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Understanding the Big Hill Dome Surface Uplift: Historical InSAR Study

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Abstract

The Big Hill salt dome, located in southern Texas, is one of four sites operated by the U.S. Strategic Petroleum Reserve (SPR). Since 2002 there has been an ongoing trend of measured surface uplift documented towards the eastern region of the site, whereas subsidence, though minor, has continued to occur across the rest of the site. In order to better understand the subsurface dynamics, historic interferometric synthetic aperture radar (InSAR) data were acquired. InSAR involves the processing of multiple satellite synthetic aperture radar scenes acquired across the same location of the Earth's surface at different times to map surface deformation. The analysis of the data can possibly detect millimeters of motion spanning days, months, years and decades, across specific sites. The intent in regards to the Big Hill site was (1) to confirm the surface uplift trend recorded by land survey, (2) to understand the regional surface behavior, and (3) to possibly be able to better understand the subsurface source causing the uplift. Our analysis of the InSAR data confirmed the validity of the subsidence trends shown by the historic monument subsidence data, and also provided new insight into the mechanical behavior of the caprock and salt dome. Ultimately, this knowledge will further our understanding of the geologic forces at the salt/caprock interface which are currently affecting well integrity at the site.

Key words: Subsidence, Salt Domes, Strategic Petroleum Reserves, Instrumentation and Monitoring, Geology

Introduction

The U.S. Strategic Petroleum Reserve (SPR) is a stockpile of emergency crude oil to be tapped into if a disruption in the nation's oil supply occurs. The SPR is comprised of four salt dome sites located within Texas and Louisiana (Figure 1). Subsidence surveys have been conducted either annually or biennially at all four sites over the life of the program. Monitoring of surface behavior is a first line defense to detecting possible subsurface cavern integrity issues. In recent years the SPR Big Hill site, located in southeastern Texas, has experienced a host of well failures. In conjunction the subsidence surveys have indicated surface uplift predominantly along the eastern perimeter and to a lesser extent along the western perimeter of the site. Over the center of the field there has been a general decrease in subsidence rate over time.

Big Hill subsidence surveys began in 1989 with only 38 monuments being measured, with 28 of those being well heads. In 2002, 135 monuments were added which improved coverage and extended the monitoring beyond the caverns to both the east and west of the field. Surface uplift was first noted after the addition of the 135 monuments. Since 2002, Big Hill subsidence trends have shown continuous surface uplift towards the eastern region of the site, whereas subsidence, though minor, has continued to occur across the rest of the site (Lord, 2013; Lord, 2012; Lord, 2009; Ehgartner & Bauer, 2004). A definitive reason for the recorded rise in surface elevation has not been determined. To date, known subsurface geology and cavern closure rates do not correlate to the recorded uplift.

In an effort to try and understand the subsurface dynamics historic interferometric synthetic aperture radar (InSAR) data was acquired and processed by CGG. InSAR involves the processing of multiple satellite synthetic aperture radar scenes acquired across the same location of the Earth's surface at different times to map surface deformation. The analysis of the data can possibly detect millimeters of motion spanning days, months, year and decades, across specific sites. The intent in regards to the Big Hill site was (1) to confirm the surface uplift trend recorded by land survey, (2) understand the regional surface behavior, and (3) possibly be able to better understand the subsurface source causing the uplift. This report describes the InSAR analysis results, how those results compare to the historical collection of land survey data, and what additional information the data has provided towards identifying the source causing the response recorded at the surface.

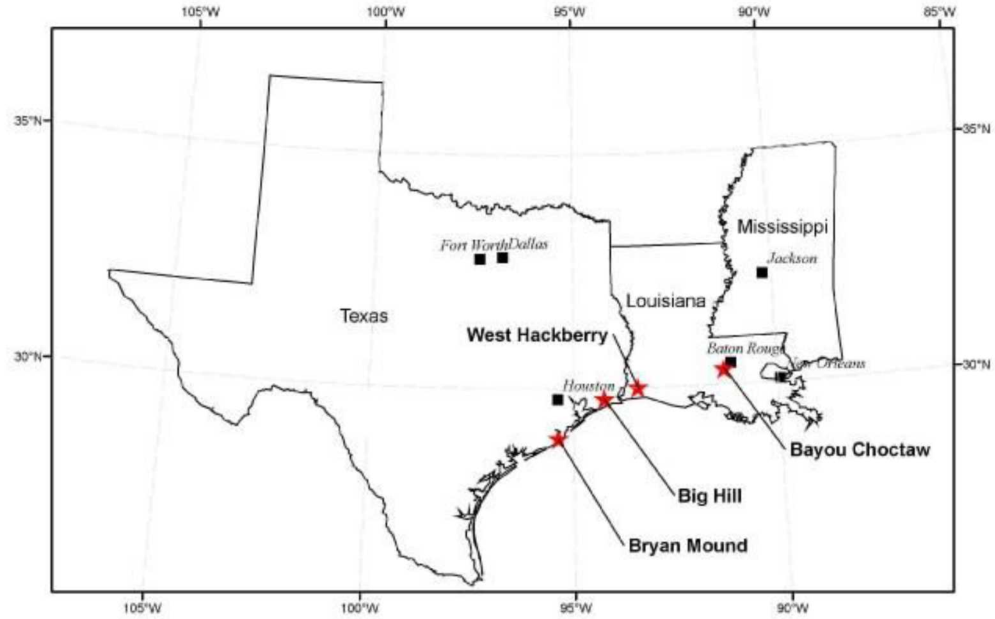

Figure 1. Locations of the four SPR storage sites.

Geology

The Big Hill salt dome is generally cylindrical in shape, and leans towards the south with the top of salt being relatively flat at a depth at approximately 1600 feet (Figure 2). The flanks are not smooth, but rather exhibit a crenulated fabric. The salt overhangs largely to the south with less prominent overhangs present along both the western and eastern sides of the salt flanks.

