PS Houston, Texas, Area Geomorphology: Investigating Surfaces Above Salt Domes Using GIS and Remote Sensing*

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Abstract

The Gulf Coast is a major source of oil and gas for the United States. In Texas, an oil field over a salt dome known as Spindletop started the Texas Oil Boom. Salt domes are great traps because they are mostly impermeable and create an upward structure for oil and gas to accumulate. Several salt domes have been documented in and around the Houston area such as Pierce Junction, Mykawa, and Webster to name a few. The diapirism of the salt domes can be attributed to regional extension and sedimentation. Monitoring the topographical changes directly above salt domes can give insight to subsurface movements of the salt. Geographic Information System (GIS) and remote sensing techniques are used to quantify surface movements of the salt domes in the Houston area. Data collected by Light Detection and Ranging (LiDAR) and Global Positioning System (GPS) allow detection of surface changes on a centimeter to millimeter scale. Preliminary statistical analysis of Digital Elevation Models (DEM) over a span of 12 years (1996, 2001, and 2008) showed increased surface changes over some salt dome locations. GPS studies from Engelkemeir (2008) and the Harris-Galveston Subsidence District (HGSD) show most of Houston is subsiding. Areas that are not subsiding or rising are mostly over known salt dome locations. Gravity surveys will be conducted over these areas to ensure that it is salt under these areas. Areas over salt domes should have a significantly different reading compared to areas without a salt dome. Quantitatively tracking surface movements of salt domes can be an easier and cheaper alternative to subsurface monitoring. Variations or abnormal movements may signify regional tectonic activity.

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Introduction

Surface deformation has been an ongoing problem in the Houston Metropolitan area because of the city's location in a passive margin where faulting and subsidence are common. According to previous studies the causes of the surface deformation are typically attributed to anthropogenic activities, mainly the subsurface withdrawals of oil, gas, and groundwater. However, the majority of the studies done have not accounted for the vast amount of salt underneath the Houston area and its role in the surface deformation. The objective of this study was to identify areas of surface deformation in the greater Houston area and their possible relationship with subsurface salt movements. To accomplish this, I integrated three kinds of data: 1) GPS 2) LiDAR (Airborne and TLS) and 3) Gravity. GPS data revealed subsidence and uplift in Harris County. DEMs generated from airborne LiDAR revealed changes between salt domes and their surrounding areas. TLS data collected over the Pierce Junction site, chosen for accessibility and depth, revealed vertical changes over the surface above the salt dome. Gravity data acquired over Pierce Junction salt dome also revealed changes in the subsurface. Groundwater withdrawal may be a large influence in the surface deformation of the Houston area, but salt related surface deformation should be more closely studied to quantify its influence.

