Illinois County Geologic Map
ICGM Monroe-SD

Sinkhole Distribution and Associated Karst Features of Monroe County, Illinois

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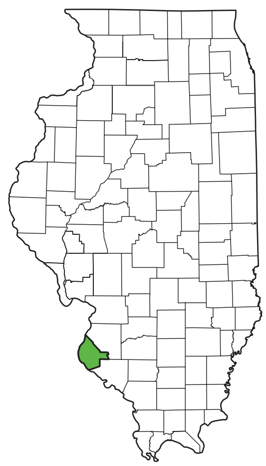

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Introduction

An estimated 23 percent of the bedrock surface area of Illinois is carbonate rock, 35 percent of which is concentrated within the state's five known karst regions (fig. 1). Karst is defined by Ford and Williams (1989) as "…terrain with distinctive hydrology and landforms arising from a combination of high rock solubility and well developed secondary porosity." Characteristic features of karst terrain include sinkholes, caves, large springs, fluted rock outcrops, blind valleys, swallow holes, solution-enlarged crevices, and a well-defined epikarst soil-bedrock interface in outcrops (White 1988, Ford and Williams 1989). Mapping of karst areas in Illinois began in the mid-1990s by the Illinois State Geological Survey (ISGS) (Panno and Weibel 1996, Weibel and Panno 1997). Delineation and inventory of karst features are important because of the susceptibility of karst terrain to groundwater contamination and the unique problems associated with construction of buildings and roads in karst areas. For example, state regulations can require special modifications to facilities such as confined animal feeding operations (CAFOs) that are sited in known karst regions of Illinois.

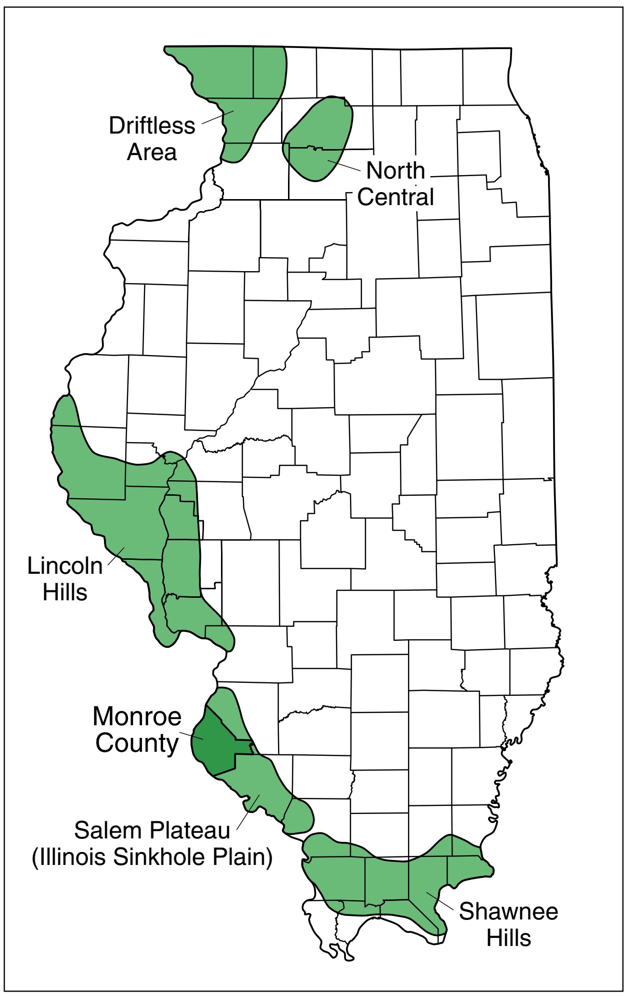

Figure 1 Karst regions of Illinois (Weibel and Panno 1997).

Figure 2 Aerial photograph of the sinkhole plain in Monroe County looking west toward the Mississippi River showing sinkholes and ponded sinkholes. (Photograph by Joel M. Dexter).

Situated in southwestern Illinois principally within Monroe, Randolph, and St. Clair Counties, the Illinois sinkhole plain contains the highest concentration of karst features within the state (fig. 2). Sinkholes are a distinctive rural landscape feature, and large springs are common and typically points of resurgence for groundwater basins (Panno et al. 2001, Hackley et al. 2007). The bedrock geology of the sinkhole plain is Mississippian-age limestone (main map) with an overburden of loess and glacial till averaging less than 8 m (26.25 ft) in thickness (Herzog et al. 1994). The thin overburden, the abundance of solution-enlarged crevices in the limestone bedrock, and the relative ease of collapse of loess and glacial till into those crevices are responsible for the large number of cover-collapse sinkholes (Panno 1996). Solution-enlarged crevices are abundant with crevice widths ranging from less than 1 cm to several meters, and widths of 15 cm to 30 cm (approximately 6 in to 12 in) are typical. In these areas the overlying sediment tends to collapse into the crevices, and the sediment is subsequently transported away from the crevices by inflowing recharge water and shallow groundwater. The character of the overlying sediment, the intensely creviced bedrock, and perhaps prehistoric periods of drought have combined to produce the very high density of sinkholes present in the sinkhole plain (Panno et al. 2011a, 2011b). Recent work by Lindsey et al. (2010) has shown that sinkhole density is an important parameter contributing to aquifer vulnerability. Based upon data collected from karst areas in Alabama, Florida, Missouri, Pennsylvania, and Tennessee, Lindsey et al. developed three categories