At Big Hill the caprock is comprised of a lower anhydrite zone overlain by a limestone and gypsum zone, both of which are diagenetic alterations of anhydrite. The top of caprock is approximately 300 feet below surface (Figure 3). The caprock is unusually thick and ranges in thickness between 850-1300 feet in the SPR storage region. Drilling encountered lost circulation issues and cores show that the caprock internal structure is very complicated. The caprock structure exhibits vugs, faults (Figure 4), and fractures, all of which were caused by dissolution of the underlying salt during dome growth and hence the collapse of the salt-caprock interface, resulting in a highly permeable caprock.

At Big Hill, salt spines, mapped by Magorian and Neal (1988), appear as anticlinal features within the dome. A shear zone is interpreted to fall between caverns 104, 109, and 114, and caverns 103, 108, and 113 based on subsurface correlations (Figure 4). The shear zone correlates with the major fault mapped on top of the caprock by Neal and others (1993).

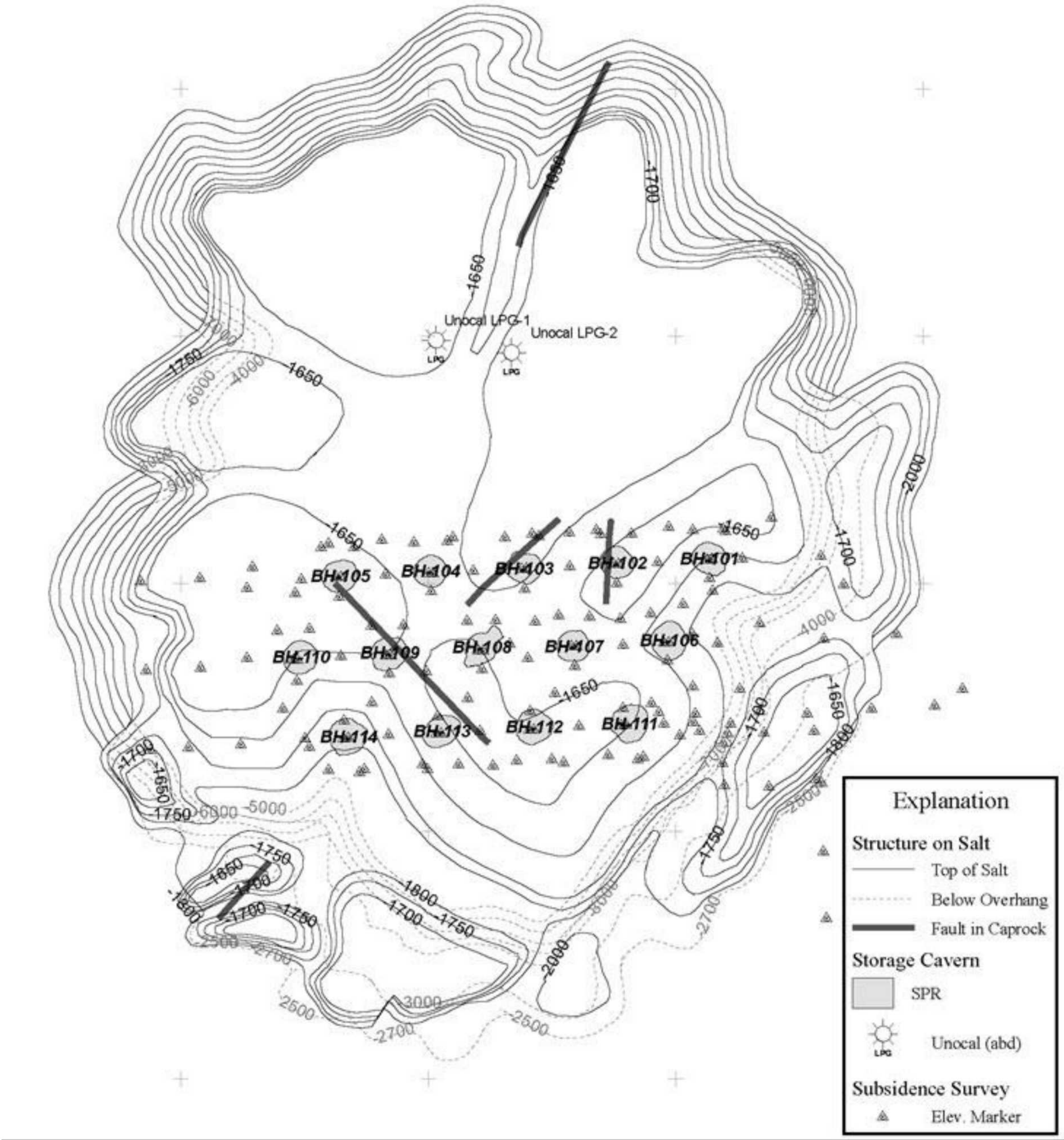

Figure 2. 2005 Big Hill top-of-salt structure contour map.

