

## ASSESSING SINKHOLE POTENTIAL AT WINK AND DAISSETTA, TEXAS USING GRAVIMETRY AND RADAR INTERFEROMETRY

*Jeffrey G. Paine, Bureau of Economic Geology, The University of Texas at Austin*

*Sean Buckley, Center for Space Research, The University of Texas at Austin*

*Edward W. Collins, Bureau of Economic Geology, The University of Texas at Austin*

*Clark R. Wilson, Department of Geological Sciences, The University of Texas at Austin*

*Wade Kress, Texas Water Science Center, U.S. Geological Survey*

### Abstract

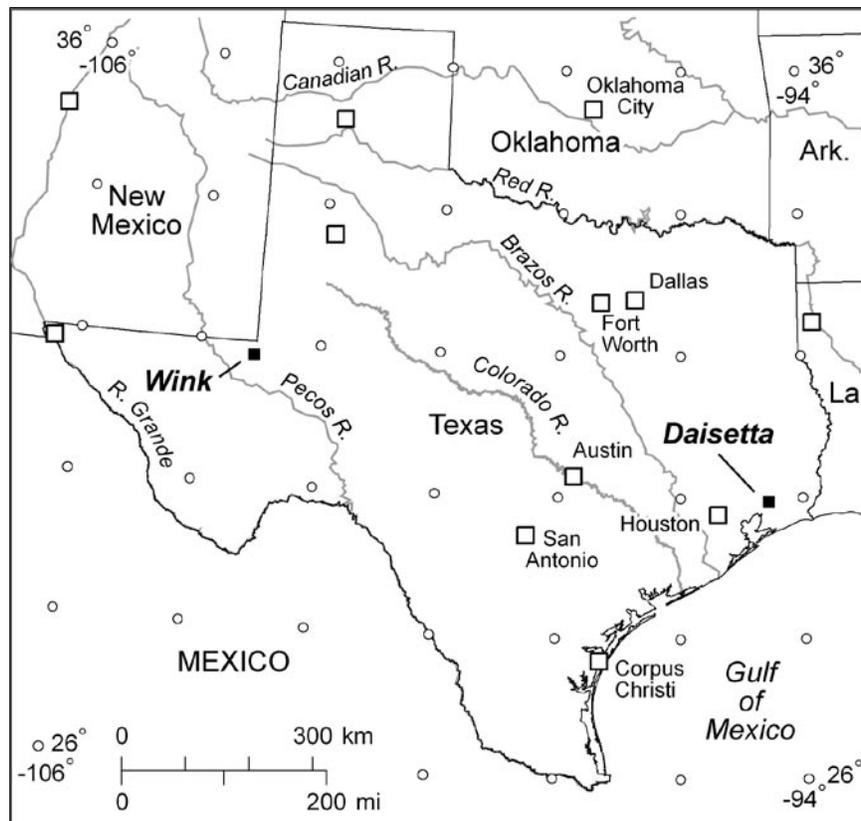
Large sinkholes (50 to 200 m in diameter) formed over Permian bedded salt near Wink in western Texas in June 1980 and May 2002 and on the flank of a salt dome at Daisetta, Texas in May 2008. Residents, government officials, and industry representatives would like to better understand the potential for sinkhole formation and growth. We are applying several geophysical methods to better understand sinkhole precursors and assess the potential for future sinkhole development. At Wink, limited data on vertical ground movement from standard surveying has been greatly extended by satellite-based radar interferometry, which we are using to delineate areas having recent movement and determine rates of movement. Results from interferometry are guiding acquisition of high-resolution gravity data, which has identified shallow-source mass deficits that indicate potential for continued subsidence or sinkhole formation. At Daisetta, we are using interferometry to determine whether vertical movement preceded sinkhole collapse and gravimetry to identify areas where shallow mass deficits exist across the salt dome. These initial data are helping to design a more comprehensive subsurface investigation and develop a monitoring program based on radar interferometry and geodetic GPS measurements.

### 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 (Figure 1, right; Figure 2), limestone karst in central Texas, and bedded Paleozoic salt beneath the High Plains of northern Texas and within the Permian basins of western Texas (Figure 1, left). Over several hours on May 7, 2008, formation of a large



**Figure 1:** (left) View of Wink Sink 2 in 2008, six years after initial collapse. (right) View of the 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 the perimeter of both sinkholes.