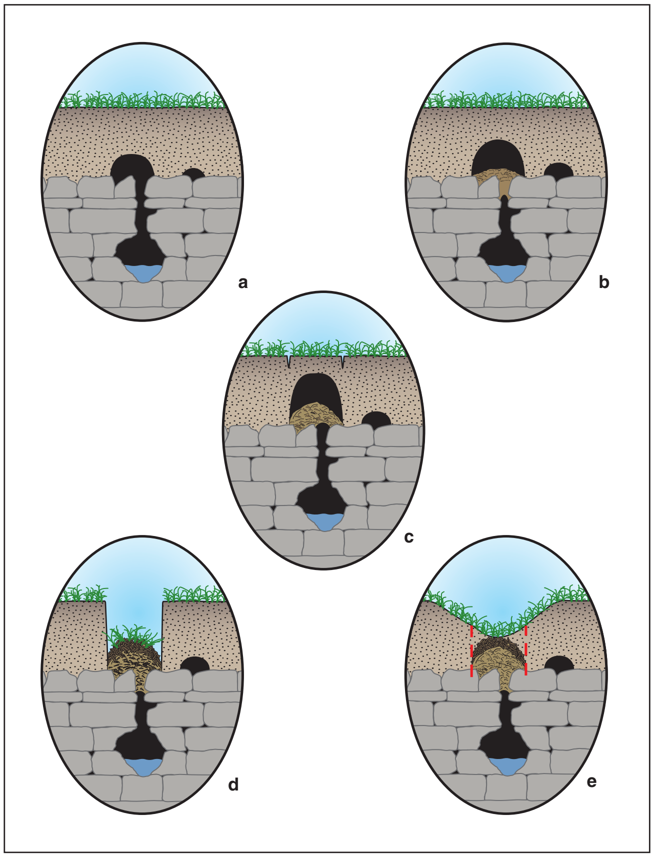

Figure 3 The formation of cover-collapse sinkholes begins with collapse of unconsolidated sediment into a bedrock crevice and/or cavity (a). A dome-shaped cavity in the sediment forms at the bedrock surface and propagates to the surface (b, c). Ultimately, the surface materials collapse into the void creating a cylindrical hole (d) that erosion converts into a bowl-shaped depression (e). From Panno et al. (2004).

of sinkhole density: low (<1 sinkhole/100 km^2 or approximately 39 mi^2), medium (1–25 sinkholes/100 km^2), and high (>25 sinkholes/100 km^2).

The primary objective of this study was to inventory and catalog sinkhole and associated karst features in Monroe County, Illinois (main map). Monroe County is situated within the heart of the sinkhole plain, and cover-collapse sinkholes are common (fig. 3). Lindsey et al. (2010) determined that nitrate concentrations in groundwater, indicative of anthropogenic contamination typically associated with agricultural lands, were significantly greater in karst terrain characterized by medium to high sinkhole density than in areas with low sinkhole density. Agricultural lands account for an estimated 73 percent of the surface area of Monroe County (ISGS 2001). Analysis of sinkhole density for the U.S. Geological Survey (USGS) 7.5-minute Columbia, Waterloo, and Renault quadrangles, which contain the majority of sinkhole features for Monroe County (main map), shows a density several hundred times greater than the low end of Lindsey et al.'s high sinkhole density category (Panno et al. 2008a, 2008b, 2008c).

Although Panno (1996) estimated that the sinkhole plain contains approximately 10,000 cover-collapse sinkholes, there has been no previous detailed inventory to determine their precise numbers and geographic locations. Tabulation of closed depressions present on USGS 7.5-minute topographic quadrangle maps is traditionally used as a primary information source for a regional inventory of sinkhole features (figs. 4 and 5). Monroe County contains all or portions of 15 USGS 7.5-minute topographic quadrangles (fig. M2 on main map). Their elevation data have source dates ranging from 1952 to 1986, and the maps use a mixture of mostly 10-foot and some 20-foot contour intervals. A problem is that many sinkholes are shallower than these contour intervals, and therefore are not represented on the USGS maps as depression contours. Therefore, the resulting map-based inventory underestimates sinkhole numbers, and, for an intensely karstified area such as Monroe County, the undercounting can be significant. A comprehensive inventory of karst features is needed to more accurately characterize the fabric and geometry of the shallow karst aquifer within Monroe County.

Materials and Methods

USDA Agricultural Adjustment Administration

A previous investigation by Luman and Panno (2011) showed that photointerpretation of historical aerial photography provides an accurate and efficient method for identification and delineation of palimpsest, or relict, sinkhole features not symbolized on USGS 7.5-minute topographic quadrangle maps. Analysis of two topographic quadrangle maps determined that an average of one-third of the sinkhole features were overlooked using only tabulation of depression contours compared with results obtained by photointerpretation of the historical aerial photography.

Created in 1933 and subsequently managed by the U.S. Department of Agriculture, the Agricultural Adjustment Administration (AAA) acquired first-time, nationwide aerial photography during the summer months of 1936–1941 for the purpose of estimating cropland acreages. The AAA aerial photography provided the means by which the federal government undertook large-scale mapping of the nation's landscape for the first time since the Land Ordinance Act of 1785 (Weems 2003), and the program is regarded as one of the earliest applications of aerial photography on such a large geographic scale anywhere in the world (Earth Observation Magazine 2004). The acquisition of AAA aerial photography in Illinois was completed prior to the general introduction of mechanized farming practices, at a time when horse- and mule-drawn equipment was still prevalent across much of Illinois. Because pesticide and fertilizer applications were mostly unknown during this period, crops were planted at much lower plant densities to enable cultivation. Surficial geologic features such as sinkholes can therefore easily be discriminated through the mature summer crop canopy on these early AAA aerial photographs.

