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Airborne and Ground Surveys of the April 2023 Daisetta Sinkhole, Liberty County, Texas

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FIGURES

INTRODUCTION

On Sunday, April 2, 2023, a sinkhole formed on the northwestern flank of the Hull salt dome in the city of Daisetta, Texas (fig. 1). This nearly circular sinkhole (figs. 2 and 3), having a water-filled diameter of about 70 m, is located adjacent to the southwestern edge of the larger 2008 Daisetta sinkhole. At the request of the Liberty County Office of Emergency Management, Bureau researchers visited the sinkhole on April 8, 2023 to map concentric fissures and scarps around the new sinkhole; conduct a drone-based, structure-from-motion survey to obtain high-resolution images and construct a post-collapse topographic map of the sinkhole area; measure water depth in both sinkholes; acquire differential GPS elevations for drone imagery georeferencing and elevation-change detection; and use a passive seismic method to estimate the

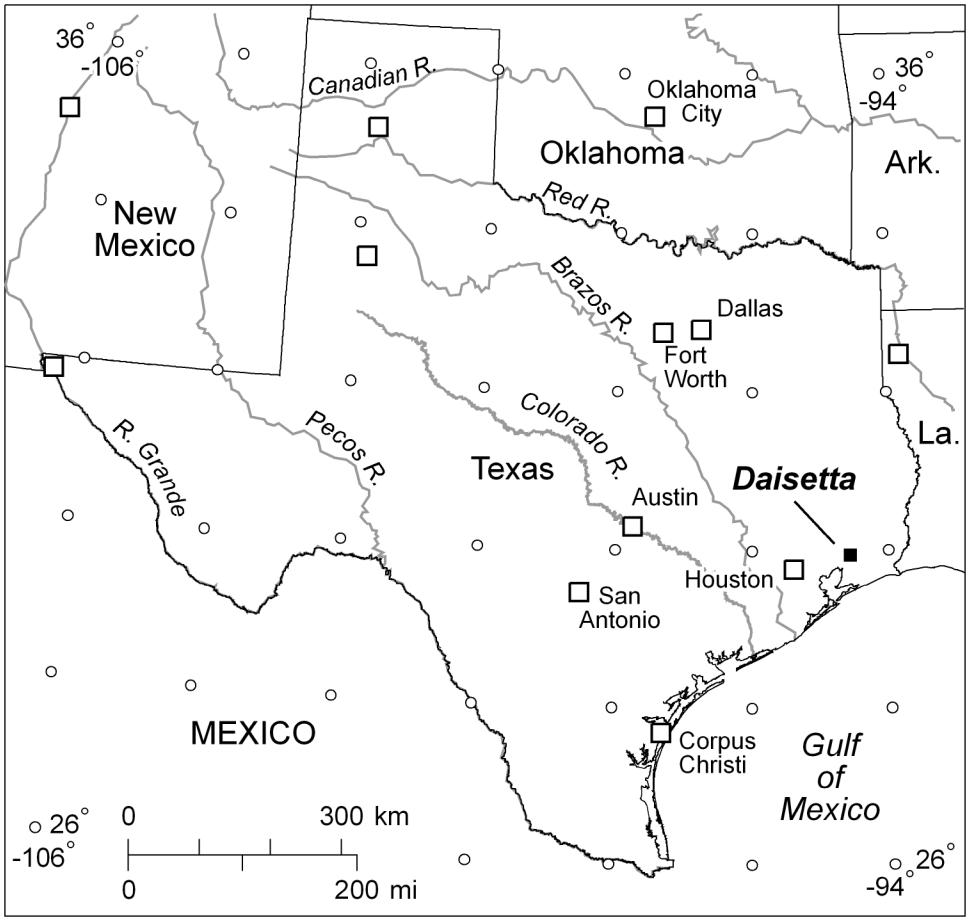

Figure 1. Map of Texas showing the Daisetta sinkhole area on the Texas Coastal Plain.

Figure 2. Oblique drone image of the 2008 and 2023 sinkholes, Daisetta, Texas, acquired on April 8, 2023. “F” denotes areas of prominent concentric fissures, scarps, and cracks. View to the east–northeast.

Figure 3. View to the northeast across the 2023 Daisetta sinkhole. The 2008 sinkhole is in the background beyond the tilted yellow-gray building.

depth to cap rock or salt along the highway near the sinkhole. Data acquired during the initial site visit is intended to provide useful information on the sinkhole (including affected area, water depth, and expansion potential) to emergency responders and the public.

Hull Salt Dome

Daisetta is located on a low hill that is due to the presence of the underlying Hull salt dome, a relatively common situation for the Texas–Louisiana Coastal Plain (Halbouty, 1967; Seni and Kyle, 1986). Depth to the top of the Hull salt mass shallows to less than 1,000 ft (300 m) (fig.4) at the crest of the dome. Reported depth to salt on the crest of Hull dome is 595 ft (180 m) (Judson and Stamey, 1933; Hawkins and Jirik, 1966). Gulf Coast salt domes commonly are mantled by a cap rock, consisting of varying amounts of anhydrite, gypsum, and calcite, in a layered sequence from bottom to top. The adjacent sediments may be cemented locally by calcite to form what is referred to as "false cap rock." Reported depths to cap rock on the crest of Hull dome are 260 to 285 ft (79 to 87 m) (Judson and Stamey, 1933; Hawkins and Jirik, 1966; Beckman and Williamson, 1990). The 2008 and 2023 Daisetta sinkholes occur adjacent to each other on the perimeter of the salt dome (fig. 4). Although the cause of the recent Daisetta sinkholes is unknown, sinkholes are relatively common features associated with shallow salt domes (Mullican, 1988) owing to the presence of highly soluble salt and the potential for subsurface voids to form (and overlying strata subsequently sink or collapse) as a result of salt dissolution and other processes.

