INVESTIGATION OF A SINKHOLE IN OGLE COUNTY, NORTHWESTERN ILLINOIS, USING NEAR-SURFACE GEOPHYSICAL TECHNIQUES

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Abstract

A sinkhole measuring 40 m in diameter and up to 6.5 m deep occurs within the Nachusa Grasslands, near the town of Franklin Grove, northwestern Illinois. This area, dedicated to prairie conservation and restoration, is owned and operated by The Nature Conservancy. Several meters of unconsolidated sand, gravel, and clay overlie the St. Peter sandstone, beneath which lies karstic Prairie du Chien dolomite. Investigations included electromagnetic (EM) conductivity profiles, resistivity soundings, 2D resistivity, and ground-penetrating radar (GPR), supplemented by conductivity logs, soil cores, and tree core studies. These data indicate the sandstone averages about 5 m deep near the sinkhole rim and the sinkhole is about 115 years old. Nearby residential wells indicate an average static water level of 11 m below the surface, so the water table currently lies well below the sinkhole floor. GPR sections show abrupt termination of the bedrock reflector near the sinkhole rim, suggesting formation by collapse. Geophysical investigations also identified possible hydraulic conduits associated with the sinkhole. Specifically, GPR profiles, at 50 and 100 MHz, provide the highest resolution images of the subsurface and indicate possible conduits (soil pipes) near the sinkhole rim as diffraction hyperbolas 2-3 m below the surface. GeoProbe™ conductivity logs showing unusually low conductivity, and sudden probe drops, also suggest the presence of shallow soil cavities around the sinkhole. However, dye poured into various low spots on the sinkhole floor was never recovered, despite numerous sampling locations.

Introduction

Understanding sinkhole formation processes and age of formation are important in assessing land stability and in reconstructing geomorphic history. Identification of hydraulic conduits linking sinkholes with the underlying groundwater system is equally important in characterizing groundwater recharge and identifying potential contaminant pathways. This paper describes the use of near-surface geophysics, combined with tree-ring dating, to attack these two problems.

Site Description

This study is focused on an isolated sinkhole (locally referred to as the “Stone Barn Road sinkhole”) in Ogle County, northwestern Illinois. This area, dedicated to prairie conservation and restoration, is owned and operated by The Nature Conservancy and is now a bison preserve. The sinkhole lies in an upland area with shallow bedrock, approximately 15 km southeast of the edge of the officially defined “Driftless Area,” of the upper Mississippi River basin as shown in Figures 1 and 2. The nearest town is Franklin Grove, IL, about 6 km to the southeast; the unincorporated community of Lost Nation, with its golf course and artificial lake, lies about 1 km to the north. Figure 2 is a Lidar image of the sinkhole area. The data was acquired by a twin engine, fixed wing aircraft operated by Aero-Metric. Data was

Figure 1. Location of the study area (circle) relative to the Driftless Area (shaded) in northwestern Illinois (after Wilson, 2013).
acquired at an elevation of 1500 m above mean terrain with a horizontal accuracy of 0.27 m. Elevation accuracy (95% confidence interval) was 0.10 m (open terrain), 0.23 m (forested areas), and 0.079 m (man-made structures). A photo of the sinkhole is shown in Figure 3.

**Geological setting**
The study site lies approximately 7 km southwest of the Sandwich fault, a major structural feature in northern Illinois (Kolata et al., 1978). This normal fault juxtaposes Cambrian and early Ordovician sedimentary rocks to the south (the oldest rocks cropping out in Illinois) with late Ordovician sediments to the north. Average displacement along the fault is about 150 m.

**Figure 2.** Lidar image of the study site. Stone Barn Rd. sinkhole is circled.

**Figure 3.** Photo of the sinkhole floor in early spring.

**Figure 4.** A stratigraphic section of the study area (after Luczaj and Masarik, 2015). The St. Peter sandstone is a part of the Ancell Group.
At the site several meters of unconsolidated sand, gravel, and clay overlie the St. Peter sandstone, beneath which lies karstic Prairie du Chien dolomite. A stratigraphic section is shown in Figure 4. These will be discussed below according to their depth below the surface.

**Unconsolidated deposits (0-4 m depth)**
Using the U.S. Dept. of Agriculture (USDA) soil classification, less than 0.15 m of organic top soil exists overlying 4.1 m of sandy clay loam. This overlies 0.6 m of sandy loam, underlain by unconsolidated sand (likely top of sandstone bedrock) at the bottom of cores. No evidence exists of glacial till at the site.