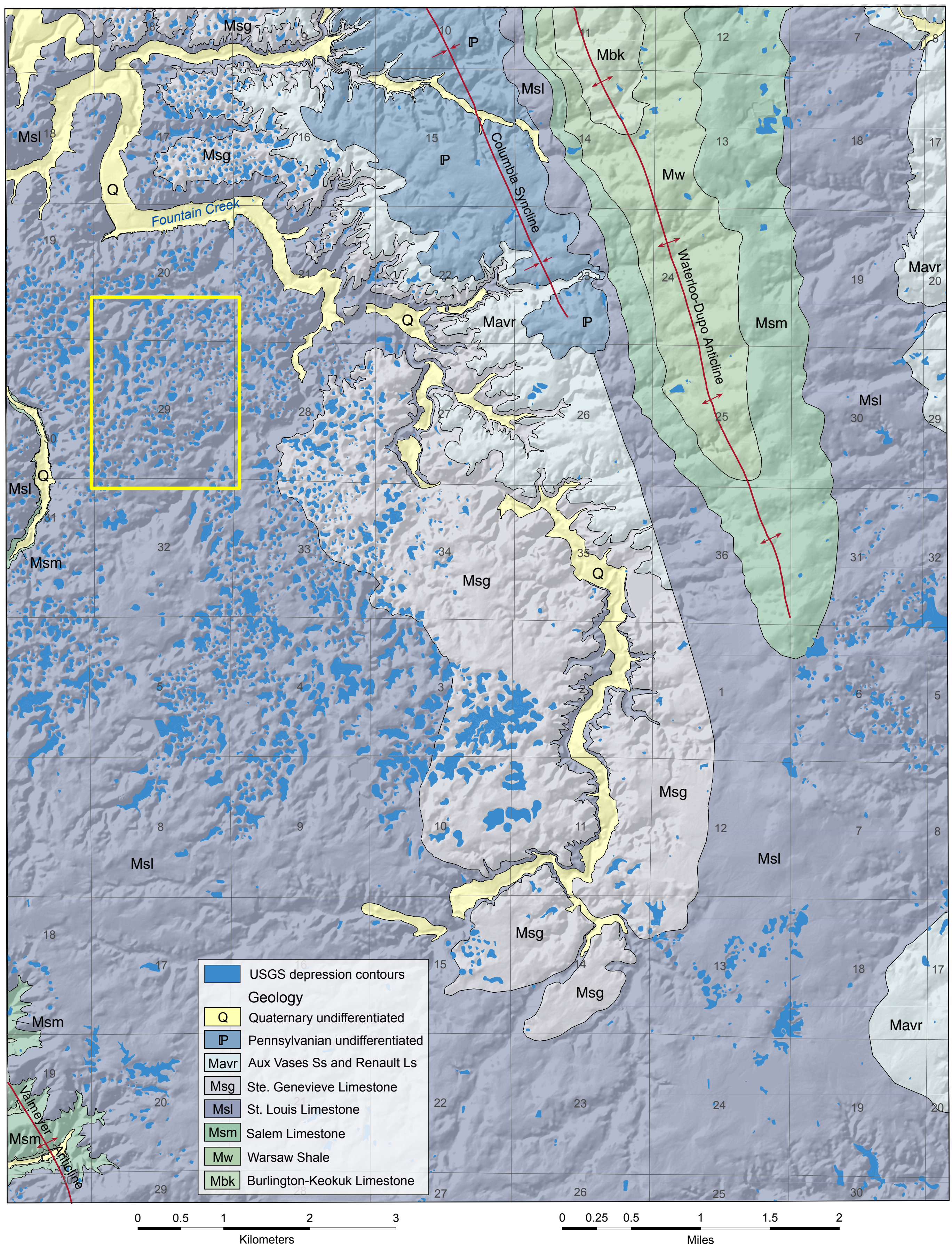

Figure 4 Sinkhole distribution as characterized by closed depression contours for the USGS 7.5-minute Waterloo Quadrangle. Contour interval is 10 feet. Sinkhole areas are highlighted in blue. Bedrock geology from Denny (2000). Yellow outline indicates area shown in detail in figures 7, 8, and 10.

