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ORIGINAL ARTICLE

Geophysical records of anthropogenic sinkhole formation in the Delaware Basin region, Southeast New Mexico and West Texas, USA

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Abstract A significant minority of sinkholes that formed in gypsum bedrock in the Delaware Basin region are of human origin. These anthropogenic sinkholes are often associated with improperly cased abandoned oil wells or with solution mining of salt beds in the shallow subsurface. In July 2008, a sinkhole formed abruptly at the site of a brine well in northern Eddy Co., New Mexico. The well operator had been injecting fresh water into underlying salt beds and pumping out the resulting brine for use as oil field drilling fluid. Borehole problems had prevented the operator from conducting required downhole sonar surveys to assess the dimensions of subsurface void space. The resulting sinkhole formed in just a few hours by catastrophic collapse of overlying mudstone and gypsum and in less than 1 month had reached a diameter of 111 m and a depth of 64 m. Fortuitously, a seismometer had been deployed 13 km southeast of the brine well a few months earlier and precursor events were captured on the seismograph record a few hours before the subsurface cavity breached the surface. Four months later, another sinkhole collapse occurred in northern Eddy Co., again associated with a brine well operation. These events prompted the New Mexico Oil Conservation Division to review its regulations regarding brine well operations in the southeastern New Mexico oil fields. A third brine well within the city limits of Carlsbad, N. Mex., has been shut down to forestall possible sinkhole development in this more densely populated area. Electrical resistivity surveys have been conducted adjacent to the Eddy Co. sinkholes to assess the potential for additional subsidence or collapse events in the future.

Keywords New Mexico · Sinkholes · Electrical resistivity · Solution mining · Delaware Basin

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Introduction

Sinkholes and karst fissures formed in gypsum bedrock are common features of the lower Pecos region of west Texas and southeastern New Mexico. New sinkholes form almost annually, often associated with upward artesian flow of groundwater from regional karst aquifers that underlie evaporitic rocks at the surface (Martinez et al. 1998; Land 2003a, 2006). A significant minority of these sinkholes are of anthropogenic origin, including the well-known Wink sinks in Winkler Co., Texas (Fig. 1). The Wink sinks probably formed by dissolution of salt beds in the upper Permian Salado Formation (Fig. 2), in association with improperly cased abandoned oil wells (Johnson et al. 2003). Powers (2003) reports that a sinkhole that formed near Jal, N. Mex., was probably the result of Salado dissolution related to an improperly cased water well. These sinkholes overlie the middle Permian Capitan Reef aquifer (Fig. 1). In the case of the Wink sinks, Johnson et al. (2003) observe that hydraulic head of water in the Capitan Reef is locally above the elevation of the Salado Formation. Undersaturated water rising along the borehole by artesian pressure may have contributed to subsurface dissolution and collapse of the Wink sinkholes.

Background

The lower Pecos region includes the city of Carlsbad in Eddy County, N. Mex. Evaporitic rocks, primarily gypsum,