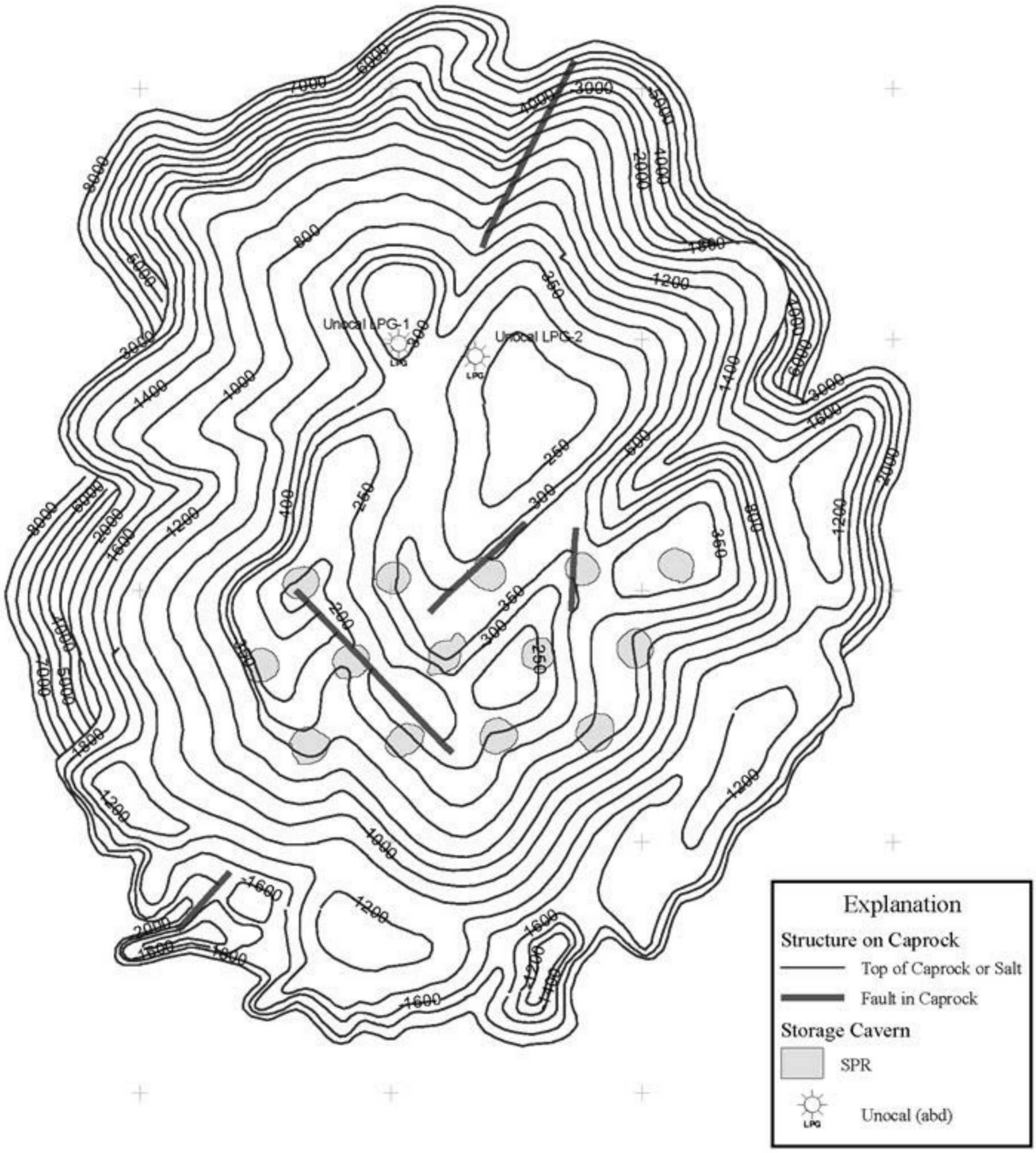

Figure 3. 2005 Big Hill top-of-caprock structure contour map.

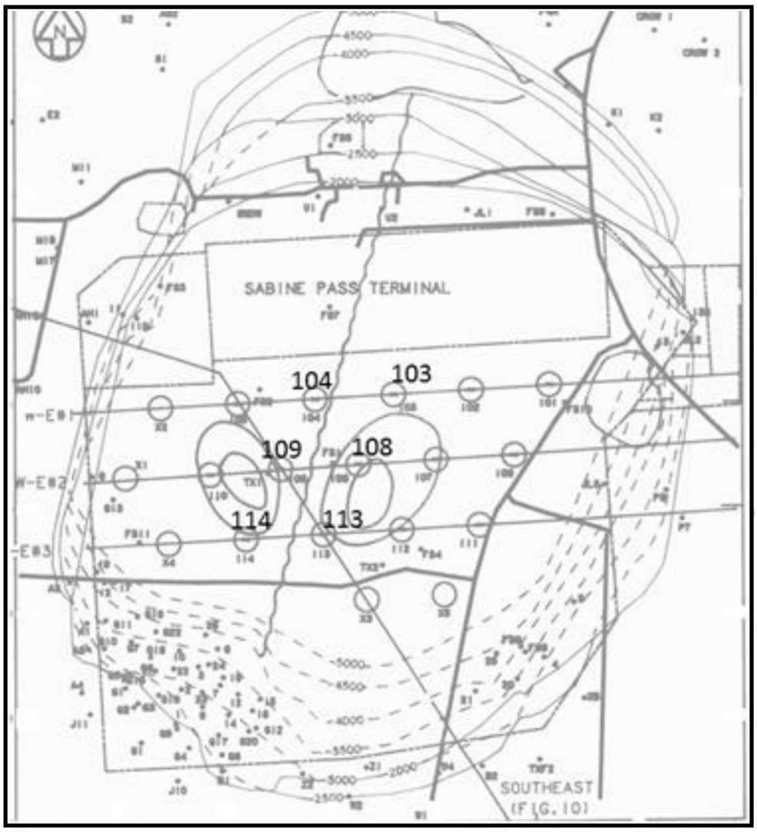

Figure 4. Big Hill top-of-salt structure map displaying location of interpreted spines and corresponding shear zone (Figure 1 from Magorian and Neal, 1988).

Subsidence

Measuring subsidence rates is one tool to monitor cavern integrity. Typically, cavern closure will be expressed at the surface as subsidence. However, at Big Hill, cavern closure rates are occurring at a greater rate than represented by the subsequent surface subsidence (see Figure 5). Three of the SPR sites exhibit very good agreement between subsidence and cavern closure volumes. Out of the four SPR dome sites, Big Hill salt has the fastest creep rate, but the lowest surface subsidence rate. This discrepancy is due to the very thick caprock. Subsidence effects are most likely distributed over a greater surface area.

Subsidence surveys have been conducted annually or biennially since 1989 over the Big Hill site. Since 2002, with the addition of 135 new monuments, elevation measurements have indicated continuous surface uplift, specifically over the eastern edge of the site. Figure 6 displays the latest subsidence rates calculated between May 2012 and July 2014. Note the lightest shades of gray indicate uplift. A definitive reason for the uplift has yet to be determined, but continued rise in elevation will eventually, if not already, impact well integrity.