2008 Sinkhole

Over several hours on May 7, 2008, a large sinkhole (about 170-m diameter) formed on the northwestern edge of the Hull salt dome. Imagery acquired the following day (fig. 5) revealed a water-filled central collapsed area measuring about 100 m east–west and 115 m north–south surrounded by a heavily fissured, partly collapsed area 25 to 35 m wide that eventually filled with water. At collapse, some fissures formed beyond the area that eventually filled with water. Various aspects of the 2008 sinkhole were investigated by the Railroad Commission of Texas,

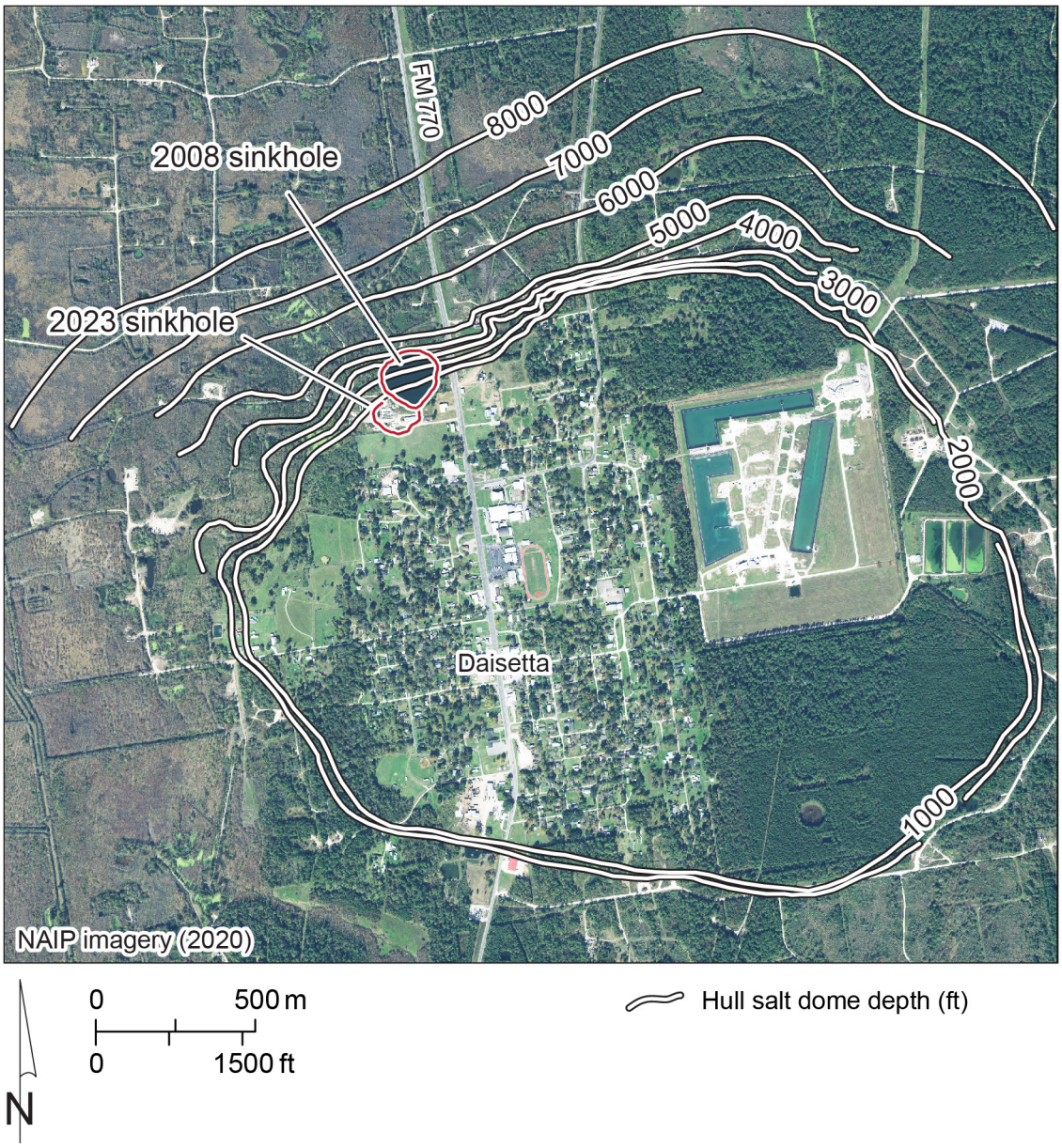

Figure 4. Map of the Daisetta, Texas area showing the May 7, 2008 and April 2, 2023 sinkhole locations and depth contours (in feet) to the top of the Hull salt dome superimposed on 2020 National Agriculture Inventory Program (NAIP) imagery from the Texas Natural Resources Information System. Depths to the top of salt were provided by Quail Creek Oil Company.