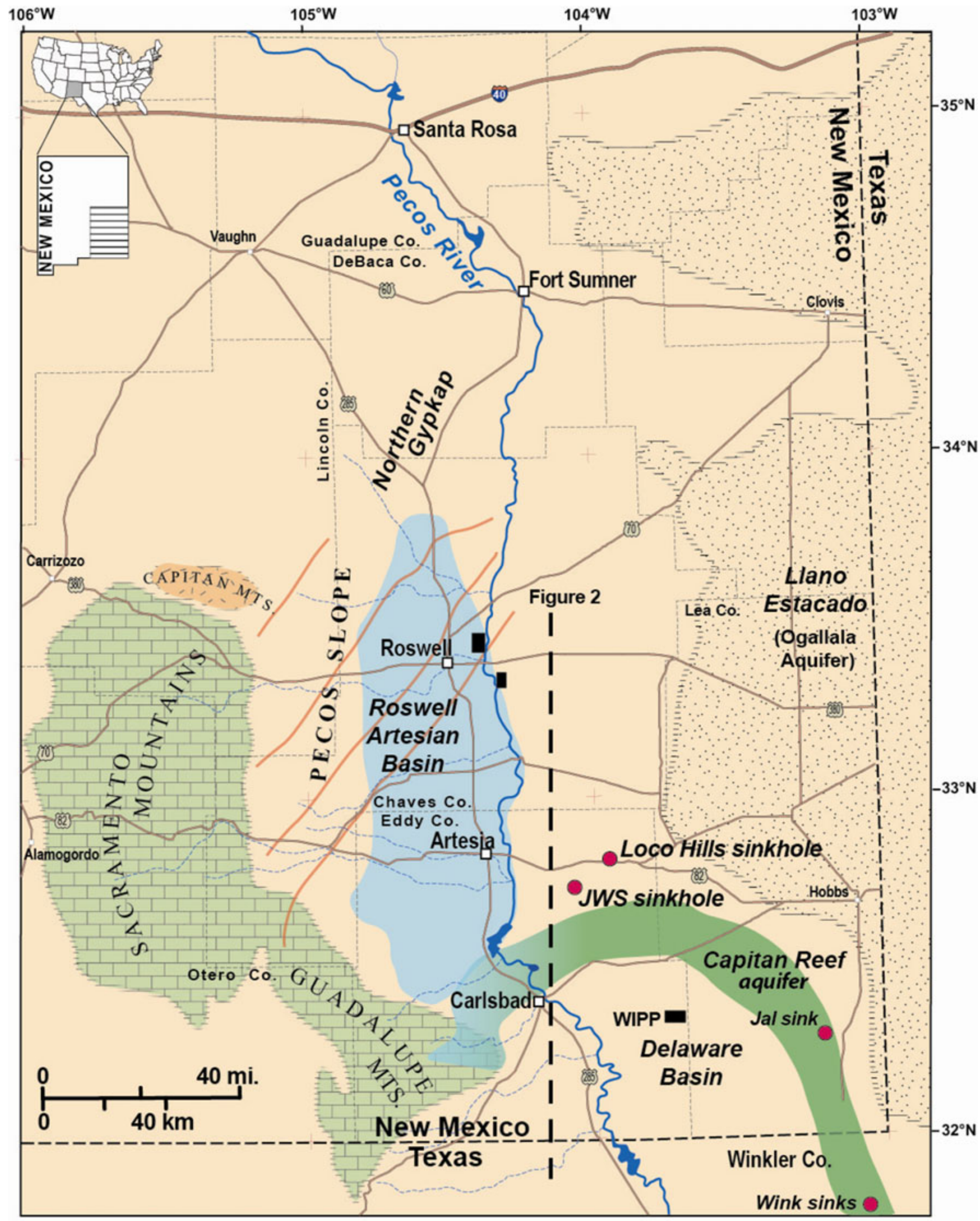

Fig. 1 Regional map of southeastern New Mexico and adjoining areas of west Texas, showing location of sinkholes discussed in text and their position with respect to the Capitan Reef

are widely distributed in the Carlsbad region both at the surface and in the subsurface (Bachman 1984; Hill 1996). Carlsbad is located on the Northwest Shelf of the Delaware Basin (Fig. 2), a large hydrocarbon-producing sedimentary basin occupying over 44,000 km^2 in west Texas and southeastern New Mexico (Land 2003b). The uppermost part of the Delaware Basin section is comprised of about 1,700 m of redbeds and evaporites of upper Permian age (Lucas 2006a, b). This section includes the Salado formation (Fig. 2), which in the subsurface of the Delaware Basin consists of about 710 m of bedded halite and argillaceous halite. Rare amounts of potassium salts (sylvite and