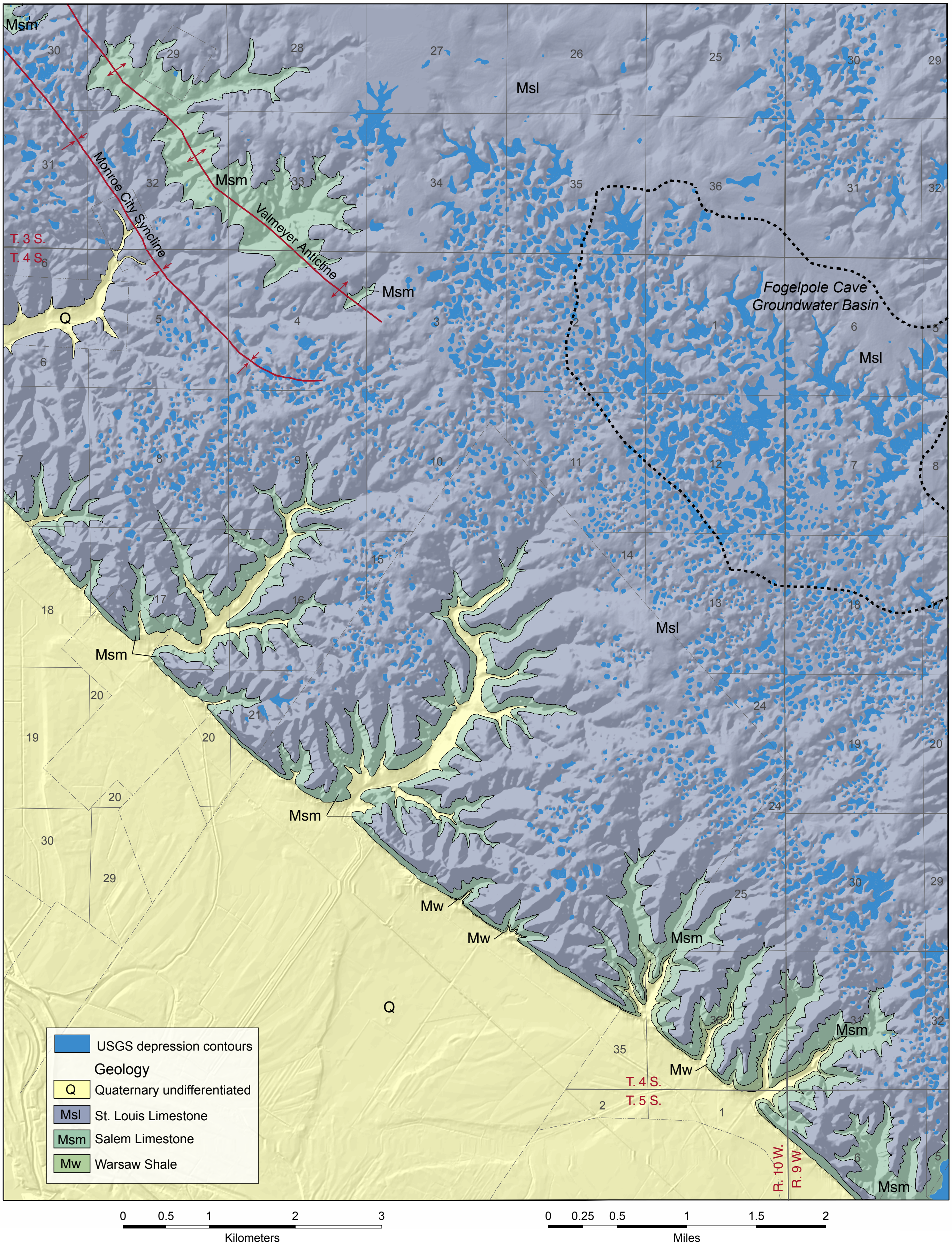

Figure 5 Sinkhole distribution as delineated by closed depression contours for the USGS 7.5-minute Renault Quadrangle. Contour interval is 20 feet. Sinkhole areas are highlighted in blue. Bedrock geology from Devera (2000).

All of the individual frames of 1936–1941 AAA aerial photography for Illinois have been digitized and are available online (http://www.isgs.illinois.edu/nsdihome/webdocs/ilhap/). The majority of the AAA photography for Monroe County was acquired in June and July 1940, and the digitized images possess a ground spatial resolution of approximately 1 m × 1 m (approximately 3.2 ft × 3.2 ft) per image pixel. For selected areas of the state, including Monroe County, the digitized AAA photographs have been orthorectified; that is, the geometric distortions inherent in the digitized images have been removed and projected to a standard cartographic projection. The resulting digital orthophotographs can therefore be combined with other map and image data for analysis in a geographic information system (GIS).

USGS National Aerial Photography Program

Significant changes to the land surface have occurred during the 75 years since the collection of AAA aerial photography for Illinois. For example, post-World War II mechanization dramatically altered agricultural land uses and practices. Combined with urbanization and other infrastructure modifications, the present-day landscape is often difficult to recognize on AAA aerial photographs. The USGS National Aerial Photography Program (NAPP) Digital Orthophoto Quadrangle (DOQ) imagery was therefore used for the purpose of correlation and location of karst features identified on the 1940 AAA aerial photographs.

The most recent Illinois NAPP aerial photography was acquired in March 2005 for Monroe County. Although the 2005 DOQ imagery produced from the 2005 NAPP was created in accordance with USGS specifications, it differs in that the ground spatial resolution was increased from the traditional standard of 1 m × 1 m to ½ m × ½ m per pixel. This enhanced resolution significantly improves the interpretation of ground features, providing an excellent reference source for the photointerpretation of the AAA aerial photography.

Because AAA aerial photography was acquired during the summer months, delineation of sinkholes is obscured in wooded areas, which are abundant across the Illinois sinkhole plain region. Agricultural lands avoid low areas that generally contain exposed bedrock in this region, and such areas remain undeveloped. Using the leaf-off NAPP aerial photography, sinkhole features can more easily be detected within these wooded areas.