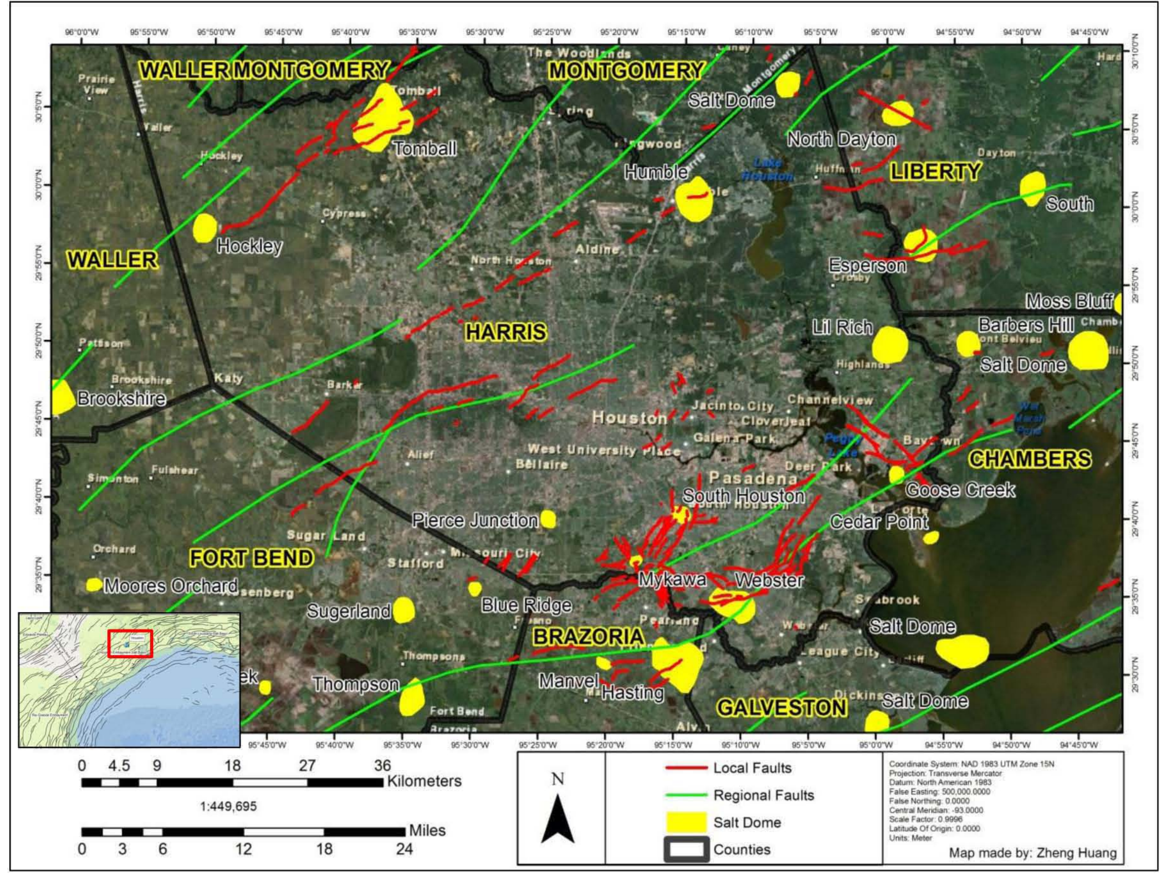
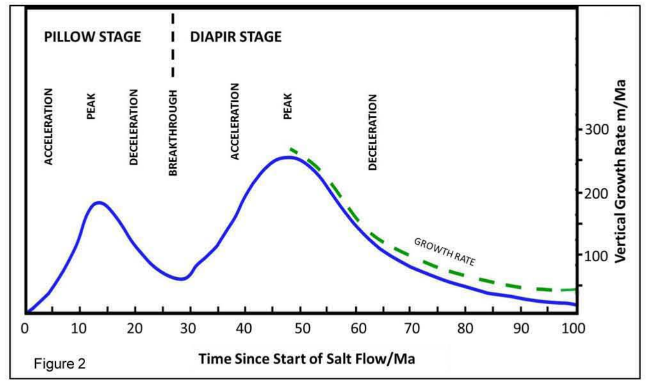


Figure 1: The Houston Metropolitan area within Harris County, Texas, USA. The red lines represent local faults (Brown et al., 1974; Verbeek & Clanton, 1978; White & Morton, 1997; Engelkemeir & Khan, 2008) and the green lines represent regional faults (Ewing & Lopez, 1991). The yellow polygons represent Gulf Coast salt domes (Huffman et al., 2004).

Objective

Influences on subsidence from groundwater and petroleum withdrawal are well documented. However, the roles of salt and salt domes have not been widely considered in the surface deformation of the Houston area. The objective of this work was to identify areas of surface deformation in the greater Houston area and their possible relationship with subsurface salt movements.



Salt Movement Rates

Jackson and Seni (1983) showed Texas salt domes had maximum gross growth rates of 400 to 450 m/Ma, which is roughly 0.45 mm/yr of growth. The growth rates were not continuous and thought to be more cyclic. Jackson and Talbot (1986) (blue line) compiled data from 436 salt domes in the United States Gulf Coast and produced a model for average salt dome growth and their cycles. Pittman (1994) (dashed line) noted maximum growth of the salt domes in the greater Houston followed closely to Jackson and Talbot's (1986) growth rates (Figure 2).

Methods

DEM Height Computation:

The polygon technique used by Engelkemeir (2008) was employed to examine changes between the centers of the salt dome relative to its surround areas. For each polygon the average elevation within is assumed to provide an acceptable measure of the elevation (Engelkemeir, 2008). Five polygons were created for each salt dome location. Four outside polygons surround the salt dome on the north, south, east, and west. One polygon was created within the area of the salt dome. The polygons were created to avoid artifacts within the DEM.