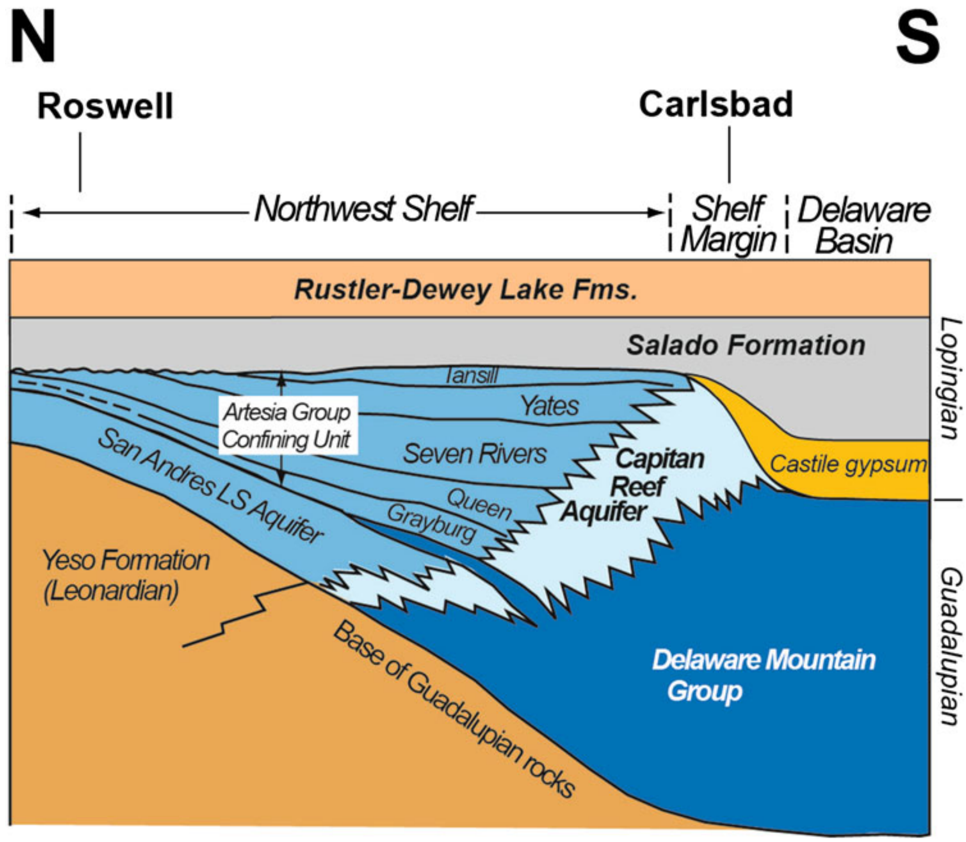

Fig. 2 Diagrammatic north–south stratigraphic section showing shelf-to-basin facies relationships in the Delaware Basin region. *Line* of section shown in Fig. 1. Modified from Hiss (1975)

langbeinite) occur in the McNutt potash zone near the center of the formation (Cheeseman 1978). Clastic material makes up less than 4 % of the Salado (Kelley 1971). Potash ore is mined from the McNutt potash zone in underground mines a few kilometers east of Carlsbad. The formation is also the host rock for the Waste Isolation Pilot Plant (WIPP), a repository for transuranic radioactive waste in eastern Eddy County.

The Salado Formation thins to the north and west by erosion, halite dissolution, and onlaps onto the Northwest Shelf of the basin. Because of the soluble nature of Salado rocks, the unit is very poorly exposed in an outcrop belt several kilometers east of the Pecos River valley (Fig. 3). In that area the Salado is represented by 10 to 30 m of insoluble residue consisting of reddish-brown siltstone, occasional gypsum, and greenish and reddish clay in chaotic outcrops. In most areas the Salado outcrop is covered by a few meters to tens of meters of pediment gravels and windblown sand (Kelley 1971; McCraw and Land 2008).

