BW - ______5______

GENERAL CORRESPONDENCE

YEAR(S):

2005 - Present

File Abstract
BW-5
State 24 Well #1 Brine Well (API #30-015-02036)
Jim's Water Service
J-24-18S-28E Eddy County
Class III well under UIC

Permits, Renewals, & Mods Thumbnail

• **3/7/08** renewal of discharge permit from OCD sent to Sherry Glass of JWS 11413 US Hwy 82 in Artesia 88210. Renewal will expire on 12/19/11.

> Condition 11.C. *The owner/operator (O/O) shall ensure that all exposed pits, including lined pits and open top tanks (8 feet in diameter or larger) shall be fenced, screened, netted, or otherwise rendered non-hazardous to wildlife, including migratory birds.*
>
> Condition 12.A. *The O/O shall test all underground process/wastewater pipelines at least once every 5 years to demonstrate their mechanical integrity, except lines containing fresh water or fluids that are gases at atmospheric temperature and pressure…*
>
> Condition 15. *Spill Reporting. The O/O shall report all unauthorized discharges, spills, leaks and releases and conduct corrective action…The O/O shall notify both the OCD District Office and the Santa Fe Office within 24 hours and file a written report within 15 days.*
>
> Condition 18. *Unauthorized Discharges. The O/O shall not allow or cause water pollution, discharge or release of any water contaminant that exceeds the WQCC standards…unless specifically listed in the permit application and approved herein. An unauthorized discharge is a violation of this permit.*
>
> Condition 21.D. *The maximum operating surface injection and/or test pressure measured at the wellhead shall not exceed 137 psig unless otherwise approved by the OCD.*
>
> Condition 21.E. *Conduct an annual open to formation pressure test…At least once every 5 years and during well work-overs the salt cavern formation will be isolated from the casing/tubing annulus and the casing pressure tested…*
>
> Condition 21.F. *The operator shall provide information on the size and extent of the solution cavern and geologic/engineering data demonstrating that continued brine extraction will not cause surface subsidence, collapse or damage to property, or become a threat to public health and the environment. This information shall be supplied in each annual report. OCD may require the operator to perform additional well surveys, test, and install subsidence monitoring in order to demonstrate the integrity of the system. If the operator cannot demonstrate the integrity of the system to the satisfaction of the Division then the operator may be required to shut-down, close the site and properly plug and abandon the well.*
>
> Condition 21.G. *The volumes of fluids injected (fresh water) and produced (brine) will be recorded monthly and submitted to the OCD Santa Fe Office in the annual report.*
>
> Condition 21.H. *Provide an analysis of the injection fluid and brine with each annual report. Analysis will be for General Chemistry (Method 40 CFR 136.3)…*

• **4/7/08** OCD receives $1,700.00 check dated 4/3/08 and signed conditions of approval from JWS of New Mexico (part of KP Kauffman Co., Inc.) 1675 Broadway Suite 2800 in Denver, CO 80202

Recent Correspondence

• **10/28/08** letter from JWS to SLO

• **11/25/08** letter from JWS to OCD

• **12/11/08** letter from JWS to OCD

•**2/20/09** letter from JWS to OCD.

Brine pit closure plan:

File C-144 for pit closure (Done via letter of 2/24/09)

Contents of pit along with liner material to be removed, transported, and disposed at CRI Halfway facility.

5-point composite sample along with grab samples from any area beneath liner that is wet, discolored, or otherwise showing signs of contamination.

Samples to be analyzed for benzene, BTEX(8021B or 8260B), TPH (418.1), GRO, DRO (8015B) and chlorides (300.0 or 300.1) as per EPA recommended methods.

Runoff tank closure plan

Plastic tank to SE of pit will be investigated for leaks and area remediated as necessary.

(Contents of tank need to be assessed via 8260/8015/300.1)

(Contents of tank need to be properly disposed and tank needs to be removed along with any other surface infrastructure such as concrete curbs and metal piping)

Chloride assessment of surrounding soils will also be undertaken. (Additional analyses may need to be undertaken based on results from tank contents)

Both pit and tank area

Re-contour and re-vegetate

No artificial irrigation (fresh water way be applied, but on no more than 3 occasions in the next 12 months)

Topsoil added, as needed

70% cover of native vegetation w/o noxious weeds (seed mix needs to be approved by SLO)

Groundwater investigation

Install one well upgradient (NW? no location provided) of sinkhole.

Field assess groundwater fromwell for TDS

Based on TDS results, see if additional downgradient wells are needed.

8 inch bore via air rotary to maximum depth of 245 ft (adjust for surface elevation)

Log lithology via cuttings

4 inch PVC well with 20 ft of 10-slot

Backfill w/ 10-20 silica sand from TD to 2 ft above screen

5-foot bentonite seal via tremie

Balance of annulus to surface w/ neat Portland

Minimum 10 volumes of purging by disposable bailer prior to sampling

Purge water poured on surface.

(need to allow time for stabilization)

DTW and TD measured

Sample filtered in field to 0.45 micron

Aliquot field-checked for specific conductance to determine TDS (assuming 1:1 relationship)

Split sample for general chemistry including cation and anion concentration, hardness, TDS, pH and conductivity

C-141 Release Notification to be filed.

Bill Richardson
Governor
Joanna Prukop
Cabinet Secretary
Reese Fullerton
Deputy Cabinet Secretary

Mark Fesmire
Director
Oil Conservation Division

June 24, 2009

Mr. Raymond M. Gorka
K.P. Kauffman Company, Inc.
World Trade Center
1675 Broadway, 28th Floor
Denver, Colorado 80202-4628

Re: Approval for Closure of Brine Pit and Preliminary Groundwater Investigation
Jim's Water Service Brine Facility (BW-5)
Unit Letter J, Section 24, Township 18 South, Range 28 East, NMPM
Eddy County, New Mexico

Ray,

The Oil Conservation Division (OCD) has reviewed your submittals of February 20 and February 24, 2009 regarding closure of the brine pit and a preliminary groundwater investigation at the former Jim's Water Service facility (Permit BW-5) southeast of Artesia. Based on those submittals, the proposed actions are approved with the following additional conditions:

Brine Pit Closure:

Soil samples are to be analyzed for:
- Benzene, toluene, ethylbenzene, and total xylenes by either EPA Method 8021B or 8260B
- Total Petroleum Hydrocarbons by EPA Method 418.1
- Both Gasoline Range Organics and Diesel Range Organics by EPA Method 8015B
- Chlorides by EPA Method 300.0

Runoff Tank Closure:

When OCD personnel were on-site during January of this year, the tank contained fluids with a noticeable hydrocarbon odor. The contents of the tank must be analyzed by the methods stated above. The contents of the tank must be properly disposed based upon those analyses and the tank removed.