GPS Velocity:

GPS data is currently collected continuously by The Harris-Galveston Subsidence District (HGSD) and National Geodetic Survey (NGS). It consists of a combination of Periodically Active Monitor (PAM) units and Continuously Operating Reference Stations (CORS) stations. These site collected data in 30 second intervals 24 hours a day. This extensive network is used to monitor subsidence. A linear regression was used to find the rate of subsidence at some of the PAM sites.

Gravity:

The objective of the gravity survey was to identify any subsurface movement of the salt dome over time. Two lines, one north-south and one east-west, were designed over the crest of the Pierce Junction salt dome. Each lines location was assessed for environmental variables (seismic noise, wind vibration, and elevation differences), location reoccupation, and safety. The target depth is about 250 m. This is known from previous publications from Teas (1935) and Holzer & Bluntzer (1984). The station spacing was set to 100 m to provide adequate resolution to identify the salt dome. Two sets of survey were conducted at two various times.

DEM Height Computation Results

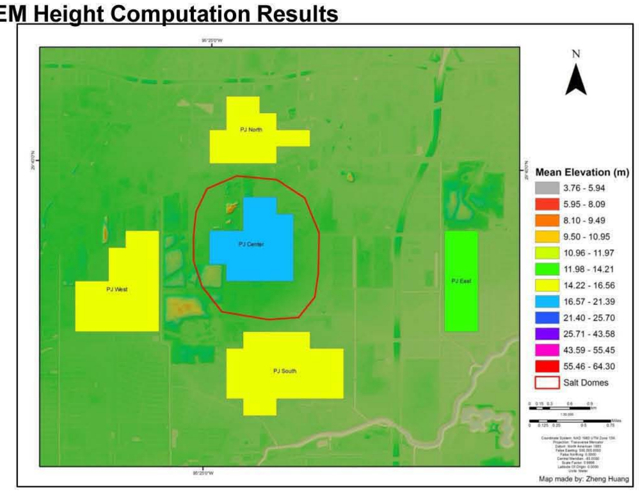


Figure 3: Polygon based DEM height computations for Pierce Junction salt dome. Color scale is set to mean elevation (m) for 2008 which was extracted from the Zonal Statistics as Table tool from ArcGIS 10. The background is a hillshade image of the 2008 DEM. Notice the polygons were created to avoid the anomalies in the DEM.

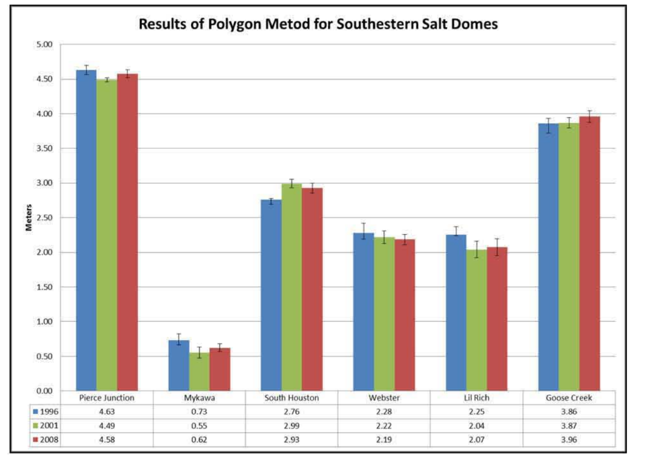


Figure 4: Comparison of the mean elevation of the central polygon versus one of the outer polygons for southeastern salt domes. There is no trend over most domes but there is change in relative elevation differences between the center dome area and the adjacent outer area. A negative trend is seen over the Webster salt dome.

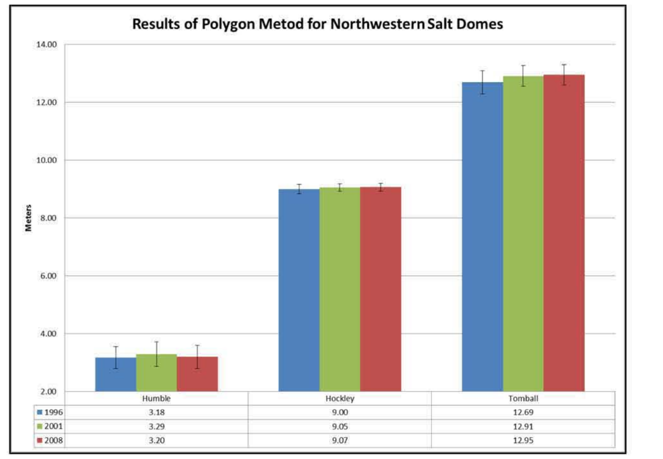


Figure 5: Comparison of the mean elevation of the central polygon versus one of the outer polygons for northwestern salt domes. Again there is no trend over most domes but there is change in relative elevation differences between the center dome area and the adjacent outer area. A positive trend Is seen over the Tomball salt dome.