Sinkhole formation

Around 8:15 on the morning of July 16, 2008, a driver for Jim's Water Service, a local oil field service company based in Carlsbad, N. Mex., was inspecting a brine well located on state trust land 35 km northeast of Carlsbad. While on location, the driver noticed a rumbling noise and quickly vacated the site. Minutes later, a large sinkhole abruptly formed, engulfing the brine well and associated structures (Fig. 4). The well operator had been solution mining the Salado Formation by injecting fresh water and circulating it through the 86-m-thick section of halite until the water reached saturation. The resulting brine was then sold as oil field drilling fluid. The brine well was being operated under permit from the New Mexico Oil Conservation Division (NMOCD).

This sinkhole, referred to as the JWS sinkhole, was initially several tens of meters in diameter and filled with water to a depth of about 12 m below land surface. Large concentric fractures developed around the perimeter of the sink threatening the integrity of County Road 217, 100 m to the south. By July 24, the originally vertical walls of the sinkhole had begun to collapse and the sink continued to grow in diameter over the course of the next 2 weeks. By July 28, the walls of the sink had developed an angle of about 45° to within 10 m below ground level, above which the sides of the sink were vertical. The water originally present had subsided into the subsurface (Fig. 5). There are no significant sources of groundwater at shallow depth in the immediate vicinity of the sink. The water is assumed to have been solution mining fluid that was forced up the debris chimney in the initial stages of collapse and is now

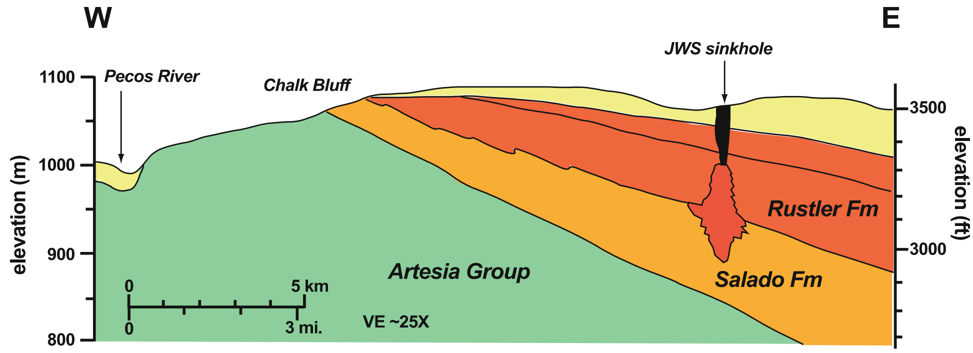

Fig. 3 West–east cross-section showing stratigraphic section penetrated by JWS sinkhole. Unnamed surface material is pediment gravel and windblown sand

Fig. 4 JWS sinkhole on 7/19/2008, 3 days after initial catastrophic collapse. Water in sink is ~12 m below ground level. View to south, with County Road 217 in background

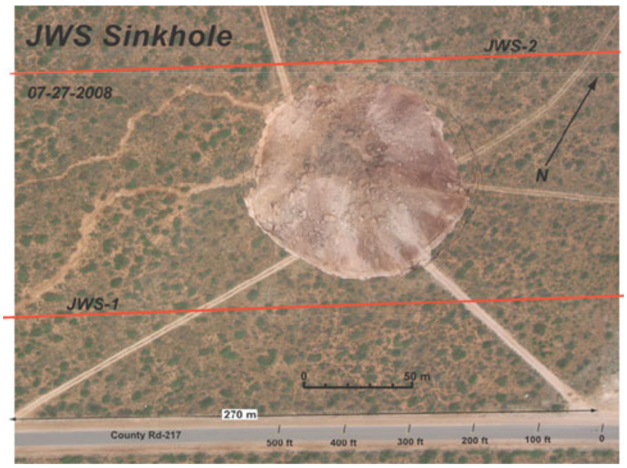

Fig. 5 JWS sinkhole on 7-27-2008 showing post-collapse drainage and broadening. *Red lines* show locations of electrical resistivity surveys conducted in September, 2010

stored in pore space in the resulting collapse breccia and in shallow, porous zones of the overlying Rustler and Dewey Lake Formations. By this time the sinkhole had attained a diameter of about 111 m based on air photo interpretation. Representatives of the State Land Office used a range finder to estimate a maximum depth of 45 m.