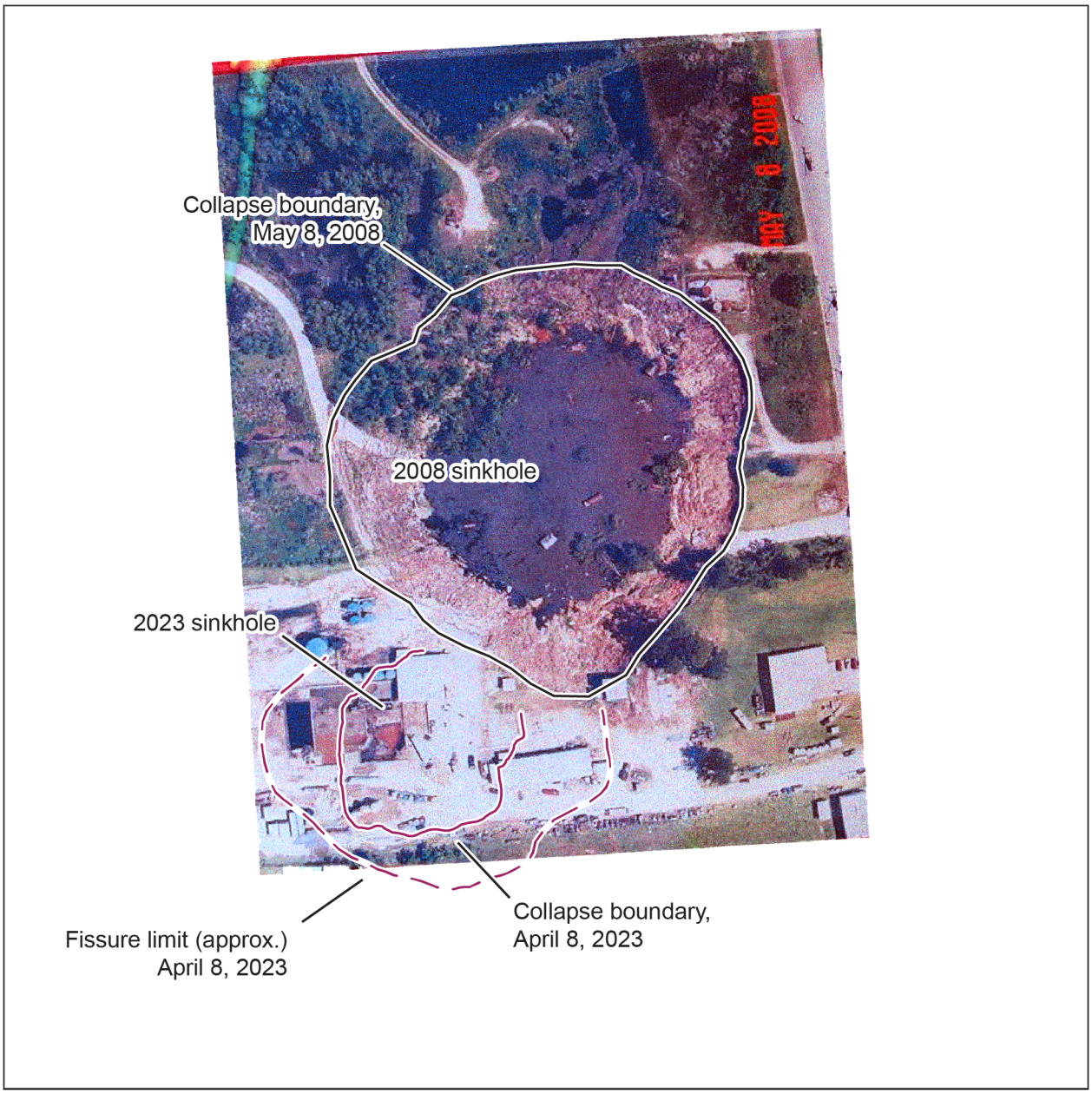

Figure 5. Aerial photograph of the 2008 Daisetta sinkhole taken the day after it collapsed. Also shown are the boundary of the water-filled collapsed area and the outer limit of fissures associated with the April 2023 sinkhole. Photograph by Aerial Viewpoint.

the Texas Commission on Environmental Quality (Traylor, 2009), consulting geologists and engineers (Corrigan Consulting, 2009; Howe and Norman, 2009), the Bureau of Economic Geology (Bureau) (Paine and others, 2009a,b,c; Paine and others, 2012), and the U.S. Geological Survey (USGS) (Kasmarek, 2009).

Recent (2022) aerial imagery shows that the 2008 Daisetta sinkhole has expanded minimally beyond the outline of the area that had partly or fully collapsed in 2008 (fig. 6) prior to the new collapse on April 2, 2023. Water depths shortly after collapse were reported to be 75 to 80 ft (23 to 24 m) (Howe and Norman, 2009).

The USGS acquired airborne lidar data in 2016 to produce a high-resolution (1-m cell size) digital elevation model (DEM) of the topography of the area (fig. 7). The DEM shows the 2008 sinkhole to be surrounded by low areas on the northwest flank of the Hull salt dome, which underlies the higher-elevation areas southeast of the sinkhole.

Development of the April 2023 Sinkhole

The sinkhole collapse on April 2, 2023 occurred adjacent to the larger 2008 sinkhole (fig. 6) over a few hours, with collapse reported to have continued intermittently to April 4 (Payne, 2023). Before the rapid collapse phase, the first reported evidence of ground movement at the site included separation of a concrete slab from a metal-frame building on the east side of the new sinkhole, nearly 16 months before full collapse. This feature was reported by a work crew visiting the site in early December 2021 and was confirmed and photographed (fig. 8) by the Liberty County Assistant Fire Marshal during a site visit on December 10, 2021 (N. Holcomb, personal communication, 2023).

