Assessing Collapse Risk in Evaporite Sinkhole-prone Areas Using Microgravimetry and Radar Interferometry

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ABSTRACT

Geophysical and remote-sensing methods were applied to better understand sinkhole precursor movement and assess the potential for sinkhole development in evaporitic areas. The approach is illustrated with two examples over bedded salt deposits and a salt dome in Texas, USA. Large sinkholes (90 to 200 m in diameter) formed over Permian bedded salt near Wink in western Texas in June 1980 and May 2002, and on the flank of a coastal-plain salt dome in Daisetta in May 2008. Residents, government officials, and industry representatives wish to better understand the potential for sinkhole formation and growth in both areas. At Wink, limited spatial and temporal data on vertical ground movement from standard surveying has been greatly extended by satellite-based radar interferometry, which was used to delineate areas having recent movement and determine rates of movement. Results from interferometry guided site-specific investigations that included acquisition of high-resolution gravity data, which identified shallow-source mass deficits that indicate potential for continued subsidence or sinkhole formation. At Daisetta, interferometry was used to determine that no detectable subsidence preceded sinkhole collapse (indicating sudden collapse once the upward-migrating void reached a depth that allowed the cohesiveness of overlying semiconsolidated sediments to be overcome), and gravimetry was used to identify other areas where shallow mass deficits exist across the salt dome. Data from both areas can be used to construct risk maps, design comprehensive subsurface investigations, and develop monitoring programs based on repeat radar interferometry and geodetic GPS measurements.

Introduction

Sinkholes are a common geologic hazard in many parts of the world (*e.g.,* Beck, 1995; Johnson and Neal, 2003; Bell *et al.*, 2005). In Texas, sinkholes are associated with bedded Paleozoic salt beneath the High Plains of northern Texas and within the Permian basins of western Texas (Fig. 1(a); Fig. 2), limestone karst in central Texas, and shallow salt domes of eastern Texas and the Coastal Plain (Fig. 1(b)). The recent development of two large sinkholes over evaporitic deposits in or near communities has highlighted the need to determine the locations and likelihood of dissolution-induced subsidence or collapse in sinkhole-prone areas. Two noninvasive methods—interferometric synthetic aperture radar (InSAR) and microgravimetry—offer the complementary benefits of quantifying vertical ground movement that may precede sinkhole collapse (InSAR) and quantifying the extent and magnitude of shallow mass deficits that would indicate areas with the potential for sinkhole-related subsidence or collapse (microgravimetry). We employed both methods to a) examine ground movement and identify shallow mass deficits near sinkholes in west Texas bedded evaporite deposits and on the Texas Coastal Plain associated with a salt diapir (Fig. 2), and b) illustrate the potential of microgravimetry and radar interferometry to help assess risk of sinkhole development in evaporitic karst terrain.

Wink Sinkholes, Permian Basin

Two large sinkholes formed in June 1980 (Wink Sink 1) and May 2002 (Wink Sink 2) near the communities of Wink (Fig. 2) and Kermit in the Permian Basin of western Texas (Baumgardner *et al.*, 1982; Johnson, 1989; Collins, 2000; Johnson *et al.*, 2003). These sinkholes formed in the Hendrick Oil Field

(a)

(b)

Figure 1. a) Wink Sink 2 in 2008, six years after initial collapse. b) Daisetta sinkhole toward the north, seven days after collapse on May 7, 2008. Debris and crude oil are floating on water filling the sinkhole. The sinkholes are roughly circular with a diameter of about 200 m. Fissures are common around both sinkholes.

(discovered in 1926) at the western margin of the Central Basin Platform above the Permian Capitan Reef complex, which underlies nearly 300 m of Permian interbedded salt and anhydrite at depths of 400 to 670 m. Wink Sink 1, formed on June 3, 1980, measured 110-m across and 34-m deep at the time of collapse. On aerial photographs taken in 2004, it has an approximately circular outline that is 94- to 117-m across and is elongated to the northeast-southwest. The sinkhole encircles the Hendrick No. 10-A, a 780-m deep well that was drilled in 1928, produced oil from the Tansill and Yates formations below the salt section, and was abandoned in 1964 (Baumgardner *et al.*, 1982). Flow of fresh or unsaturated saline water from above or below

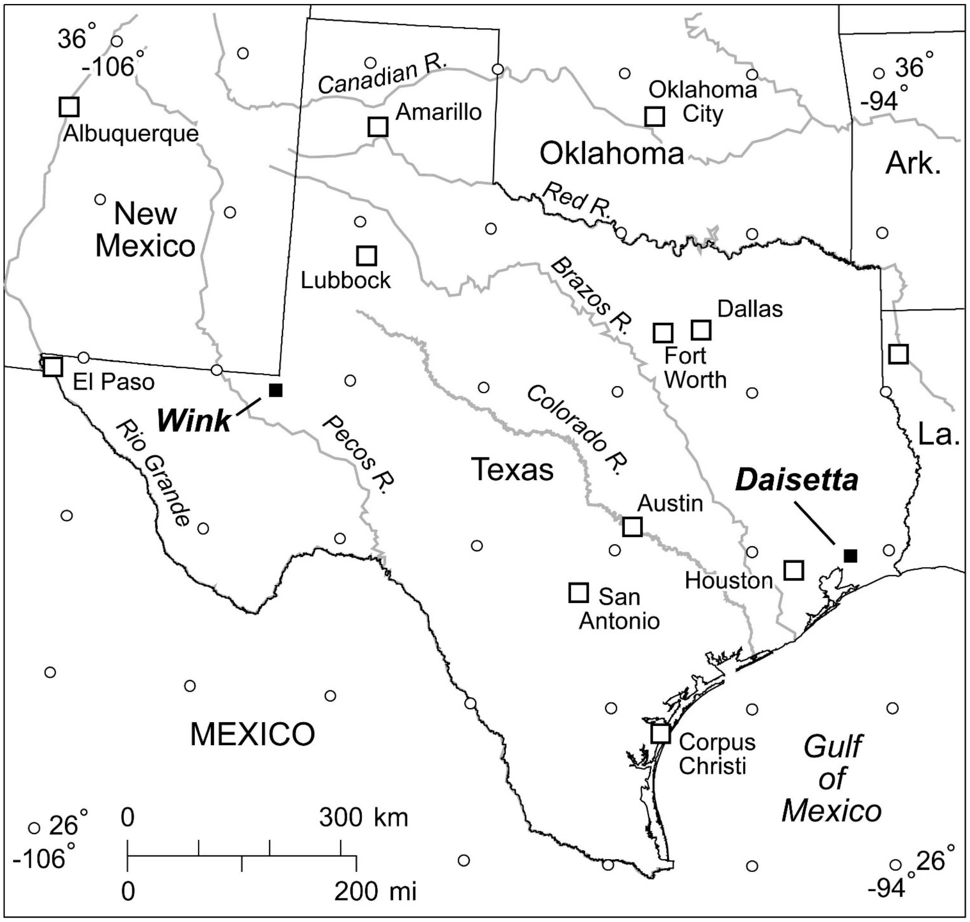

Figure 2. Map of Texas showing the Wink (above bedded salt in the Permian Basin, west Texas) and Daisetta (coastal plain salt diaper province) sinkhole areas.

