Electrical resistivity surveys of anthropogenic karst phenomena, southeastern New Mexico

Lewis Land, New Mexico Bureau of Geology and Mineral Resources, and National Cave and Karst Research Institute, New Mexico Institute of Mining and Technology, 400-1 Cascades Avenue, Carlsbad, New Mexico 88220, lland@gis.nmt.edu;
George Veni, National Cave and Karst Research Institute, New Mexico Institute of Mining and Technology, 400-1 Cascades Avenue, Carlsbad, New Mexico 88220

Abstract

A small but significant number of sinkholes and other karst phenomena in southeastern New Mexico are of human origin and are often associated with solution mining of salt beds in the shallow subsurface. In 2008 two brine wells in a sparsely populated area of northern Eddy County, New Mexico, abruptly collapsed as a result of solution mining operations. The well operators had been injecting fresh water into underlying salt beds and pumping out brine for use as oil field drilling fluid. A third brine well within the city limits of Carlsbad, New Mexico, has been shut down to forestall possible sinkhole development in this more densely populated area. Electrical resistivity surveys conducted over the site of the brine well confirm the presence of a large, brine-filled cavity beneath the we0llhead. Laterally extensive zones of low resistivity beneath the well site represent either open cavities and conduits caused by solution mining or highly fractured and/or brecciated, brine-saturated intervals that may have formed by sagging and collapse into underlying cavities. The data also indicate that significant upward stoping has occurred into overlying strata.

Introduction

On July 16, 2008, a brine well cavity in northern Eddy County, New Mexico, abruptly collapsed. The resulting sinkhole engulfed the brine well and associated structures, and ultimately grew to approximately 111 m in diameter with an estimated depth of 45 m (Land 2009; Land and Aster 2009). Jim's Water Service, an oil field service company, had been solution mining the Salado Formation by injecting fresh water down the well and circulating it through the 86-m-thick section of halite until the water reached saturation. The resulting brine was then pumped to the surface and sold as oil field drilling fluid. The brine well operated on state trust land under permit from the New Mexico Oil Conservation Division (NMOCD). The collapse became known as the JWS sinkhole after the well operator. Less than four months later, on November 3, another brine well collapse occurred in northern Eddy County north of the small community of Loco Hills, forming a sinkhole of similar dimensions. The Loco Hills brine well was also a solution mining operation in the Salado Formation on state trust land (Fig. 1).

These brine well collapses in 2008 prompted NMOCD to review its regulations regarding brine well operations in the southeastern New Mexico oil fields. During this review,

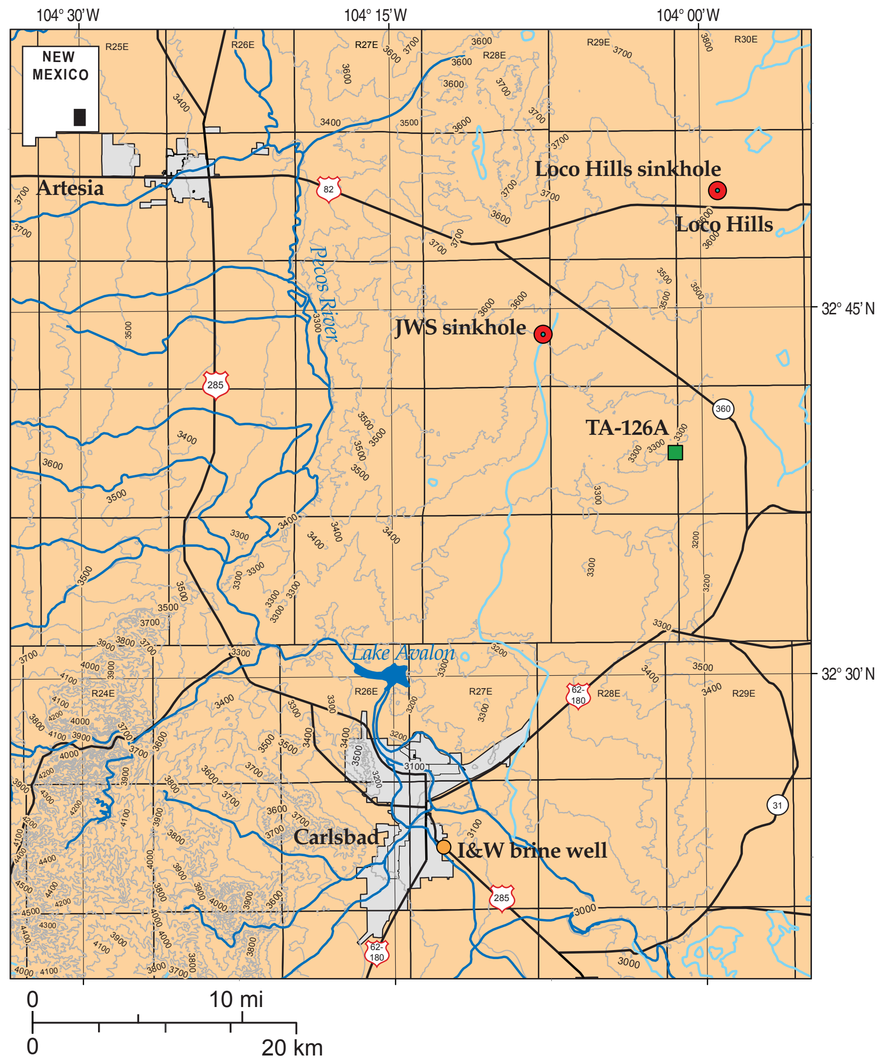

FIGURE 1—Map of sinkhole and brine well locations in Eddy County, New Mexico. Green square shows location of TA-126A, a transportable array seismometer that recorded the JWS sinkhole collapse (Land and Aster 2009; Land 2011). Pecos River and its tributaries indicated by dark blue lines. Light blue lines are ephemeral streams and playas.

the I&W brine well was identified within the city limits of Carlsbad (Fig. 1) as having a similar geologic setting and pumping history. The I&W facility originally involved two wells, which conducted solution mining of the Salado Formation almost continuously since 1979. Eugenie #1 was drilled first with the intent of being a single-well brine producer. However, after a short period of poor production, Eugenie #2 was drilled approximately 100 m to the northwest as a freshwater injection well. The two wells were connected by hydraulic fracturing, and brine was produced from Eugenie #1. After June 2000 Eugenie #2 was shut in, and solution mining was conducted as a single-well operation through Eugenie #1, wherein freshwater was injected through the annulus and brine withdrawn through suspended tubing (Goodman et al. 2009).