Additional soil analyses beyond the assessment of chloride concentration will need to be performed based on the laboratory results of the tank contents.

Both Pit and Tank Areas:

Any other surface infrastructure such as concrete curbs and metal piping must be removed.

The pit, tank, and loading area must be re-contoured to reflect local grade and re-vegetated using a seed mix pre-approved by the State Land Office.

Preliminary Groundwater Investigation:

No specific location for installation of the "upgradient" monitoring well has been provided. Forward same to the OCD as soon as possible before beginning field work.

During drilling of the Nix & Curtis Gulf State #2 well in 1955 (re-entered for brine production in 1979), a significant water-bearing sand was encountered from depths of 225 to 245 feet below surface. One of the intents of this investigation is to establish if this zone contains protected groundwater. Assuming the subsurface bedding is horizontal, the depth of drilling must take into account the relative change in surface elevation between the location of the brine well and that of any investigatory well.

A minimum of 24 hours is required for well stabilization after development or other purging before depth to water measurements can be made. Such measurements should be made with an accuracy of no less than 0.01 feet. The top-of-casing elevation of all investigatory wells must be established relative to mean sea level with equivalent accuracy.

If data derived from sampling of the "upgradient" investigatory well indicates groundwater is protected, at least two additional wells must be installed in areas downgradient from the sinkhole. Those wells must be monitored to determine the magnitude and direction of potentiometric gradients and sampled to see if brine forced upward during collapse has degraded the water quality.

If you have any questions, please feel free to contact me at (505) 476-3465 or by email at *jim.griswold@state.nm.us*. On behalf of the staff at the OCD, I wish to thank you and your staff for your cooperation during this review process.

Respectfully,

Jim Griswold
OCD Environmental Bureau

JG/jg

cc: Mike Bratcher, OCD District 2
Jim Carr, State Land Office

DISCLOSURE, ASSUMPTION OF THE RISK, WAIVER AND INDEMNIFICATION:

Access to Sinkhole Site

Jim's Water Service Brine Well-State 24 Well #1 (Unit J, Section 24, Township 18 South, Range 28 East)
Eddy County, New Mexico

DISCLOSURE:
I understand that I am being given access to the Sinkhole Site by a representative/employee of the State of New Mexico expressly for research purposes. I further understand that the Sinkhole Site is defined as that area contained within the fence-line and that the site poses serious hazards, including by way of example only and without limitation: uneven terrain, crumbling earth, sinkholes, changeable weather conditions and wildlife. There is a risk of my becoming ill or injured in an area remote from medical care and the State of New Mexico cannot guarantee the availability of emergency medical services or emergency transportation to medical facilities.

ASSUMPTION OF THE RISK:
I fully recognize the dangers of entering the Sinkhole Site and I voluntarily assume all Risks associated with entrance to the site.

WAIVER:
I hereby waive any right I may have to seek damages from the State of New Mexico or any Department/Division/Agency thereof (including but not limited to the New Mexico State Land Office, the New Mexico Energy Minerals and Natural Resources Department and the New Mexico Oil Conservation Division), its Employees and Contractors, for any injury I may sustain as a result of my entry onto the Sinkhole Site.

_______________________________ _______________________
Signature Date

_______________________________ _______________________
Print Name Title/Position

Organization Name: ______________________________________Phone: ________________

Street Address: ____________________________________

City: _____________ State: __________ ZIP: ________

Emergency Contact: ____________________________________ Phone: ________________

Geophysical Records of Anthropogenic Sinkhole Formation in the Delaware Basin Region, Southeast New Mexico and West Texas, USA

Lewis Land [1]

[1] National Cave & Karst Research Institute, and New Mexico Bureau of Geology & Mineral Resources, New Mexico Institute of Mining & Technology, 1400 Commerce Dr., Carlsbad, NM, 88220, 575-887-5508, lland@gis.nmt.edu

ABSTRACT

A significant minority of sinkholes 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 one month had reached a diameter of 111 m and a depth of ~64 m. Fortuitously, a seismograph 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, NM 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.

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 karstic aquifers that underlie evaporitic rocks at the surface (e.g., Martinez et al., 1998; Land, 2003a; Land, 2006). A significant minority of these sinkholes are of anthropogenic origin, including the well-known Wink Sinks in Winkler Co., Texas (Figure 1). The Wink Sinks probably formed by dissolution of salt beds in the upper Permian Salado Formation (Figure 2), in association with improperly-cased abandoned oil wells (Johnson et al., 2003). Powers (2003) reports that a sinkhole that formed near Jal, New Mexico, was probably the result of Salado dissolution related to an improperly-cased water well. These sinkholes overlie the middle Permian Capitan Reef aquifer (Figure 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.

Figure 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.