the salt section, possibly through natural or induced fractures or the borehole itself, is the most likely cause of salt dissolution and collapse at Wink Sink 1 (Baumgardner *et al.*, 1982; Johnson *et al.*, 2003). Wink Sink 2 formed 1.6 km south of Wink Sink 1 on May 21, 2002. This sinkhole has expanded from its original surface width of 137 m to an oval shape with widths ranging from 185 to 250 m, also elongated in the northeast-southwest direction. Both Wink sinkholes have an elongation ratio of about 1.3. Wink Sink 2 encircles the Gulf WS-8, a water-supply well that was drilled through the salt section to 1,092 m in 1960 and is estimated to have yielded 800 million bbl of water for waterflood operations in the Hendrick Field (Johnson *et al.*, 2003). The cause of collapse at Wink Sink 2 has not been determined, but is thought to be related to the WS-8 well (Johnson *et al.*, 2003).

Daisetta Sinkhole, Texas Coastal Plain

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 beneath the city of Daisetta (Figs. 1(b) and 2) drew national media attention in the United States. Daisetta is situated on high ground less than 300 m above the top of the Hull salt dome, a structure that pierces semiconsolidated Tertiary sediments on the Texas coastal plain (Halbouty, 1967; Traylor, 2009). The sinkhole encircles several oil and gas well locations and is located adjacent to a licensed disposal well, any of which could provide conduits or mechanisms for removal of subsurface salt or sediments that led to collapse of overlying strata during sinkhole formation. The impact of the sinkhole on the community was exacerbated by its location adjacent to the main highway through Daisetta and 0.5 km or less from residences, businesses, and a public school. During sinkhole collapse, salt water flowed from three oil and gas wells around the perimeter of the Hull dome, heightening concern that additional sinkholes could form in the area.

At Daisetta and Wink, as in similar settings worldwide, the issues that concern residents, government officials, and industry representatives are the same: how did the sinkholes form, will they continue to expand, and where might new sinkholes form that would threaten public safety and infrastructure? While the specific cause of each sinkhole may never be known with certainty, remote sensing and geophysical methods such as InSAR and microgravimetry can help understand critical issues such as the existence and location of precursor ground deformation, current subsidence rates over large areas, and the location of shallow mass deficits that indicate the potential for future gradual subsidence or collapse.

Methods

We acquired gravity data to examine subsurface density variations at Wink and Daisetta in May and June 2008 using a Scintrex CG-5 relative gravimeter with a fused-quartz sensor capable of 1 microgal (μgal) reading resolution and less than 10 μgal standard deviation (Scintrex Limited, 2006). A gravity base station was selected at each site and was occupied before, during, and after gravity data were acquired for each line. Elapsed time between base-station reoccupations was typically two hours or less. Latitude, longitude, and elevation data, which are necessary to accurately correct the gravity data (Telford *et al.*, 1990; Butler, 1991; Society of Exploration Geophysicists of Japan, 2004), 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 and 1-second sample interval were acquired. Select gravity stations were reoccupied multiple times to establish measurement repeatability. 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 differential GPS-derived elevation data with the raw gravity measurements, removing instrument and tidal drift determined from base-station reoccupations, 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 for the gravitational effect of off-line topography. In these low-relief areas, we expect that off-line terrain effects have a negligible influence on the gravity measurements except on lines immediately adjacent to the sinkholes where effects of sinkhole mass deficits are present. This influence is used at Daisetta to estimate sinkhole depth.

Satellite-based interferometric synthetic aperture radar (InSAR) measures centimeter-scale surface motion toward or away from the radar instrument at approximately 100 m pixel postings over 100-km × 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. At Daisetta, we processed three Advanced Land Observation Satellite (ALOS, launched by the Japanese Space Agency in January 2006) PALSAR (polarimetric L-band) radar interferograms collectively spanning the time period from December 2006 to April 2008, the month preceding sinkhole collapse. At Wink, interferograms were used to determine net movement during the six months from January to July 2007.

Wink Sinkholes: Interferometry and Gravimetry over Bedded Salt

At Wink, we used InSAR to detect recent vertical movement over a large area surrounding the 1980 and 2002 sinkholes. InSAR results were used to focus more intensive field, geophysical, and subsurface investigations on areas that show evidence of recent subsidence. An initial radar interferogram of the Wink area, constructed from satellite-based radar data acquired on January 1 and July 4, 2007, depicts the net change in surface elevation between those two dates. Most of the larger region surrounding the communities of Wink and Kermit shows no evidence of significant uplift or subsidence, but three notable areas of subsidence are evident on an enlarged part of the interferogram in the vicinity of Wink Sinks 1 and 2 (Fig. 3(a)). Subsidence areas and rates (as great as 30 cm/yr) generally match those determined from previous leveling surveys conducted by industry representatives, from a 1999 reconnaissance survey before the collapse of Wink Sink 2 (Collins, 2000; Johnson *et al.*, 2003), and by comparing elevations determined photogrammetrically from 1968 aerial photographs and from the 2000 Shuttle Radar Topographic Mission (SRTM). In subsidence area 1, a circular area about 300-m across surrounding Wink Sink 1, total subsidence was 10 cm or less between January and July 2007. Subsidence area 2 is about 400-m across and is centered about 480 m north-northeast of Wink Sink 2. Maximum subsidence was about 10 cm between January and July 2007. Subsidence area 3 is about 850-m across and is centered about 1 km east-northeast of Wink Sink 2. Maximum subsidence was about 15 cm between January and July 2007.