Figure 6 shows the complementary nature of 1940 AAA and 2005 NAPP aerial photography for a particularly karstified area of St. Clair County, Illinois, located in Sections 34–35, T1N, R10W. Circular patterns diagnostic of cover-collapse sinkholes, quite apparent on the 1940 image, are obscured or have largely been erased on the 2005 image. During the 65-year time interval between the two aerial photographs, farm operators have remediated sinkholes through the installation of stand pipes and infilling; decades of use by large-scale farming equipment has altered the original soil surface; and the widespread adoption of conservation tillage methods beginning in the 1980s have all combined to nearly eradicate the visual evidence of many of the karst features within the Illinois sinkhole plain.

USGS 7.5-minute Topographic Map Data

The USGS one-third arc second, 10 m (approximately 32 ft) nominal horizontal resolution digital elevation model (DEM) data for Monroe County, Illinois, were acquired from the USGS National Elevation Dataset (NED) (http://ned.usgs.gov/). The DEM data were used to identify and delineate structural lineaments within Monroe County, which are difficult or impossible to discern on aerial photography. Contours published on USGS 7.5-minute topographic quadrangles are the primary source information used to produce USGS DEM data, and the source dates of the topographic information range from 1962 to 1986 for the upland areas of Monroe County and from 1995 to 1999 for the area within the Mississippi River floodplain.

In addition to the DEM data, the USGS large-scale digital line graph data (DLG) for the hypsography (elevation) feature class were acquired from the USGS EarthExplorer website (http://edcsns17.cr.usgs.gov/NewEarthExplorer/). The USGS DLG hypsography feature layer data were processed to show only the depression contours present on published USGS 7.5-minute quadrangle maps. As previously mentioned, depression contours have historically been used by geologists as surrogates for sinkhole locations.

GIS Analysis

Orthorectified 1940 AAA and 2005 NAPP aerial photography, USGS DEM and DLG data, and digitized statewide bedrock geology were assembled into an ArcGIS file geodatabase structure. All sinkhole features in Monroe County were photointerpreted and inventoried using the orthorectified 1940 AAA aerial photography as the primary data source and compared with the 2005 NAPP DOQ aerial photography. The centroids of all sinkholes were digitized and catalogued with a numeric identifier. Structural lineaments were delineated using the DEM data.

Results and Discussion

Karst Geology and Hydrogeology

Cover-collapse sinkholes in Monroe County form in loess and glacial till that overlie the creviced Mississippian-age, St. Louis and Ste. Genevieve Limestone bedrock (main map) (Denny 2000, Devera 2000). These limestone formations are nearly pure calcium carbonate and are easily dissolved by rainwater, snowmelt, and soil water (Panno et al. 1997). Sinkholes are concentrated in two major areas of the county, which are largely encompassed by the USGS 7.5-minute Waterloo and Renault quadrangles (fig. M2 on main map)). These areas exhibit sinkhole densities as high as 95 per km^2 (approximately 37 per mi^2) (Angel et al. 2004) and contain