GPS Velocity Results

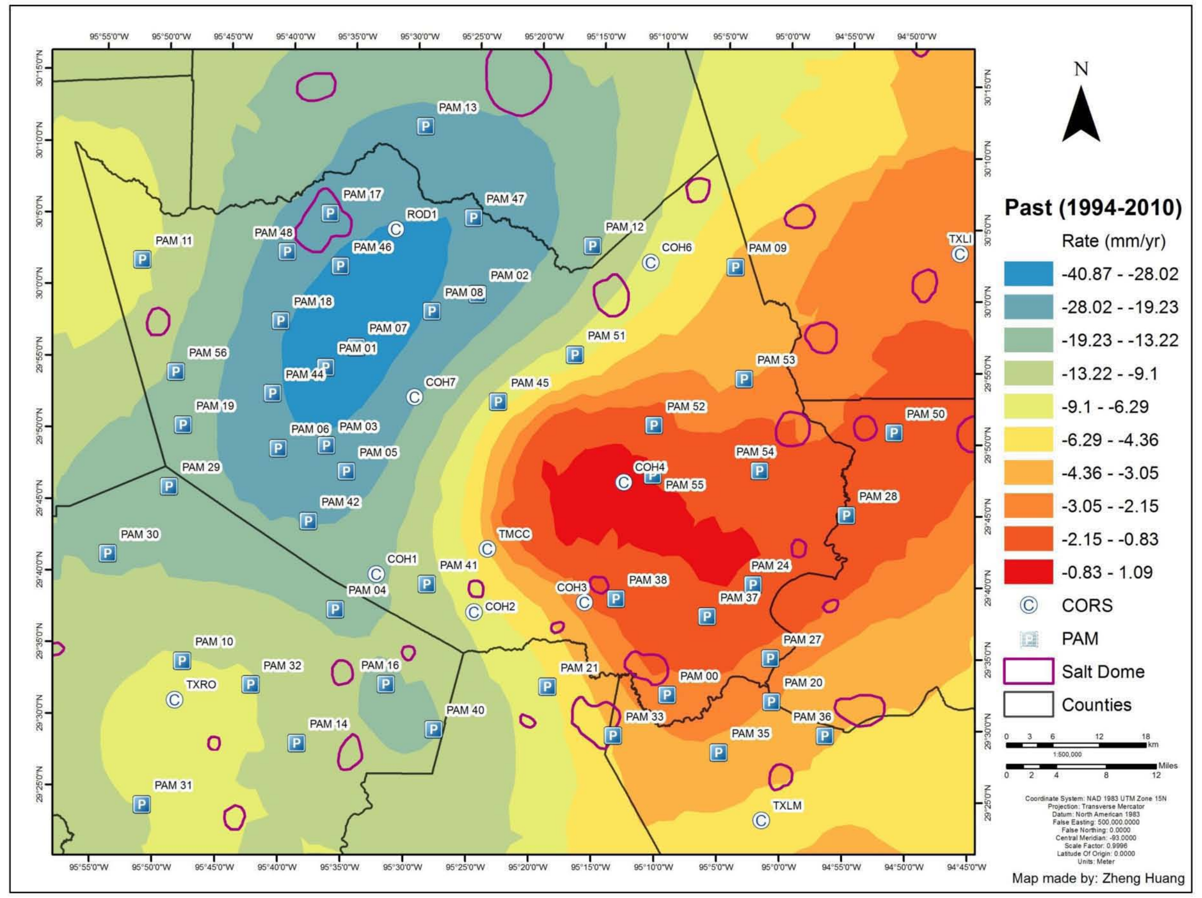


Figure 6: Kriging surface displaying GPS (PAM and CORS) derived surface deformation in the greater Houston area for the years 1994 through 2010. The area is extensively covered by both CORS and PAM GPS stations. As seen in this surface there is an area of subsidence in the northwest and an area of uplift in the southeast. One key difference is the distribution of salt domes in the two areas. In the southeast there are more known salt domes relative to the northwest. This may suggest some association between uplift and salt diapirism.