Unlike the JWS and Loco Hills sinkholes, which are located in relatively remote areas in northern Eddy County, the I&W operation is sited in a more densely populated area within the city of Carlsbad near the BN&SF rail line and the intersection of two major highways known as the "South Y" (Fig. 2). The Carlsbad Irrigation District (CID) South Canal is approximately 50 m south of the Eugenie #1 wellhead, and the immediate

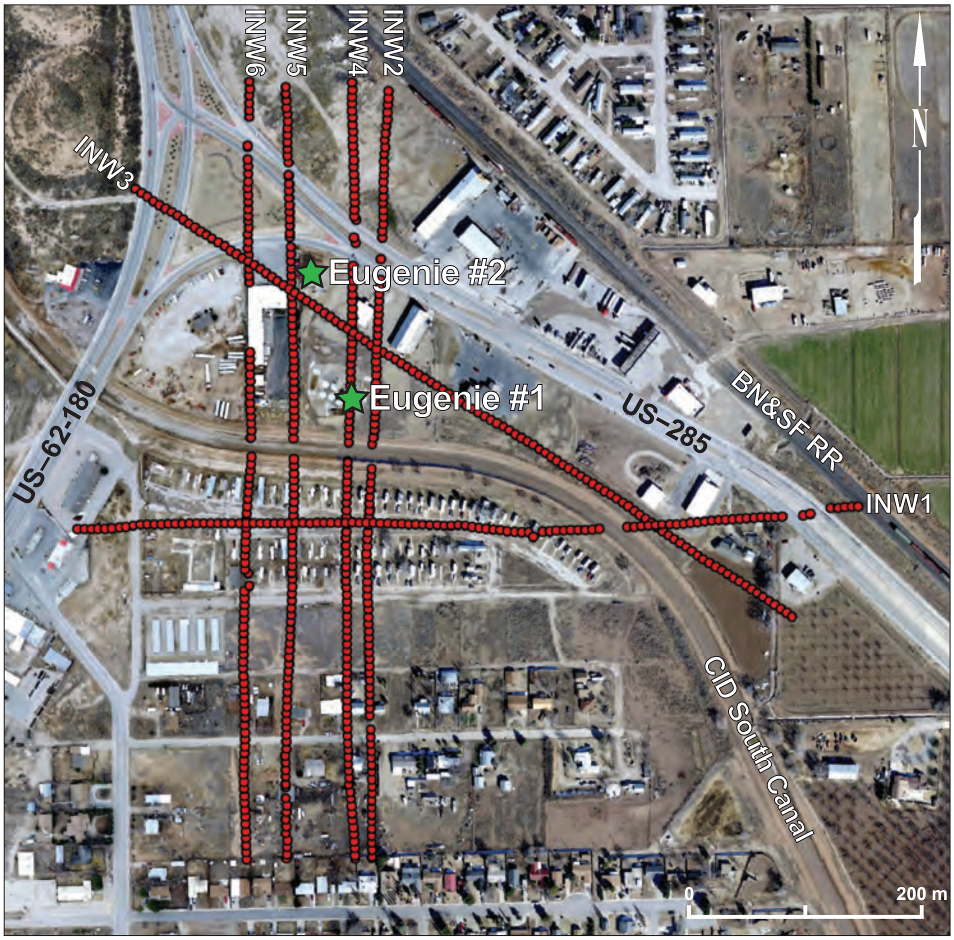

FIGURE 2—Air photo of I&W brine well facility and surrounding area, Carlsbad, New Mexico. Locations of Eugenie #1 and Eugenie #2 wells are shown by green stars. Electrical resistivity survey lines INW 1 through 6 are indicated by red dotted lines. Each dot represents one of the electrodes in the survey line (electrodes lacking GPS coordinates are not shown).

area also includes a feed store, truck stop, mobile home park, and Jehovah's Witness church. A catastrophic collapse in this area would inflict extensive damage to individual property and civic infrastructure.

Following the collapse of the JWS sinkhole, NMOCD ordered closure of the I&W brine well and initiated site characterization and evaluation by its consultant, RESPEC Consulting and Services. The city of Carlsbad and Eddy County established several committees to assess the possibility of and prepare for a potential collapse. As their first priority, they developed a monitoring, alarm, and emergency response system to prevent loss of life in the event a catastrophic collapse occurs. When NMOCD research funds were depleted, the city continued monitoring and studying the cavity through RESPEC and established a technical advisory subcommittee, which reviewed and advised on RESPEC's results.

Most of that research focused on an array of tiltmeters and related devices that measure shifts, subsidence, and cracks in the immediate vicinity of the brine well. The technical advisory subcommittee discussed the possibility of filling the cavity to prevent collapse, but only in general terms. Until characterization of the cavity is complete, reliable selection of the best method and materials to prevent a collapse is not possible. Two attempts were made to measure the dimensions of the cavity, using seismic and sonar methods discussed below, but the downhole sonar survey provided an incomplete image of the cavity because of borehole obstacles. NMOCD then contracted DMT Technologies to conduct a magnetotelluric survey of the site (Woods 2011), and the National Cave and Karst Research Institute (NCKRI) to conduct an electrical resistivity survey. These surveys were expected to map the cavity's approximate size, shape, and lateral extent, which is crucial to remediating the cavity while minimizing the risk of accidentally inducing a collapse. This report provides results of the electrical resistivity survey.

Geologic setting

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, 2006). A small but significant number of these sinkholes are of anthropogenic origin, including the well-known Wink sinks in Winkler County, Texas (Fig. 3). The Wink sinks probably formed by dissolution of salt beds in the upper Permian Salado Formation (Fig. 4), 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 (Fig. 3). 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.

The city of Carlsbad is located on the Northwest Shelf of the Delaware Basin (Fig. 3), a large hydrocarbon-producing sedimentary basin in west Texas and southeastern New Mexico (Land 2003b). Evaporitic rocks, primarily gypsum, are widely distributed in the Delaware Basin region both at the surface and in the subsurface (Bachman 1984; Hill 1996). The uppermost part of the Delaware Basin section is composed of approximately 1,700 m of red beds and evaporites of late Permian age (Lucas 2006a, 2006b). This section includes the Salado Formation (Fig. 4), which in the subsurface of the Delaware Basin consists of approximately 710 m of bedded halite and argillaceous halite. Rare amounts of potassium salts (sylvite and langbeinite) are 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 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" approximately 5 km east of the Pecos River valley. In that area the Salado is represented by 10–30 m of insoluble residue consisting of reddish-brown siltstone, local 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).

Borehole records from Eugenie #1 indicate that the Salado Formation is 42 m thick at the I&W site, and consists of bedded halite with thin interbeds of limestone and