Guided by InSAR topographic-change results, we acquired gravity measurements at 150 locations along five profile lines near Wink Sink 1, Wink Sink 2, and the large subsiding area east of Wink Sink 2 (Fig. 3(b)). Gravity station spacing was 20 m along each of the

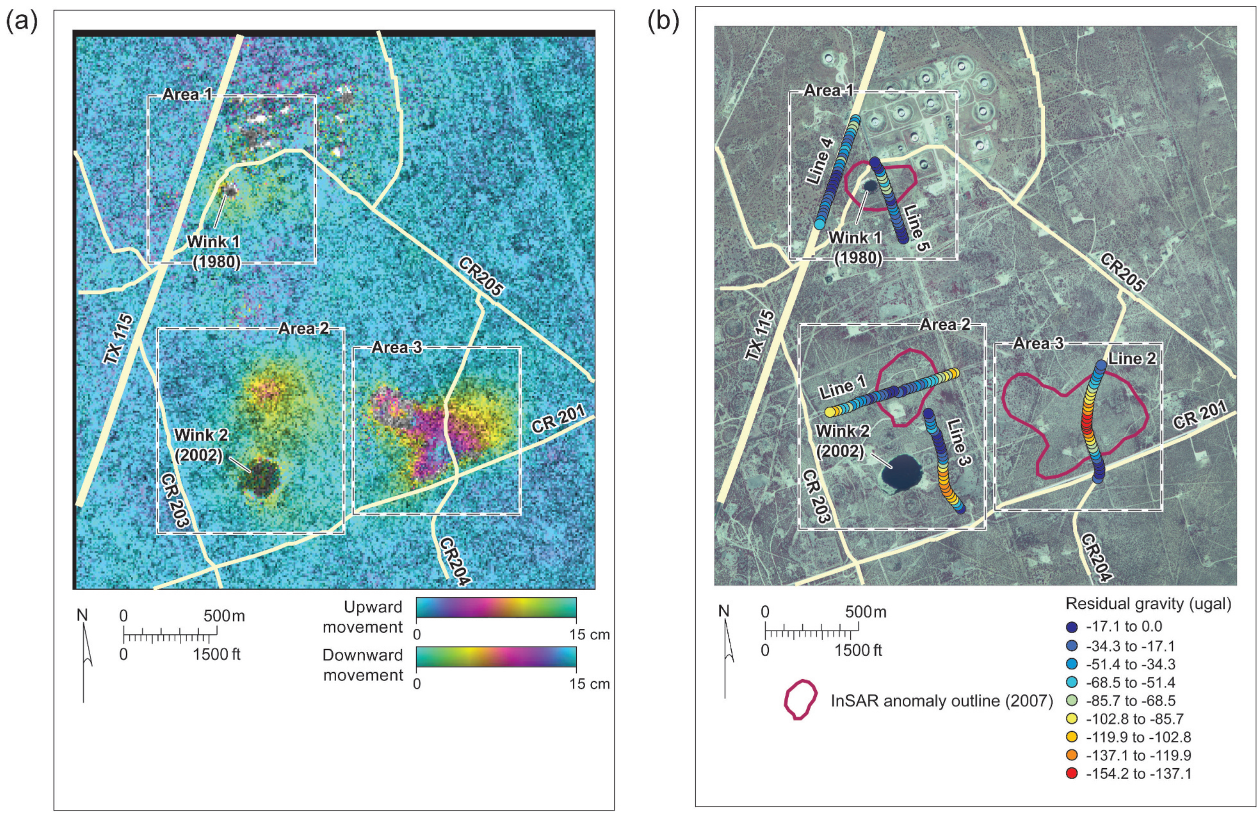

Figure 3. a) InSAR interferogram for the Wink sinkhole area depicting ground movement toward or away from the satellite between January 1 and July 4, 2007. Significant areas of subsidence include area 1 around Wink Sink 1, area 2 north-northeast of Wink Sink 2, and area 3 east-northeast of Wink Sink 2. b) Residual gravity anomalies following removal of the regional gravity trend superimposed on a 2004 aerial photograph. Negative anomalies indicate shallow-source density deficits.

lines. These data, after correction for drift, location, and along-line elevation, show that gravity values generally decrease from east to west across the area over a total range of about 2.4 milligals (mgal). These trends match those shown on regional maps and in detailed (but lower sensitivity) gravity surveys acquired in the area after collapse of Wink Sink 1 in 1980 (Baumgardner *et al.*, 1982). The regional gradient is large enough to mask local effects in the area around the Wink sinkholes. When regional trends are removed, the gravity residuals (Fig. 3(b)) allow identification of local gravity lows caused by shallow-source mass deficits.

Prominent residual gravity lows were identified on line 3 near Wink Sink 2 and line 2 within the large subsiding area east of Wink 2 (Figs. 3(b) and 4). The larger of these gravity lows, which reaches about 160 µgal on line 2, is located on the northern flank of a topographic low along a road (Fig. 4(b) and 5(b)). Field inspections in June and November 2008 revealed numerous concentric fissures and compression features crossing fields and roads with apertures ranging from less than 1 cm to more than 50 cm. The fissures mapped in subsidence area 3 are found along the southern perimeter of the 2007 InSAR anomaly (Fig. 4) and damaged a recently paved road, indicating active deformation. Interpreted mass deficits in the shallow subsurface beneath County Road 204 suggest that there is potential for significant further subsidence or collapse. No gravity data have been acquired along County Road 201 on the southern edge of the InSAR anomaly, but fissures and new road cracks confirm that subsidence continues. We do not know whether mass deficits exist beneath this road that would suggest the possibility of further subsidence or possible collapse.

Line 1, which crosses a subsiding area between Wink Sinks 1 and 2 identified in the 2007 InSAR data, shows neither a prominent residual gravity low nor a large topographic depression (Figs. 3(a) and 5(a)). These results indicate the lack of a significant shallow mass deficit in the subsiding area, which suggests that any subsurface dissolution is accompanied by subsidence of overlying strata that has filled subsurface voids. Subsidence may continue, but there appears to be little evidence for sudden sinkhole development in the near future.