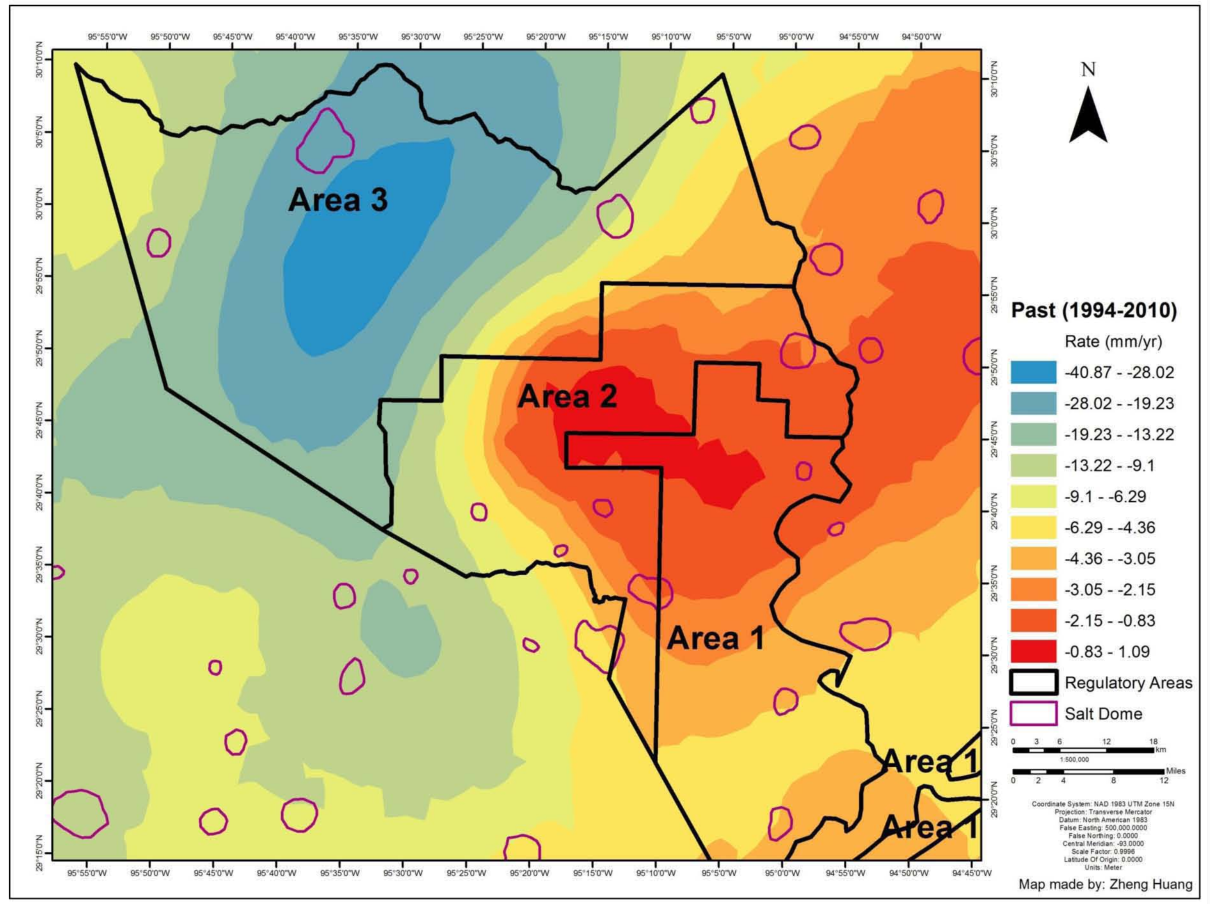


Figure 7: The three areas according to the Harris-Galveston Subsidence District 1999 Regulatory Plan. Groundwater withdrawal rates for areas one (8.4 MGD), two (36.9 MGD), and three (195.5 MGD) in Harris-Galveston County. It would appear groundwater withdrawal is the main contributor to the sub subsidence experienced in the northwestern region of Harris County.