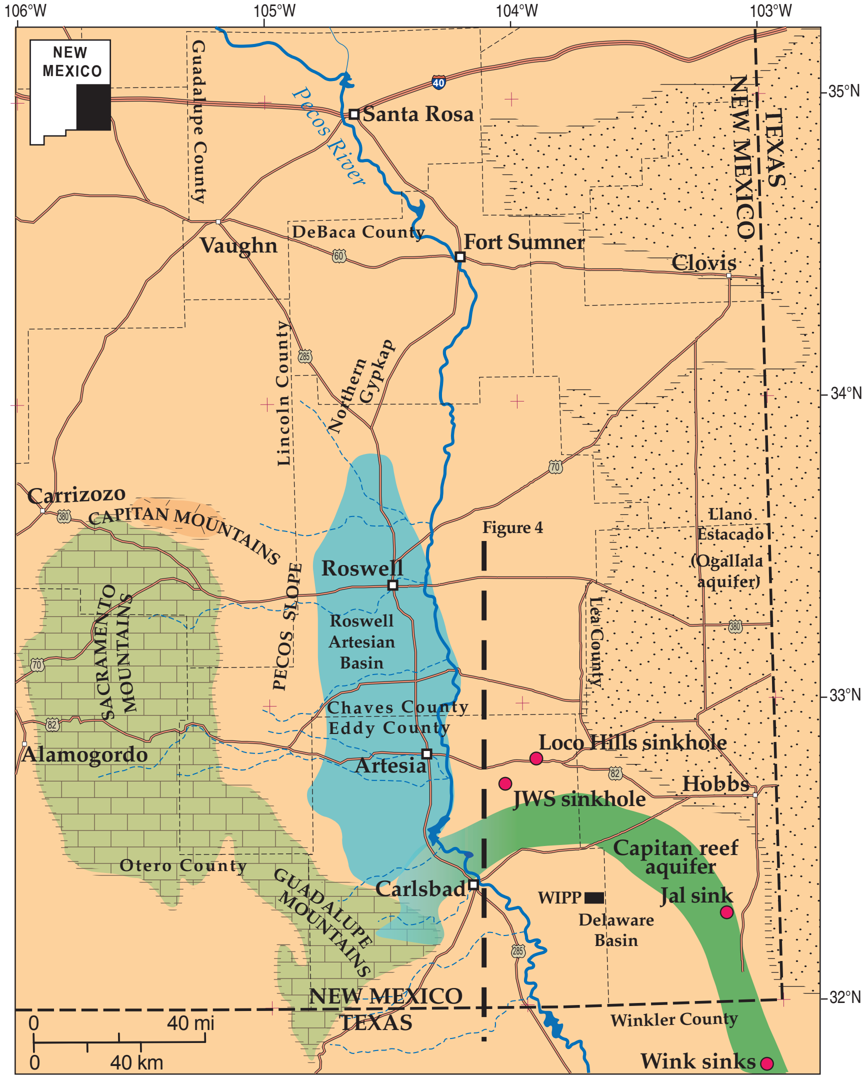

FIGURE 3—Regional map of southeastern New Mexico and adjoining areas of west Texas, showing locations of sinkholes discussed in text and their position with respect to the Capitan reef.

blue shale near the base of the section. The Salado is overlain by 87 m of mudstone, gypsum, and dolomite of the Rustler Formation, and 52 m of unconsolidated to partially consolidated Pecos River floodplain alluvium (Fig. 5).

Previous work

A two-dimensional (2-D) seismic reflection survey conducted in August 2009 identified a roughly pear-shaped cavity in plan view beneath the I&W site (Goodman et al. 2009). The north end of the cavity was narrower than the approximately 120 m long by 90 m wide south end. Seismic interpreters with RESPEC suggested that the larger apparent diameter at the south end of the survey could be due to uncontrolled hydrofracturing from Eugenie #2 to Eugenie #1, combined with the subsequent single-well solution mining from Eugenie #1 (Goodman et al. 2009). The subsurface cavity as interpreted from the seismic survey does not extend south beyond the CID South Canal. However, this may simply reflect the fact that no seismic lines were shot south of the canal due to limitations in funds and as the first attempt to delineate the cavity without any previous knowledge of its extent.

In March 2011, DMT Technologies conducted a high-resolution magnetotelluric (MT) survey of the I&W site. The MT survey identified a subsurface void covering an area of 104,400 m^2 (25.8 acres) and extending south of the CID South Canal (Woods 2011). A number of MT stations showed a void-like response well above the projected top-of-salt, suggesting that there had been significant roof fall, or possibly a highly brine-saturated fracture system in the roof above the top-of-void. DMT interpreters also noted the absence of a basal resistivity marker at the bottom of the salt section, suggesting that the original cavity floor may have scoured deep enough to remove the blue shale lithologic unit at the base of the Salado Formation.

Electrical resistivity methods

On April 6–11, 2011, personnel with NCKRI and the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) conducted an electrical resistivity (ER) survey of the I&W brine well site, assisted by personnel from RESPEC and Madron Services. ER surveys are a common and effective geophysical method for detection of subsurface voids. The basic operating principle for an ER survey involves generating a direct current, or an alternating current of very low frequency, between two metal electrodes implanted in the ground, while measuring the ground voltage between two other implanted electrodes. Given the current flow and voltage drop between the electrodes, differences in subsurface electrical resistivity can be determined and mapped.

Resistivity profiles illustrate vertical and lateral variations in subsurface resistivity. The presence of water or water-saturated soil or bedrock will strongly affect the results of a resistivity survey. Air-filled caves or air-filled pore space in the vadose zone are easy to detect using the ER method, since air has near-infinite resistivity, in contrast with more conductive surrounding bedrock. By contrast, subsurface voids filled with brine would be indicated by zones of very low resistivity (< 15 ohm-m). A resistivity survey conducted by NCKRI in 2010 adjacent to the JWS sinkhole clearly indicated the presence of a large brine-filled cavity approximately 80 m below ground level (Land 2011).

Six 2-D resistivity survey lines were deployed using an AGI SuperSting R8/IP™ resistivity meter with a 112 electrode array. Figure 2 shows the position of the arrays and all electrodes that were surveyed by GPS. High-precision coordinates could not be obtained for some electrode positions and are not shown in Figure 2, but their locations were approximated for data processing without significantly reducing the quality of the data. Each array included a few deactivated electrodes where the arrays crossed roads, and capturing data from those locations was not logistically feasible. Four of the six lines were arranged in north-south parallel order in an attempt to create a 3-D image of the subsurface by merging of the 2-D data. The remaining two lines were perpendicular and oblique to the four to determine if any notable cavity extends east or west of them.

The presence of urban infrastructure presented significant challenges to this study. ER is a long-recognized method for effective detection and imaging of subsurface cavities in karst and other terrains but is infrequently used in urban areas, partly because of the logistical challenge of establishing long linear transects around infrastructure and traffic. In addition, cultural interference from metal fences, buildings, railroads, and buried metal storage tanks and utility lines (water, natural gas, etc.) may capture and deviate part of the electrical current and render some resistivity measurements useless due to high errors. As such measurements are eliminated from

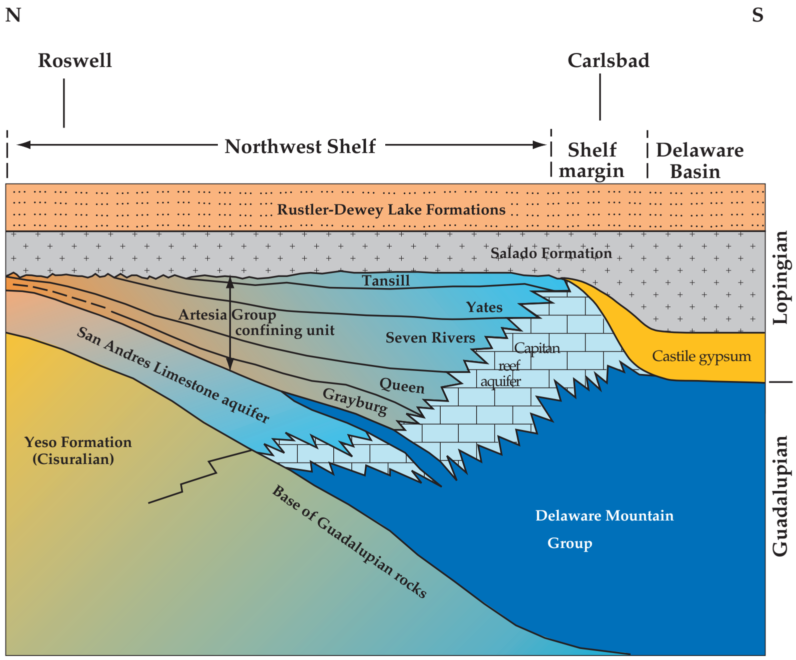

FIGURE 4—Diagrammatic north-south stratigraphic section showing shelf-to-basin facies relationships in the Delaware Basin region. Line of section shown in Figure 3. Modified from Hiss (1975).