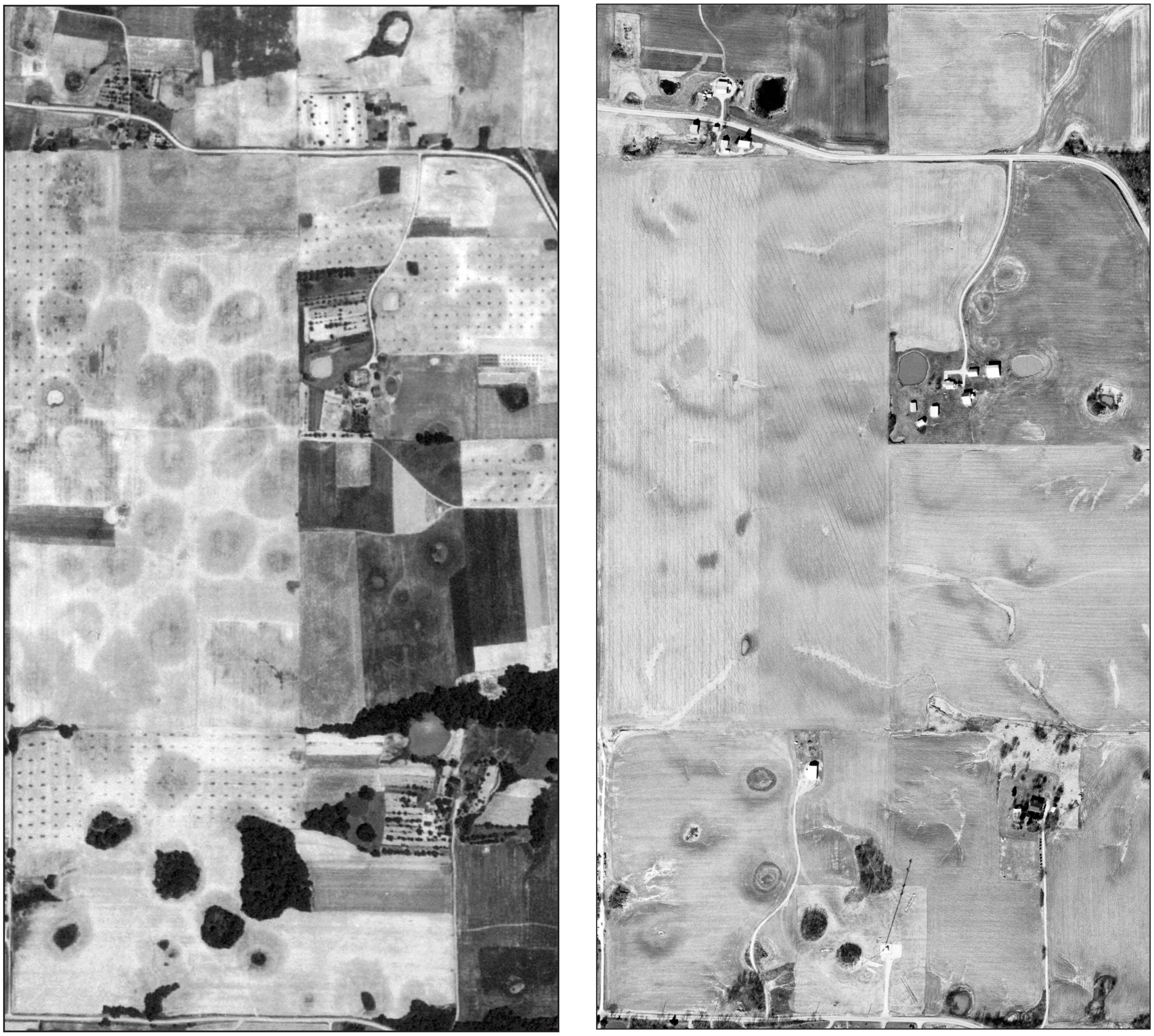

Figure 6 July 5, 1940, USDA AAA aerial photograph (a) compared with a March 3, 2005, USGS NAPP aerial photograph (b) illustrating the distinctive appearance of sinkhole features on historical aerial photography. Scale is approximately 1 inch = 750 ft.

relatively long (>10 km; approximately 6.2 mi) to medium length (1 to 2 km; approximately 0.6 mi to 1.2 mi) caves and abundant solution-enlarged crevices visible in outcrops, road cuts, and quarries.

Examination of the main map shows that the greatest density of sinkholes is situated on the upland areas adjacent to Fountain Creek, a prominent joint-controlled stream valley west of Waterloo, Illinois, and upland areas in southern Monroe County. The largest sinkholes are positioned towards the headwaters of known and suspected cave systems (Panno et al. 2011a). Smaller, shallower sinkholes are crevice-controlled and scattered throughout the county. Area analysis of the closed depressions showed that the largest sinkholes in the Fountain Creek area are nearly 10.1 hectares (25 acres), with an average sinkhole size of 0.2 hectares (0.5 acre) (fig. 4). The average sinkhole size in the southern Monroe County is 0.8 acres (0.3 hectares) and ranges from (6.1 to 30.4 hectares (15 acres to nearly 75 acres). The largest sinkholes are associated with the Fogelpole Cave groundwater basin (fig. 5). In this region, sinkholes appear to be segments of a larger stream valley that is now draining into sinkholes.

Cover-Collapse Sinkhole Inventory

This *Sinkhole Distribution and Associated Karst Features of Monroe County, Illinois* map represents the first time karst features have been inventoried in Illinois. There is a high degree of correlation between the map analysis and photointerpretation, but it is only when a detailed comparison is made that the contribution of the historical aerial photography is fully realized. As an example, AAA and NAPP aerial photographs were analyzed for a representative area

Figure 7 USDA AAA aerial photograph acquired on September 5, 1940, for a portion of the Waterloo Quadrangle (see fig. 4 for location). Lighter-toned perimeters of sinkholes are due to the raised rims and the prevailing dry surface conditions. Sinkholes located within wooded areas of the photograph are completely obscured by the late summer leaf canopy.

Figure 8 USGS NAPP aerial photograph acquired on March 6, 2005, for the same portion of the Waterloo Quadrangle as figure 7. Sinkhole ponds are indicative of much wetter surface conditions than are shown on the USDA AAA photograph. Because the photograph was collected during late winter leaf-off conditions, sinkholes within the wooded areas can be distinguished through the barren canopy.