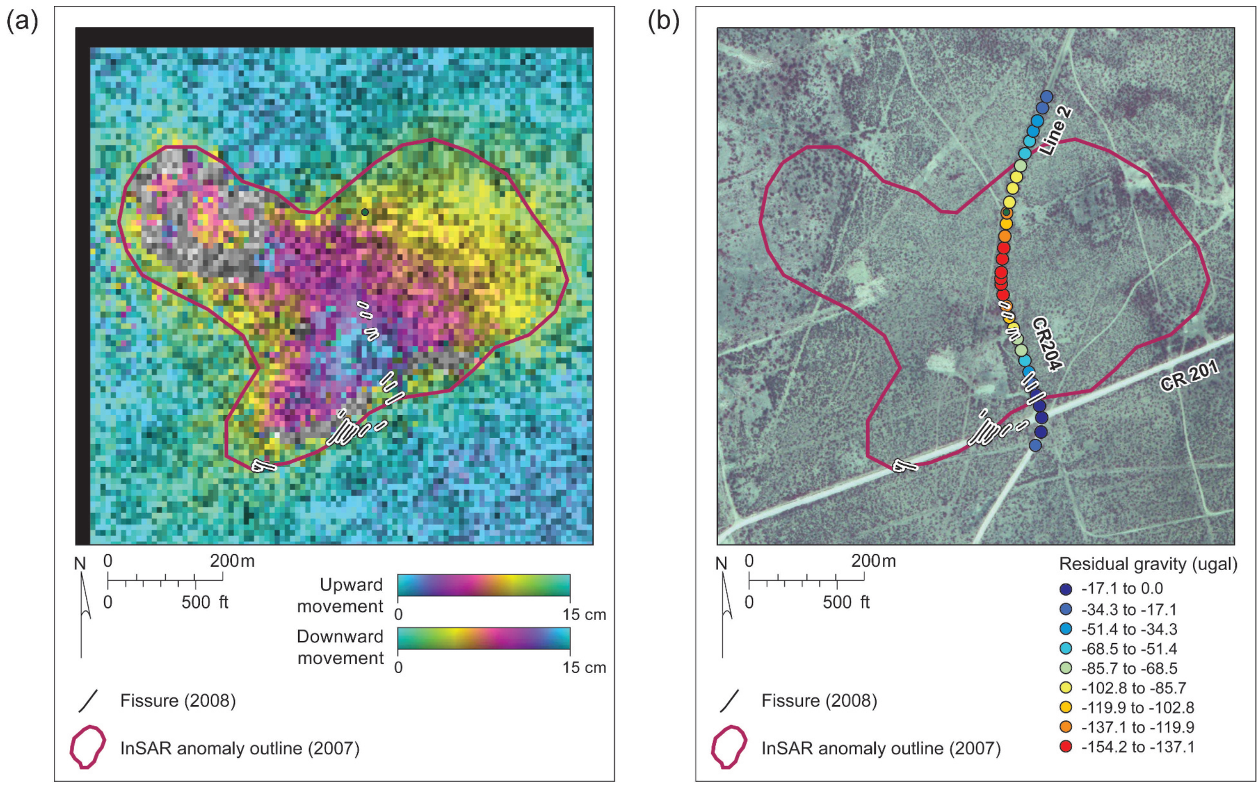

Figure 4. a) InSAR interferogram (January 1 to July 4, 2007) east of Wink Sink 2 (area 3, Fig. 3). b) Residual gravity values along line 2. Also shown are fissures mapped along roads in June and November 2008.

The relatively large residual gravity anomaly detected on line 3 along a private road east of Wink 2 reaches about 140 µgal and is not associated with a 2007 InSAR anomaly or a prominent topographic low (Figs. 3(b) and 5(c)). We interpret this local gravity low to be caused by a shallow mass deficit that could lead to future subsidence or sinkhole development near Wink Sink 2.

Near Wink Sink 1, 2007 InSAR data indicate relatively minor subsidence. Line 4, located along a highway outside of the subsiding area, shows relatively small differences in elevation and residual gravity values that do not suggest the presence of significant shallow mass deficits beneath the highway (Fig. 5(d)). Line 5, located adjacent to Wink Sink 1, crosses a 2007 InSAR anomaly and reveals a relatively minor local gravity low on the northern flank of the topographic low about 30 m east of the sinkhole (Figs. 3(b) and 5(e)). The lowest residual gravity values are located 280 to 380 m along the line, which coincides with the nearest approach to the sinkhole, suggesting that this part of the residual gravity anomaly is influenced by proximity to Wink Sink 1 and the lack of correction for off-line terrain effects. The residual gravity low of 50 µgal or less that is evident southward from the sinkhole boundary may indicate that shallow mass deficits do exist beneath the southern flank of the topographic low. Further subsidence and sinkhole expansion is possible in this area.

Daisetta: Gravimetry and Interferometry in a Salt-Dome Province

As a rapid-response effort to address a sudden geologic event affecting public safety, we conducted InSAR analysis on pre-collapse data and a reconnaissance gravity survey three weeks after the May 7, 2008 formation of a large (200-m diameter) sinkhole above the northwest flank of a salt dome in the community of Daisetta, Texas (Figs. 1(b), 2, and 6). InSAR analysis covering the 16 months before collapse (December 2006 to April 2008), conducted using data acquired by the Japanese ALOS system since its launch in January 2006, detected no subsidence at or near the sinkhole before collapse.

The purpose of the gravity survey was to examine evidence for local reductions in strength of the gravity field caused by possible shallow subsurface mass deficits near the sinkhole and along major roads. We acquired gravity data at 243 locations along six lines in and around Daisetta (Fig. 6). During sinkhole collapse, salt water flowed to the surface through three wells located across the crest of the dome, leading to concern about the possible presence of