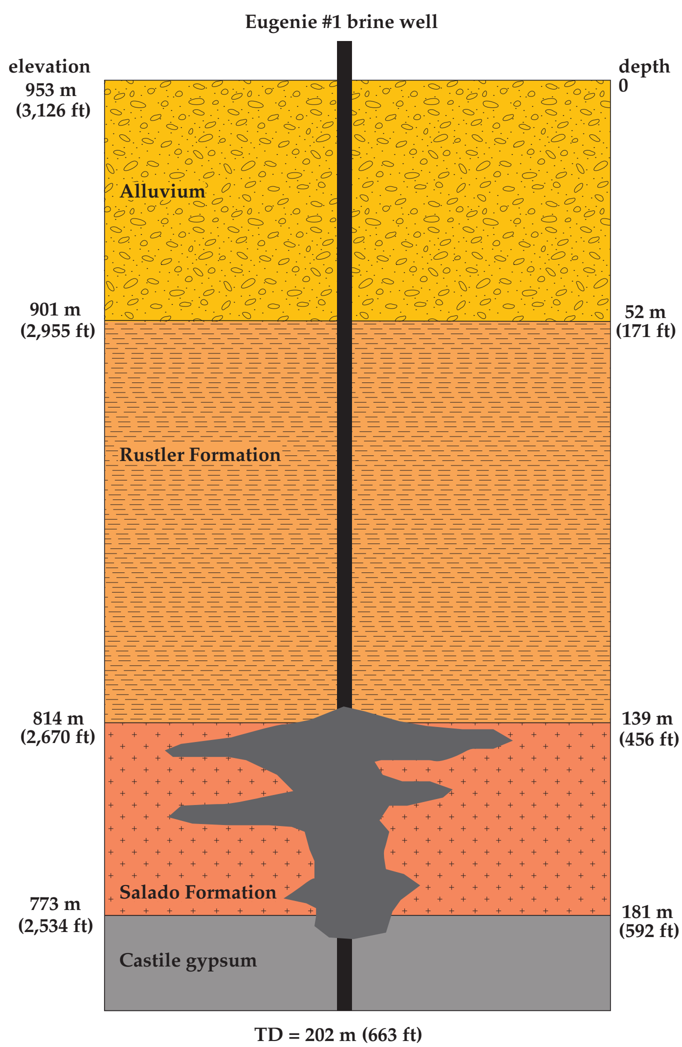

FIGURE 5—I&W Eugenie #1 borehole profile, showing subsurface stratigraphy at that location in Carlsbad. The cavity shown in the profile is schematic since its precise dimensions are unknown.

the data set, fewer data remain for analysis, and image resolution and accuracy of interpretation decrease. ER was selected for use at the I&W well because NCKRI staff believed that, through optimizing field conditions and careful planning of transect locations to avoid known infrastructure, useful interpretable data could be collected given the exceptionally high resistivity contrast between the halite bedrock and brine in the target cavities. This conclusion followed a survey of city and county records for buried infrastructure, as well as evaluating infrastructure on the ground and in aerial photographs.

The depth of investigation for an ER survey is directly related to length of the array of electrodes—the longer the array, the greater the penetration that can be obtained. For the I&W survey, electrode spacing was 6 m, and the full array length for each survey line was approximately 680 m. A standard dipole-dipole array configuration used to survey each ER line attained depths of approximately 130 m. To achieve a greater depth of investigation, the arrays were also coupled to an "infinity electrode," creating a pole-dipole configuration. This method uses an additional electrode that is theoretically deployed at an infinite distance from the main array, and is accomplished in practice by placing the infinity electrode at a far distance from the array. Using the pole-dipole configuration extended the depth of the survey through the entire potential vertical range of the cavity. The infinity electrode cable was deployed southeast along the right-of-way of the CID canal for a length of 2,000 m, where the infinity electrode was implanted in the ground.

Stainless steel stakes 45 cm long were used as electrodes. Each electrode was covered by a bright yellow canvas bag with English, Spanish, Chinese, and symbolic warnings that no one touch them to prevent electrical shock. The stakes were driven at least 20 cm into the ground and then soaked with about 4 l of a saline solution composed of approximately 16 g of salt per liter of fresh water, to create optimal electrical connectivity with the ground. Some electrodes were implanted in areas of concrete and asphalt pavement, where 1-cm-diameter by 25-cm-deep holes were drilled to insert the electrodes for maximum electrical connectivity. Each electrode location was marked on the ground with a spray paint dot and identifying code to facilitate near-future reoccupation if needed.

EarthImager-2D™ software was used to process the resistivity data. The software uses a forward and inverse modeling procedure to create a synthetic data set based on measured apparent resistivity. This is an iterative process; a root-mean-square (RMS) error is calculated for each new iteration. Noisy data points are automatically removed as part of the inversion process, based on pre-defined criteria for data removal, over the course of several iterations until the RMS error is reduced to an