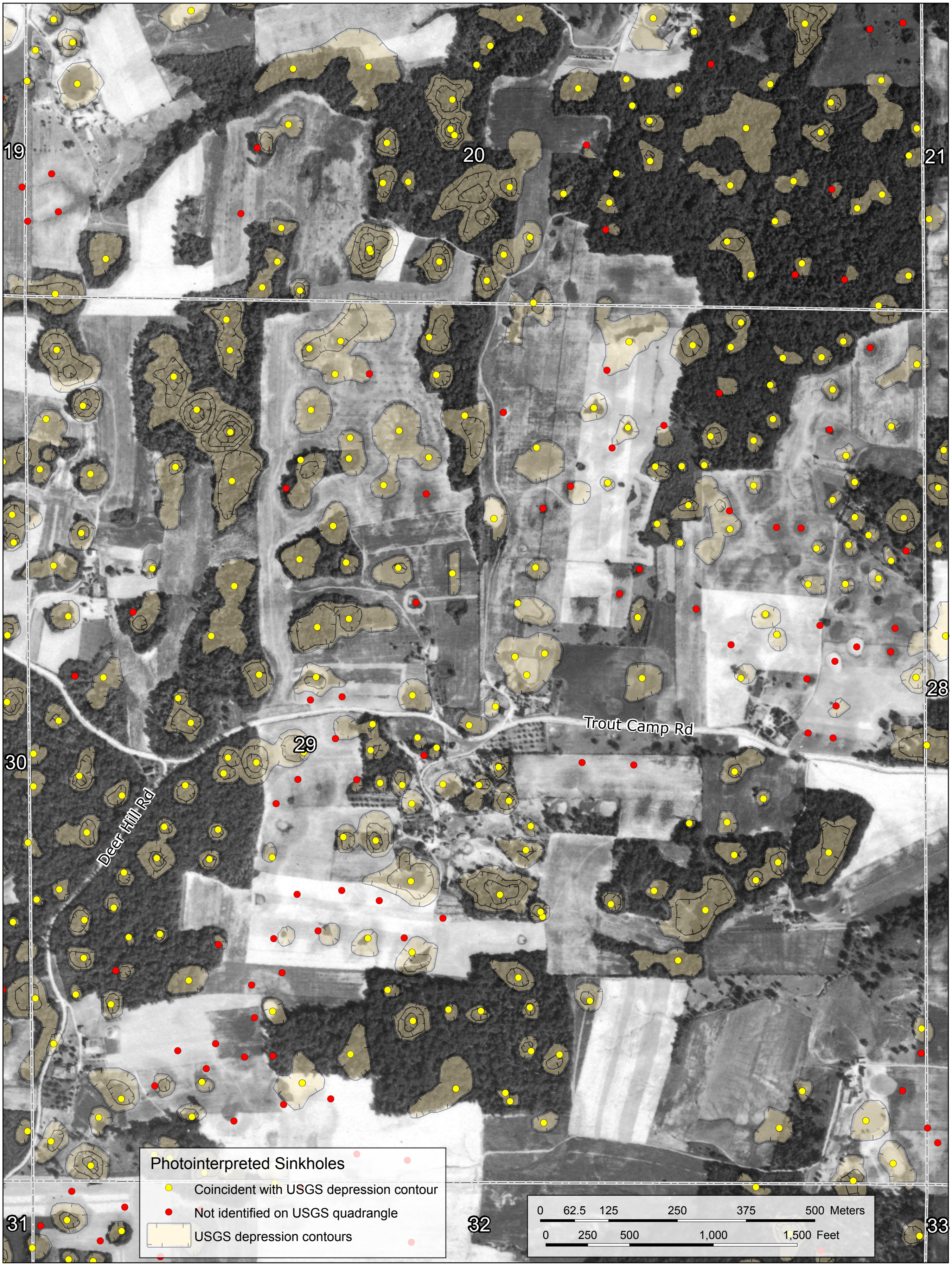

Figure 9 1940 and 2005 photointerpretation showing distribution of sinkhole centroids for the same portion of the Waterloo Quadrangle shown in figures 7 and 8. Note the correspondence with depression contours and how several sinkholes are not identified using the topographic quadrangle map because of the 10-foot contour interval.

within the Waterloo Quadrangle. The acquisition date for the AAA aerial photography is September 5, 1940 (fig. 7). Historical weather records for Waterloo, Illinois, show much lower than average precipitation for September 1940. For the period of 1933–1944, the September average was 8.6 cm (3.4 inches) and only 2.6 cm (0.07 inch) for September 1940, near the same time when the AAA aerial photographs were acquired. The exceptional dryness during this time, which was typical during much of the 1930–1940 Dust Bowl period, further accentuates sinkhole delineation. Sinkhole rims have a lighter photo tone contrasted against the somewhat wetter (darker) and sometimes vegetated centers of the sinkholes. However, it is difficult to identify extremely large sinkholes using aerial photointerpretation alone because of the complex nature of land use within these karst features and the subtle nature of sinkhole drainage. Drains, the openings at the base of sinkholes through which surface runoff enters bedrock, are apparent on USGS 7.5-minute topographic quadrangle maps, but they are not all visible on aerial photography. The NAPP aerial photography for the Waterloo Quadrangle area was acquired on March 6, 2005. The much wetter nature of the land surface on the NAPP aerial photograph is apparent from the many visible sinkhole ponds (fig. 8), but these are shown as dry areas on the 1940 AAA aerial photograph (fig. 7).

The composite results of the map-based and photo interpretation for the selected area show that many sinkhole features were overlooked based on map analysis alone (fig. 9). The majority of additional sinkholes were identified from visual inspection of the AAA aerial photography. These sinkholes are relatively shallow and are not symbolized on USGS 7.5-minute quadrangle maps (note the absence of depression contours on fig. 9). Previous studies showed that 2,727 and 3,127 closed depressions are present on the USGS 7.5-minute Waterloo and Renault quadrangles, respectively (Panno et al. 2008b, 2008c). These estimates were based solely on the contour information derived from the two topographic quadrangle maps. Subsequent research using a combined photointerpretation and GIS approach yielded 3,630 sinkhole features for the Waterloo Quadrangle, and 4,060 sinkhole features for the Renault Quadrangle (Luman and Panno 2011). This represents and increase of 903 (33.1 percent) and 933 (29.8 percent) sinkhole features for the Waterloo and Renault quadrangles, respectively. The inventory of sinkholes for Monroe County using the AAA and NAPP aerial photography yielded a total of 8,890 cover-collapse sinkholes (main map); with a calculated maximum density of 125 sinkholes per km^2 (approximately 48 mi^2).

Fracture Traces and Lineaments

Fracture traces are defined as linear features less than 1 km in length (0.62 mi), and lineaments are defined as linear features greater than 1 km in length. Delineation of fracture traces and lineaments from direct inspection of aerial photography is a technique that has been used since the early 1950s for oil, gas, and mineral exploration. Lattman and Parizek (1964) and Parizek (1976) extended this work to groundwater resources by identifying and examining major lineaments to define zones of increased weathering, porosity, and permeability within carbonate rock. Fracture traces and lineaments appear as surface sags, depressions, straight streams and valley segments, abrupt changes in valley alignment, and aligned springs and sinkholes.