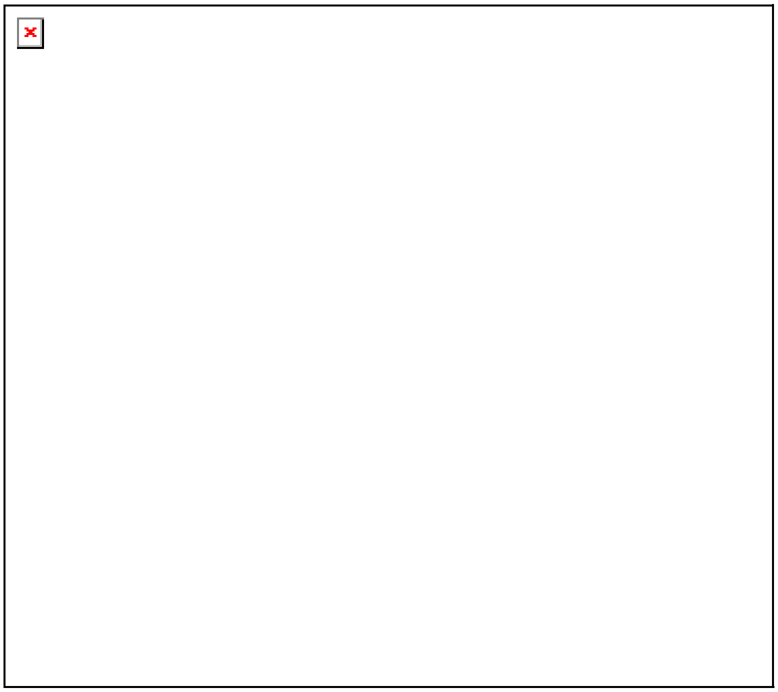

Figure 2: Diagramatic north-south stratigraphic section showing shelf-to-basin facies relationships in the Delaware Basin region. Line of section shown in Figure 1.

BACKGROUND

The lower Pecos region includes the city of Carlsbad in Eddy County, New Mexico. Evaporitic rocks, primarily gypsum, 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 (Figure 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 ~1700 m of redbeds and evaporites of upper Permian age (Lucas, 2006a; 2006b). This section includes the Salado Formation (Figure 2), which in the subsurface of the Delaware Basin consists of ~710 m of bedded halite and argillaceous halite. Rare amounts of potassium salts (sylvite and langbeinite) occur in the 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 onlap 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 ~5 km east of the Pecos River valley (Figure 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 16th, 2008, a driver for Jim's Water Service, a local oil field service company based in Carlsbad, NM, 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 (Figure 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 ~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 two 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, and the water originally present had subsided into the subsurface (Figure 5). There are no significant sources of groundwater at shallow depths in the immediate vicinity of the sink, so 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 stored in pore space in the resulting collapse breccia, and in shallower porous zones of the overlying Rustler and Dewey Lake Formations. By this time the sinkhole had attained a diameter of ~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.

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

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

Figure 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.

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 ~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 the JWS brine well (Figure 6). This transportable seismograph is a component of the National Science Foundation’s EarthScope USArray continental seismic investigation program that is presently imaging the North American continent at a mean station spacing of approximately 75 km. About 6 hours 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 ~5 microns/s (Figure 7). These seismic events probably reflect subsurface spalling during upward stoping 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).

Figure 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.

Figure 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 hours of apparent precursor ground motion associated with sinkhole formation. Estimated time of surface breaching (8:15am) indicated by vertical red line. Seismograph TA125 (lower plot), located 50.3 km from the site, showed no obvious candidate precursor signals.

In the aftermath of formation of the JWS sinkhole, another water supply company voluntarily abandoned an injection brine well located within the city limits of Carlsbad (Figure 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, ~17 km northeast of the JWS sink (Figure 6). The Loco Hills Sinkhole is also associated with a brine well that was shut in 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 ~150 m below land surface. The deepest cavern was ~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 U.S. National Park Service and Bureau of Land Management conducted electrical resistivity (ER) surveys adjacent to the JWS sinkhole. Two 2-D resistivity surveys were conducted northwest and southeast of the sinkhole (Figure 5) using an AGI SuperSting R-8™ resistivity meter with a 112 electrode pole-dipole array. Electrode spacing was 6 meters, 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™ software was used to process the resistivity data. Both lines were located approximately 15 meters 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 a 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, with RMS error factors ranging from 28 – 32%. Over 3000 data points were collected during each survey; however, during initial processing, 32 – 44% of these data points were flagged for removal by the EarthImager software. Most of the data removed were negative apparent resistivity values, or fell below the minimum voltage setting (0.1 mV). A software option to suppress noisy data was used 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, since so many data points are filtered out during processing. However, both resistivity profiles appear to provide useful records of subsurface conditions in the vicinity of the JWS sinkhole (Figure 8). 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 ~1030 m ASL, roughly 75 m above the top of the Salado Formation.) The JWS-2 profile shows an abrupt increase in apparent resistivity at ~950 m ASL, from ~70 to several hundred ohm-meters (Figure 8-A). This increase in resistivity across the profile very likely 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 still provides 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.

Within the Salado section of the JWS-2 profile, apparent resistivities vary from ~600 to >4700 ohm-meters. A wedge-shaped area of relatively lower apparent resistivity underlies the approximate position of the JWS sinkhole projected onto the survey line. If we assume this area of lower apparent resistivity is not an artifact of the noisy data set, it may indicate the presence of a lower-resistivity breccia zone filling the pre-existing cavity excavated during solution-mining activity.

An area of high apparent resistivity is also present at the southwest end of the JWS-1 line at ~950 m ASL (Figure 8-B). However, the high-resistivity zone subsides below the maximum depth of investigation near the center of the ER profile. Assuming the higher-resistivity section represents the top of the Salado Formation, profile JWS-1 indicates a broad swale in the top of the Salado, presumably the result of subsidence associated with the solution-mining process.