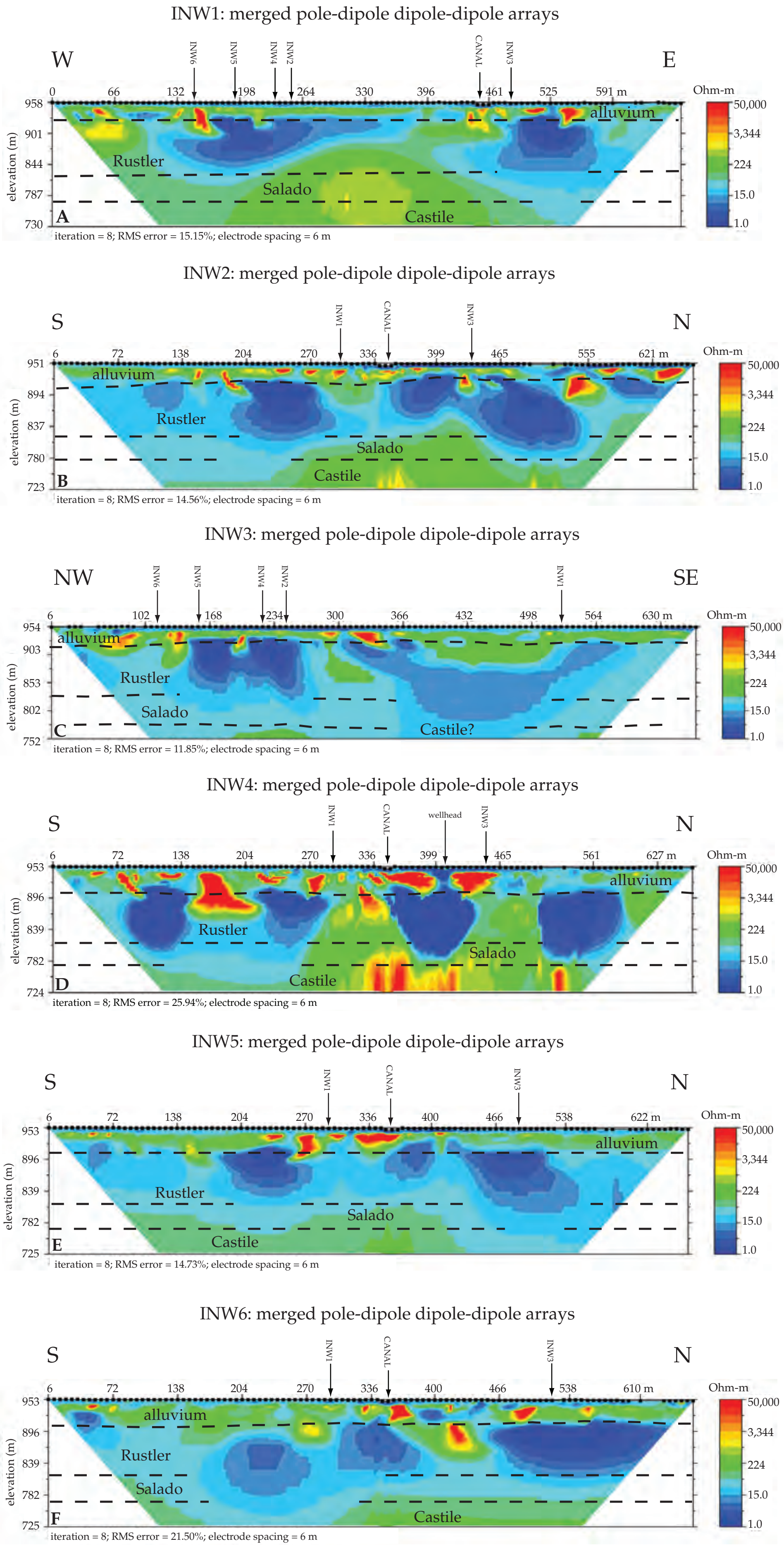

FIGURE 6—**A**—Resistivity line INW1. In this and subsequent figures, arrows show intersections with other ER lines. **B**—Resistivity line INW2. **C**—Resistivity line INW3. **D**—Resistivity line INW4. **E**—Resistivity line INW5. **F**—Resistivity line INW6.

acceptable level. Every iteration requires the removal of a certain number of data points to attain smoother model output, and ideally the iterative process will terminate before too much useful data are filtered out.

The number of data points collected in the field is a function of array configuration and number of electrodes. We employed both dipole-dipole and pole-dipole arrays for each survey line, and used EarthImager software to merge the data from the two array configurations to maximize both resolution and depth of investigation. One advantage of this procedure is that it yields several thousand data points. Thus, even when a noisy data set requires removal of a large number of data points (10–15%) during the iterative process, a substantial amount of data is still available for interpretation.

Our original proposal included development of a 3-D resistivity model of the survey area, based on merging 2-D data collected from the four parallel north-south lines. Ideally, line spacing for such a procedure should not exceed twice the electrode spacing of the array—in this case, 12 m. Preliminary 3-D models were run; however, because of the dense concentration of residential and commercial buildings and other infrastructure in parts of the survey area, our line spacing was approximately 25–50 m, so the resolution of our 3-D model was too poor to yield meaningful results.

The profiles were terrain-corrected using elevation data collected with a survey-grade Topcon GR3™ GPS receiver. The EarthImager software incorporates the elevation data into the inverse modeling procedure to provide estimates of the elevation of subsurface phenomena. The accuracy and resolution of elevation/depth estimates is approximately half the electrode spacing (in this case, 3 m) in the upper half of the profile generated by EarthImager, and is equivalent to the electrode spacing (6 m) in the lower half of the section (Brad Carr, Advanced Geosciences Inc., pers. comm. 2011). Thus the error for depth estimates for this survey is no greater than approximately 6 m.

Results and discussion

The I&W site presented significant logistical challenges in conducting an electrical resistivity survey. We deployed electrical cable across roads with high traffic volume, across the CID irrigation canal, through chain link fences, and across densely populated areas in the mobile home park and housing development south of the canal.

In spite of these and many other obstacles, we obtained coherent results on ER profiles that in most cases attained a maximum depth of investigation of approximately 228 m (748 ft), extending below the base of the Salado salt beds.

Results of the six survey lines are shown in Figures 6A–6F. Stratigraphic boundaries indicated on the resistivity profiles are based on borehole records from the Eugenie #1 well (Fig. 5). The most prominent features on all of the lines are distinct pods and broader zones of low resistivity (< 15 ohm-m) in the depth range occupied by the Rustler Formation, and extending downward into the Salado. Four low-resistivity pods that appear more or less continuous across the survey area are indicated as zones A, B, C, and D on the north-south lines shown in Figure 7.

All geophysical methods provide non-unique solutions, and an accurate interpretation of any geophysical survey requires an understanding of the geologic context combined with ground truth. In the case of the I&W survey, low-resistivity zones within the Rustler may indicate: (1) a brine-filled cavity formed by dissolution of salt beds in the Salado Formation that has stoped upward into overlying strata in the Rustler; and/or (2) highly fractured and/or brecciated zones within the Rustler that are saturated with brine.

High clay content will also produce a low-resistivity response in an ER survey. However, we would not expect clay layers to display such vertically extensive yet laterally discontinuous geometries in the floodplain setting where the surveys were conducted.

Line INW4 (Fig. 6D) is especially informative because it was deployed within approximately 2 m of the Eugenie #1 wellhead, thus passing directly over the subsurface cavity that had been excavated during solution mining operations. Pump tests have confirmed that the cavity is filled with brine, providing ground truth to support the geophysical interpretation. The position of the wellhead is shown at approximately 411 m on the north-south profile. A well-defined pod of very low resistivity occupies the entire Rustler section below the wellhead and extends downward into the Salado. The base of the Salado Formation and the underlying Castile gypsum are poorly resolved on all of the profiles because of attenuation of the resistivity signal at greater depths. However, the base of the Salado appears as a local area of high resistivity beneath the wellhead on line INW4. A vertical zone of low resistivity that links the Rustler low-resistivity pod to the surface is probably caused by conductive material in the well casing, an interpretation supported by an EarthImager-generated synthetic model based on this scenario (Fig. 8). The increase in resistivity near the base of the Salado section may indicate the presence of mudstone and dolomite breccia deposited