**Figure 2:** Map of Texas showing the Wink and Daisetta sinkhole areas.

sinkhole (about 200-m diameter) on the northwest flank of the Hull salt dome underlying the city of Daisetta drew local and national media attention. Two similarly sized sinkholes formed in June 1980 (Wink 1) and May 2002 (Wink 2) in an oilfield over Permian salt beds near the communities of Wink and Kermit in western Texas (Baumgardner and others, 1982; Johnson, 1989; Collins, 2000; Johnson and others, 2003). At Daisetta and Wink, the issues of concern to 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, remote sensing and geophysical methods such as radar interferometry, gravity, and electrical methods can help understand critical issues such as the existence 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.

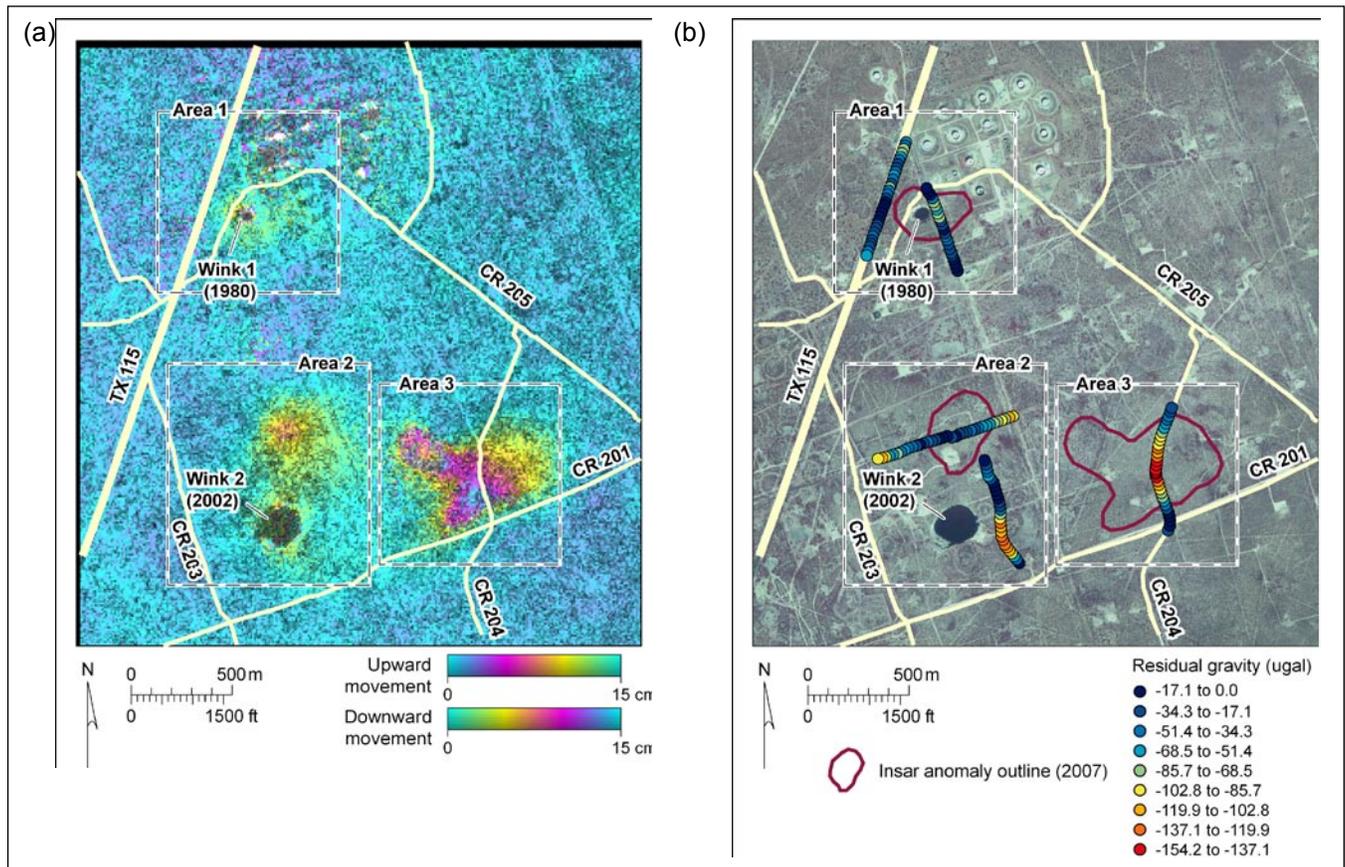
## Methods

We acquired gravity data 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 ( $\mu\text{gal}$ ) reading resolution and less than 10  $\mu\text{gal}$  repeatability. A gravity base station was selected at each site 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. Latitude, longitude, and elevation data, which is 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. 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 areas. The only area where local topographic effects might influence the gravity measurements significantly is adjacent to the sinkholes.