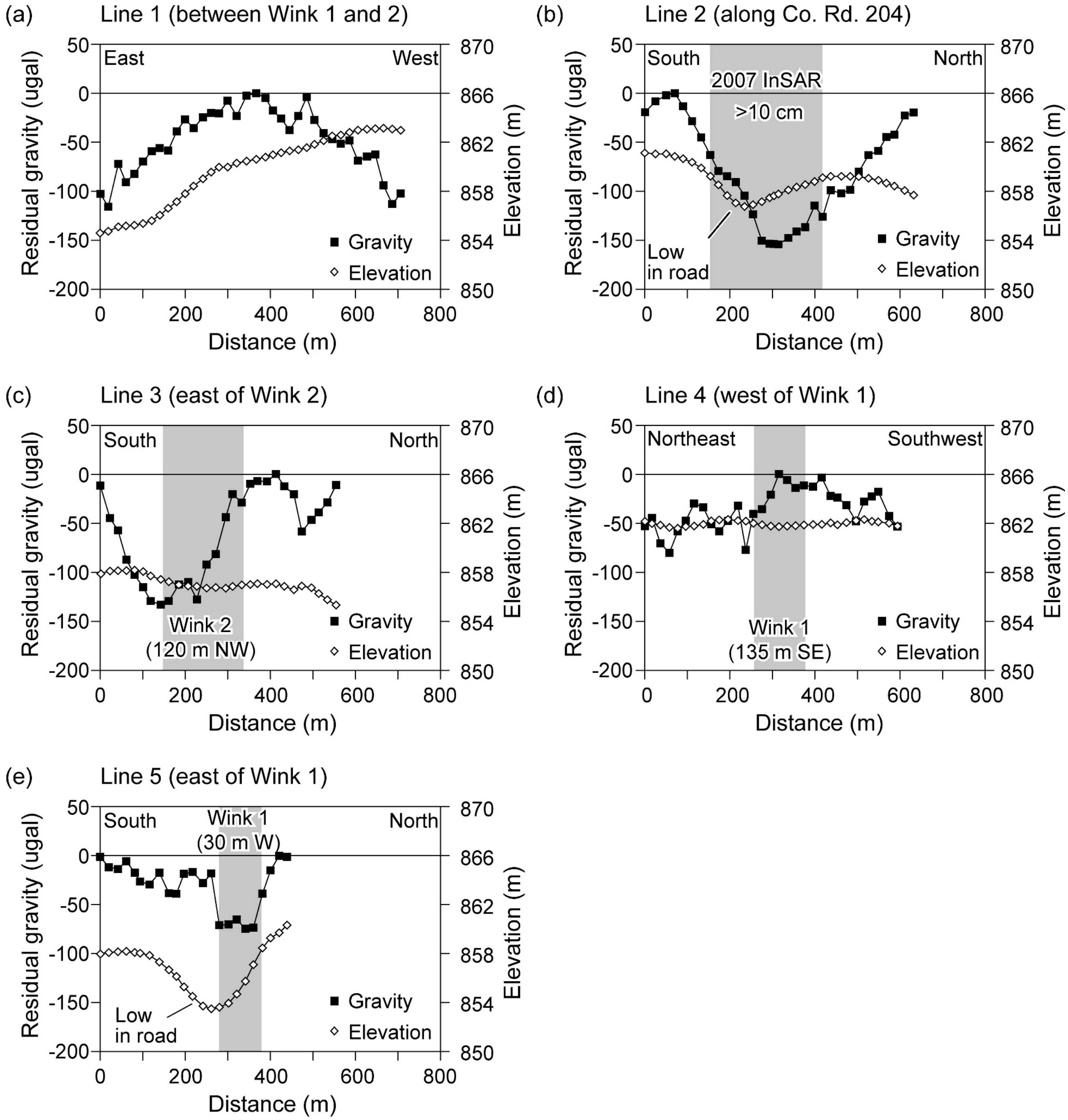

Figure 5. Elevation (white diamonds) and residual gravity (black squares) calculated from 2008 Wink gravity data (line locations shown on Fig. 3(b)). a) Line 1 along an east-west line between Wink Sinks 1 and 2; b) line 2 across a topographic depression along a county road; c) line 3 along a road east of Wink Sink 2; d) line 4 along a highway west of Wink Sink 1; and e) line 5 along a road east of Wink Sink 1. Shaded areas represent position of sinkhole boundaries at the nearest approach to the lines (lines 3, 4, and 5) or extent of InSAR-measured subsidence greater than 10 cm (line 2).

dissolution conduits beneath the city. The longer gravity lines (1 and 2, acquired at 40-m spacing) were intended to intersect possible significant shallow mass deficits between the sinkhole and the salt-water flow sites across the dome. Gravity station spacing was 10 m along lines near the sinkhole (lines 3 through 6, Fig. 6).

Drift-, tide-, latitude-, and elevation-corrected gravity measurements reveal at least three areas with relatively low gravity values (Figs. 6 and 7) along lines 1 through 6. A relative low reaching about 100 μgal extends about 600 m along line 1 (the north-south line across Daisetta; Figs. 6 and 7(a)). A low reaching