Gravity

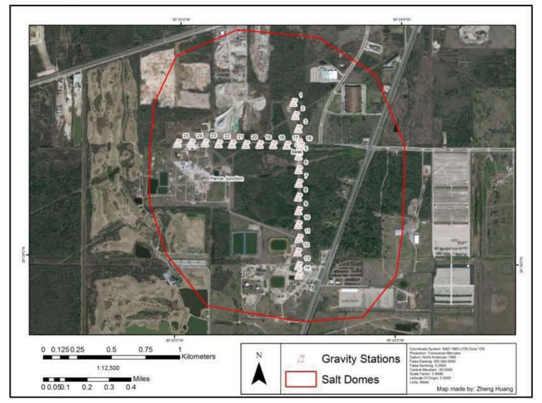


Figure 8: Gravity data collected for the Pierce Junction N-S line was done over the estimated center of the salt dome. Higher gravity readings were observed at the estimated center dome location. Gravity readings became lower as the station progressed south. There was a gravity difference of 0.36 mGal from the start of the survey to the end of the survey for May 5th, 2011. A gravity difference of 0.44 mGal from start to finish was observed for the September 28th, 2011 gravity survey.The E-W profile displayed much more variability between the two scanning periods of May and September. A difference of 0.27 mGal was seen from the May survey and a difference of 0.19 mGal for the September survey

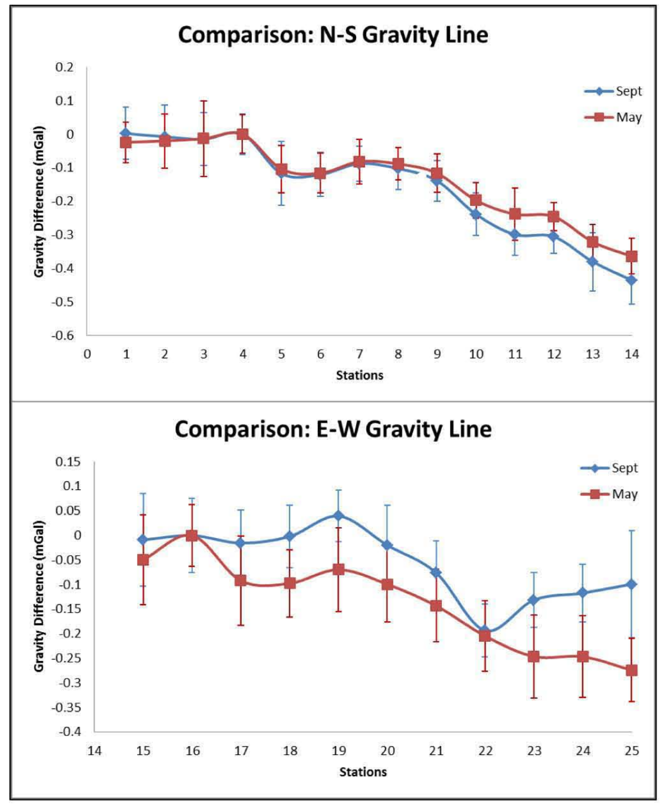


Figure 9: Gravity differences observed in this study may be attributed to subsurface salt movement, changes in water level, or field acquisition procedures. If the salt is rising beneath Pierce Junction the increase in gravity difference from figure 3.7 could represent a subsurface increase in salt within the center dome area. The 0.08 mGal of difference between the two sets of surveys may show a uniform rise in the salt dome from the north, south, east, and west. The positive anomaly observed at Pierce Junction is counter to most gravity reading above salt domes. However, the positive anomaly may be attributed to how close the Pierce Junction salt dome is to the surface. The change from negative to positive density contrast is demonstrated by Nettleton (1976).

Conclusion

GPS, LiDAR, and gravity are all powerful tools. The GPS data documented substantial subsidence and uplift in the Houston area. These surface deformations may suggest continued salt withdrawal and salt diapirism. DEM derived from LiDAR documented elevation changes between areas within the salt domes and their surroundings. This could suggest salt movement, possibly the result of secondary salt withdrawal during diapirism. The changes in the gravity measurements could be another indicator of subsurface salt movements. Although salt withdrawal and salt diapirism could cause all the observed results another large factor comes into question, groundwater. Groundwater withdrawals have been targeted as one of the main causes of subsidence in the Houston area for decades. This extremely impactful anthropogenic factor may skew most if not all natural surface deformation in the greater Houston area. Natural factors that may influence subsidence such as salt withdrawal may be largely overshadowed by groundwater withdrawals.

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