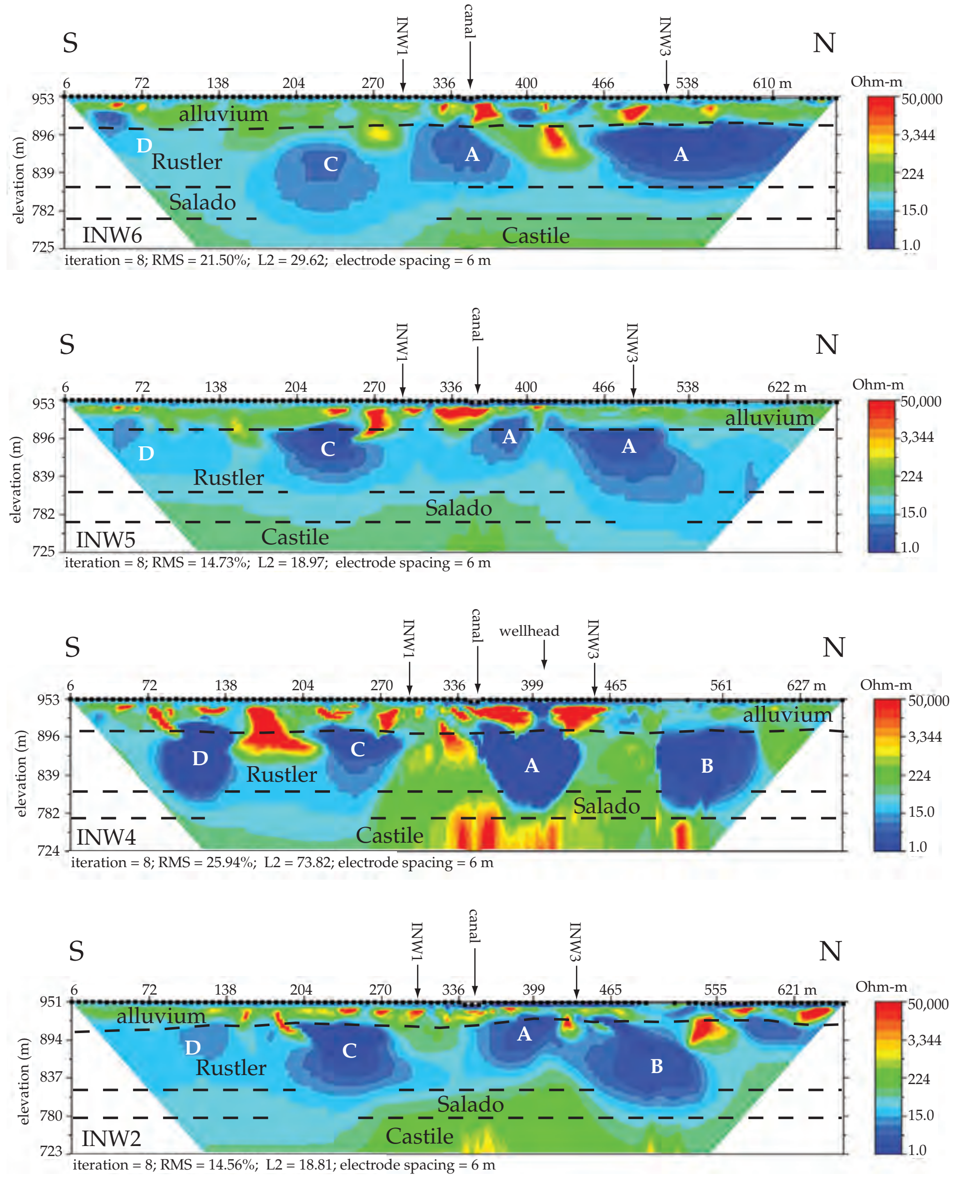

FIGURE 7—Comparison of the four north-south resistivity profiles INW2, INW4, INW5, and INW6.

at the bottom of the cavity due to upward stoping into the Rustler. The July 2010 sonar survey of Eugenie #1 mapped a cavity roughly 45 m in diameter (Van Sambeek 2010a), which correlates closely to the diameter of the low-resistivity area in the Salado below the wellhead in line INW4. Probing of the floor for additional cavities to survey by sonar revealed material consistent with breccia at a depth that corresponds with the increase in resistivity near the base of the Salado; the ceiling of the cavity was not defined in the sonar survey.

The distribution of low-resistivity intervals that may represent brine-filled cavities is shown outlined in yellow in Figure 9. The most distinctive interval, labelled zone A, is present on all four north-south lines (Fig. 7) as well as the northwest-southeast line INW3 (Fig. 6C), which provides a tie for the north-south lines. Zone A extends from Eugenie #1 to Eugenie #2 and farther north beneath the intersection of US–285 and US–62–180. This elongate low-resistivity interval probably represents a solution cavity within the Salado that formed along the fracture system between Eugenie #1 and #2, created during solution mining operations. The extension of zone A northwest of Eugenie #2 suggests that the hydrofracturing was not confined to the area between the two wells. Zone B is another well-defined pod of low resistivity, visible on the north ends of lines INW2 and INW4, that extends beneath US–285. Zone C, underlying the mobile home park south of the canal, is present on all four north-south lines and east-west line INW1, and almost links to zone A on line INW6. Zone D is clearly defined only at the south end of line INW4. Zones A through D all appear connected to varying degrees by conductive intervals of somewhat higher resistivity that may represent brine-saturated fractured sections within the Rustler.

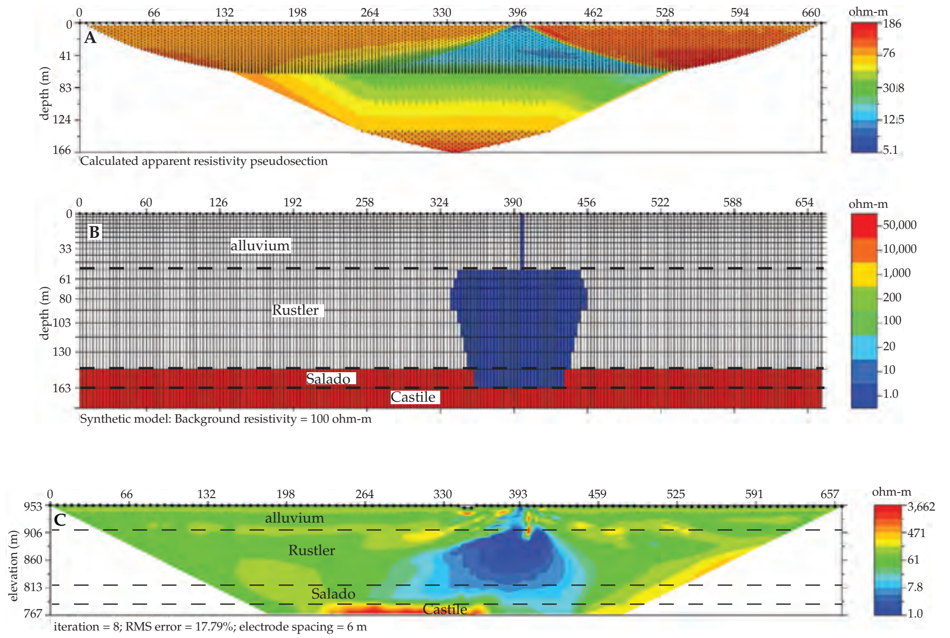

FIGURE 8—Calculated apparent resistivity pseudosection (**A**) based on synthetic model (**B**), assuming a cavity developed in the Rustler Formation of dimensions similar to cavity imaged on line INW4 (Figs. 6D and 7), and linked to the surface by a vertical zone of low resistivity intended to represent conductive material in the well casing. Inverse model (**8C**) is derived from data generated from synthetic model (**8B**).