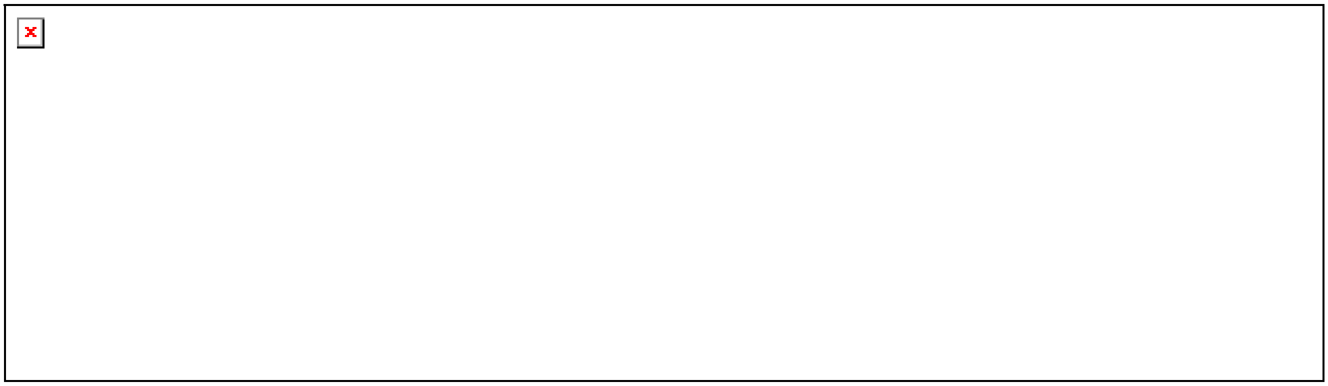

Figure 8-A: Electrical resistivity profile JWS-2, conducted on northwest side of JWS sinkhole (Figure 5).

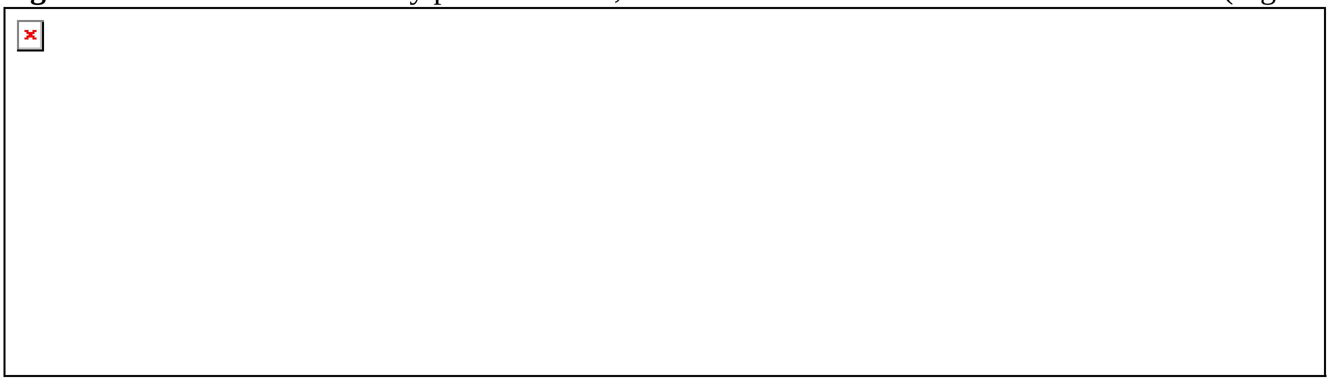

Figure 8-B: Electrical resistivity profile JWS-1, conducted on southeast side of JWS sinkhole (Figure 5).

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 (e.g., Koper et al., 2000). However, this may be the first documented seismologic record of catastrophic sinkhole formation. Results from resistivity profiles show that even very noisy data may provide useful and coherent information about subsurface karst phenomena.

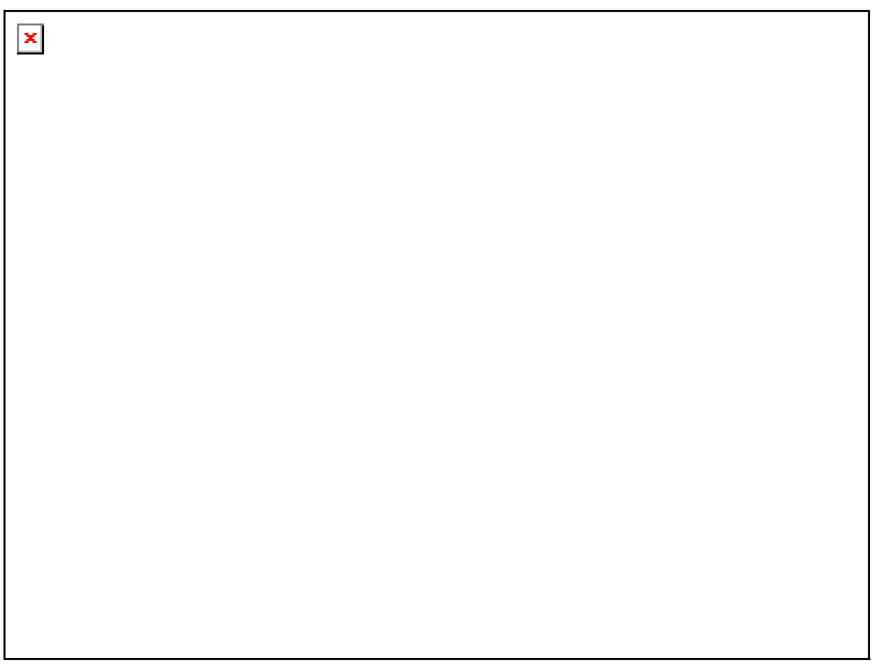

Figure 9: JWS sinkhole on 11/18/2008. Note continued presence of concentric fractures. Boulders visible on

left flank of sinkhole are approximately car-size.

ACKNOWLEDGEMENTS

Dr. Richard Aster, Earth and Environmental Science Dept., New Mexico Institute of Mining and Technology, provided interpretation of seismograph records (Land and Aster, 2009). Electrical resistivity surveys were conducted with field assistance from Dianne Gillespie (National Cave and Karst Research Institute), Sam Squillace (U.S. National Park Service), Deanna Younger (U.S. Bureau of Land Management), Mark Lewis (U.S. Bureau of Land Management), and John Corcoran (Fort Stanton Cave Study Group).

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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 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 one month had reached a diameter of 111 m and a depth of ~64 m. Fortuitously, a seismograph 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, NM 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.