Aerial imagery has been acquired under the National Agriculture Imagery Program (NAIP) at two-year intervals since the early 2000s at a resolution of 2 m or better, which is sufficient to detect change related to sinkhole formation. Aerial imagery flown since the 2008 sinkhole formed, including NAIP imagery acquired in 2008, 2010, 2012, 2014, 2016, 2018, 2020, and 2022, reveals that a water-filled topographic low developed after October 12, 2020 and before

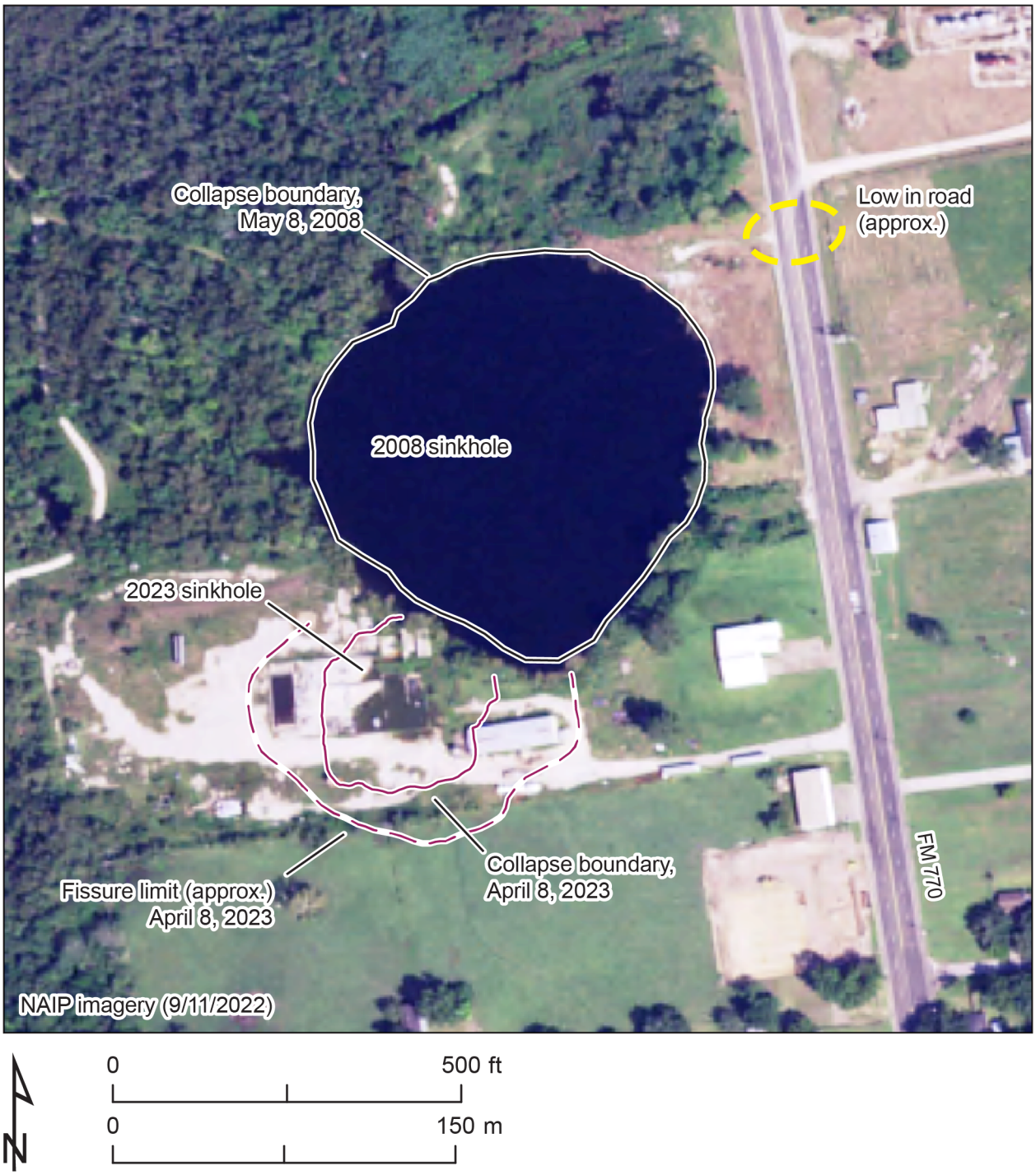

Figure 6. Map of the Daisetta sinkhole area showing the collapse-area boundary on May 8, 2008 (one day after the 2008 collapse), the boundary of the April 2023 collapse (from drone imagery acquired by the Bureau on April 8, 2023), and the approximate location of a low area on FM 770 reported by Liberty County staff. Imagery is from the National Agriculture Imagery Program (NAIP) and was acquired on September 11, 2022, about seven months before the April 2023 collapse. A water-filled topographic low is evident near the center of the 2023 sinkhole outline.

