PRELIMINARY INVESTIGATIONS OF SUBSIDENCE, COLLAPSE, AND POTENTIAL FOR CONTINUED GROWTH OF THE DAISETTA SINKHOLE, LIBERTY COUNTY, TEXAS

by

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Report prepared for

Railroad Commission of Texas
Contract No. UTA08-648

October 2009

INTRODUCTION

Sinkholes are a common geologic hazard in many parts of the world. In Texas, sinkholes are associated with shallow salt domes of eastern Texas and the Coastal Plain, limestone karst in central Texas, and bedded Paleozoic salt beneath the High Plains of northern Texas and within the Permian basins of western Texas. Over several hours on May 7, 2008, formation of a large sinkhole (about 200-m diameter) on the northwest flank of the Hull salt dome underlying the city of Daisetta (Figures 1 and 2) drew local and national media attention. As a rapid-response effort to address a sudden geologic event affecting public safety, researchers from the Jackson School of Geosciences conducted a reconnaissance gravity survey three weeks after the May 7 sinkhole collapse (Figure 3). The purpose was to examine evidence for local reductions in strength of the gravity field caused by possible shallow subsurface mass deficits near the Daisetta sinkhole and

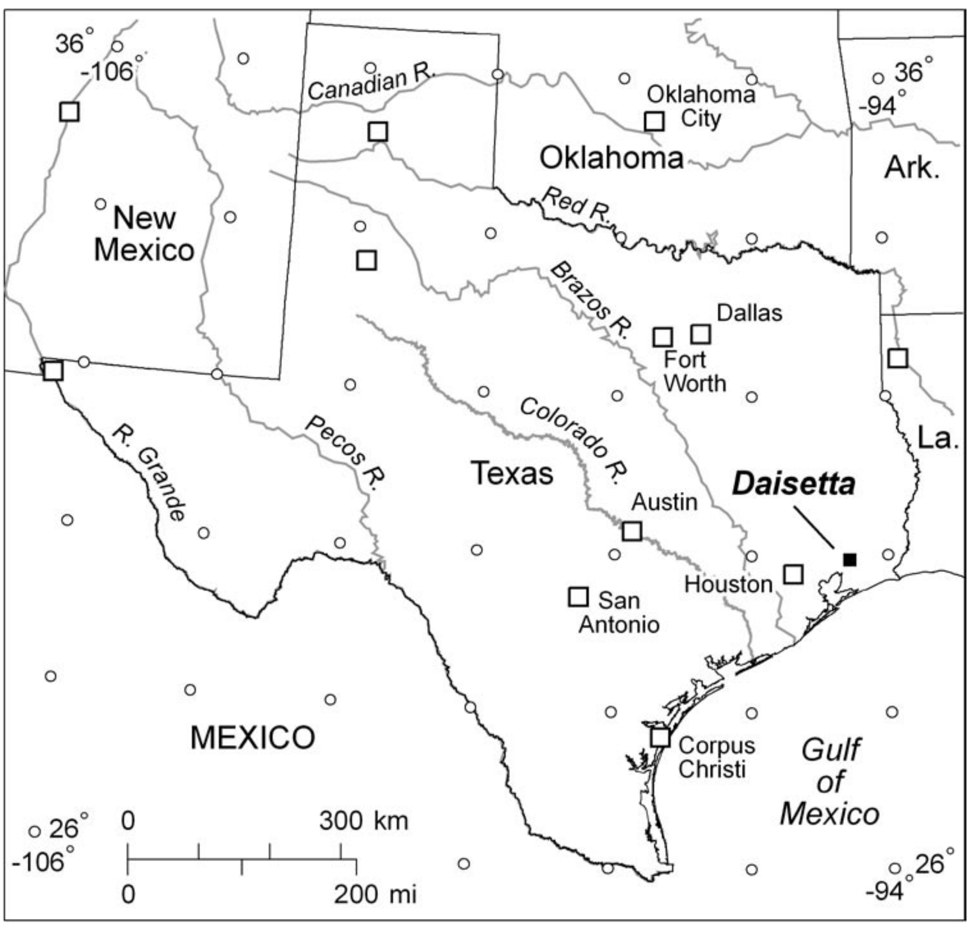

Figure 1. Map of Texas showing the Daisetta sinkhole area.

Figure 2. View of the Daisetta sinkhole toward the north on May 14, 2008, seven days after collapse. Debris and crude oil are floating on water filling the sinkhole. The sinkhole is roughly circular with a diameter of about 200 m. Fissures are common around the sinkhole perimeter.

Figure 3. Acquiring gravity measurements using a Scintrex CG-5 gravimeter along FM 770 in Daisetta, Texas, May 27, 2008.

along major routes through Daisetta. Initial results were summarized in a July 2008 report (Paine and others, 2008). Since completion of that report, Bureau researchers have further analyzed the gravity data acquired in May 2008 and have conducted modeling studies to examine the range of possible subsurface mass deficits that could cause the small anomalies observed at Daisetta. In addition, researchers at the Center for Space Research at The University of Texas at Austin have analyzed satellite-based interferometric synthetic aperture radar (InSAR) data to examine whether there was evidence for pre-collapse ground motion at and near the sinkhole site. Results of the geophysical studies have been presented at a January 2009 public meeting in Daisetta (Paine and others, 2009a) and at a March 2009 geophysical conference in Fort Worth, Texas (Paine and others, 2009b) and are included in this summary.

