to produce contour crenulations. On the other hand, the crests of the ridges are nearly horizontal, and the sinkholes near the crests are not evident from the contours because their depths are much less than the contour interval.

Thus, the expression of a sinkhole (or other circular topographic feature) on a contour map is dependent on the size (width and depth) of the sinkhole, the scale at which the map is prepared, the slope of the ground surface around the sinkhole, and the contour interval at which the topography is sampled. It is possible to determine, for any given location on a contour map, the minimum sinkhole size that will consistently be expressed by the contours. This minimum size will change over the extent of a contour map as the slope changes. Conversely, it is also possible to determine the scale and contour interval that will be necessary to consistently indicate the presence of sinkholes of a given minimum size.

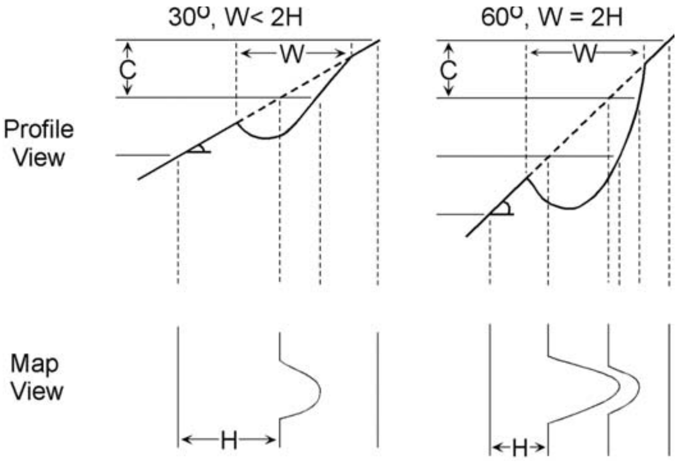

Figure 5. This figure shows the importance of slope in the expression of sinkholes of a given width on a contour map. Width, W, and contour interval, C, are held constant between the 2 drawings. Despite having the same width as the sinkhole on the right, the sinkhole on the left is represented by only one contour crenulation because the slope it is on is less steep than that on the right.

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