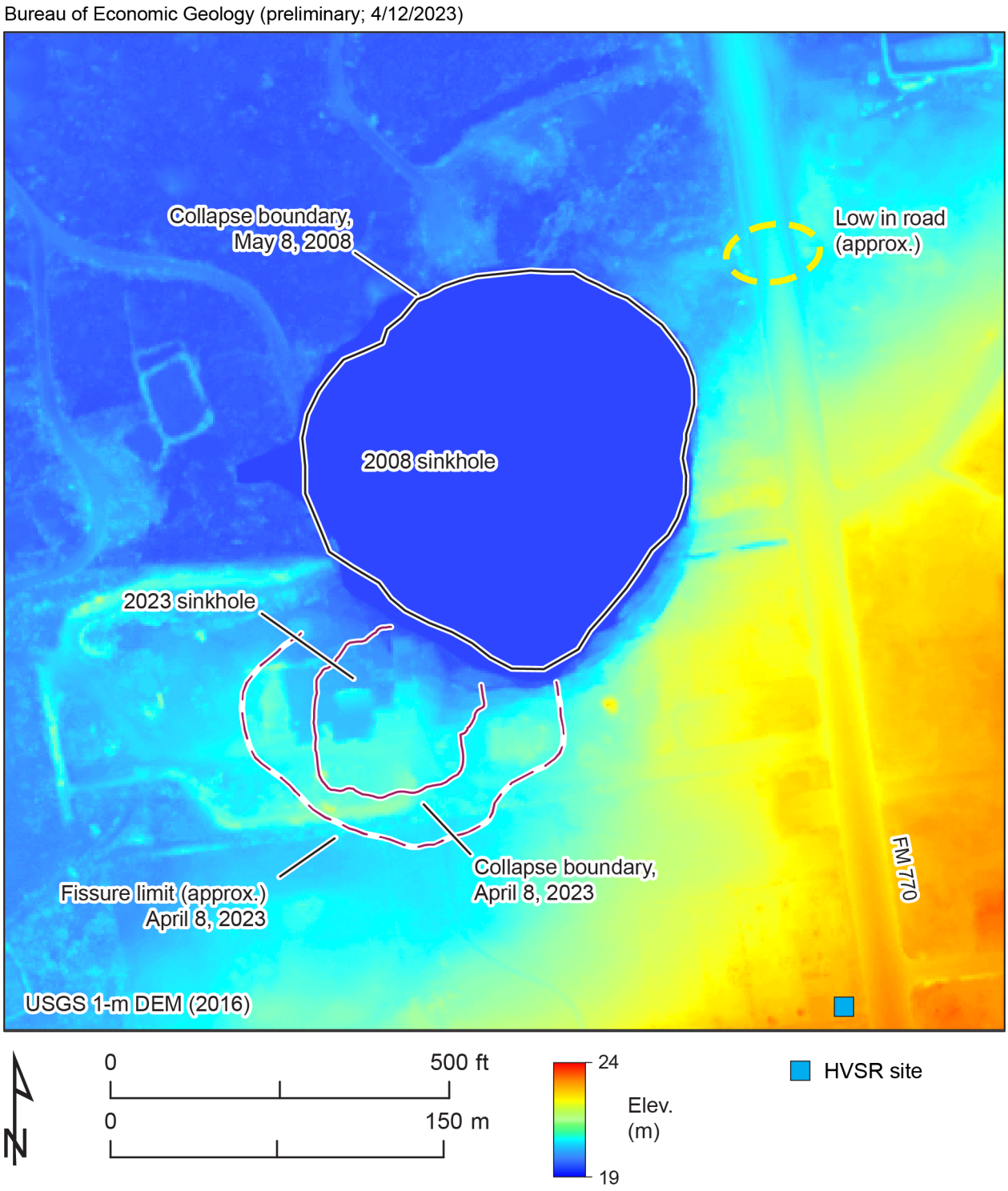

Figure 7. Map of the Daisetta sinkhole area showing the collapse boundary on May 8, 2008 (one day after the 2008 collapse), the boundary of the April 2023 collapse (from drone imagery acquired by the Bureau on April 8, 2023), the approximate location of a low area on FM 770, and the location of a passive HVSR seismic measurement used to estimate depth to cap rock or salt. Features are superimposed on a high-resolution digital elevation model of ground elevation acquired by the USGS in 2016, about seven years before the April 2023 collapse.

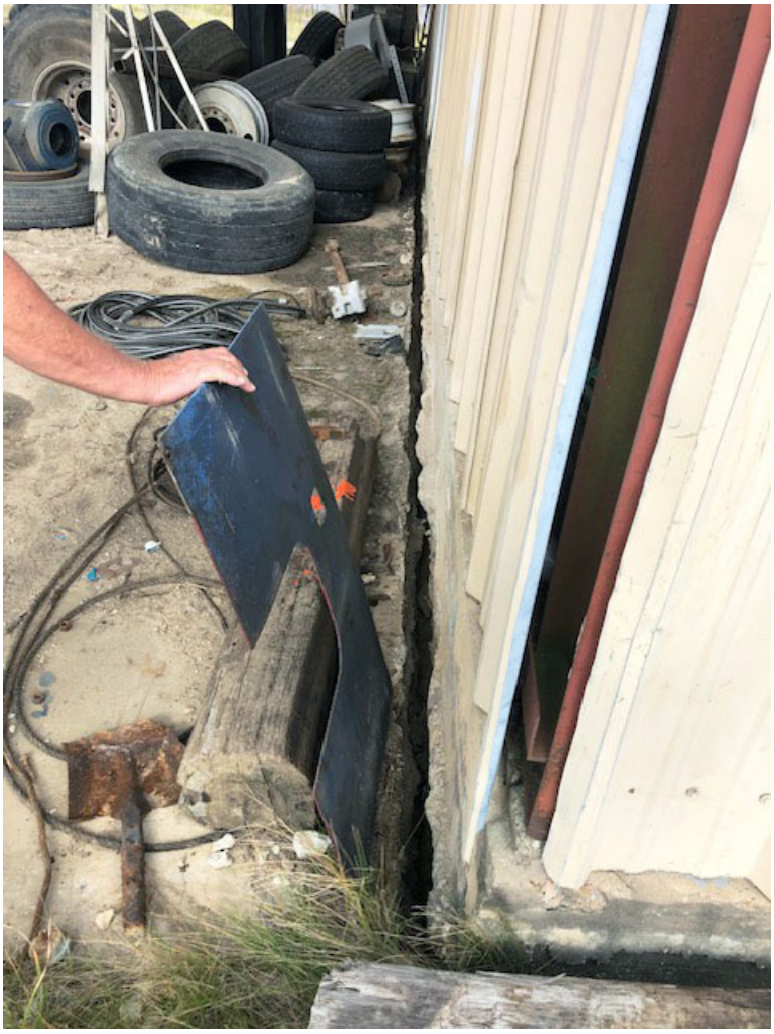

Figure 8. Concrete slab separation beneath a metal-frame building just east of the 2023 collapse area. Photographed on December 10, 2021 by Nat Holcomb. This is the first reported evidence of ground instability within the collapse area of the April 2023 sinkhole.

September 11, 2022 (fig. 6). The water-filled low was about 30 m in diameter on the 2022 imagery and is located at the approximate center of the 2023 collapse area. The low is not evident on the 2016 DEM (fig. 7) or the October 2020 imagery.