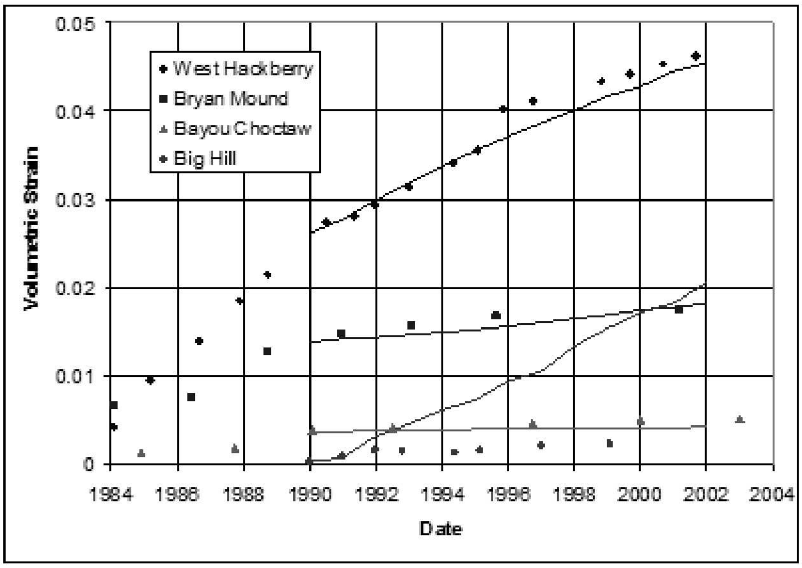

Figure 5. Volumetric strain versus time based on subsidence measurements (symbols) and CaveMan Cavern analyses (solid lines). (Figure 7 from Ehgartner & Bauer, 2004).

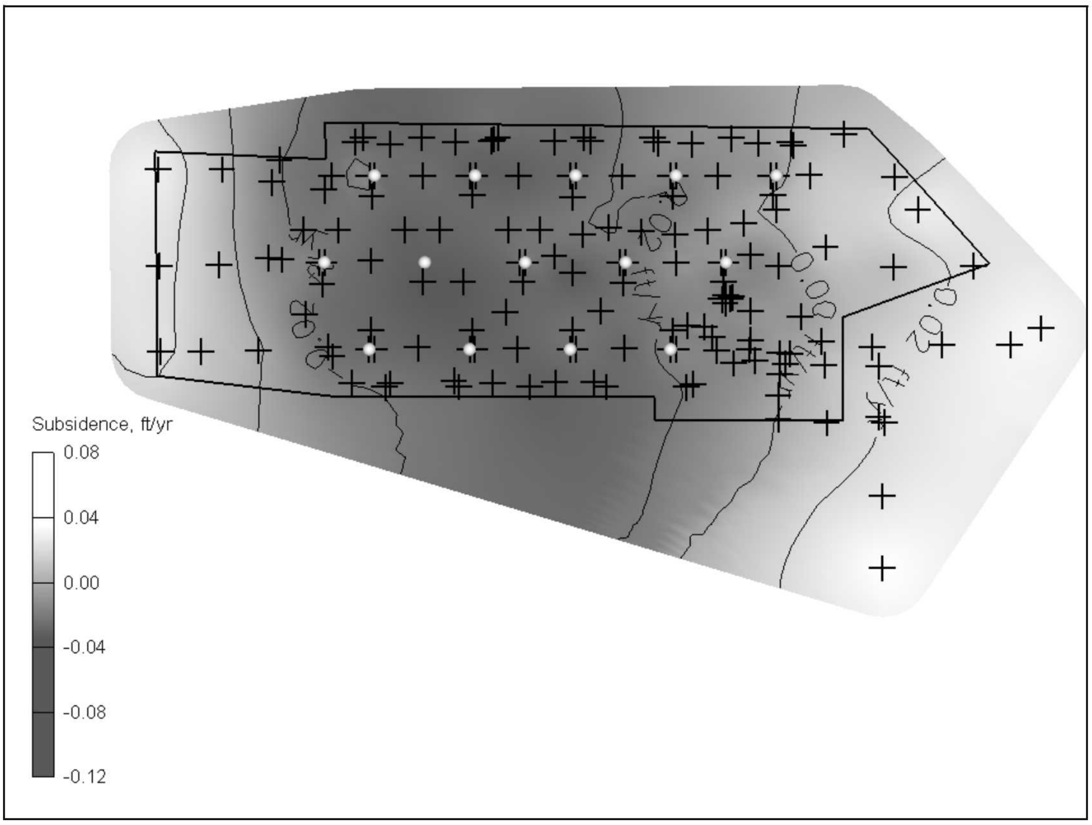

Figure 6. Contour plot of subsidence rates (ft/yr) from May 2012 to July 2014. Monument locations are noted by crosses. Cavern well locations are depicted as white circles.

It is unclear what is triggering the recorded rise in surface elevation. The dome structure-contour maps do not correlate to the measured elevation highs (Figure 7). The mapped spine in the southeastern side of the dome does not account for the elevation gains recorded in both the structural low to the west of the feature nor with the region directly off the dome to the east. Of additional interest would be the surface behavior of regions over other structural highs located around the periphery of the dome, but the DOE does not have monument coverage in those regions outside the SPR property lines.