METHODS

We acquired gravity data at 243 locations along six lines in and around Daisetta (Table 1), which is situated on high ground less than 300 m above the top of the Hull salt dome (Figure 4). During development of the sinkhole, salt water flowed to the surface through oil or gas wells located south of the sinkhole and across the crest of the dome (Figure 4a), leading to concern about the possible presence of dissolution conduits beneath Daisetta. Two long gravity lines (40-m station spacing) were acquired along FM 770 from north to south across Daisetta and from east to west along Pine Street. These lines were intended to intersect possible significant shallow mass deficits between the sinkhole and the salt-water flow sites across the dome. Gravity station spacing

Table 1. Daisetta gravity survey acquisition parameters, May 27-29, 2008.

Instrument	Scintrex CG-5
Sensitivity	< 10 microgal (μgal)
Elevation control	Trimble R7 RTK GPS
Station spacing (Lines 1 and 2)	40 m
Station spacing (Lines 3, 4, 5, and 6)	10 m
Measurement locations	243
Measurement readings	500
Reading duration	30 or 60 s

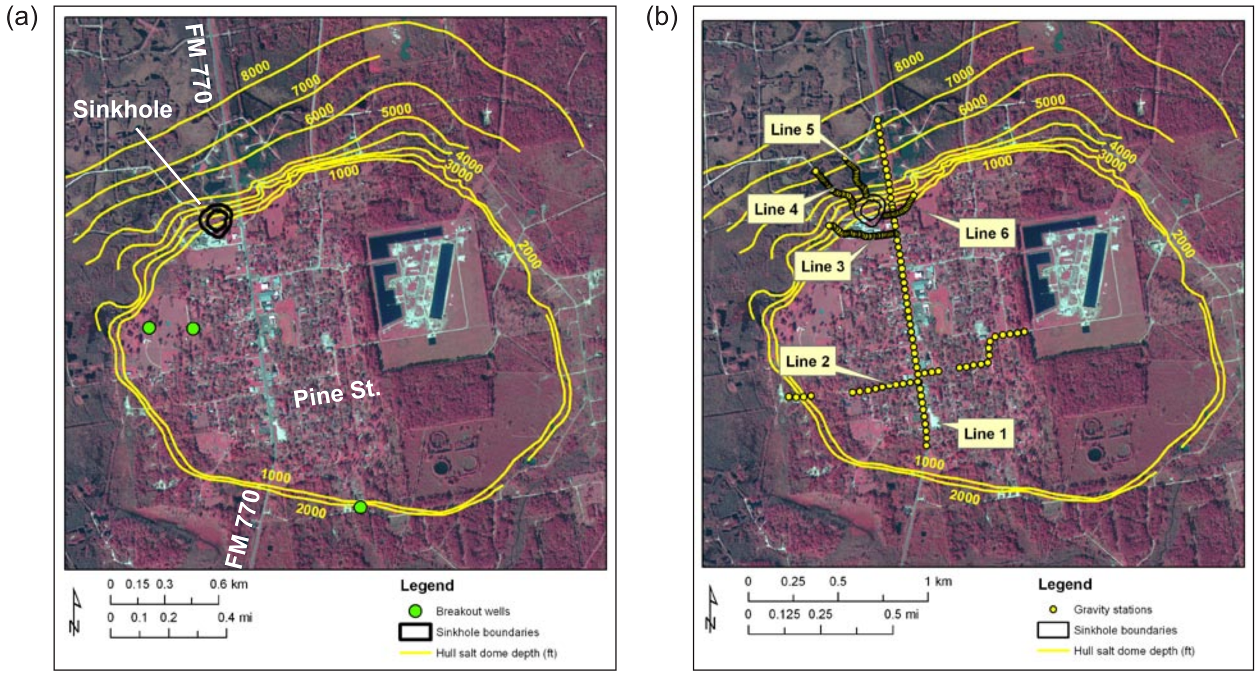

Figure 4. (a) 2004 aerial photograph of the Daisetta, Texas area showing the May 7, 2008 sinkhole location, contoured depth to the top of the Hull salt dome, and wells that flowed salt water during collapse. (b) Daisetta gravity lines 1 through 6. Small circles represent gravity measurement locations. Aerial photograph is a false-color infrared image from Texas Natural Resources Information System (TNRIS). Depths to the top of salt were provided by Quail Creek Oil Company.

was 10 m along the remaining four short lines near the sinkhole, which were intended to identify gravity lows adjacent to the sinkhole that might suggest growth direction. Gravity measurements on these lines approach the sinkhole edge as shown on aerial photographs taken on May 8, the day after initial collapse.

We acquired gravity data at Daisetta on May 27-29, 2008 using a Scintrex CG-5 relative gravimeter with a fused-quartz sensor capable of 1 microgal (µgal) reading resolution (about one billionth of the earth's gravitational strength at the land surface) and less than 10 µgal repeatability. A gravity base station was selected east of the sinkhole at a benchmark established and surveyed by staff at Texas A&M University – Corpus Christi and was occupied before and after gravity data were acquired for each line. Elapsed time between base-station reoccupations was typically two hours or less, which enabled accurate corrections for instrument drift and tidal effects. Latitude, longitude, and elevation data, which are necessary to accurately correct the gravity data, were obtained using a differentially corrected, real-time kinematic GPS system (Trimble R7). At each gravity station, at least two measurements of 30- to 60-second duration were acquired during quiet traffic periods. Processing of the gravity data included selecting the best gravity measurements of two or more taken at each location (as determined from standard deviation and out-of-range values), combining GPS-derived elevation data with the raw gravity measurements, removing instrument and tidal drift, correcting for differences in measurement location latitude, and correcting for differences in elevation (free-air correction) and for the gravitational attraction of the layer between the surface locations and the reference elevation datum (simple Bouguer correction). We did not attempt a full terrain correction because we have no adequate topographic models of the area. The gentle relief characteristic of the area precludes a significant topographic effect on the gravity data.