PRELIMINARY RESULTS OF BUREAU FIELD STUDIES

Drone-Based Imagery

An aerial survey flown over the 2008 and 2023 sinkhole area on April 8, 2023 using an unmanned drone acquired both oblique (fig. 2) and vertical images of the sinkhole area. Imagery

was processed using control points surveyed using differential GPS methods with a Trimble R8 GPS receiver. The georeferenced image (fig. 9) achieved a resolution of 3 cm per pixel, which is sufficient to accurately map the boundary of the area affected by the new sinkhole and delineate most fissures and scarps in the partly collapsed area surrounding the water-filled part of the sinkhole.

Water Depth Measurements

Drone-based measurements of water depth in the 2008 and 2023 sinkholes employed a graduated, weighted string lowered into the sinkholes by the drone while observers used binoculars (fig. 10) to count string gradations at 1-m intervals as the line entered the water and determine water depth when the weight reached bottom and the line slackened. The maximum water depth in the 2008 sinkhole is 23 m (fig. 9), similar to the depth reported shortly after collapse in 2008 (Howe and Norman, 2009). The maximum water depth measured in the 2023 sinkhole is 9 m (fig. 9).

Fissures, Scarps, and Cracks

High-resolution drone imagery, ground observations, and GPS measurements documented the presence of scarps (ground opening with vertical offset), fissures (some lateral displacement and ground opening, but little or no vertical offset), and concentric cracks (little displacement) surrounding the water-filled collapse area of the April 2023 sinkhole (figs. 11 and 12). Scarps are more common near the water's edge, grading outward to fissures and finally to subtle cracks with minimal displacement. The zone having scarps, fissures, and cracks extends to between 12 m and about 35 m from the water's edge (fig. 6). Similar features formed during the 2008 collapse. Some of these features around the 2008 sinkhole were submerged as the water level rose, while others remain outside the water-filled part of the 2008 sinkhole. Water level in the 2023 sinkhole equals the current level in the 2008 sinkhole. Oblique views of the two adjacent sinkholes show migration of murky, sediment-laden water from the 2023 sinkhole into the 2008 sinkhole (fig. 13).

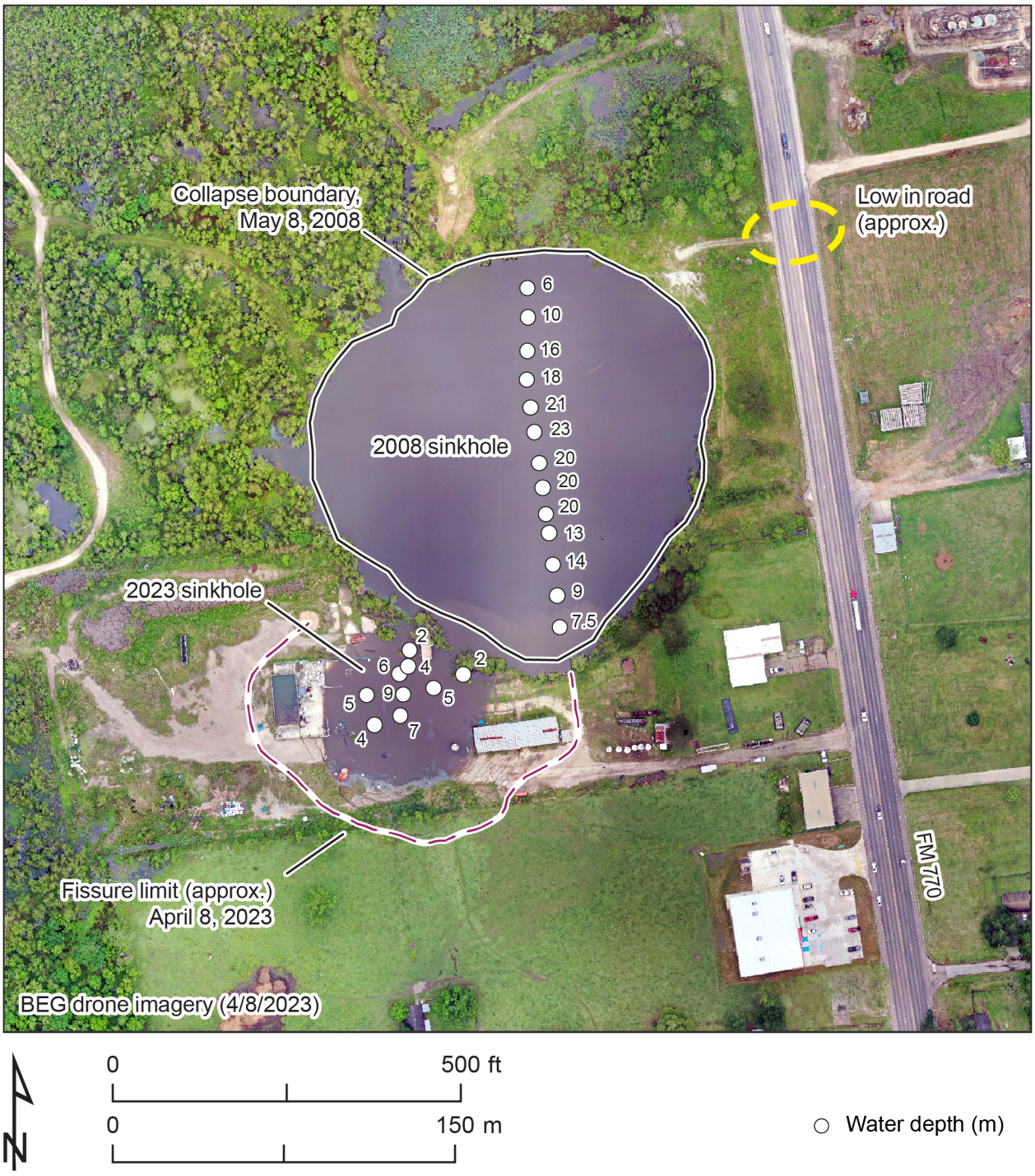

Figure 9. Drone-based imagery of the 2008 and 2023 sinkhole area, northern Daisetta. Image acquired on April 8, 2023, six days after the collapse of the 2023 sinkhole and the formation of concentric fissures, scarps, and cracks. Water depths were measured on April 8, 2023 using the drone.