### Wink Interferometry and Gravity

At Wink, we used satellite-based radar interferometry (InSAR) to detect recent vertical movement over a large area surrounding the sinkholes. InSAR results are being 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 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 (Figure 3a). 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 reconnais-

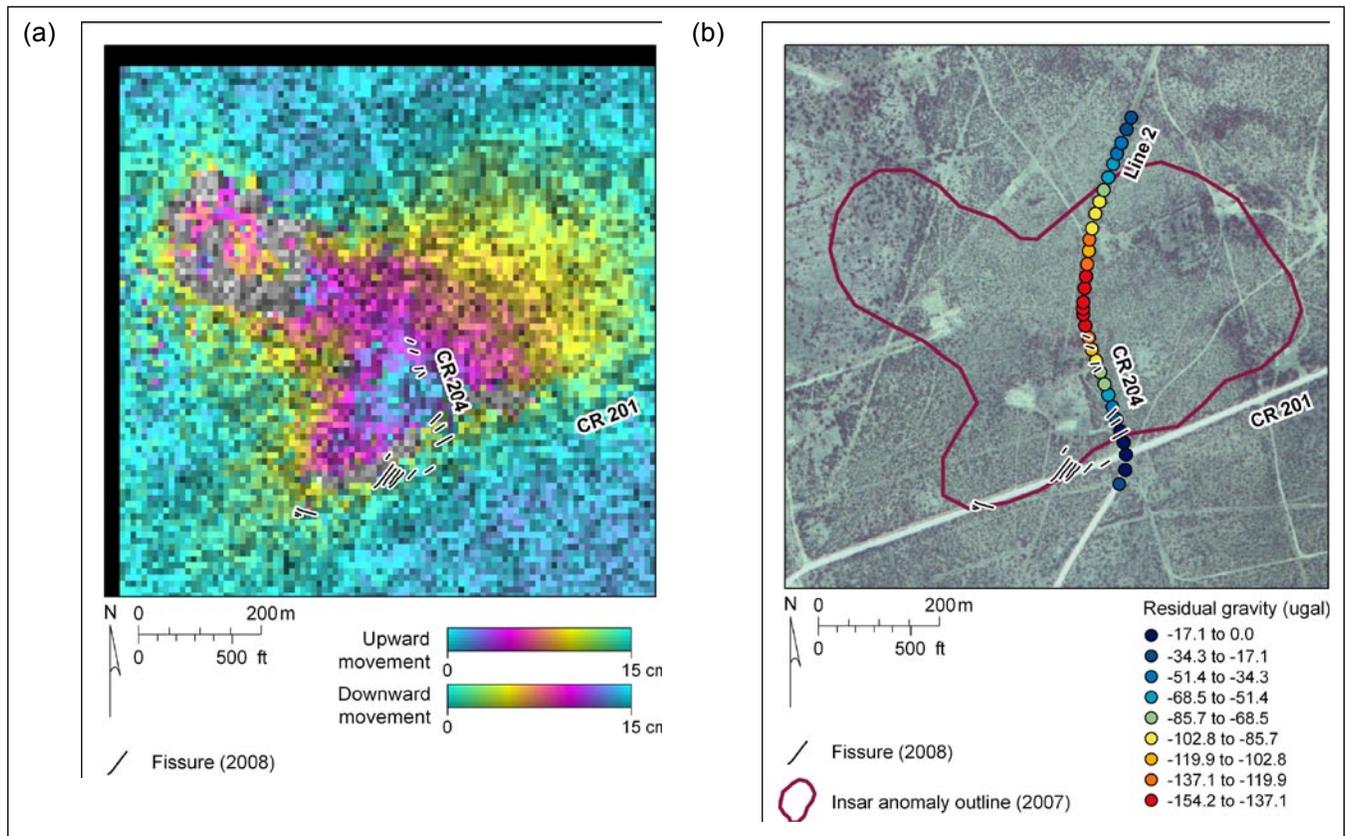


**Figure 3:** (a) InSAR interferogram for the Wink sinkhole area depicting vertical movement between January 1 and July 4, 2007. Significant areas of subsidence include area 1 around Wink Sink 1, area 2 north-northeast of Wink Sink 2, and area 3 east-northeast of Wink Sink 2. (b) Aerial photograph (2004) showing residual gravity anomalies following processing steps that removed the regional gravity trend. Negative anomalies indicate shallow-source density deficits.