GRAVITY SURVEY RESULTS

Drift-, tide-, latitude-, and elevation-corrected gravity measurements reveal at least four local areas with relatively low gravity values (Figures 5 and 6) along lines 1 through 6. Most measurement locations are outside the anomalies and show no evidence of shallow mass deficits that would suggest possible near-term sinkhole development. A relative low reaching about 100 μgal extends about 600 m along line 1 (the north-south line across Daisetta; Figures 5a and 6a) and a smaller, 60- to 80-μgal low extends more than 300 m along line 2 (the east-west line across Daisetta; Figures 5a and 6b). Near the sinkhole, notable are (a) the lack of significant gravity reductions west-northwest (line 4, Figures 5b and 6d) and south-southwest of the sinkhole (line 3, Figures 5b and 6c) despite the presence of a local topographic low and (b) minor relative gravity reductions extending a distance of about 20 m north of the sinkhole (line 5, Figures 5b and 6e) and 50 to 70 m east of the sinkhole (line 6, Figures 5b and 6f) toward the main north-south road through Daisetta (FM 770).

Gravity measurements near the sinkhole suggest that there could be some minor eastward and northwestward expansion of the sinkhole over time (up to a few tens of meters). The lows along

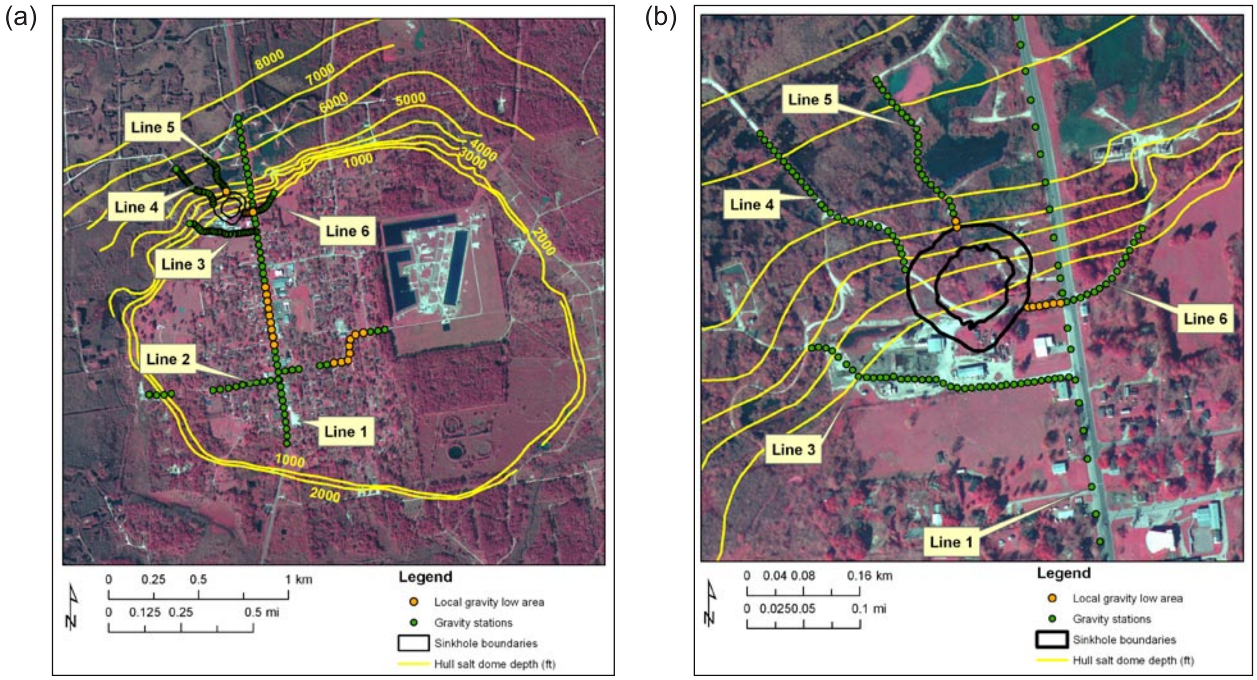

Figure 5. (a) Location of anomalous gravity lows (orange circles) on Daisetta lines 1, 2, 5, and 6. (b) Measurement locations on sinkhole-area lines 5 and 6 having relatively low gravity values (orange cirles). Depth to salt contours provided by Quail Creek Oil Company.

lines 1 and 2 in the town of Daisetta suggest that there is a mass deficit within the upper 200 m or so beneath those areas. The measured gravity lows on lines 1 and 2 could be caused by caprock thickness variations, local topography (pinnacles and saddles) on the top of the salt dome, subsurface voids, or some other source of local, shallow mass contrast. Halbouty (1967) classifies Hull Dome as a shallow dome with caprock at a depth of about 80 m and the top of salt at a depth of about 180 m. These depths are consistent with those shown on a map provided by Quail Creek Oil Company that includes data from several boreholes across the crest of the dome. These locations are annotated with depths to anhydrite or limestone caprock as shallow as 85 m and depths to salt as shallow as 208 m. In contrast, Traylor (2009) states that thin Pliocene clay directly overlies salt at Hull dome and that there is no caprock over salt, which if correct suggests that caprock thickness variations could not be the cause of the local gravity lows on lines 1 and 2. We consider the lows on lines 1 and 2 to be most likely caused by long-standing natural, geologic features related to salt-dome formation and evolution that are not likely to represent a threat of future subsidence and sinkhole formation.