**St. Peter sandstone (4 – 15 m depth)**
The St. Peter sandstone is a formation in the lower Ordovician Ancell Group. It is a fine-to-medium grained, well-rounded quartz arenite. This unit extends from Minnesota to as far south as Missouri and east-west from Nebraska to Illinois (Willman, 1975). Its commercial name, widely used as a fracking proppant, is “Ottawa sand.”

**Prairie du Chien dolomite (below 15 m depth)**
Early Ordovician dolomite lying on Cambrian strata and unconformably overlain by the St. Peter sandstone consists of the Shakopee dolomite, New Richmond sandstone, underlain by the Oneota dolomite. The Shakopee and Oneota are highly karstified and associated with hundreds of caves and sinkholes in the upper Midwest (e.g. Willman, 1975; Alexander, 1980; Ruhl, 1989).

**Geophysical Surveys**
Many studies and articles explore the use of geophysical methods to characterize sinkholes, or identify filled sinkholes (e.g. Carpenter et al., 1998; Al-fares et al., 2002; Ahmed and Carpenter, 2003; Dobbecki and Church, 2006). In this study geophysical methods were used in a phased and sequential manner; first employing reconnaissance methods, such as EM conductivity surveys and resistivity soundings, followed by more detailed methods, such as GPR and 2D resistivity over anomalous or critical areas. Figure 5 shows all survey lines. Geophysical interpretations were verified and calibrated.

![Figure 5. Image of the sinkhole showing geophysical survey lines.](image-url)
Figure 6. Conductivity logs obtained with the GeoProbeTM at various locations around the sinkhole. Possible air-filled voids and bedrock levels are noted.
using Geoprobe™ borings and conductivity logs. In addition to the geophysical surveys, tree core samples were used to determine the age of trees within the sinkhole. High-resolution Lidar images were also examined and a dye tracing experiment was conducted.

Calibration/verification of geophysical methods were achieved through GeoProbe™ borings and conductivity logs (Figure 6) outside the sinkhole that encountered sandstone bedrock beneath 2.7-5.8 m of unconsolidated sediment. Records of local private wells indicate pre-pumping water table depths of 9.1-22.6 m. Hand-auger and shovel digging within the bottom of the sinkhole revealed bedrock at about 0.5 m beneath the surface in places.

**EM Conductivity Surveys**
Several EM conductivity surveys were conducted around and within the sinkhole. This method was used as a reconnaissance tool to identify areas for more detailed surveys. These were performed with Geonics EM31 and EM34 conductivity meters, which have different depth responses: in the vertical dipole the EM31 has maximum response at about 2 m whereas the EM34 at a coil spacing of 10 m has a maximum response at about 5 m depth. Thus the EM31 response was too shallow to show bedrock variations, although it might show soil voids. The EM34 had sufficient depth penetration to see bedrock variations. The EM34 survey reveals elevated conductivity in a southwest-northeast trend and reduced conductivity in a north-south direction. The vertical dipole data is much nosier than the horizontal dipole data. The elevated conductivity in the southwest-northeast direction may indicate a deepening of the bedrock in that direction, perhaps coincident with a karst conduit incised into the subcropping bedrock surface. Relatively low conductivities occur in east-west and north-south orientations, suggesting bedrock highs or open air-filled fractures in those directions. The EM31 surveys also showed areas of sharply reduced soil conductivity that could be locations of air-filled voids in the soil.

**Resistivity Soundings**
Two resistivity soundings revealed the vertical structure of soil and bedrock around the sinkhole. One was performed directly east of the sinkhole and the other slightly south of the sinkhole rim. Sounding 1 and its layered model (from inversion using the program Resixp [Interpex, 1988]) is shown in Figure 7. It reveals low resistivity sediments overlying high resistivity unsaturated St. Peter sandstone overlying lower resistivity saturated St. Peter sandstone and Prairie du Chien formation.

**2D Resistivity Profiles**
**Sinkhole Floor**
Two-dimensional (2D) dipole-dipole array resistivity transects were made over the western portion of the sinkhole floor in east-west and north-south directions using an AGI Sting/Swift R1 system with 20 electrodes and a dipole width of 1 m. An east-west profile is shown in Figure 8 after inversion for true resistivity with the program Res2Dinv (Loke, 1998). The high resistivity is
interpreted as bedrock whereas the low resistivity materials are interpreted as clay, silt and/or saturated materials. The east-west profile (Figure 8) shows abrupt termination of the high-resistivity bedrock on the sides, but also an apparent bedrock “shelf” that extends westward across the floor of the sinkhole. The much shorter north-south profiles are consistent with the east-west profile, but only show low resistivity materials below the west-central part of the sinkhole.