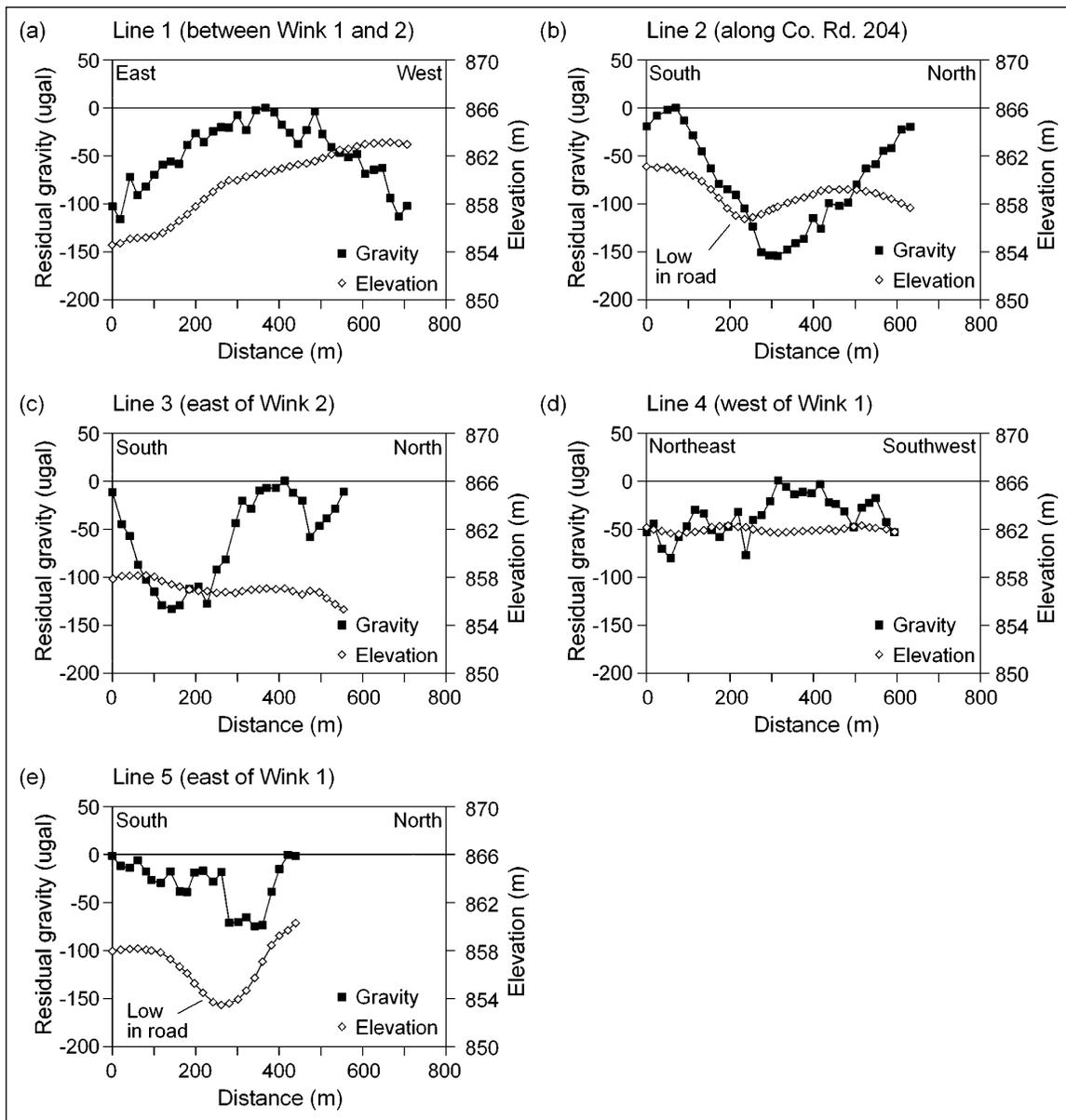
sance survey before the collapse of Wink Sink 2 (Collins, 2000; Johnson and others, 2003), and by comparisons of elevations determined photogrammetrically from 1968 aerial photographs and from the 2000 Shuttle Radar Topographic Mission (SRTM). In subsidence area 1, a circular area about 300-m across 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 (Figure 3b). Gravity station spacing was 20 m along each of the lines. These data, after correction for drift, location, and elevation, show that gravitational strength generally decreases 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 and others, 1982). The regional gradient is large enough that local effects are masked in the area around the Wink sinkholes. When regional trends are removed, the gravity residuals (Figure 3b) allow identification of local gravity lows that delineate 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 (Figures 3b and 4). The larger of these gravity lows, which reaches about 160  $\mu\text{gal}$  on line 2, is located on the northern flank of a topographic low along a county road (Figure 4b and 5b). Field inspections in June and November 2008 revealed numerous fissure and compression