Solution mining

During solution mining operations a subsurface void is excavated. Most cavern excavation occurs at the top of the void space since the injected fresh water floats on top of the denser brine. A cushion of crude oil or diesel fuel may be injected into the void to protect the cavern roof and ensure that cavern excavation occurs outward rather than upward (this procedure was not applied in the brine well operation that produced the JWS sinkhole). Brine well operators in New Mexico are required to conduct periodic pressure tests and downhole sonar surveys to assess the size and proportions of the cavern being excavated. However, borehole problems prevented the operator from conducting these surveys and the resulting collapse was unanticipated.

Based on borehole records, the top of the Salado Formation is 121 m below ground level and the formation is 86 m thick at the site of the JWS sinkhole. The brine well operator had set casing 6 m below top of salt and suspended tubing for open-hole fresh water injection down to the base of the salt section. Assuming the resulting cavern was 80 m high and originally shaped like an inverted cone, simple volumetric calculations indicate a roof diameter of about 80 m (Land 2009; Land and Aster 2009). Apparently, the mechanical strength of the mudstone and gypsum in the overlying Rustler and Dewey Lake Formations was insufficient to prevent upward stoping of the cavern roof causing eventual catastrophic surface collapse.

Results and discussion

Seismograph record

On March 15, 2008, an EarthScope Transportable Array three-component broadband seismograph TA126A was installed near the Intrepid Potash Mine 13 km southeast of