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 karstic aquifers that underlie evaporitic rocks at the surface (e.g., Martinez et al., 1998; Land, 2003a; Land, 2006). A significant minority of these sinkholes are of anthropogenic origin, including the well-known Wink Sinks in Winkler Co., Texas (Figure 1). The Wink Sinks probably formed by dissolution of salt beds in the upper Permian Salado Formation (Figure 2), in association with improperly-cased abandoned oil wells (Johnson et al., 2003). Powers (2003) reports that a sinkhole that formed near Jal, New Mexico, was probably the result of Salado dissolution related to an improperly-cased water well. These sinkholes overlie the middle Permian Capitan Reef aquifer (Figure 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.

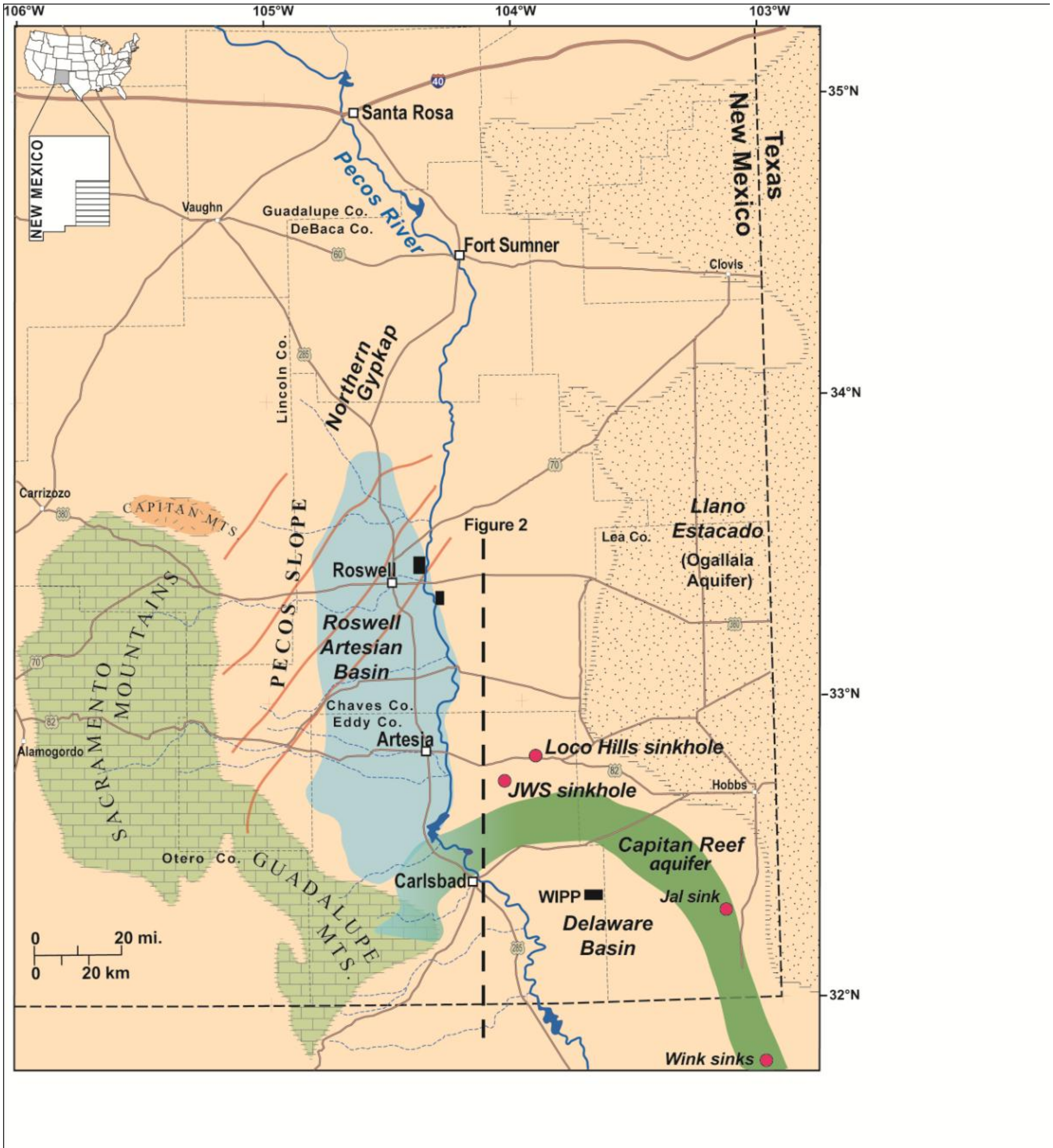

Figure 1: Regional map of southeastern New Mexico and adjoining areas of west Texas, showing location of sinkholes discussed in text, and their position with respect to the Capitan Reef.

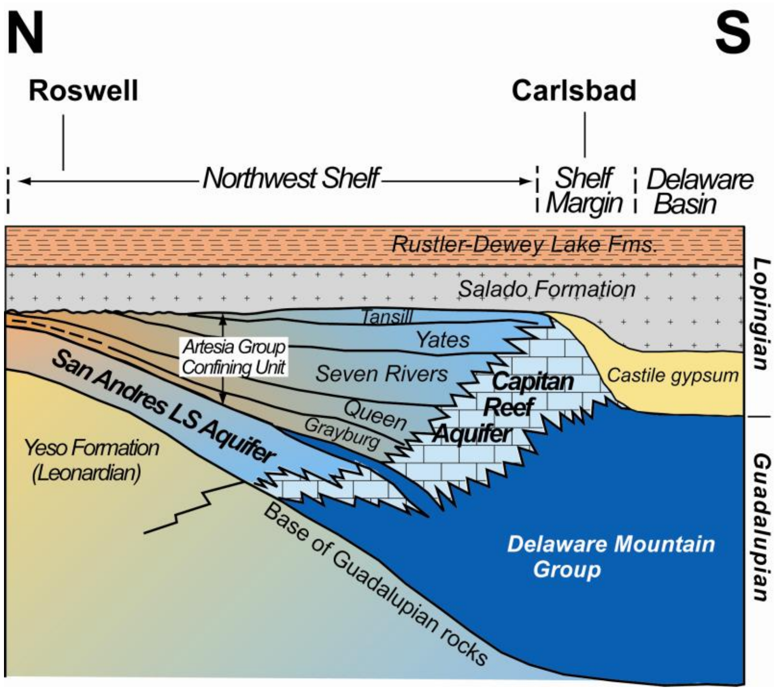

Figure 2: Diagramatic north-south stratigraphic section showing shelf-to-basin facies relationships in the Delaware Basin region. Line of section shown in Figure 1.