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



**Figure 5:** Elevation and residual gravity values calculated from 2008 Wink gravity data (Figure 3b). (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.

features crossing fields and roads. The fissures mapped in subsidence area 3 are found along the southern perimeter of the 2007 InSAR anomaly (Figure 4) and have damaged a recently repaved county road. Interpreted mass deficits in the shallow subsurface beneath County Road 204 suggest that there is potential for significant further subsidence or collapse in this area. No gravity data have been acquired yet along County Road 201, but fissures and new road cracks confirm that subsidence continues in this area. We do not yet know whether mass deficits that would suggest the possibility of further subsidence or possible collapse exist beneath this road.

The relatively large residual gravity anomaly detected on line 3 along a lease road east of Wink 2 reaches about 140  $\mu\text{gal}$  and is not associated with a 2007 InSAR anomaly or a prominent topographic low (Figure 3b). Our preliminary conclusion is that this local gravity low indicates the presence of a shallow mass deficit that could lead to future subsidence or sinkhole development near Wink Sink 2.

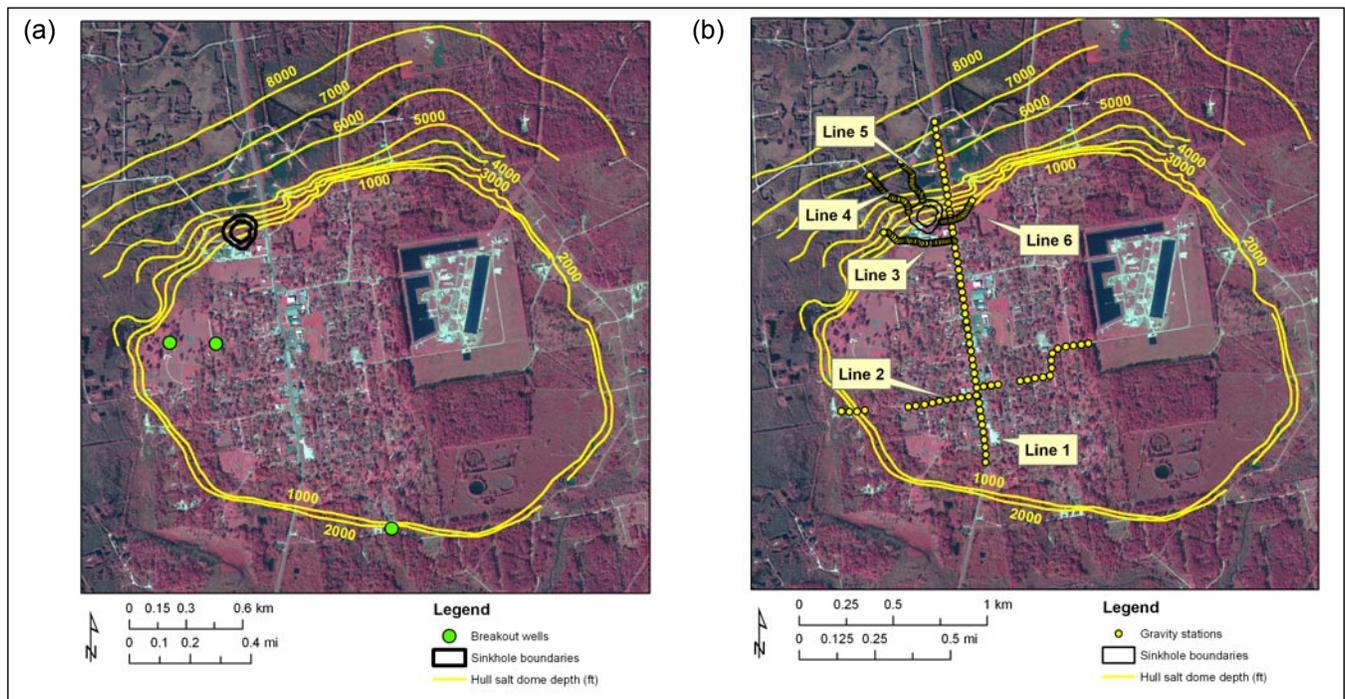
Line 1, which crosses a subsiding area between Wink Sinks 1 and 2 identified in the 2007 InSAR data, shows neither a prominent residual gravity low nor a large topographic depression (Figures 3a and 5a). These results indicate the lack of a significant shallow mass deficit in the subsiding area, which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