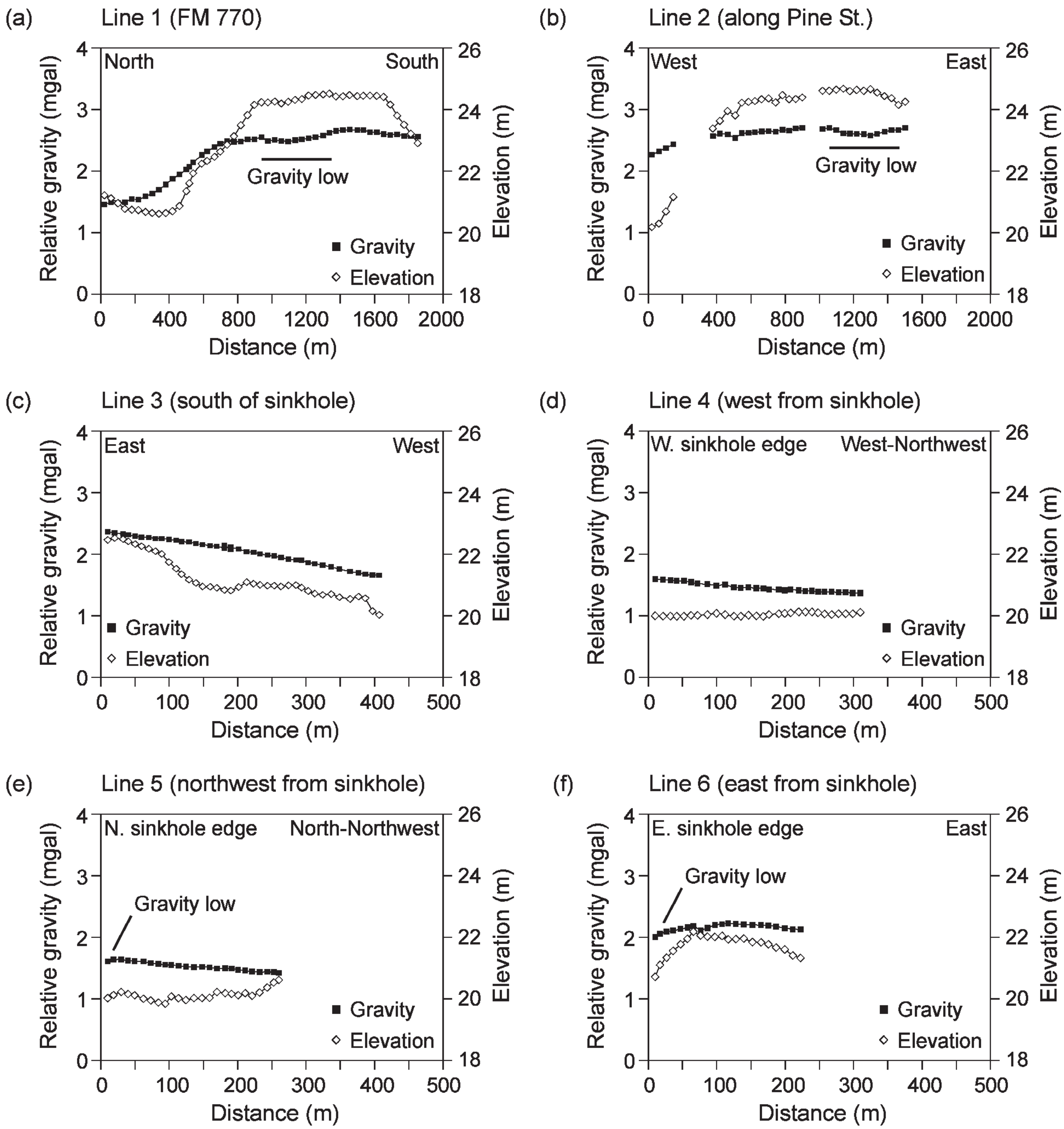

Figure 6. Elevation and relative gravity values (in milligals) calculated from 2008 Daisetta gravity data (Figure 5). (a) Line 1 in a north-south orientation across Daisetta; (b) line 2 in an east-west orientation across Daisetta on Pine Street; (c) line 3 in an east-west orientation south of the sinkhole on the southern part of the DeLoach property; and lines extending (d) westward, (e) northwestward, and (f) eastward from the edge of the sinkhole.

GRAVITY MODELING

Density variations associated with the subsurface configuration of various sediment and rock types and possible water-filled voids are the principal sources of the residual gravity anomalies measured at Daisetta. The shapes and magnitudes of the local gravity lows combined with possible subsurface density variations reveal information about the range of possible depths, thicknesses, and lateral extents of subsurface mass deficits that could cause the lows. We employed three-dimensional cellular modeling to compare predicted gravity measurements for various subsurface density configurations with measured gravity reductions to determine the limits of possible causes of the anomalies and place a maximum bound on sinkhole depth. For modeling purposes, we used reported densities (Figure 7) for saline water to represent the density of possible water-filled voids at and above the salt contact (about 1.1 g/cm^3), wet sandstone to represent semiconsolidated Tertiary and Quaternary sediments above the dome (about 2.2 g/cm^3), rock salt to represent Hull salt dome (2.2 g/cm^3), and anhydrite to represent cap material reported in exploratory borings (about 2.9 g/cm^3).