BACKGROUND

The lower Pecos region includes the city of Carlsbad in Eddy County, New Mexico. Evaporitic rocks, primarily gypsum, 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 (Figure 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 ~1700 m of redbeds and evaporites of upper Permian age (Lucas, 2006a; 2006b). This section includes the Salado Formation (Figure 2), which in the subsurface of the Delaware Basin consists of ~710 m of bedded halite and argillaceous halite. Rare amounts of potassium salts (sylvite and langbeinite) occur in the 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 onlap 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 ~5 km east of the Pecos River valley (Figure 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 16th, 2008, a driver for Jim's Water Service, a local oil field service company based in Carlsbad, NM, 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 (Figure 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 ~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 two 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, and the water originally present had subsided into the subsurface (Figure 5). There are no significant sources of groundwater at shallow depths in the immediate vicinity of the sink, so 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 stored in pore space in the resulting collapse breccia, and in shallower porous zones of the overlying Rustler and Dewey Lake Formations. By this time the sinkhole had attained a diameter of ~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.

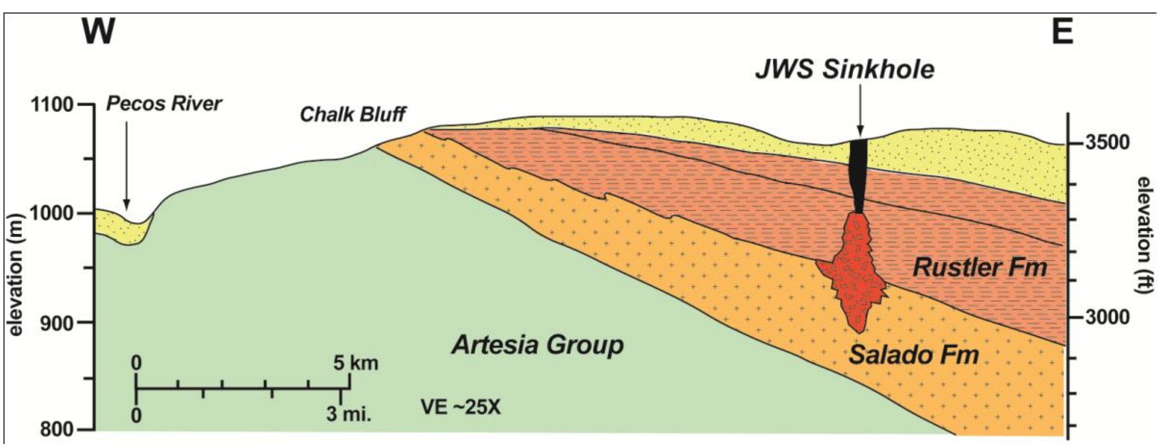

Figure 3: West-east cross-section showing stratigraphic section penetrated by JWS sinkhole. Unnamed surface material is pediment gravel and windblown sand.

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

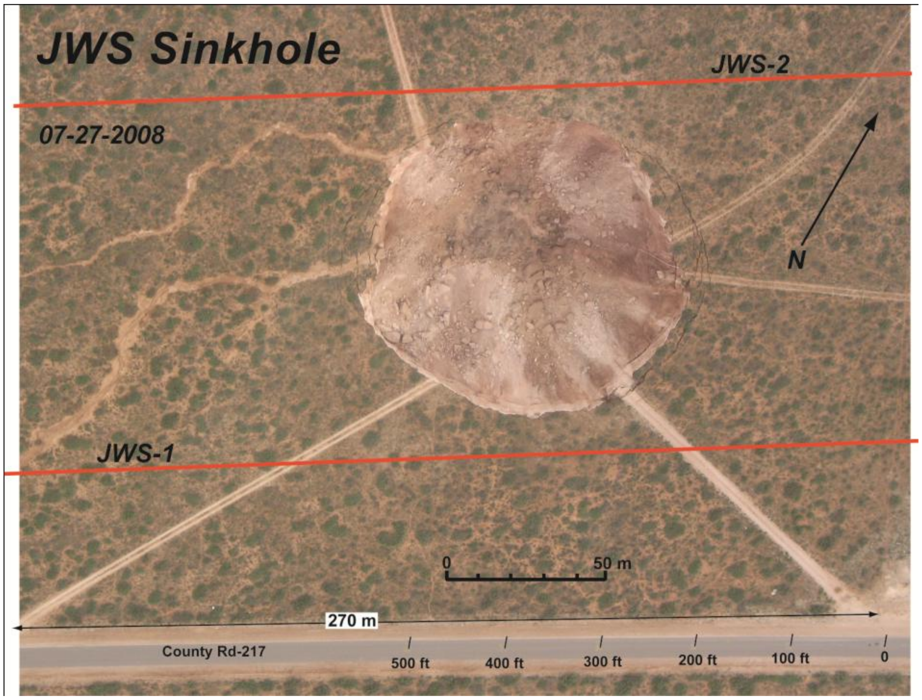

Figure 5: JWS sinkhole on 7-27-2008 showing post-collapse drainage and broadening. Red lines show locations of electrical resistivity surveys conducted in September, 2010.

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 ~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 the JWS brine well (Figure 6). This transportable seismograph is a component of the National Science Foundation's EarthScope USArray continental seismic investigation program that is presently imaging the North American continent at a mean station spacing of approximately 75 km. About 6 hours 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 ~5 microns/s (Figure 7). These seismic events probably reflect subsurface spalling during upward stoping 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).