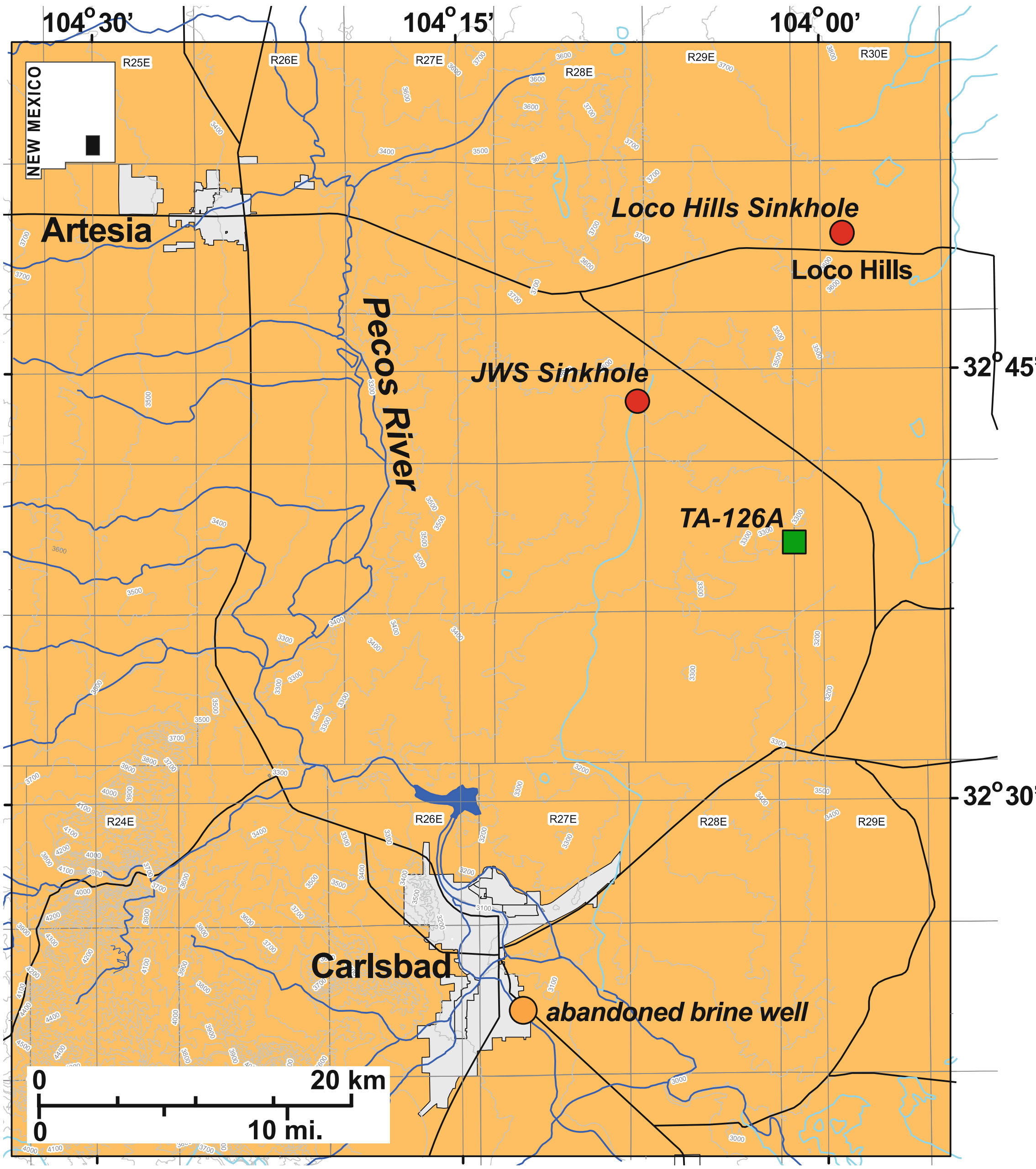

Fig. 6 Map of study area in Eddy Co., New Mexico, showing locations of the JWS and Loco Hills sinkholes with respect to Transportable Array seismograph TA126A. Southernmost *filled circle* shows the location of an abandoned brine well within city limits of Carlsbad

the JWS brine well (Fig. 6). This transportable seismograph is a component of the National Science Foundation's EarthScope US Array continental seismic investigation program that is presently imaging the North American continent at a mean station spacing of approximately 75 km. About 6 h before surface disruption at the site of the brine well, TA126A began recording high-frequency (>5 Hz) seismic signals with vertical ground motion velocity amplitudes of about 5 microns/s (Fig. 7). These seismic events probably reflect subsurface spalling during upward stopping of the cavern roof with seismic energy resulting from the fall of material into the solution cavity. Another transportable array seismograph 50 km west of the site showed no obvious record of sinkhole formation indicating that these high-frequency seismic waves do not travel very far due to the shallow source of the seismic event and high near-surface attenuation (Land and Aster 2009). The absence of any signal on other seismographs in the area also makes it unlikely that a naturally occurring seismic event might have triggered the collapse.

In the aftermath of formation of the JWS sinkhole, another water supply company voluntarily abandoned an

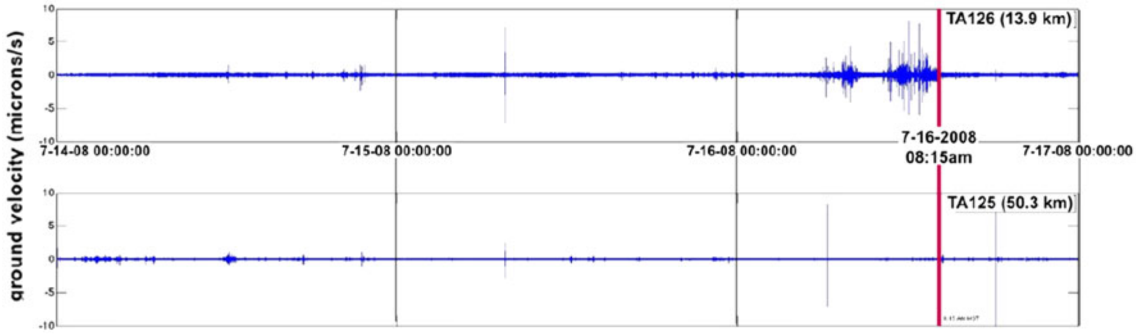

Fig. 7 Transportable array seismograph TA126-A 3-day high-pass (filtered above 5 Hz) record of vertical ground velocity (*upper plot*), located 13.9 km southeast of JWS sinkhole, showing more than 6 h of apparent precursor ground motion associated with sinkhole formation. Estimated time of surface breaching (8:15 a.m.) indicated by *vertical red line*. Seismograph TA125 (*lower plot*), located 50.3 km from the site, showed no obvious candidate precursor signals