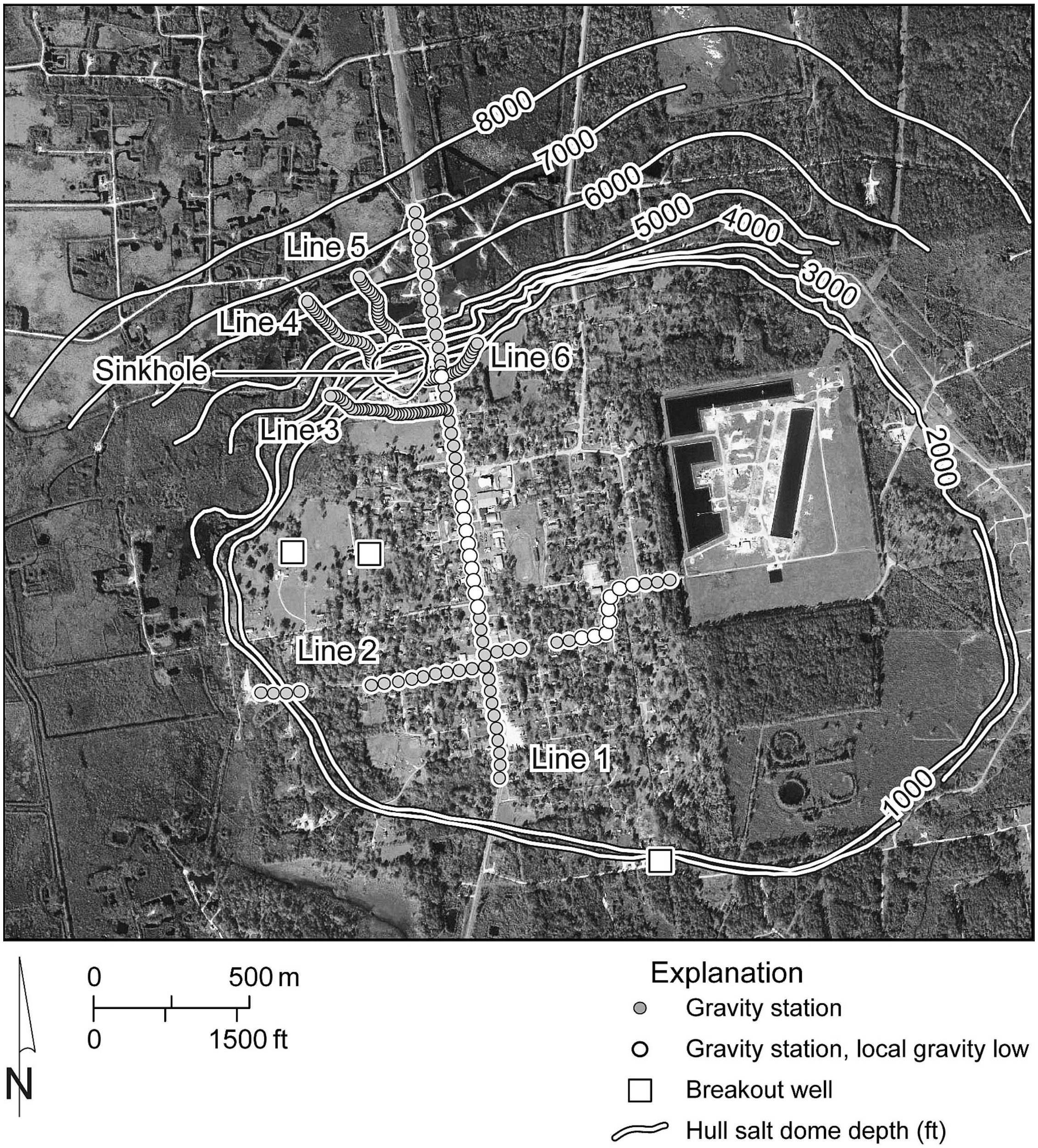

Figure 6. Location of the May 7, 2008 sinkhole in Daisetta superimposed on 2004 aerial photograph, gravity measurement locations on lines 1, 2, 3, 4, 5, and 6, contoured depth to the top of the Hull salt dome, and locations of wells that flowed salt water during sinkhole collapse. White-filled circles denote locations of relatively low residual gravity values.

120 μgal extends more than 300 m along line 2 (the east-west line across Daisetta; Figs. 6 and 7(b)). Near the sinkhole, notable are a) the lack of significant gravity reductions west-northwest (line 4, Figs. 6 and 7(d)) and south-southwest of the sinkhole (line 3, Figs. 6 and 7(c)) despite the presence of a local topographic low, and b) a relative gravity reduction extending about 50 m east of the sinkhole across the main road through town (line 6, Figs. 6 and 7(f)).

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

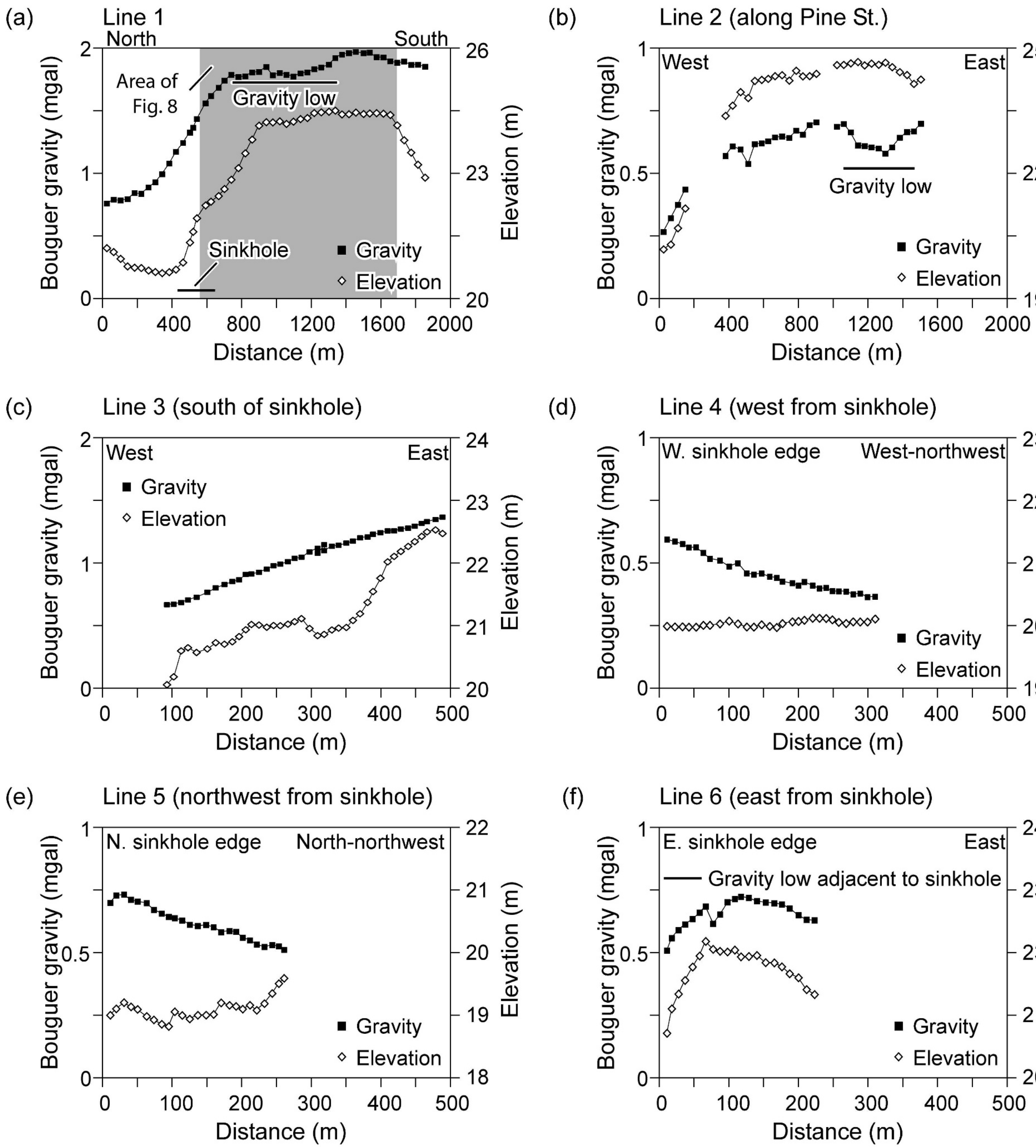

Figure 7. Elevation (white diamonds) and relative gravity (black squares) calculated from 2008 Daisetta gravity data (Figure 6). a) Line 1 in a north-south orientation across Daisetta; b) line 2 in an east-west orientation across Daisetta; c) line 3 in an east-west orientation south of the sinkhole; and lines extending d) westward, e) north-westward, and f) eastward from the edge of the sinkhole. Detail of the relative gravity low in the shaded portion of line 1 (a) is shown on Fig. 8.

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 data from several boreholes across the crest of the dome. The lows are 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.

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 depth, thickness, and lateral extent of subsurface mass deficits that could cause the lows. We employed three-dimensional discrete element 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 densities of 1.1 g/cm^3 to represent possible saline water-filled voids at and above the salt contact, 2.2 g/cm^3 to represent saturated, semiconsolidated Tertiary and Quaternary sediments above the dome, 2.2 g/cm^3 to represent the Hull salt dome, and 2.9 g/cm^3 to represent anhydrite cap material reported in exploratory borings.