Figure 10. Bureau staff flying the drone to lower a graduated, weighted string into the 2008 Daisetta sinkhole and observing the string to determine water depth (fig. 9).

Figure 11. Vertical drone image of the southern part of the April 2023 sinkhole showing concentric fissures (F) and scarps (S) surrounding the water-filled collapse area.

Figure 12. Fissures, scarps, and slump blocks on the east side of the April 2023 collapse area. View to the west across the 2023 sinkhole.

Figure 13. Oblique drone view to the south showing a sediment-laden plume of water flowing from the 2023 sinkhole into the 2008 sinkhole.

Elevation Change and Monitoring

Differential GPS measurements were acquired at 193 sites (fig. 14) on April 8, 2023 to provide lateral and vertical control for the drone survey, for comparison with previous elevations obtained from the 2016 DEM to show possible subsiding areas (such as the topographic low on FM 770), and to serve as a baseline for monitoring future elevation change. The largest elevation losses over that period are for sites located near the 2023 sinkhole, where measured elevation loss is as great as 1.3 m. Sinkhole water depths as deep as 9 m indicate greater elevation losses within the water-filled part of the sinkhole. Significant elevation change was not measured in the low area crossing FM 770, suggesting there has been little recent subsidence there.

Similar patterns of elevation loss are evident from comparisons of elevation determined from the 2023 drone survey and elevations obtained from the 2016 DEM (fig. 15). Greatest elevation loss outside of the water-filled area is observed on the southern and eastern margins of the 2023 sinkhole, where elevation loss between 2016 and 2023 is as great as 1.75 m.

Depth to Cap Rock or Salt

Limited information exists on the depth to the top of salt in the vicinity of the 2008 and 2023 Daisetta sinkholes. These features are located on the edge of the dome where the depth to salt increases rapidly to the northwest (fig. 4). The sinkhole area may also be underlain by false cap (Traylor, 2009) adjacent to the dome crest. Passive seismic measurements using the HVSR (horizontal to vertical spectral ratio) method (Nakamura, 1989; Lane and others, 2008) along FM 770 (fig. 7) were used to estimate depth to a rigid layer (presumably cap rock or salt) on the northwest part of the dome crest. Seismic records exhibited a strong resonance peak at 0.91 Hz. Assuming an average shear-wave velocity for the area of 237 m/s (Li and others, 2022) for strata overlying the dome, depth to cap rock or salt is about 65 m, somewhat shallower than other reported depths to cap rock at Hull dome (79 to 87 m; Judson and Stamey, 1933; Beckman and Williamson, 1990). The difference may be attributable to an inaccurate shear velocity estimate or natural variations in depth to cap rock or salt across the dome.