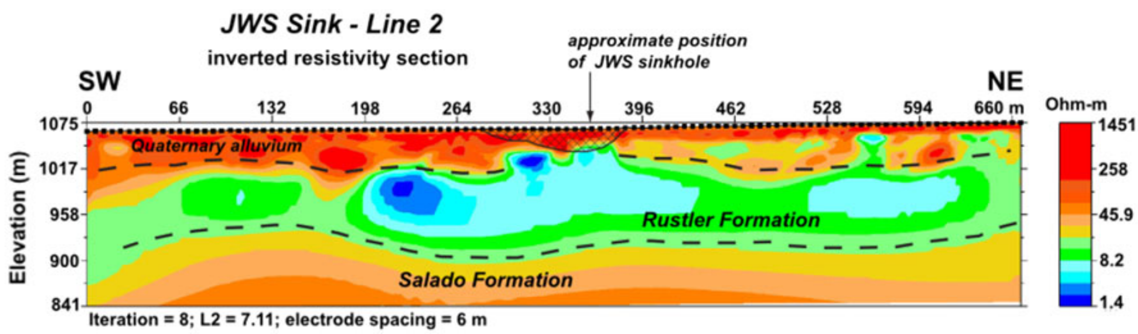

Fig. 8 Electrical resistivity profile JWS-2, conducted on northwest side of JWS sinkhole (Fig. 5)

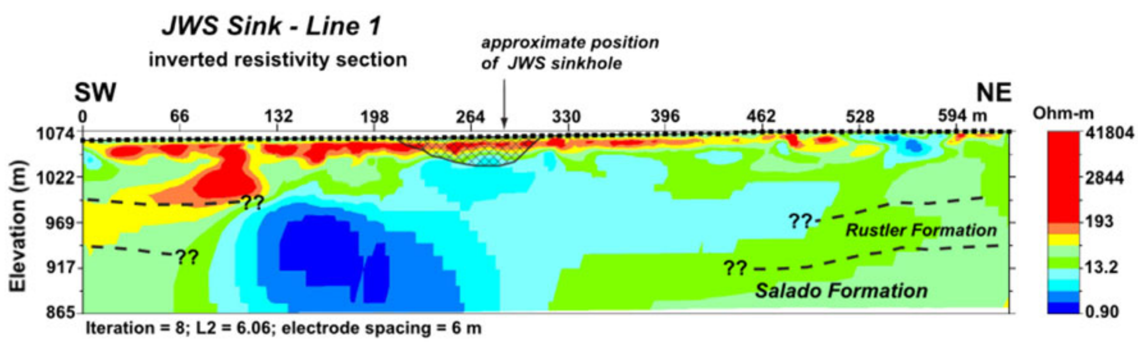

Fig. 9 Electrical resistivity profile JWS-1, conducted on southeast side of JWS sinkhole (Fig. 5)

injection brine well located within the city limits of Carlsbad (Fig. 6). NMOCD ordered a review of regulations covering all brine wells across the state. Then, on November 3, 2008, a new sinkhole formed north of the community of Loco Hills, approximately 17 km northeast of the JWS sink (Fig. 6). The Loco Hills sinkhole is also associated with a brine well that was shut 3 months earlier after it failed a mechanical integrity test as part of the statewide review. Downhole surveys conducted in 2001 showed three stacked voids, the uppermost located about 150 m below land surface. The deepest cavern was about 180 m in diameter in 2001, and the upper two caverns were about one-third that size. The closest EarthScope Transportable Array seismic station to the Loco Hills sinkhole was again TA126A (20.5 km), but no obvious precursor seismic signals were detected prior to formation of the sinkhole.