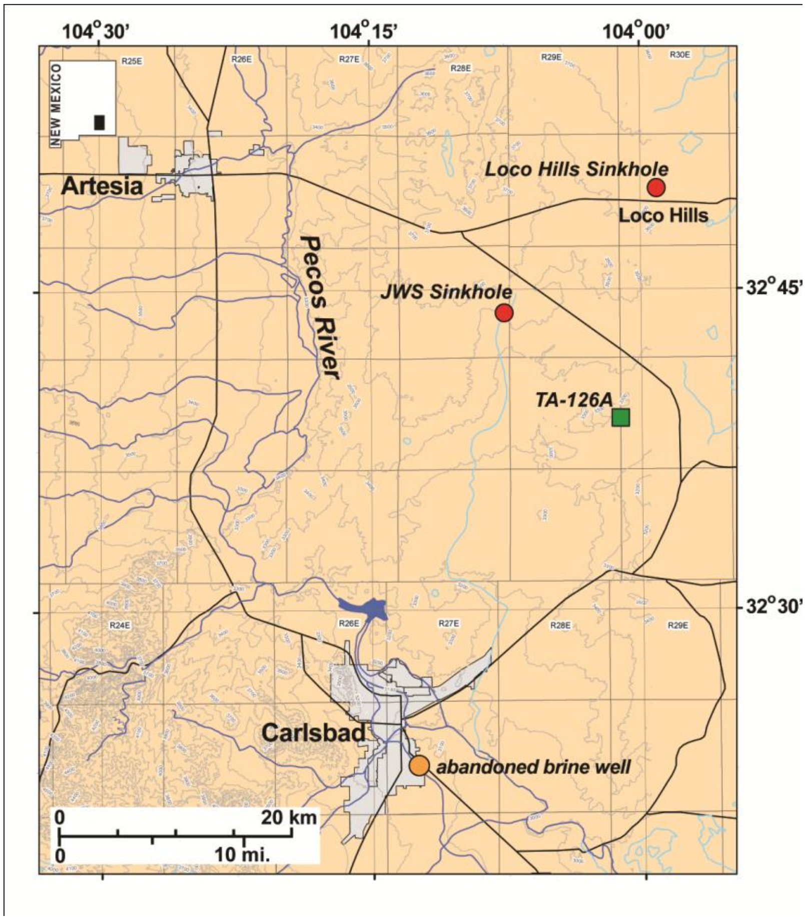

Figure 6: Map of study area in Eddy Co., New Mexico, showing locations of the JWS and Loco Hills sinkholes with respect to Transportable Array seismograph TA126A. Southernmost filled circle shows the location of an abandoned brine well within city limits of Carlsbad.

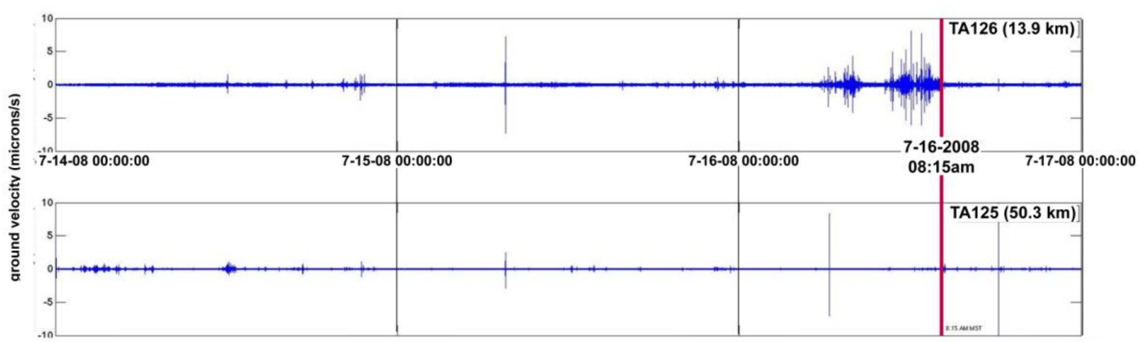

Figure 7: Transportable array seismograph TA126-A 3-day high-pass (filtered above 5 Hz) record of vertical ground velocity (upper plot), located 13.9 km southeast of JWS sinkhole, showing more than 6 hours of apparent precursor ground motion associated with sinkhole formation. Estimated time of surface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

In the aftermath of formation of the JWS sinkhole, another water supply company voluntarily abandoned an injection brine well located within the city limits of Carlsbad (Figure 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, ~17 km northeast of the JWS sink (Figure 6). The Loco Hills Sinkhole is also associated with a brine well that was shut in 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 ~150 m below land surface. The deepest cavern was ~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 U.S. National Park Service and Bureau of Land Management conducted electrical resistivity (ER) surveys adjacent to the JWS sinkhole. Two 2-D resistivity surveys were conducted northwest and southeast of the sinkhole (Figure 5) using an AGI SuperSting R-8™ resistivity meter with a 112 electrode pole-dipole array. Electrode spacing was 6 meters, 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™ software was used to process the resistivity data. Both lines were located approximately 15 meters 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 a 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, with RMS error factors ranging from 28 – 32%. Over 3000 data points were collected during each survey; however, during initial processing, 32 – 44% of these data points were flagged for removal by the EarthImager software. Most of the data removed were negative apparent resistivity values, or fell below the minimum voltage setting (0.1 mV). A software option to suppress noisy data was used 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, since so many data points are filtered out during processing. However, both resistivity profiles appear to provide useful records of subsurface conditions in the vicinity of the JWS sinkhole (Figure 8). 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 ~1030 m ASL, roughly 75 m above the top of the Salado Formation.) The JWS-2 profile shows an abrupt increase in apparent resistivity at ~950 m ASL, from ~70 to several hundred ohm-meters (Figure 8-A). This increase in resistivity across the profile very likely 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 still provides 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.

Within the Salado section of the JWS-2 profile, apparent resistivities vary from ~600 to >4700 ohm-meters. A wedge-shaped area of relatively lower apparent resistivity underlies the approximate position of the JWS sinkhole projected onto the survey line. If we assume this area of lower apparent resistivity is not an artifact of the noisy data set, it may indicate the presence of a lower-resistivity breccia zone filling the pre-existing cavity excavated during solution-mining activity.