A major justification for the gravity survey immediately after sinkhole collapse was to acquire information that would determine whether there was evidence for the presence of significant voids beneath Daisetta that could be sites of future subsidence or sinkhole formation, particularly given the concern about possible conduits across the dome between the sinkhole on the northwest flank of the dome and a breakout well on the south side of the dome. Salt is highly soluble in fresh water; the principal concern thus was potential water-filled cavities at the top of the dome. Our models considered the gravity effects of water-filled voids in salt as well as the density contrast between possible anhydrite caprock and semiconsolidated clastic deposits to help constrain the size of subsurface features required to match the size and strength of the observed local gravity anomalies.

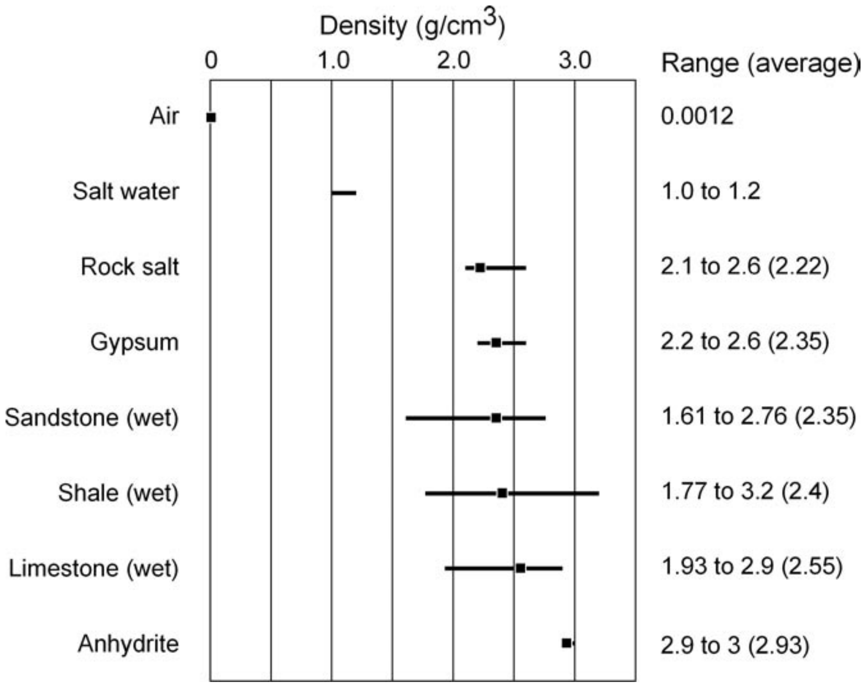

Figure 7. Density of materials similar to those beneath the surface at Daisetta. Density data from several sources, including Telford and others (1990).

Water-filled Voids at the Top of Salt

Because borehole data showed the top of salt at a depth of about 200 m regardless of whether caprock is present, we chose that depth for modeling scenarios that considered a cylindrical mass deficit of varying diameter and height. The assumed density contrast for water-filled voids in salt is about 1.0 g/cm^3 (Figure 7). Residual gravity values for the line 1 anomaly, calculated by subtracting corrected values at each station from a value linearly interpolated from stations outside the low area, reach about 100 μgal over a distance of about 600 m (Figure 6a and 8). Water-filled cylinders with a depth of 200 m and a diameter of 200 m (the same as the sinkhole) provide a reasonable fit with observed gravity residuals for a cylinder height of 20 m (Figure 8). This can be interpreted to imply that, if a water-filled void the width of the sinkhole at the top of the salt dome were the cause of the local gravity low observed along line 1, it could be no more than 20 m thick. Similarly shaped gravity anomalies could be calculated from smaller-diameter cylinders of greater thickness. The mass deficit associated with the smaller residual gravity anomaly on line 2, which reaches 60 to 80 μgal along a 300-m-long segment, would be correspondingly smaller in width and thickness.

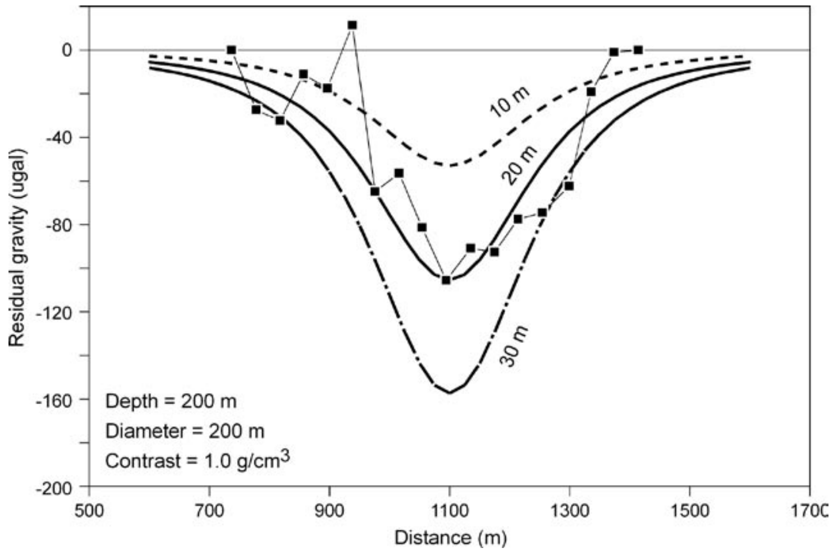

Figure 8. Residual gravity (black squares) along Daisetta line 1 compared to modeled response from 200-m diameter cylinders 10-, 20-, and 30-m tall at a depth of 200 m. Density contrast is 1.0 g/cm^3, approximately the difference between typical bulk densities of saline water and sandstone.