Electrical resistivity surveys

In September 2010, National Cave and Karst Research Institute (NCKRI) personnel and assistants from the US National Park Service and Bureau of Land Management conducted electrical resistivity (ER) surveys adjacent to the

JWS sinkhole. Two 2-dimensional resistivity surveys were conducted northwest and southeast of the sinkhole (Fig. 5) using an AGI SuperSting R-8^{TM} resistivity meter with a 112 electrode pole-dipole array. Electrode spacing was 6 m, and the full array length for both surveys was approximately 680 m. The profiles were terrain-corrected using elevation data collected with survey-grade GPS receivers. EarthImager-2D^{TM} software was used to process the resistivity data. Both lines were located approximately 15 m from the edge of the JWS sinkhole, and the center of each array was positioned near the projected center of the sink.

The field setting of the JWS sinkhole presents significant challenges for conducting electrical resistivity surveys. The sinkhole is surrounded by a chain-link fence which acts as an electrical conductor during survey operations. In addition, the sink is located in an area where there is high concentration of oil and gas production and oil field infrastructure. Buried pipelines in the vicinity of the JWS sinkhole probably act as subsurface electrical conductors. The ER dataset is thus exceptionally noisy, and a software option to suppress noisy data was necessary to facilitate processing and provide coherent resistivity imagery.

Use of a software filter to suppress noisy data raises questions about the validity of the results. However, both resistivity profiles appear to provide useful records of subsurface conditions in the vicinity of the JWS sinkhole (Figs. 8, 9). Maximum depth of investigation is approximately 230 m. Borehole geophysical logs from the original brine well indicate that the top of the Salado Formation occurs at an elevation of 954 m above sea level (ASL). The base of the sinkhole occurs at about 1,030 m ASL, roughly 75 m above the top of the Salado Formation. The JWS-2 profile shows an increase in apparent resistivity at about 920 m ASL (Fig. 8). This increase in resistivity across the entire profile probably represents high electrical resistivity of the bedded salt lithology of the Salado Formation in contrast with more conductive lithologies in the overlying Rustler mudstones and dolomites. Thus, at a minimum, the noisy ER data set appears to provide a reasonably coherent representation of the subsurface stratigraphy. More conductive zones in the shallower part of the profile may represent local perched aquifers within the Rustler section containing brine that was injected into them during the sinkhole collapse event. A near-surface horizon of very high apparent resistivity probably reflects air-filled porosity within Quaternary alluvium in the unsaturated zone.

A zone of high apparent resistivity in Quaternary alluvium is also present on the JWS-1 profile on the southeast side of the sinkhole (Fig. 9). However, the subsurface stratigraphy deeper in the section is very poorly represented on the resistivity profile. Instead, most of the profile is dominated by a broad zone of very low apparent resistivity approximately 130 m wide and slightly offset from the position of the JWS sinkhole projected onto the survey line. Resistivity values of less than 5 Ω m are consistent with high salinity groundwater and strongly suggest the presence of a large, brine-filled cavity about 80 m below ground level.

Conclusions

Geophysical tools such as electrical resistivity and reflection seismic methods are frequently used to investigate karst hazards in sinkhole-prone areas. However, formation of the JWS sinkhole has provided a unique opportunity to couple data from seismologic investigations with conventional resistivity surveys. Seismic recordings have been used in the past in a forensic capacity to analyze catastrophic events in southeastern New Mexico, such as pipeline exposions (Koper et al. 2000). However, this may be the first documented seismologic record of catastrophic sinkhole formation.

Results from electrical resistivity profiles show that even very noisy data can provide useful and coherent information about subsurface karst phenomena. ER surveys conducted adjacent to the JWS sinkhole indicate that a large brine-filled cavity is present approximately 80 m below the surface beneath the sinkhole.

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