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 saltwater-flowing wells on the south and west sides of the dome (Fig. 6). Salt is highly soluble in fresh water; thus, the principal concern was potential water-filled cavities at the top of the dome. The models considered the gravity effects of water-filled voids in salt as well as the density contrast between possible anhydrite caprock and semiconsolidated sediments to help constrain the size of subsurface features required to match the extent and magnitude of the observed local gravity anomalies.

Water-filled Voids at the Top of Salt

Because borehole data showed the top of salt at a depth of about 200 m, 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. Residual gravity values for the line 1 anomaly, calculated by establishing a linear regional trend and subtracting gravity values at each station from the regional trend, reach about 100 μgal over a distance of about 600 m (Figs. 7(a) and 8). Although the general shape and magnitude of the residual anomaly is clear, the residuals show significant station-to-station variation that are likely to be caused by corrections associated with small elevation errors related to degraded GPS signals where trees partly obstruct the view of the sky. 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 (Fig. 8(a)). This can be interpreted to imply that if a water-filled void the width of the sinkhole at the top of the salt dome was 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 narrower residual gravity anomaly on line 2, which reaches as much as 120 μgal along a 360-m long segment, could be correspondingly shallower and smaller in width and thickness than the deficit beneath line 1.

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 caprock atop the dome 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 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 (Fig. 8(b)). 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 thick cylindrical body having the density of anhydrite with one of typical sediment density. This possible magnitude of caprock thickness change appears reasonable, given reported caprock thicknesses of 100 m or more. Local variations in caprock thickness could create mass deficits large enough to account for the gravity lows observed on lines 1 and 2.

Sinkhole Depth Estimates

Estimates of sinkhole depth are important because they can be used to calculate the displacement volume during collapse and help bound mass-deficit estimates for gravity modeling. Gravity measurements adjacent to sinkholes can be used to estimate sinkhole depth when hazardous conditions might preclude physical depth measurements. Direct depth estimates for the Daisetta sinkhole varied from initial values of about 76 m (Kasmarek, 2009) made just after collapse to about 21 to 24 m after partial filling from slumping (Howe and Norman, 2009; Corrigan Consulting, 2009). Gravity data acquired on May 29, 2008 on line 6 adjacent to the sinkhole (Figs. 6 and 7(f)), after all corrections, show residual gravity values that decrease over multiple stations toward the sinkhole. This reduction can be

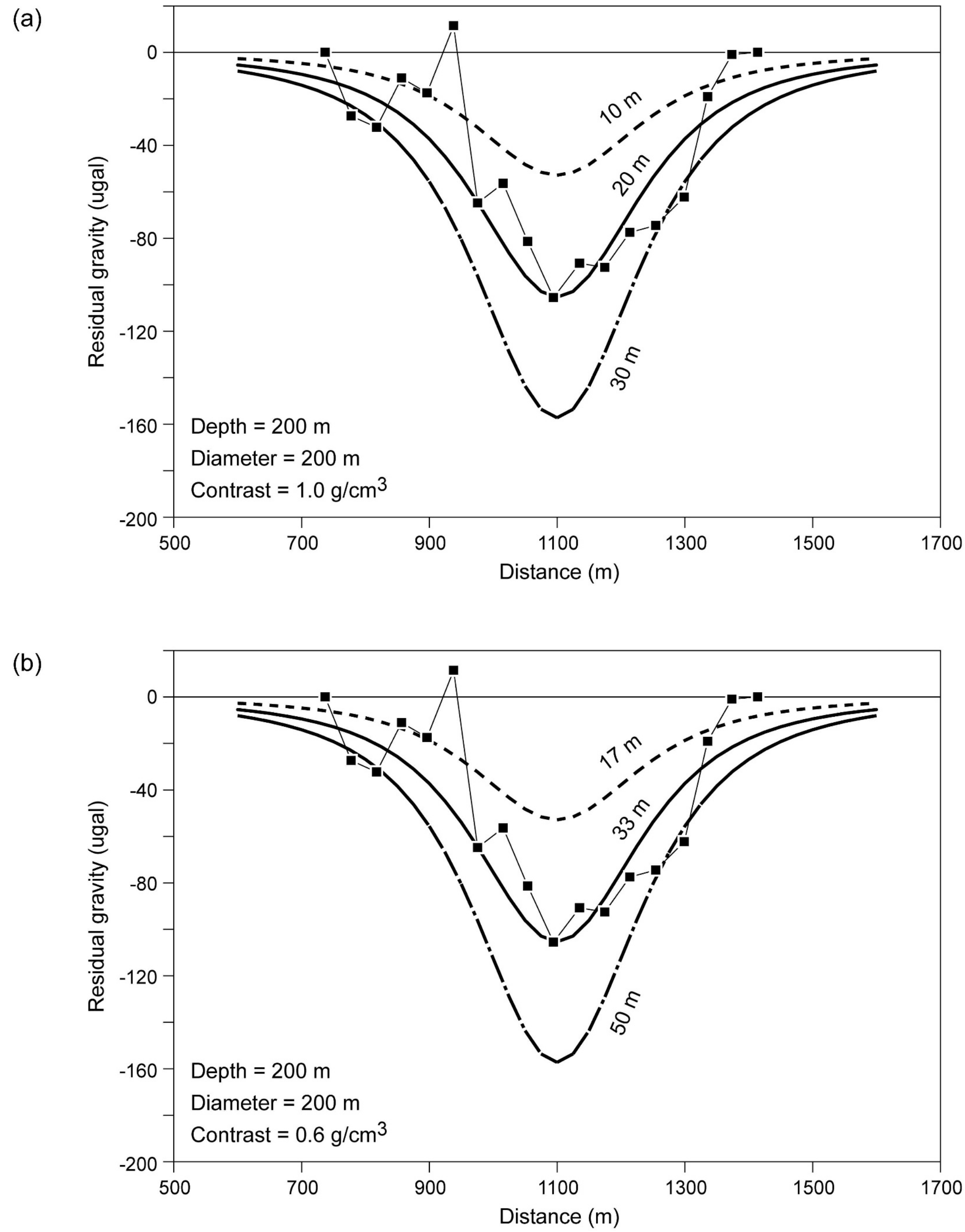

Figure 8. Residual gravity (black squares) along Daisetta line 1 compared to modeled response from 200-m diameter cylinders at a depth of 200 m. a) Response from water-filled cylinders 10-, 20-, and 30-m tall with a density contrast of 1.0 g/cm^3, approximately the difference between bulk densities of saline water and semiconsolidated sandy sediments. b) Response from cylinders 17-, 33-, and 50-m tall with a density contrast of 0.6 g/cm^3, approximately the difference between semiconsolidated sandy sediments and anhydrite.

attributed to the missing mass represented by the sinkhole, and can be used to estimate sinkhole depth at the time of the survey by modeling the sinkhole as a water-filled cylinder with a radius of 60 m at the water level on the survey date (Fig. 9, left). The volume of the sinkhole above water could be modeled as an air-filled cylinder, but its influence on the results are negligible because a) the sinkhole was nearly filled with water at the time of the survey, and b) outside the sinkhole, the sinkhole surface layer is nearly 90 degrees from the gravity vector and thus contributes little to the measured gravity values.