An area of high apparent resistivity is also present at the southwest end of the JWS-1 line at ~950 m ASL (Figure 8-B). However, the high-resistivity zone subsides below the maximum depth of investigation near the center of the ER profile. Assuming the higher-resistivity section represents the top of the Salado Formation, profile JWS-1 indicates a broad swale in the top of the Salado, presumably the result of subsidence associated with the solution-mining process.

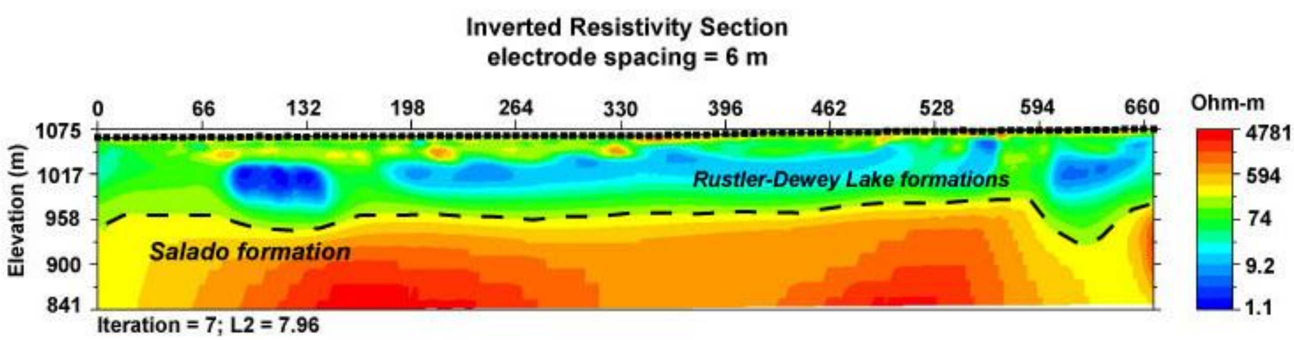

Figure 8-A: Electrical resistivity profile JWS-2, conducted on northwest side of JWS sinkhole (Figure 5).

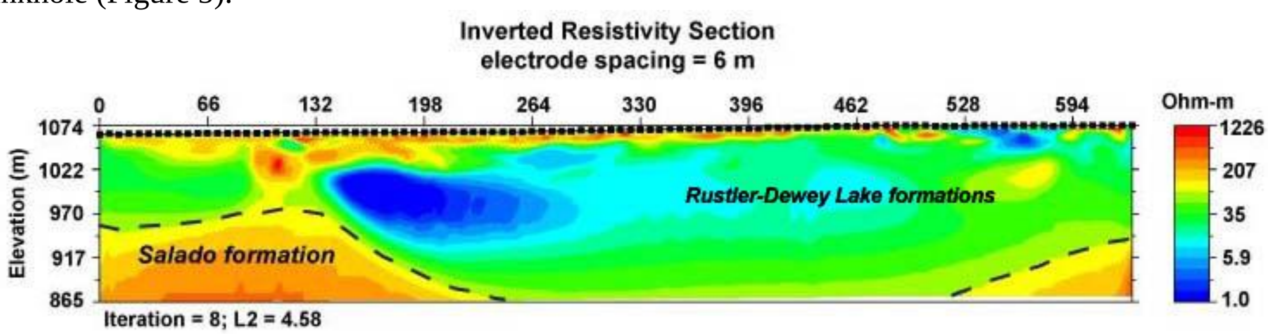

Figure 8-B: Electrical resistivity profile JWS-1, conducted on southeast side of JWS sinkhole (Figure 5).

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 (e.g., Koper et al., 2000). However, this may be the first documented seismologic record of catastrophic sinkhole formation. Results from resistivity profiles show that even very noisy data may provide useful and coherent information about subsurface karst phenomena.

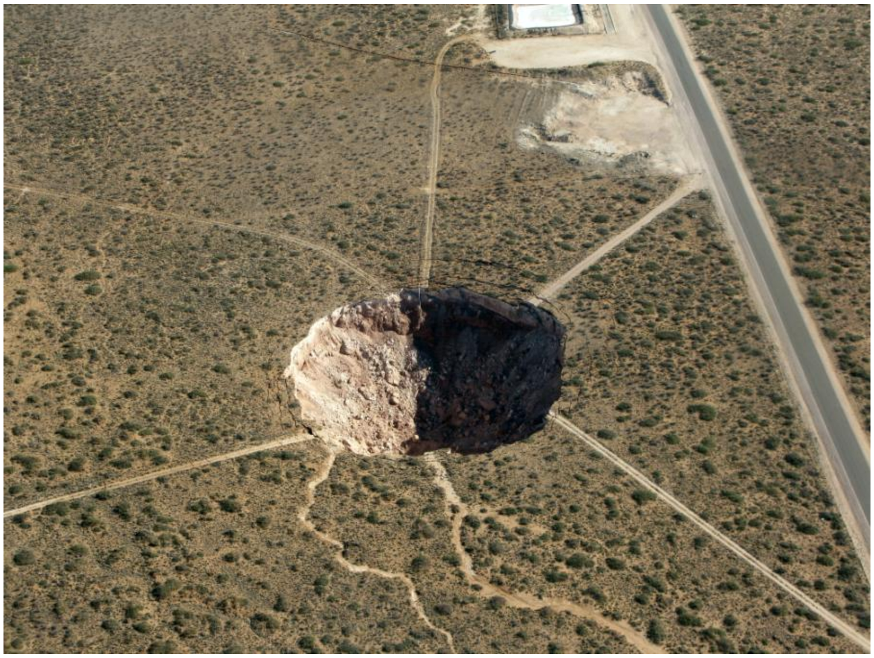

Figure 9: JWS sinkhole on 11/18/2008. Note continued presence of concentric fractures. Boulders visible on left flank of sinkhole are approximately car-size.

ACKNOWLEDGEMENTS

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