Caprock Thickness Variations at the Top of Salt

A possible source of significant shallow density variation that could cause the observed surface gravity anomalies is the presence of a caprock as well as variations in its thickness across the dome. Anhydrite and limestone are cited as caprock materials at Daisetta; both are significantly more dense than semiconsolidated clastic sediments above the dome and salt within it. Using the top of salt as an assumed depth, we modeled variations in radius and thickness of a vertical cylinder with a mass deficit of 0.6 g/cm^3 to estimate the effect changing anhydrite caprock thickness would have on observed gravity (Figure 9). Using the line 1 local gravity anomaly as an example, we matched the size of the observed anomaly by replacing a 200-m diameter, 33-m high cylindrical body having the density of anhydrite with one of typical clastic-rock density. This possible magnitude of caprock thickness change appears reasonable, given reported caprock thicknesses of 100 m or more. Reasonable local variations in caprock thickness could create mass deficits large enough to account for the gravity lows observed on lines 1 and 2.

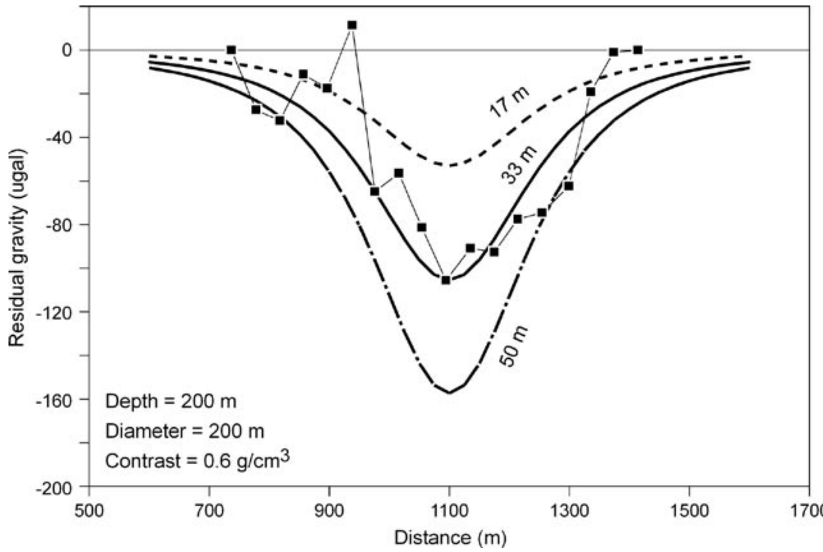

Figure 9. Residual gravity (black squares) along Daisetta line 1 compared to modeled response from 200-m diameter cylinders 17-, 33-, and 50-m tall at a depth of 200 m. Density contrast is 0.6 g/cm^3, approximately the difference between typical bulk densities of sandstone and anhydrite.

Sinkhole Depth Estimates

Estimates of the depth of the Daisetta sinkhole are important because they can be used to calculate the displacement volume during collapse and help bound mass-deficit estimates for gravity modeling. Estimates vary from initial depths of about 76 m (Kasmarek, 2009) to about 21 to 24 m currently (Howe and Norman, 2009; Corrigan Consulting, 2009). Gravity data acquired on May 29, 2008 on line 6 adjacent to the sinkhole (Figures 5b and 6f), after all corrections, show a reduction in gravitational strength that increases toward the sinkhole. This reduction may at least in part be attributable to the missing mass represented by sinkhole and can be used to estimate sinkhole depth by modeling the sinkhole as a water-filled cylinder with a radius of 60 m at the water level on the survey date (Figure 10, left).

The initial depth estimate of 76 m, presumably representing conditions immediately following collapse, generates a gravity anomaly that has a similar shape but is significantly larger than we measured at the seven stations closest to the sinkhole on May 29, three weeks after collapse (Figure 10, right). Root-mean-square (RMS) error between the observed and modeled data for those stations is 60 µgal. More recent depth estimates are represented by the modeled depth of 24 m, which generates a gravity anomaly much smaller than that measured on May 29. RMS error (97 µgal) was larger than for the deeper estimate. The best fit (RMS error of 8 µgal) was obtained using a water-filled sinkhole depth estimate of 57 m, shallower than initial estimates and deeper than more recent estimates and actual measurements after slumping and filling has occurred. The depth estimate from gravity data should be viewed as maximum depth because the model does not consider likely density reductions in the sediment-filled part of the collapse zone below the water column, which would also contribute to a local reduction in gravitational strength.