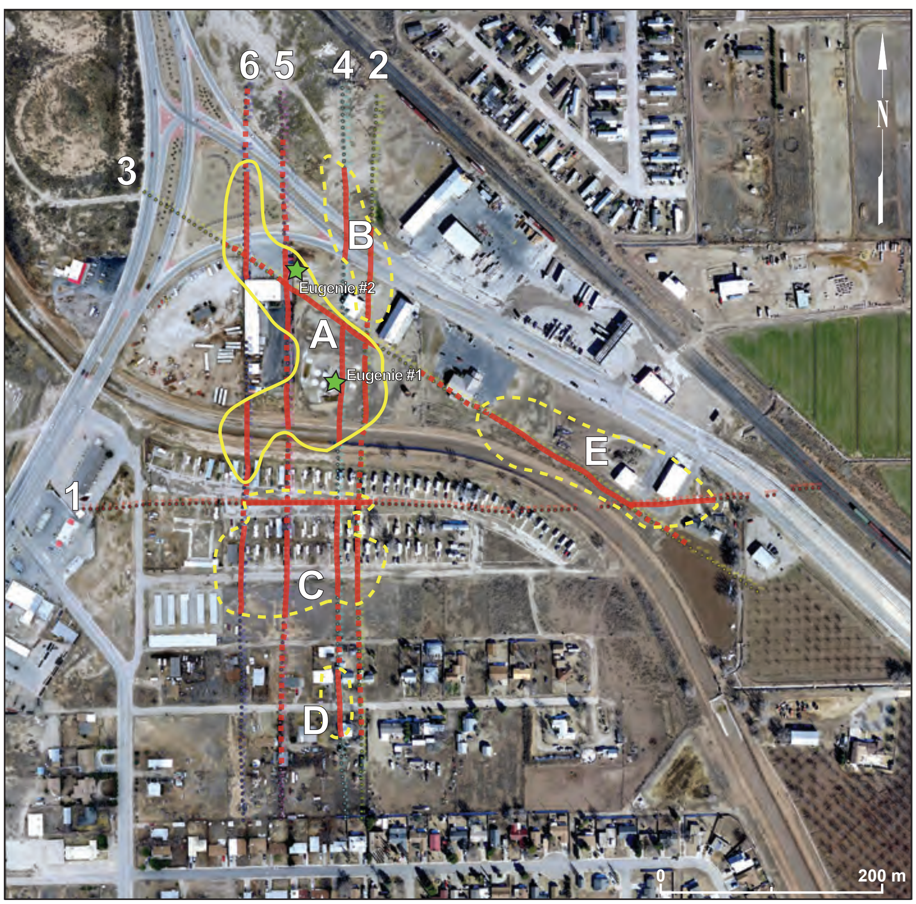

FIGURE 9—Map showing locations of possible subsurface cavities in the Rustler and Salado Formations. Solid red lines indicate areas of lowest resistivity. Much of the area outlined in solid yellow is probably underlain by a significant cavity. Areas delimited by dashed yellow lines probably have a lesser degree of cavity development and/or brine-saturated breccia. Numbers indicate resistivity lines referred to in text. Letters correspond to low-resistivity zones indicated in Figure 7.

Zone E is represented by a distinct pod of low resistivity at the east end of line INW1, and by a much broader, more resistive interval on line INW3. The relation of zone E to the low-resistivity zones beneath the I&W site is unclear, but it may represent a slug or stream of brine moving down the hydraulic gradient from the I&W well site through a more permeable section of the Rustler. The low-resistivity intervals in general do not extend upward beyond the top of the Rustler Formation, suggesting that the clay-rich basal horizon of the alluvium forms an aquitard.

Pumping records from Eugenie #1 and Eugenie #2 and volumetric calculations suggest that the brine well operation excavated roughly 170,000 m^3 (6 million cubic feet) of salt from the Salado Formation. Given the Salado's measured thickness of 42 m, if all of the low-resistivity intervals were caused by cavities in the Salado, zone A would represent approximately 900,000 m^3, zone B would represent 270,000 m^3, and zones C and D combined would represent 830,000 m^3 of void space, for a collective total of approximately 2 million m^3. It thus appears likely that a significant percentage of the low-resistivity zones represent highly fractured or brecciated sections of the Rustler Formation that are saturated with brine, rather than open void space. However, some of these brine-saturated fractured intervals may have resulted from sagging and collapse into underlying cavities and conduits.

One unexpected result of this investigation is that the brine-filled cavity cannot be readily distinguished from brine-saturated sections of the Rustler Formation. This ambiguity probably results from the highly variable total dissolved solids (TDS) content of Rustler Formation pore waters. For example, Chaturvedi (1993) reported TDS values as high as 153,500 mg/l in water samples collected in eastern Eddy County from the Culebra Dolomite, the lowermost fluid-bearing zone in the Rustler section. By contrast, water samples collected from wells near the South Y survey area had measured specific conductance values of just 2,600 and 2,700 μS/cm (M. Chapin, Jr., Sandia Labs, pers. comm. 2012). Assuming a simple linear relationship between TDS and specific conductance of

$$TDS = 0.65K \text{ (Hem 1959)}$$

we should thus expect TDS values of Rustler Formation pore waters in the study area of approximately 1,700 mg/l, and electrical resistivities of approximately 5.8 Ω-m. For comparison, the specific conductance of saturated brine is 300–500,000 μS/cm, or approximately 0.02 Ω-m resistivity.

Given the order of magnitude difference between the estimated volume of the cavity and the low-resistivity zones, it is unlikely that all of the low-resistivity intervals represent brine-filled void space. We assume that the greatest volumetric percentage of the brine well cavity is in zone A, which is

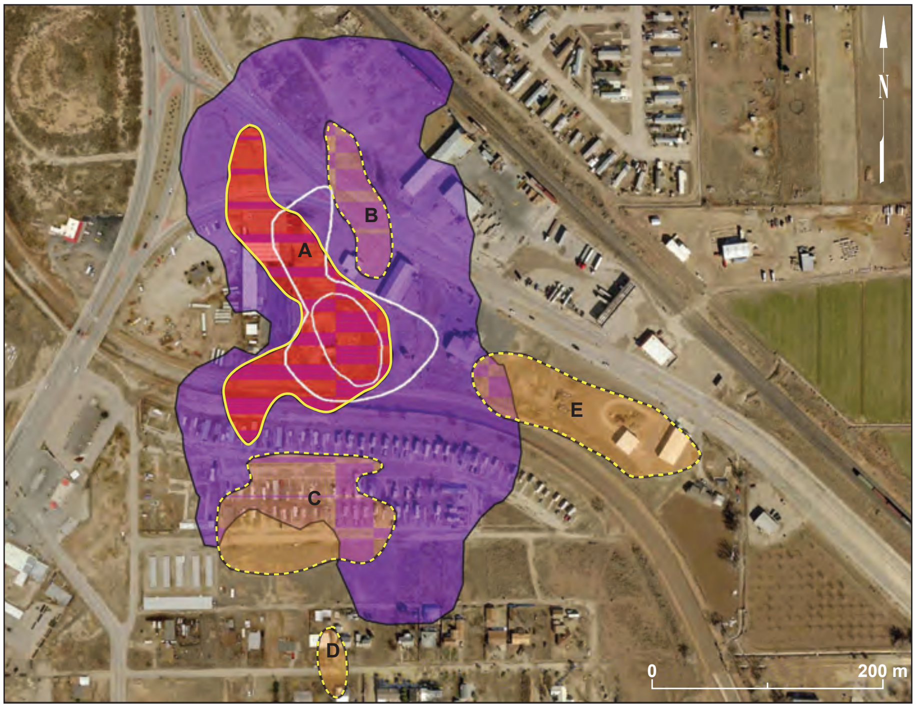

FIGURE 10—Geophysical surveys conducted at I&W brine well facility from 2009 to 2011. Low-resistivity zones defined by electrical resistivity survey are indicated by solid or dashed yellow lines, as in Figure 9. Purple shading shows area where magnetotelluric surveys identified subsurface void thickness greater than 3 m (Woods 2011). White outline indicates area where a cavern signature was identified on 2-D seismic reflection surveys (Goodman et al. 2009). Inner white oval shows the area of greatest seismic disruption. Note that none of the seismic lines extended south of the CID South Canal.

actually penetrated by the borehole. This interpretation is consistent with results of the 2-D seismic study (Goodman et al. 2009) and magnetotelluric survey (Woods 2011) of the I&W site (Fig. 10). The other low-resistivity zones may represent downgradient brine leakage into the Rustler section, as discussed above. However, the potential for smaller yet possibly collapse- or subsidence-prone cavities cannot be ruled out in the other areas (Fig. 9).