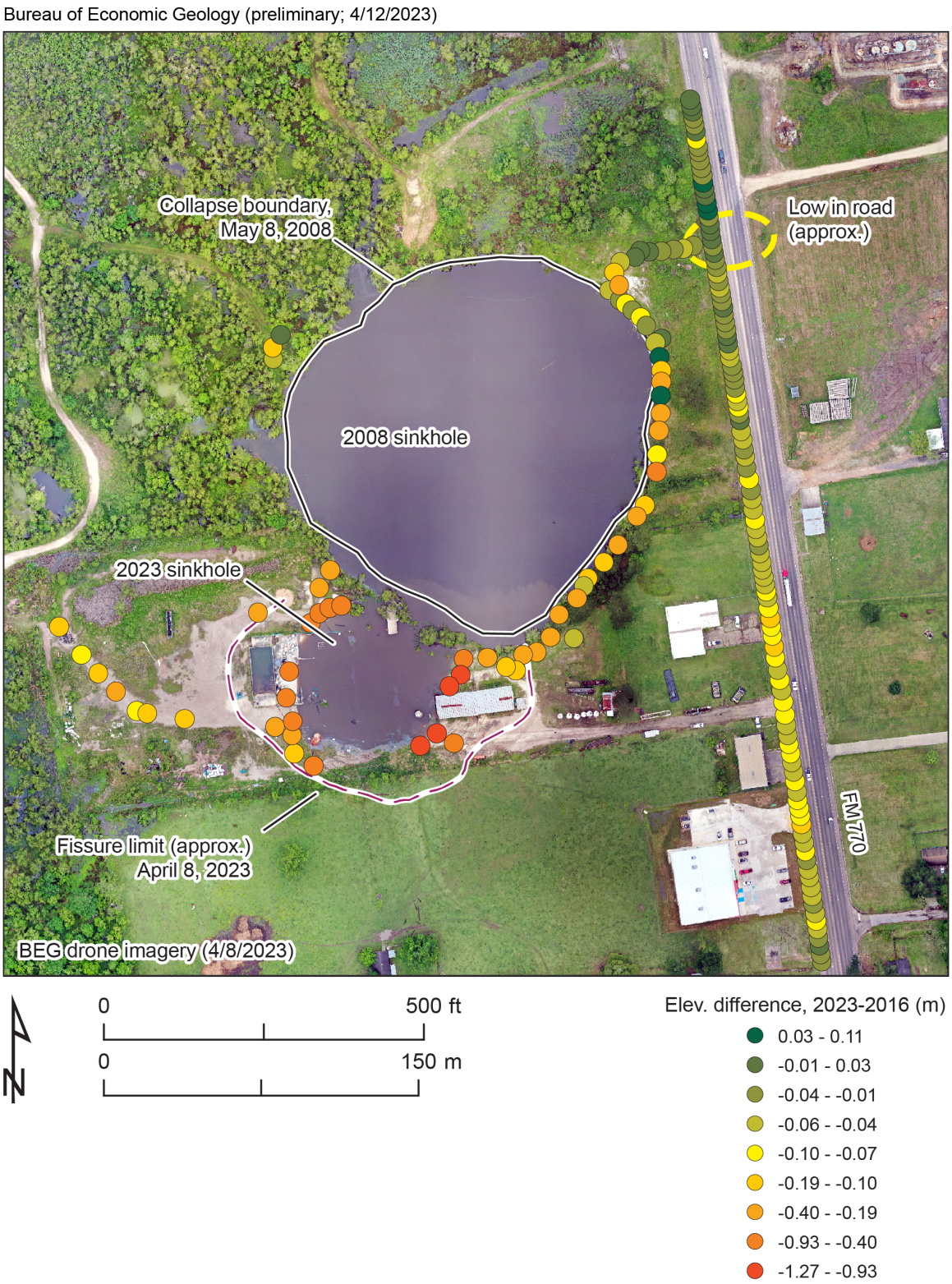

Figure 14. Apparent elevation difference between those obtained from GPS measurements on April 8, 2023 and elevations from the 2016 USGS DEM (fig. 7). Negative values indicate an apparent loss of elevation.

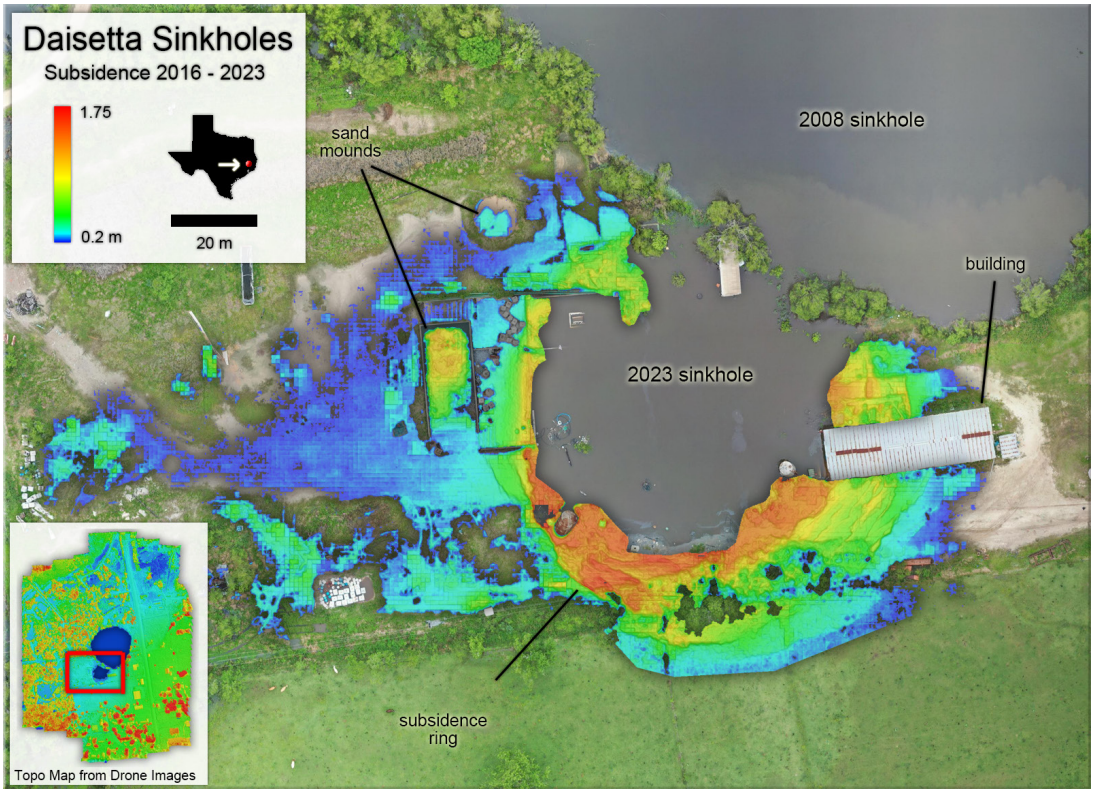

Figure 15. Apparent elevation difference between those obtained from a DEM constructed using structure-from-motion methods from the April 8, 2023 Bureau drone survey and the 2016 USGS DEM.

PRELIMINARY CONCLUSIONS

Drone imagery, differential GPS measurements, and related field studies at the Daisetta sinkholes conducted six days after 2023 sinkhole formation reveal that the new sinkhole is smaller than the 2008 sinkhole in areal extent, has shallower water depths, and has a similar halo of concentric scarps, fissures, and cracks. Pre-collapse evidence of potential sinkhole formation included (1) ground movement and related structural damage reported about 16 months before collapse, and (2) elevation loss sufficient to create a water-filled low near the center of the 2023 sinkhole outline that is evident on aerial imagery acquired seven months before collapse. Additional collapse is possible to the edge of the currently fissured halo and perhaps beyond, but the fully collapsed area could also not expand much beyond its current water-filled extent (similar to the limited growth of the larger 2008 sinkhole). Future rapid collapse similar to that observed

in 2008 and 2023 is possible in adjacent areas along the steep flank of the salt dome. Further investigations are recommended to better understand the cause and mechanism of collapse to minimize risk associated with similar possible future events.

ACKNOWLEDGMENTS

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