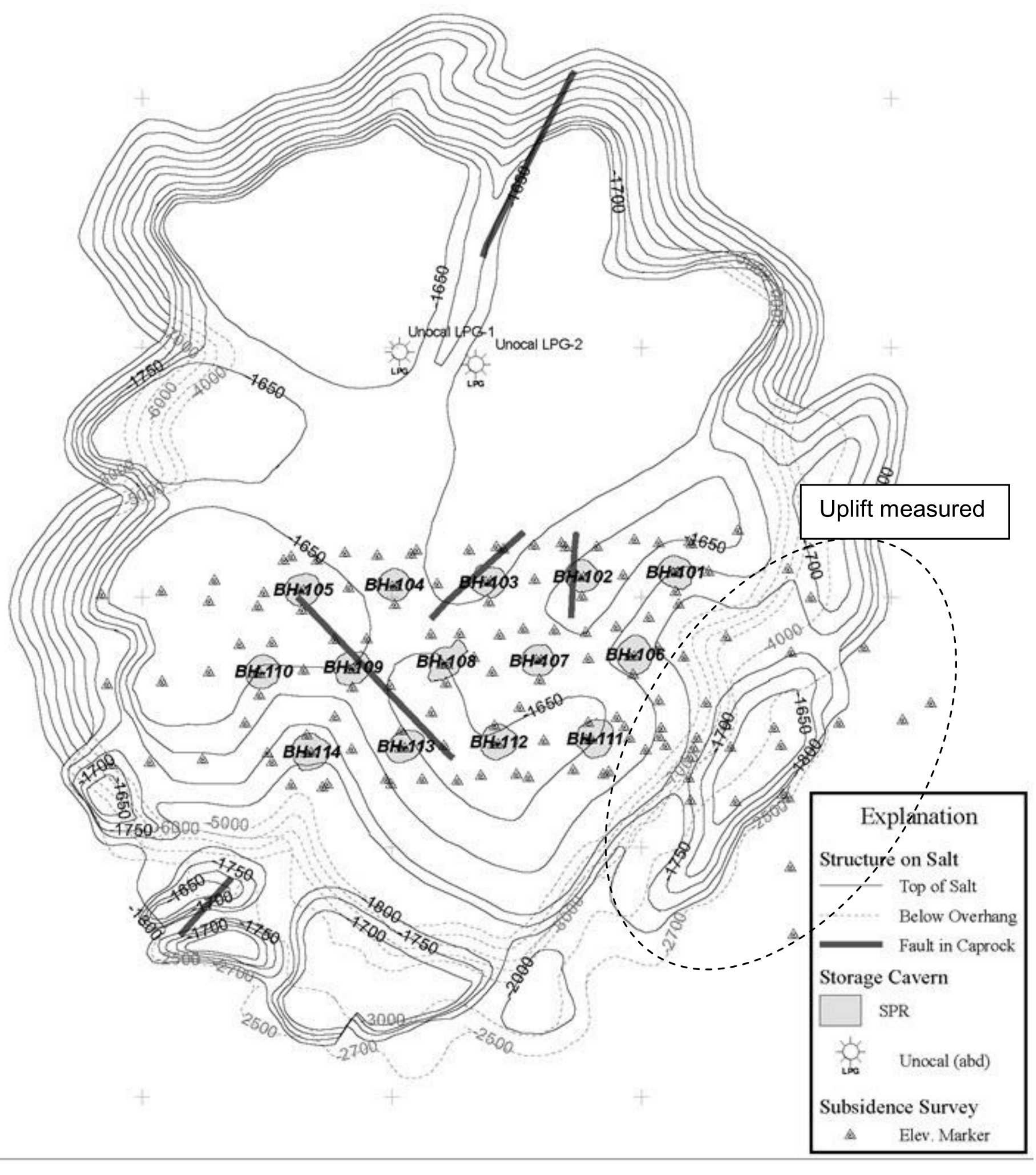

Figure 7. 2005 Big Hill top-of-structure contour map. Displaying location of land survey monuments (triangles) and region of uplift (dashed oval).

Cavern closure rates have been compared to average subsidence rates. The finding was that generally the cavern closure rates correlated with average subsidence rates calculated before the addition of 135 new monuments in 2002. Cavern closure rates no longer correlated after 2002. However, the 135 additional monuments cover regions of the Big Hill site that do not overly the cavern field. These regions are where the majority of survey measurements have been taken that record a gain in elevation.

Ehgartner and Bauer (2004) noted that the surface over the western half of the cavern field displayed uniform subsidence rates whereas the second distinct surface was identified by accumulated uplift over the eastern half of the field, near the edge of dome. The authors noted that the two identified surfaces correlate to a north-south trending active fault mapped by Neal and others, 1993 (Figure 8).

In summary, the report suggested that uplift may be due to rigid body rotation of the massive caprock, whereby faulting creates caprock blocks which are tilted downward in the subsided region above the caverns, and hinge up outside the cavern field.

Another possibility contributing to the uplift is a set of waste injection wells located south of the SPR site. The likelihood of the influence has been studied but a definitive conclusion cannot be made (Lord and Kirby, 2013).

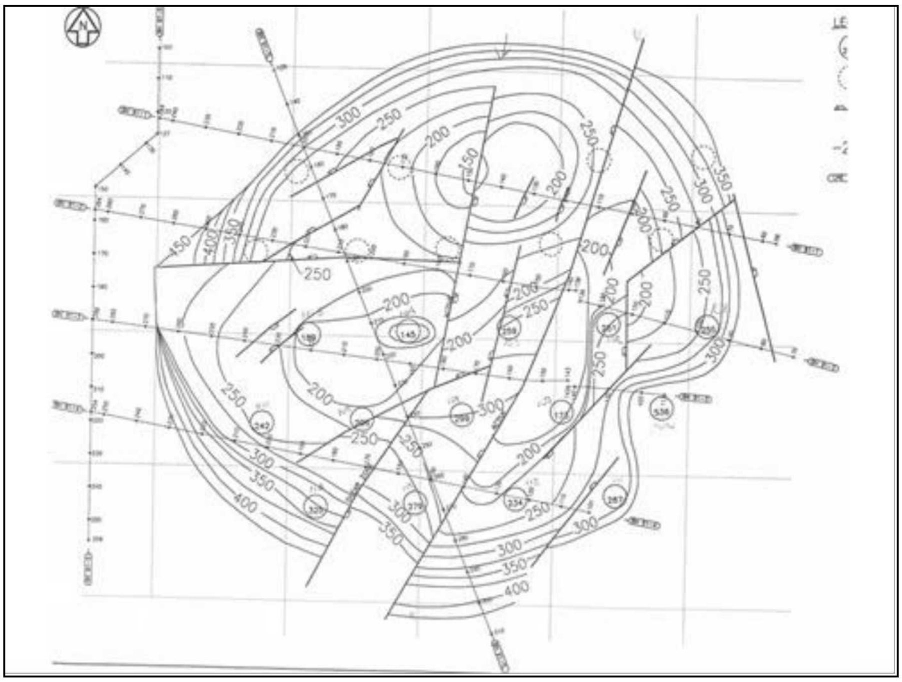

Figure 8. Top-of-caprock structure contour map with fault interpretations by Neal and others, 1993.