The results of this study indicate that the cavity recorded in the Eugenie #1 borehole sonar survey extends up into the Rustler Formation. The height of the cavity cannot be precisely resolved with the available data, which show very low resistivity values up to the contact with the overlying alluvium. Whatever Rustler is present is almost certainly highly fractured and brine-saturated based on resistivity values. Results of the magnetotelluric survey (Woods 2011) also indicated that a number of the MT stations had void-like responses well above the projected top of salt. This interpretation is supported by brine free-flowing from Eugenie #1 and instant accelerated movement recorded by the tiltmeters when the well was uncapped. This response has been interpreted as brine in the cavity buoyantly supporting much of the weight of a highly fractured ceiling that sags and forces water out of the well when it is uncapped (Van Sambeek 2010b).

The presence of such laterally extensive zones of low resistivity within the Salado section throughout the study area invites speculation about natural background processes that could produce these features. To answer this question would require continuation of our resistivity profiles beyond the surveyed area to see if the pattern of low-resistivity pods diminishes with increased distance from the brine well. Unfortunately, these data are not available at present.

Conclusions

Electrical resistivity surveys over the site of the I&W brine well operation in south Carlsbad, New Mexico, indicate that the area is underlain by extensive low-resistivity zones that represent either open cavities in the Rustler and Salado Formations caused by solution mining, and/or highly fractured and brine-saturated intervals within the Rustler Formation that may have been caused by sagging and collapse into underlying cavities. These low-resistivity zones extend to the north beneath the intersection of US–285 and US–62–180, and south beneath residential areas south of the CID South Canal. The data suggest that solution mining of the Salado Formation has caused significant upward stoping into overlying Rustler strata.

Acknowledgments

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References

Bachman, G. O., 1984, Regional geology of Ochoan evaporites, northern part of Delaware Basin: New Mexico Bureau of Mines and Mineral Resources, Circular 184, 22 pp.

Chaturvedi, L., 1993, WIPP-related geological issues; *in* Love, D. W., Hawley, J. W., Kues, B. S., Adams, J. W., Austin, G. S., and Barker, J. M. (eds.), Carlsbad region, New Mexico and west Texas: New Mexico Geological Society, Guidebook 44, pp. 331–338.

Cheeseman, R. J., 1978, Geology and oil/potash resources of Delaware Basin, Eddy and Lea Counties, New Mexico; *in* Austin, G. S. (ed.), Geology and mineral deposits of Ochoan rocks in Delaware Basin and adjacent areas: New Mexico Bureau of Mines and Mineral Resources, Circular 159, pp. 7–14.

Goodman, W. M., Schneider, J. M., Gnage, D. J., Henard, D. A., and Van Sambeek, L. L., 2009, Two-dimensional seismic evaluation of the I&W brine cavern, Carlsbad, New Mexico: RESPEC Topical Report RSI-2083, http://www.emnrd.state.nm.us/OCD/documents/RSI2083.pdf.

Hem, J. D., 1959, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey, Water-Supply Paper 1473, 269 pp.

Hill, C. A., 1996, Geology of the Delaware Basin—Guadalupe, Apache, and Glass Mountains, New Mexico and west Texas: SEPM (Society for Sedimentary Geology), Permian Basin Section, Publication 96–39, 480 pp.

Hiss, W. L., 1975, Chloride-ion concentration in groundwater in Permian Guadalupian rocks, southeast New Mexico and west Texas: New Mexico Bureau of Mines and Mineral Resources, Resource Map 4, scale 1:500,000.

Johnson, K. S., Collins, E. W., and Seni, S. J., 2003, Sinkholes and land subsidence owing to salt dissolution near Wink, Texas, and other sites in western Texas and New Mexico; *in* Johnson, K. S., and Neal, J. T. (eds.), Evaporite karst and engineering/environmental problems in the United States: Oklahoma Geological Survey, Circular 109, pp. 183–195.

Kelley, V. C., 1971, Geology of the Pecos country, southeastern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 24, 78 pp.

Land, L. 2003a, Evaporite karst and regional groundwater circulation in the lower Pecos Valley; *in* Johnson, K. S., and Neal, J. T. (eds.), Evaporite karst and engineering/environmental problems in the United States: Oklahoma Geological Survey Circular 109, pp. 227–232.

Land, L., 2003b, Regional geology of the Pecos country; *in* Johnson, P. S., Land, L., Price, L. G., and Titus, F. (eds.), Water resources of the lower Pecos region, New Mexico: science, policy, and a look to the future: New Mexico Bureau of Geology and Mineral Resources, New Mexico Decision Makers Guidebook, pp. 9–13.

Land, L., 2006, Hydrogeology of Bottomless Lakes State Park; *in* Land, L., Lueth, V. W., Raatz, W., Boston, P., and Love, D. W. (eds.), Caves and karst of southeastern New Mexico: New Mexico Geological Society, Guidebook 57, pp. 95–96.

Land, L., 2009, Anthropogenic sinkholes in the Delaware Basin region: west Texas and southeastern New Mexico: West Texas Geological Society, Bulletin, v. 48, pp. 10–22.

Land, L., 2012, Geophysical records of anthropogenic sinkhole formation in the Delaware Basin region, southeast New Mexico and west Texas, USA: Carbonates and Evaporites, v. 27, no. 1.

Land, L., and Aster, R., 2009, Seismic recordings of an anthropogenic sinkhole collapse; *in* Proceedings of the symposium on the application of geophysics to engineering and environmental problems: Environmental and Engineering Geophysical Society, 2009 Annual Meeting, Fort Worth, Texas, pp. 511–519.

Lucas, S. G., 2006a, Three Permian series; *in* Land, L., Lueth, V. W., Raatz, W., Boston, P., and Love, D. W. (eds.), Caves and karst of southeastern New Mexico: New Mexico Geological Society, Guidebook 57, pp. 60–61.

Lucas, S. G., 2006b, Ochoa Group, not Series or Stage, upper Permian of west Texas and southeastern New Mexico; *in* Land, L., Lueth, V. W., Raatz, W., Boston, P., and Love, D. W. (eds.), Caves and karst of southeastern New Mexico: New Mexico Geological Society, Guidebook 57, pp. 62–63.

Martinez, J. D., Johnson, K. S., and Neal, J. T., 1998, Sinkholes in evaporite rocks: American Scientist, v. 86, pp. 38–51.

McCraw, D. J., and Land, L., 2008, Preliminary geologic map of the Lake McMillan North 7.5-minute quadrangle map, Eddy County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map-167, scale 1:24,000.

Powers, D. W., 2003, Jal sinkhole in southeastern New Mexico: evaporite dissolution, drill holes, and the potential for sinkhole development; *in* Johnson, K. S., and Neal, J. T. (eds.), Evaporite karst and engineering/environmental problems in the United States: Oklahoma Geological Survey, Circular 109, pp. 219–226.

Van Sambeek, L., 2010a, PowerPoint presentation to the technical advisory subcommittee: RESPEC, 4 August.

Van Sambeek, L., 2010b, PowerPoint presentation to the technical advisory subcommittee: RESPEC, 6 October.

Woods, D. A., 2011, Z-Scan review former I&W facility, Carlsbad, New Mexico: DMT Technologies final report for EMNRD/Oil Conservation Division, http://www.emnrd.state.nm.us/OCD/documents/IWMagnetotelluricReport.pdf.