Visible fracture traces and lineaments were delineated using the USGS DEM data for Monroe County (fig. M1 on main map). Most of the lineaments are the result of the subsidence of sediment into solution-enlarged crevices within the county. Many lineaments are present along stream valleys as unusually straight stream segments with abrupt changes in stream direction. Fountain Creek is a good example of fracture-controlled drainage (Panno et al. 2011b) (fig. 4 and main map). Others are present as aligned sinkholes following dominant solution-enlarged crevices. Solution-enlarged crevices may be exposed in road cuts, quarry faces, and excavations. Spacing of crevices in these exposures ranges from about 3 m to 5 m (approximately 10 ft to 16 ft), and widths range from 15 cm to more than 38 cm (6 inches to 15 inches). The depth of crevices within the St. Louis Limestone can be at least 30 m (approximately 98 ft) based on observations within quarries in the area. The orientation of lineaments in Monroe County is in a roughly east-west and a north-south direction (main map), which is the same as crevice orientations observed in exposures and the trends of major structures within Monroe County. A rose diagram produced from over 100 fractures measured within Illinois Caverns shows that most of the joints within the cave, including the cave's crevice entrance, are oriented primarily N85° W; additional joints are oriented N45° W and N23° E (fig. 10).

Finally, lineaments are best exhibited within the western portion of Monroe County (main map) in areas where loess and glacial till average less than 8 m (approximately 26 ft) in thickness. Glacial sediments increase in thickness to as much as 60 m (approximately 197 ft) in the eastern part of the county (Herzog et al. 1994), and consequently fewer lineaments are discernable (main map).

Springs and Caves

Three of the longest caves in Illinois and about 50 other caves are found in Monroe County. Formation of the caves is estimated to have been initiated about 125,000 years ago, near the end of the Illinois Episode glacial period (Panno et al. 2012). An approximation of the location of these caves may be found on a map by Weibel and Panno (1997), and all are found within the St. Louis Limestone. Associated with these caves are large springs that discharge directly or indirectly from the caves (main map) and typically are located at or near the contact of the St. Louis Limestone with other formations. Recharge to the springs is fed, for the most part, by runoff directly into bedrock via sinkholes. Discharge

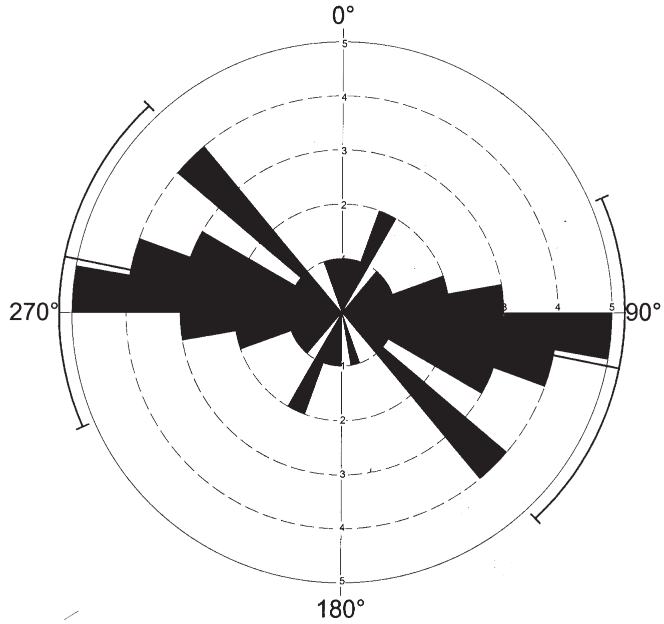

Figure 10 Rose diagram of the orientation of about 100 fractures mapped within Illinois Caverns (Panno and Weibel, ISGS, unpublished data). Most fractures within the cave and many of the crevices in the sinkhole plain trend in a roughly east-west direction.

from the springs can range from a few liters per second during low flow periods to over 900 L (approximately 32 ft^3) per second during high flow periods (Panno et al. 2007).

Conclusions

The analysis of contour information on USGS 7.5-minute topographic quadrangle maps to identify and inventory karst features is commonplace. However, the 10- and 20-foot contour intervals present on USGS quadrangle maps in the study area are too coarse to identify shallow sinkholes, resulting in an underestimation of karst features over large regions. As of this writing, LiDAR enhanced elevation data had just been acquired for the Illinois sinkhole plain, but processing of the collected data had not yet been completed. Until such detailed elevation data are more generally available, other spatial information is needed to ensure completeness and accuracy when conducting an inventory of karst features.

Mississippian-age karst features are concentrated in two locations within Monroe County, one within the area of the USGS 7.5-minute Waterloo Quadrangle and a second within the area of the USGS 7.5-minute Renault Quadrangle. The greatest sinkhole density is found in areas of known and suspected cave systems within the Illinois sinkhole plain. Lineaments are closely associated with solution-enlarged crevices that are ubiquitous throughout the region.

This study has documented that AAA historical aerial photography provides a valuable resource for delineating karst features not represented as depression contours on USGS topographic quadrangle maps. Comparison of map-based and photointerpretation approaches for two USGS 7.5-minute quadrangle map areas determined that one-third of sinkhole features are overlooked using only the depression contour information present on topographic quadrangle maps. In addition, the use of USGS DEM data for Monroe County reveals lineaments that are consistent with known orientations of solution-enlarged crevices.

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