InSAR

In an effort to try and understand the subsurface dynamics historic interferometric synthetic aperture radar (InSAR) data was acquired and processed by CGG. InSAR involves the processing of multiple satellite synthetic aperture radar scenes acquired across the same location of the Earth's surface at different times to map surface deformation. The analysis of the data can possibly detect millimeters of motion spanning days, months, year and decades, across specific sites. The intent in regards to the Big Hill site was (1) to confirm the surface uplift trend recorded by land survey, (2) understand the regional surface behavior, and (3) possibly be able to better understand the subsurface source causing the uplift. The InSAR data are presented below with discussion on how those results compare to the historical collection of land survey data, and what additional information the data have provided towards identifying the source causing the response recorded at the surface. However, it should be noted that the historic InSAR data stacks acquired were not tailored for this project, but were acquired as part of the satellites' background scientific missions; hence the data stacks are rarely optimal, but the collection of the data available provide a unique, relatively low-cost, opportunity to detect historical deformation trends.

The area of interest included both the Big Hill salt dome and the High Island salt dome and the region covering the expanse between the two domes. The High Island salt dome was included as a control sample since no storage development has occurred within the domal salt. However, once data was acquired it became clear that the sample density available over the High Island dome was too low to provide any meaningful interpretations. Therefore, these results are not included in this discussion.

Synthetic aperture radar data was acquired from the European Space Agency's (ESA) ERS-1/-2 satellites and from the Japanese Space Agency's (JAXA) ALOS satellite covering a study area that included both Big Hill and High Island. The ERS data stack is comprised of 24 scenes spanning June

1992 to November 2000. The ALOS data stack is comprised of 20 scenes spanning January 2007 to January 2011. Note there is a gap of data coverage between 2000 and 2007 when uplift was first noted at the Big Hill site. The data was analyzed for both point (PS) and distributed (DS) responses. No DS responses were identified for the ERS data. The lack of PS identified in the ERS data could have been caused by less prominent infrastructure or change in infrastructure caused by hurricanes, remediation work, etc. The PS available for analysis, which is sparse, indicates that between 1992 and 2000 the entire Big Hill region was characterized by ongoing subsidence (Figure 9).

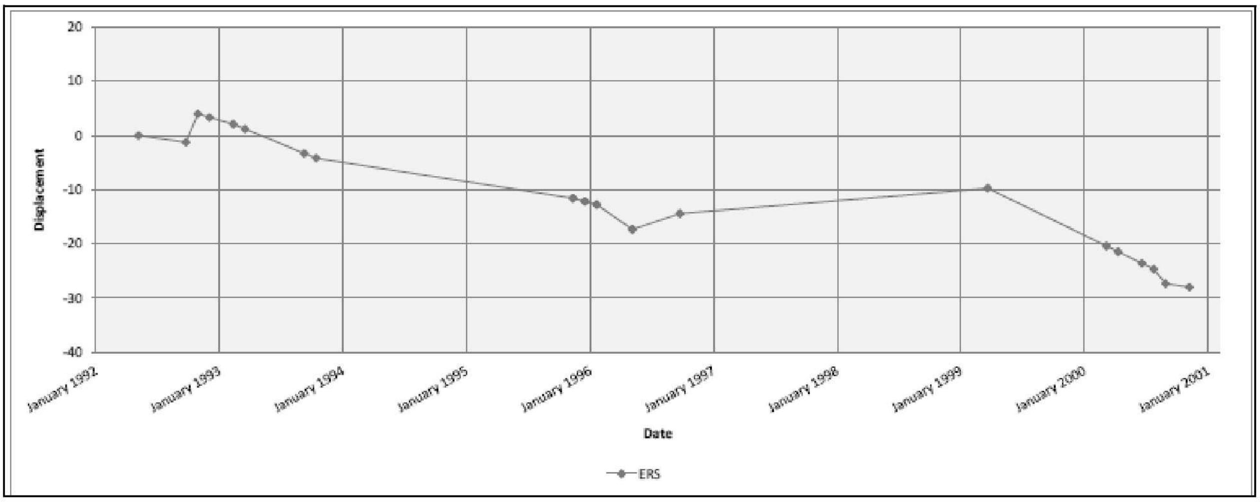

Figure 9. Averaged displacement times-series graph of all PS across Big Hill for 1992-2000

The subsidence rate on average according to the analysis of the ERS satellite data was -3.5 mm/yr between 1992 and 2000. In comparison the average rate calculated between 1992 and 1999 using the site land survey data was -3.8 mm/yr. The average was calculated from measurements recorded at only the cavern wellheads. The rates compare well.

Both PS and DS were identified within the ALOS data spanning from 2007 – 2011. The ALOS satellite data uses a longer radar wavelength than ERS, which improves temporal correlation. This along with the more regular acquisitions allowed for identification of DS across the Big Hill site. Figure 10 displays DS points distributed over the Big Hill site. Figure 11 displays the DS data broken up into groups which allows for a more in depth visualization of the surface behavior across the Big Hill site. Displayed in the plot is the cumulative displacement average for each selected group. The information from the plot infers that subsidence is occurring over the western region of the site, whereas uplift is noted along the eastern edge. The plot suggests that the subsidence behavior across the site changes from a general subsiding trend to a gradual uplift around the location of the boundary between groups 2 and 3. This location coincides, generally, with the area of the mapped caprock graben fault block (See Figure 8 above).

The time series plot (see Figure 11) indicates that a shift in subsidence rate occurred sometime between 2009 and 2010 defined by the inflection point. The western region of the site was subsiding at -15 mm/yr during 2007 and 2008, whereas the eastern edge of the site was subsiding at -2.5 mm/yr during the same time period. In 2009 the western region slowed to a rate of -2.5 mm/yr, while the eastern region began uplifting at +2.5 mm/yr.