The relatively large residual gravity anomaly detected on line 3 along a lease road east of Wink 2 reaches about 140  $\mu\text{gal}$  and is not associated with a 2007 InSAR anomaly or a prominent topographic low (Figures 3b and 5c). Our preliminary interpretation is that this local gravity low indicates the presence of 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 Texas 115 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 along the highway (Figure 5d). Line 5, located on a lease road adjacent to Wink Sink 1, crosses a 2007 InSAR anomaly and reveals a local gravity low on the north flank of the topographic low just east of the sinkhole (Figures 3b and 5e). Further subsidence and sinkhole expansion eastward is possible in this area.

### Daisetta Gravity

As a rapid-response effort to address a sudden geologic event affecting public safety, we conducted 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 small community of Daisetta, Texas (Figures 1b, 2, and 6). 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 along major routes through Daisetta. We acquired gravity data at 243 locations along six lines in and around Daisetta (Figure 6),

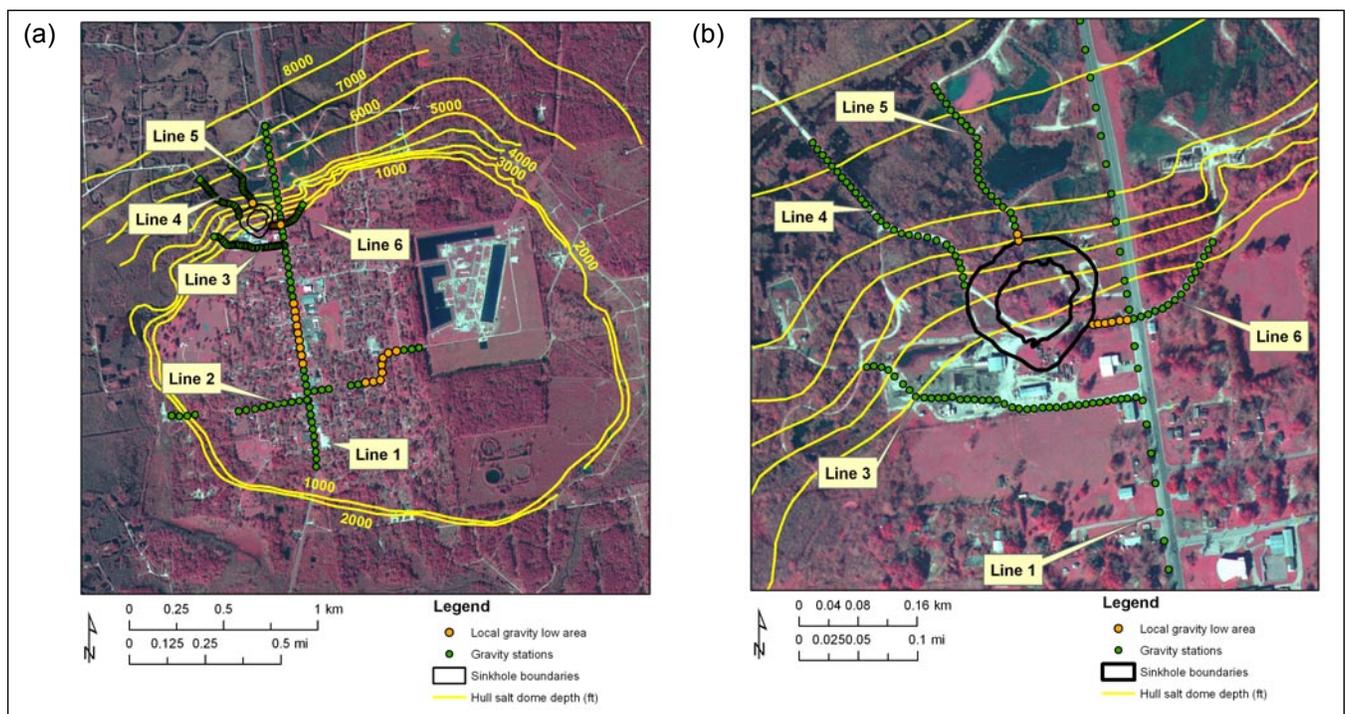


**Figure 6:** (a) 2004 aerial photograph of the Daisetta, Texas area showing the May 7, 2008 sinkhole location, contoured depth to the top of the Hull salt dome, and wells that flowed salt water during collapse. (b) Daisetta gravity lines 1 through 6.

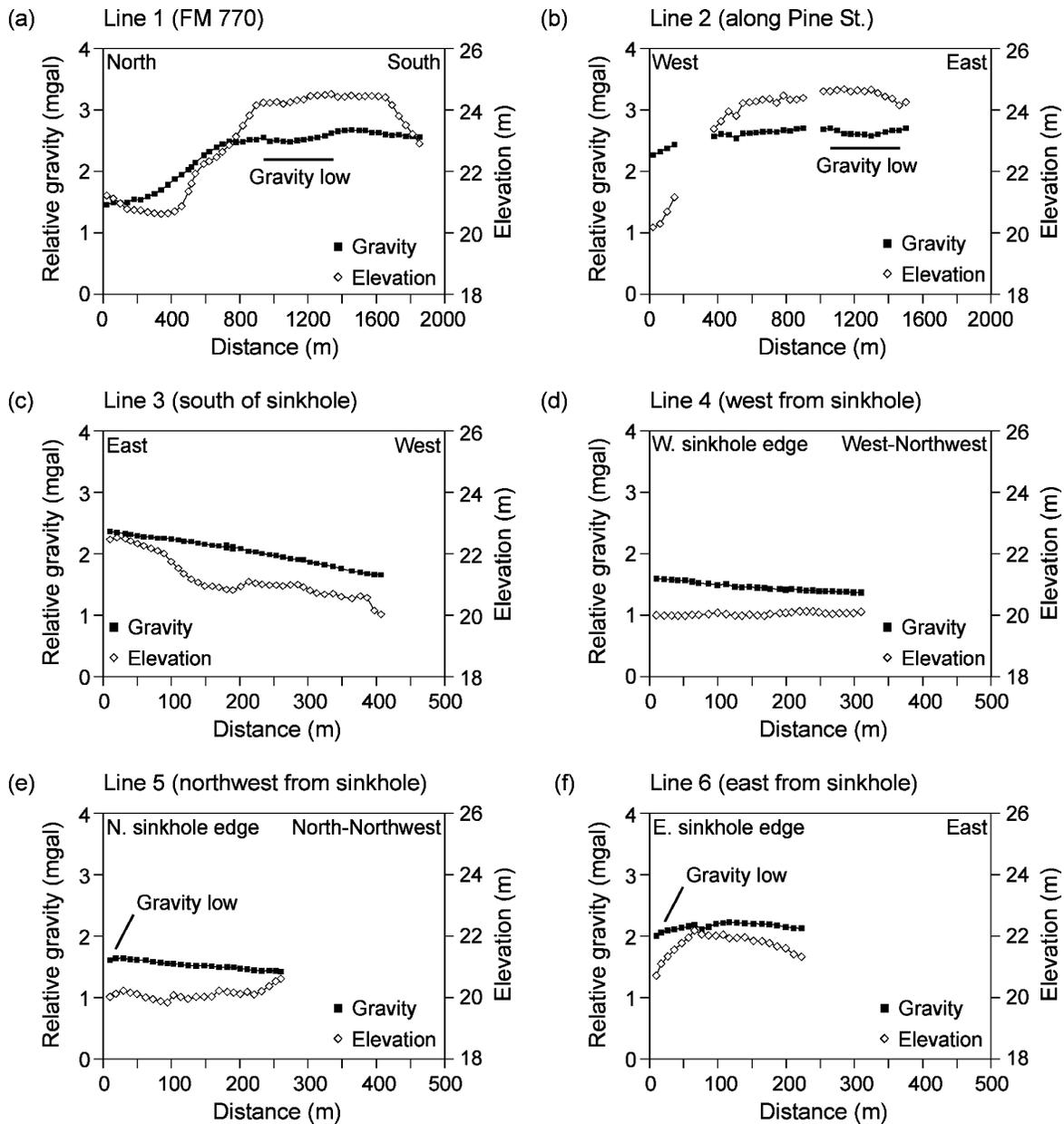
which is situated on high ground less than 300 m above the top of the Hull salt dome. During development of the sinkhole, salt water flowed to the surface through wells located south of the sinkhole and across the crest of the dome, leading to concern about the possible presence of dissolution conduits beneath Daisetta. 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). Gravity measurements adjacent to the sinkhole (lines 4, 5, and 6; Figure 7b) approach the edge of the sinkhole as shown on aerial photographs taken on May 8, the day after initial collapse. There was thus little expansion of the surface boundary of the sinkhole in the three weeks after initial collapse.