**Sinkhole Rim**
One 2D resistivity profile was made over the eastern sinkhole rim, as shown in Figure 9 (dipole width = 3 m). This profile shows a sharp truncation of high resistivity material (interpreted as bedrock) as the sinkhole rim is crossed.

**Ground-Penetrating Radar Profiles**
Ground-penetrating radar (GPR) profiles were performed at several locations around and within the sinkhole and across the sinkhole rim. Surveys were performed with a Sensors and Software pulse EKKO-IV unit equipped with 50- and 100-MHz antennas. Initial walkaway surveys were performed to establish the velocity of GPR waves, 0.08 m/s. This value is used to covert two-way reflector travel times in the profiles to depth.

**Sinkhole Floor**
One GPR survey was made across the western part of the sinkhole floor. The profile shows a myriad of diffractions, with no clear reflections. This is consistent with the 2D resistivity profiles that suggest an irregular bedrock surface, present in some places and absent in others.

**Sinkhole Rim**
The bedrock surface reflection exhibits a major change in character at the sinkhole rim as shown in Figure 10. In fact it is possibly truncated at the sinkhole rim, with the small wavelet remaining being an airwave reflection. This profile was made along the east side of the sinkhole along a profile more-or-less coincident with the 2D resistivity line shown in Figure 9.

**Evidence for Soil Piping and Subsurface Voids**
Geophysical data in various places suggests open voids may occur in the soil or bedrock. The Geonics EM31 profiles, in particular, show sudden decreases in conductivity, both northeast and southwest of the sinkhole, that could represent shallow air-filled soil voids and pipes. Borings were made in these same areas. “String-drops,” along with zones of extremely low conductivity were logged at SH01, SHNE1, SHNE03 and SHSW1, as noted in Figures 5 and 6. Figure 11 shows a GPR section with a large diffraction, apparently at the bedrock surface, possibly indicating a cave or void. Boring in the area of the diffraction also produced a string-drop.

**Discussion and Conclusions**
Our conclusions are that this is a soil-mantled collapse or caprock sinkhole (doline). Both these models involve
sudden roof collapse. Figures 12 and 13 below illustrate these models. In the case of the Stone Barn Rd. sinkhole several meters of soil mantle the bedrock, which is not shown in Figures 12 and 13. The caprock doline model, in particular, seems to be consistent with resistivity imaging of a bedrock “shelf” beneath the sinkhole floor.

Soil pipes and caves near the bedrock surface may also be present, and may provide hydraulic connections between the sinkhole and underlying or surrounding aquifers. A dye tracing test, however, failed to establish any sort of hydraulic connection between the Stone Barn Rd. sinkhole and underlying or surrounding aquifers.

Tree growth within the sinkhole is the only chronological data for dating the age of sinkhole formation. Due to nearly straight tree trunks with no evidence of “creep,” or curvature of the trunk, it is assumed the trees grew after the sinkhole had become dormant. We have inferred the youngest age of the sinkhole from the age of the old-

**Figure 10.** GPR profile across the east sinkhole rim. Abrupt change (possible truncation) in the bedrock surface reflection is circled.

**Figure 11.** GPR profile across what appears to be a cave (indicated by the diffraction circled in red) at the bedrock surface.

**Figure 12.** Collapse doline model (after Jennings, 1985).

**Figure 13.** Caprock doline model (after Waltham et al., 2005).
est trees. From tree cores taken, the oldest tree was found to be 115 years so the sinkhole probably formed suddenly at least 115 years ago.

Acknowledgements
We would like to thank the Nachusa Grasslands (operated by the The Nature Conservancy) for access to the Stone Barn Road sinkhole, the Mobil Oil Foundation NIU Fund for travel and field support, Paul Harmon of the Ogle County Health Dept, for facilitating access to the site and help in the field, Neil Dickey who operated the GeoProbe ™, and students and instructors of the 2011, 2012, 2013, 2014 NIU Environmental Geology Field Camps as well as students in the 2011 and 2013 Geol 654 Field Geophysics classes. Two anonymous reviewers also provided comments and suggestions that greatly improved this manuscript.

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