The land survey data acquired since the inception of the site indicates that the uplift across the eastern edge of the site began at least around 2002, if not earlier. 135 monuments were added in 2002 that extended beyond the eastern perimeter of the site. Figure 12 displays a sub sampling of all the data, roughly half, presenting cumulative elevation change through time. It is clear that some regions of the site have been uplifting since at least 2002, while others regions continue to subside.

Marked on the plot is the time range over which the historic ALOS InSAR data was collected. The range coincides with exactly one land survey. This may help explain why the InSAR infers uplift beginning in 2009 while the land surveys indicate uplift started as early as at least 2002. It is important to note that these are two completely different data sets that were each designed differently, where one measures a region and the other a set of points and over different frequency intervals. InSAR data is collected at a higher frequency and may detect dynamic trends seen only over a short time frame or within a small region with more data coverage than the land surveys can provide. In addition the reference point differs between the two techniques. However, both data sets confirm uplift is occurring and predominantly over the eastern region of the site.

In addition the InSAR data were analyzed from a north–south direction by plotting cumulative displacement averages for each of three horizontally selected groups spanning the site (Figure 13). The general trend noted, from a north-south direction, is that the site is subsiding at a faster rate towards the northern direction. A possible influence causing the rates to slow towards the south is the presence of a set of waste injection wells located south of the SPR site. The waste volumes have been studied, but it is not conclusive if waste injection could be contributing to the change in subsidence rates measured.

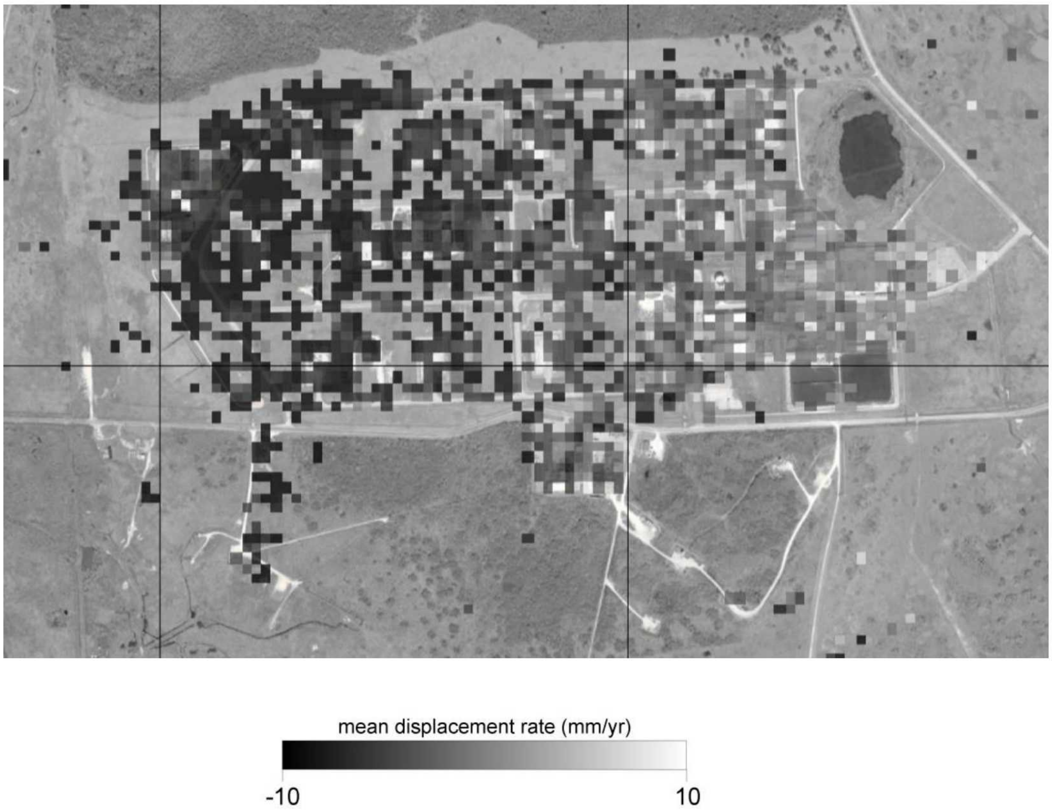

Figure 10. ALOS DS mean displacement rate (mm/yr) across Big Hill from 2007-2011.