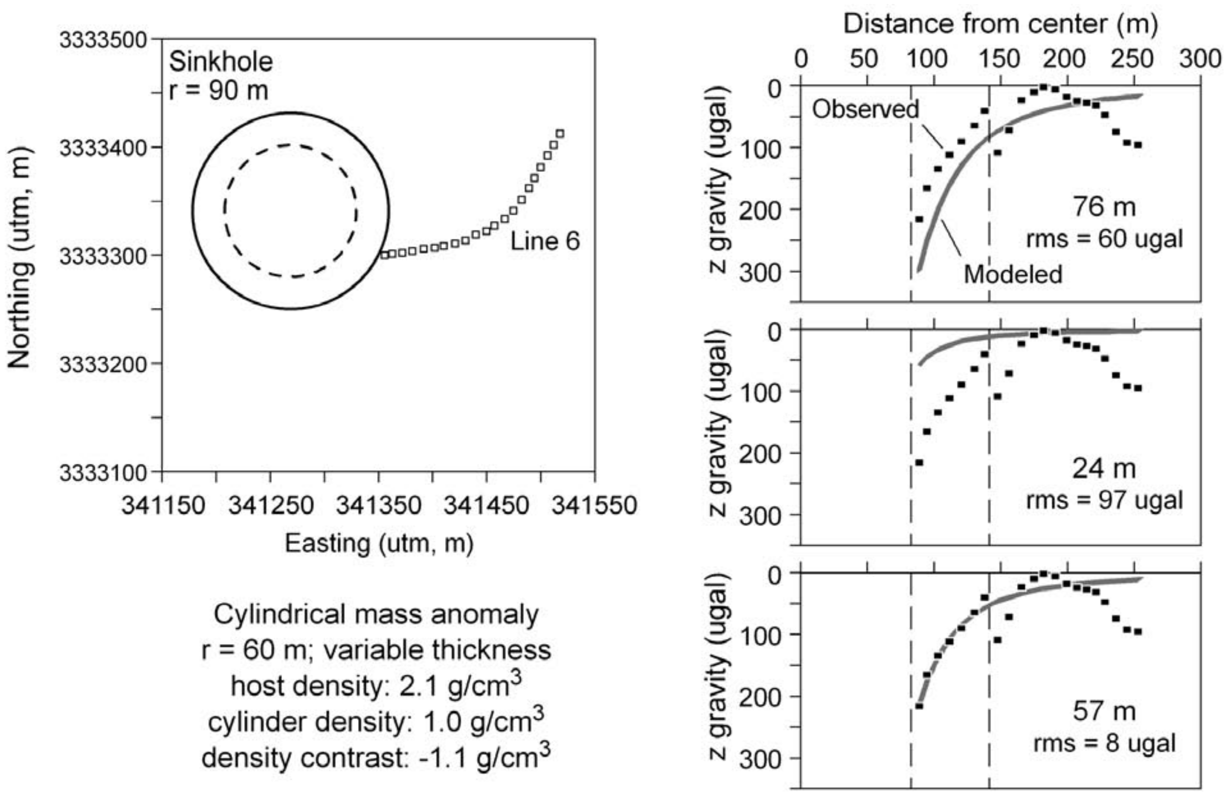

Figure 10. Gravity response for density models along line 6 adjacent to the Daisetta sinkhole (Figure 5b). (left) Schematic map of the Daisetta sinkhole outline (solid line represents upper surface of sinkhole; dashed line represents vertical water-filled cylinder representing density anomaly) showing measurement locations along line 6. (right) Observed gravity strength (boxes) with superimposed predicted gravitational strength at estimated sinkhole depths of 76 m (Kasmarek, 2009), 24 m (Howe and Norman, 2009), and a best fit of 57 m.

CONCLUSIONS

Analysis of satellite-based InSAR data (Appendix) showed no apparent ground deformation before May 2008 collapse. Reconnaissance gravity survey results show the presence of anomalously low gravity values north and east of the sinkhole, suggesting the possibility of minor northward and eastward expansion of sinkhole. Post-survey modeling indicates that some or all of the local gravity reduction adjacent to the sinkhole could be caused by absence of mass within the sinkhole. Gravity data along FM 770 and Pine Street show only two local areas of shallow mass deficit 300- to 600-m long that are most likely to be caused by long-standing geological features related to salt-dome evolution rather than voids caused by recent dissolution. Post-survey modeling of the larger anomaly along FM 770 indicates that anomalies of that magnitude could be generated by local anhydrite caprock thickness reductions of about 30 m or less, or by a water-filled void atop the salt dome over an area about 200 m across and about 20 m thick.

ACKNOWLEDGMENTS

Research described in this report was supported by a rapid-response program grant from the Jackson School of Geosciences, The University of Texas at Austin, and by the Railroad Commission of Texas (RRC) under Contract No. UTA08-648. Art Correa served as project manager at RRC. Quail Creek Oil Company provided maps and cross sections constructed from well data. RRC staff Guy Grossman, Gil Bujano, and Douglas Johnson assisted with site access and data acquisition. Daniel Prouty at Texas A&M University, Corpus Christi, provided benchmark locations and elevations. RRC staff Peter Pope, Douglas Johnson, Art Correa, and Fernando de Leon reviewed draft versions of this report.

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Daisetta Radar Interferometry Analysis Report

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Summary
We used radar interferometry (InSAR) to determine that no measureable surface deformation occurred in the months prior to the formation of the Daisetta, Texas sinkhole on May 7, 2008. Instead, the InSAR measurements reveal likely surface water level changes west of Daisetta.

Introduction
InSAR measures centimeter-scale surface motion toward or away from the satellite radar instrument at approximately 100 meter pixels postings over 100 km x 100 km areas. The ability to obtain viable InSAR deformation measurements depends on how surface radar scattering properties vary over time. For example, cultivating agricultural fields and digging, mining, and scraping of the ground surface result in poor InSAR results.

Results
We processed three ALOS PALSAR radar interferograms collectively spanning the time period from December 2006 to April 2008 (Figures 1, 2 and 3). Each cycle through phase (the color bar) represents 12.8 cm of motion toward or away from the satellite radar instrument. There is no apparent ground motion in the area of the sinkhole immediately north of the image center. The phase variations to the west (left side of image) are in an area where surface water levels may be fluctuating with time.