Drift-, tide-, latitude-, and elevation-corrected gravity measurements reveal at least four local areas with relatively low gravity values (Figures 7 and 8) along lines 1 through 6. A relative low reaching about 100  $\mu\text{gal}$  extends about 600 m along line 1 (the north-south line across Daisetta; Figures 7a and 8a) and a smaller, 60 to 80  $\mu\text{gal}$  low extends more than 300 m along line 2 (the east-west line across Daisetta; Figures 7a and 8b). Near the sinkhole, notable are (a) the lack of significant gravity reductions west-northwest (line 4, Figures 7b and 8d) and south-southwest of the sinkhole (line 3, Figures 7b and 8c) 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 7b and 8e) and 50 to 70 m east of the sinkhole (line 6, Figures 7b and 8f) toward the main road through town (FM 770).

Preliminary interpretations are 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 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. There is no evidence yet for gravity lows that would accompany significant shallow voids. We cannot yet say whether the measured gravity lows on lines 1 and 2 might be related to subsurface voids, local topography (pinnacles and saddles) on the top of the salt dome, caprock thickness variations, or some other source of



**Figure 7:** (a) Location of anomalous gravity lows (orange dots) on Daisetta lines 1, 2, 5, and 6. (b) Locations on sinkhole-area lines 5 and 6 with low gravity values.



**Figure 8:** Elevation and relative gravity values 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) northwestward, and (f) eastward from the edge of the sinkhole.

local mass contrast. We can say that areas outside the anomalies show no evidence of mass deficits that would suggest possible near-term sinkhole development. The lows on lines 1 and 2 are most likely caused by long-standing natural, geologic features related to salt-dome formation and are not likely to represent a threat of future subsidence and sinkhole formation. Nevertheless, additional gravity surveying, density modeling, and perhaps verifactory shallow drilling could better define the lateral extent and possible causes of these lows. Additional gravity surveying should also include denser coverage around Daisetta to identify other areas of shallow mass deficit.

## Conclusions

Radar interferometry (InSAR) and high-resolution gravity surveys provide important 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. Data from radar interferometry screen large areas for anomalous vertical movement and guide more intensive field investigations to areas where significant change is occurring. InSAR, owing to frequent ongoing acquisition of data, provides a ready method for monitoring future movement in sinkhole-prone areas.

At Wink, analysis of 2007 InSAR data revealed three areas undergoing anomalous subsidence at rates as high as 30 cm/yr. Follow-up 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.

Ongoing analysis of InSAR data at Daisetta has yet to yield information on pre- or post-collapse ground deformation. Preliminary gravity surveys at Daisetta, acquired within three weeks of sinkhole formation, identified anomalies adjacent to the sinkhole that suggest possible growth directions. Two gravity anomalies across part of the crest of the underlying salt dome are most likely to represent long-standing geologic features rather than recent dissolution effects. At both Wink and Daisetta, InSAR and gravity data are guiding more comprehensive surface and subsurface investigations and monitoring activities.

## Acknowledgments

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