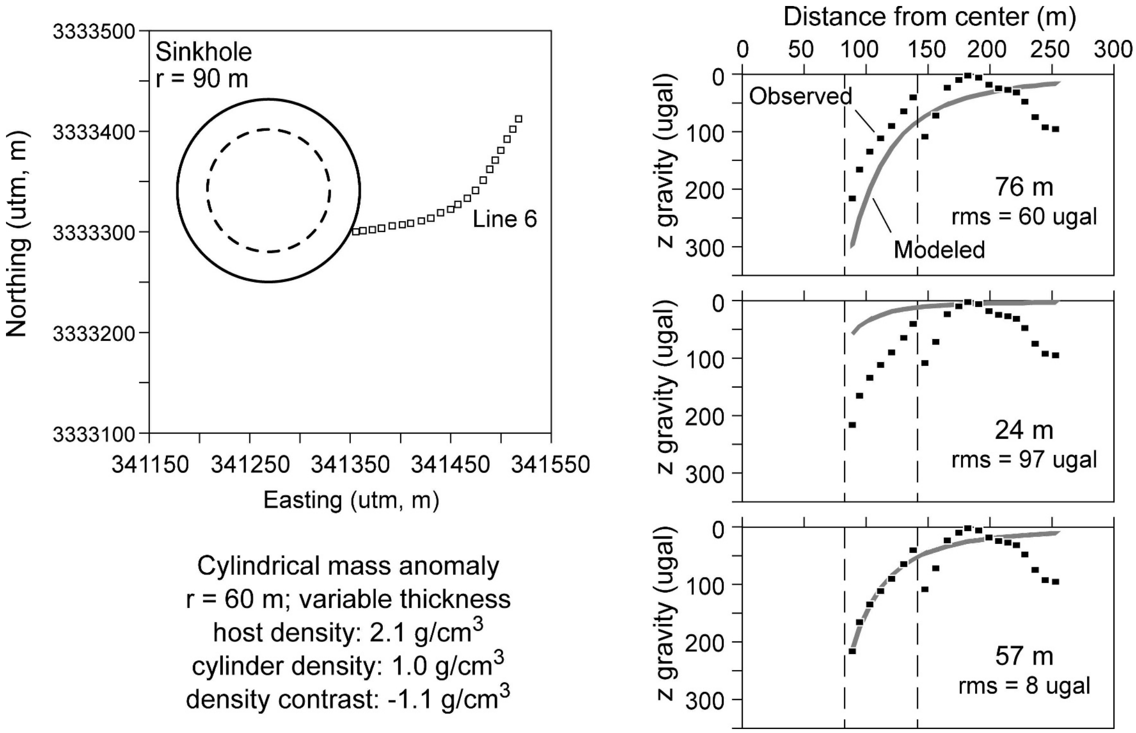

Figure 9. Gravity response for density models along line 6 adjacent to the Daisetta sinkhole (Figs. 6 and 7(f)). (left) Schematic map of the Daisetta sinkhole outline (solid line represents upper surface of sinkhole; dashed line represents vertical water-filled cylinder) showing measurement locations along line 6. (right) Observed gravity strength (boxes) along line 6 with superimposed predicted gravitational strength at estimated initial sinkhole depths of 76 m (Kasmarek, 2009), later partly-filled depths of 24 m (Howe and Norman, 2009), and a best fit of 57 m at the time of the gravity survey. Dashed lines at right represent extent of anomalous gravity residuals attributed to the sinkhole mass deficit and the stations used to calculate rms error.

The initial sinkhole depth estimate of 76 m, representing conditions immediately following collapse and before partial filling from slumping, produces a gravity anomaly that has a similar shape but is significantly larger than the anomaly we measured at the seven stations closest to the sinkhole on May 29, three weeks after collapse (Fig. 9, upper right). Root-mean-square (RMS) error between the observed and modeled data for those seven stations is 60 µgal. Direct depth measurements made after partial filling are represented by the modeled sinkhole depth of 24 m, which produces 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) for the May 29 gravity data was obtained using a water-filled sinkhole depth estimate of 57 m, shallower than initial, pre-slumping estimates and deeper than more recent measurements taken after some slumping and filling has occurred. The depth estimate from gravity data should be viewed as a maximum depth because the model does not include 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.

Conclusions

Radar interferometry (InSAR) and microgravity surveys provide useful information on recent and current land-surface deformation and the presence of shallow-source mass deficits near large sinkholes over bedded Permian evaporites in western Texas and a salt dome in southeastern Texas. InSAR analysis can be used to screen large areas for anomalous vertical movement and guide more intensive field investigations to areas where significant change is occurring. Satellite-based InSAR, owing to frequent ongoing acquisition of data, provides a ready method for monitoring future movement in sinkhole-prone areas.

Near the Wink sinkholes, which formed over bedded salt in the Permian Basin of west Texas, analysis of 2007 InSAR data revealed three areas undergoing subsidence at rates as high as 30 cm/yr. Subsequent gravity measurements identified three areas with shallow-source mass deficits in the sinkhole-prone area that are likely sites of ongoing subsidence, sinkhole expansion, or new sinkhole development.

At the Daisetta sinkhole, formed on the flank of a salt dome on the Texas Coastal Plain, InSAR analysis revealed no detectable ground deformation before collapse, possibly because of sudden failure once the void space shallowed sufficiently to allow gravity to overcome the limited cohesive strength and frictional forces keeping the overlying semiconsolidated sediments in place. Gravity data reveal anomalously low gravity values east of the sinkhole, suggesting possible minor expansion. Modeling indicates that much of the gravity reduction near the sinkhole could be caused by mass deficits within the sinkhole, allowing sinkhole depth to be estimated. Gravity data also show two areas of shallow mass deficit that are most likely caused by long-standing geological features related to salt-dome evolution rather than voids caused by recent dissolution. At both Wink and Daisetta, InSAR and gravity data can guide more comprehensive surface and subsurface investigations and monitoring activities. Both techniques would be useful as risk assessment tools in sinkhole-prone areas worldwide.

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