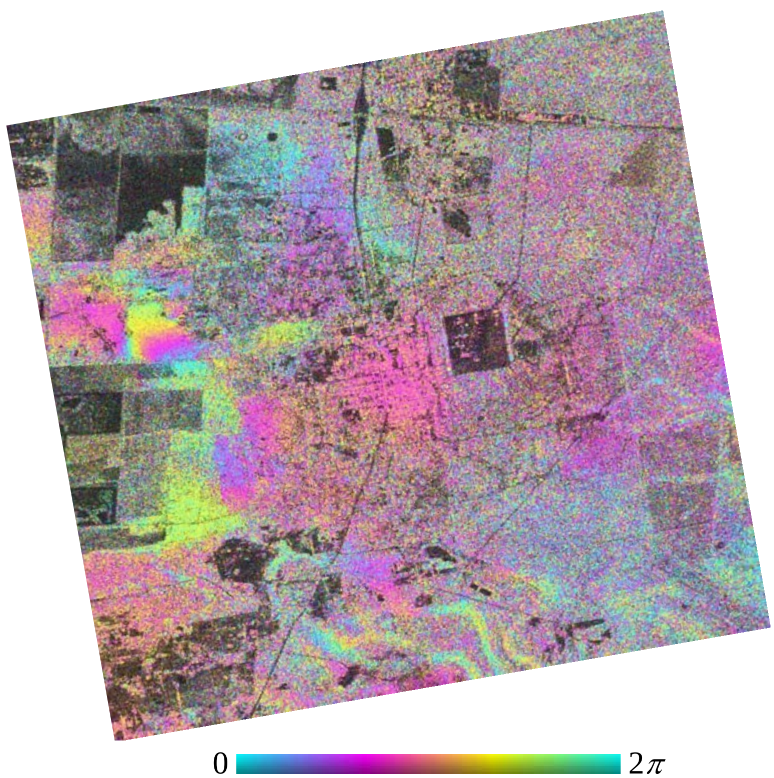

Figure 1. InSAR result spanning the period from December 7, 2006 to January 25, 2008.

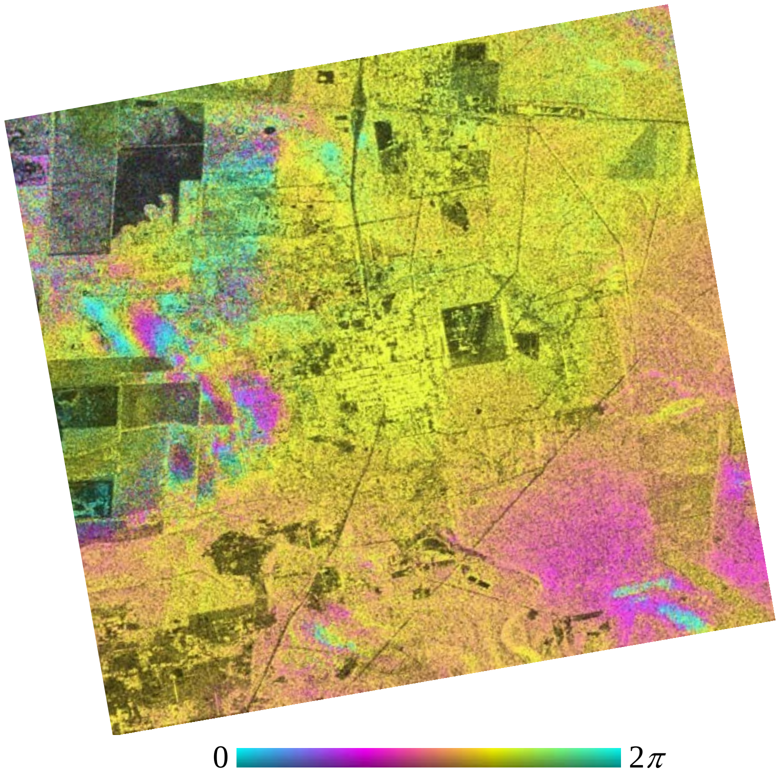

Figure 2. InSAR result spanning the period from December 10, 2007 to January 25, 2008.

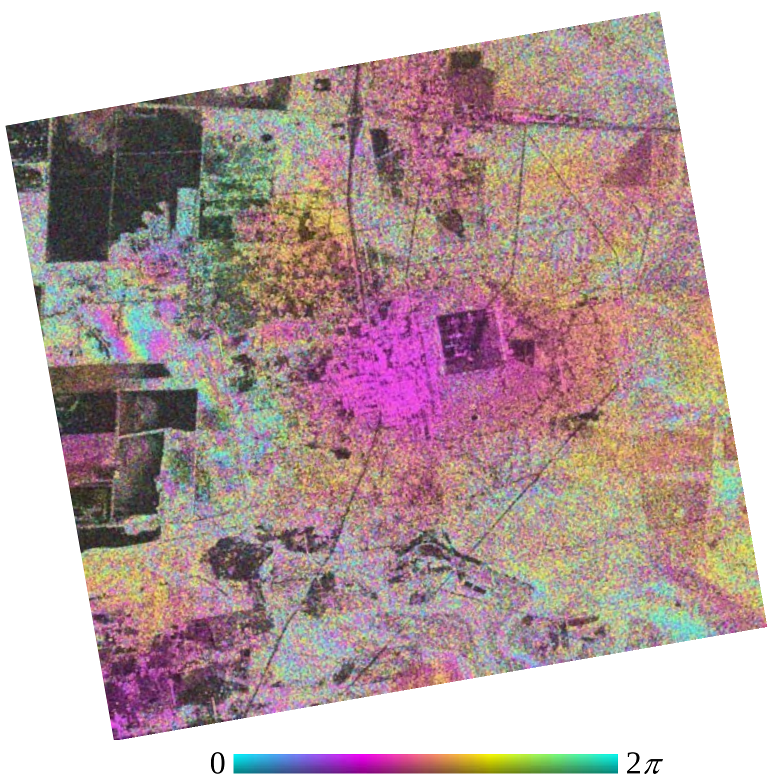

Figure 3. InSAR result spanning the period from January 25, 2008 to April 26, 2008.