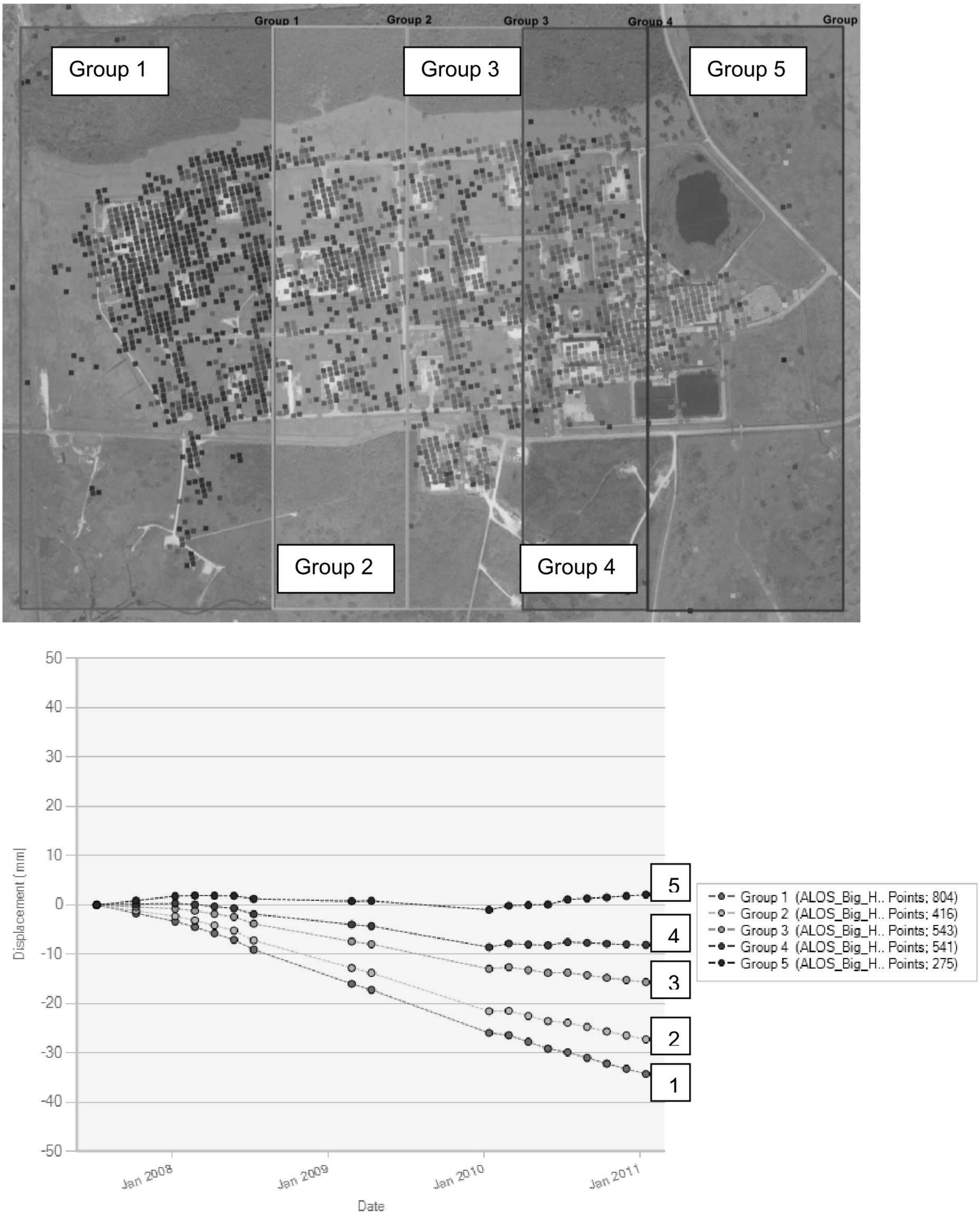

Figure 11. Vertical sliced groupings of ALOS DS data along with a plot of the cumulative displacement average (mm) for each selected group.

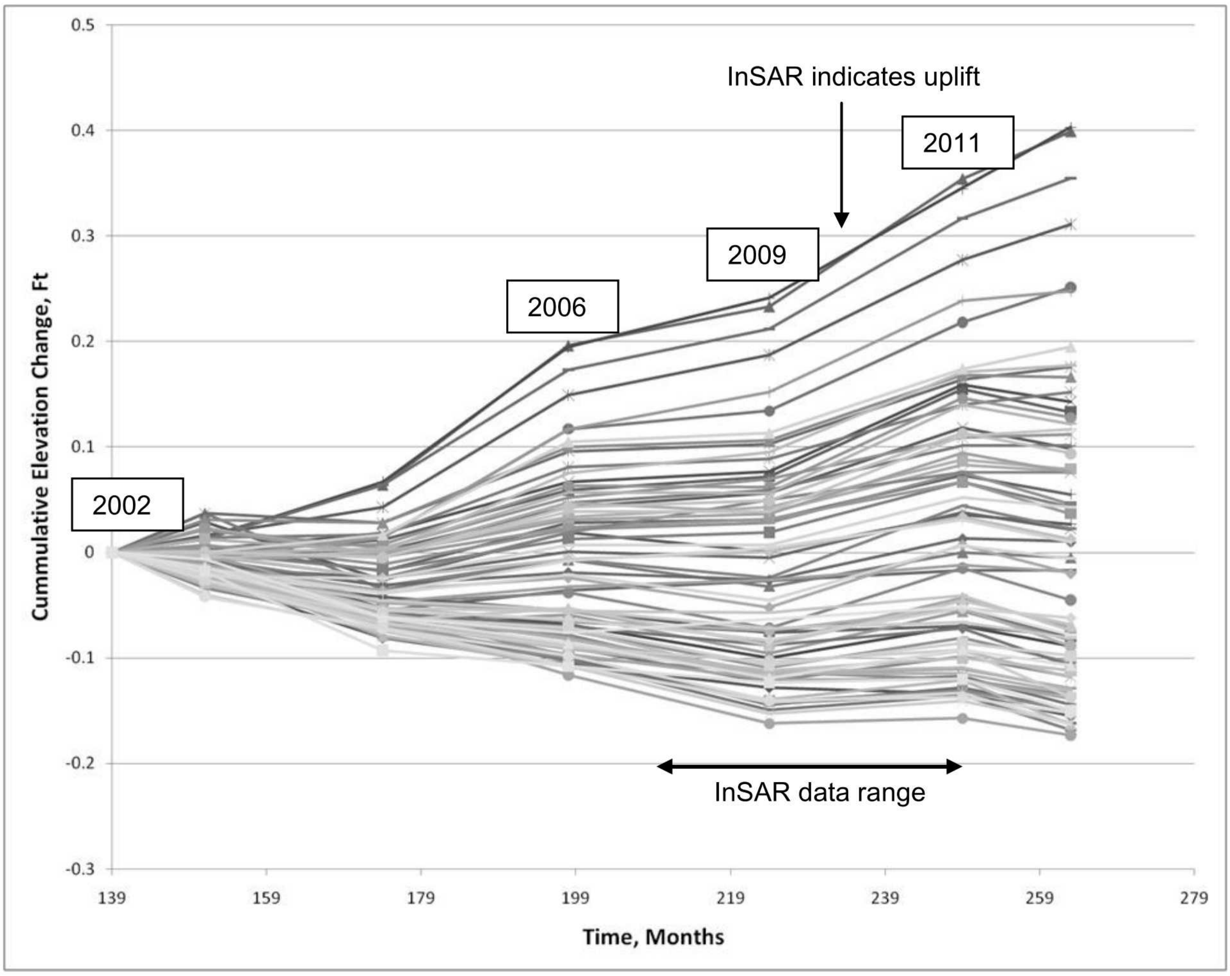

Figure 12. Plot of cumulative elevation change (ft.) over time for a subset of subsidence monuments at Big Hill.

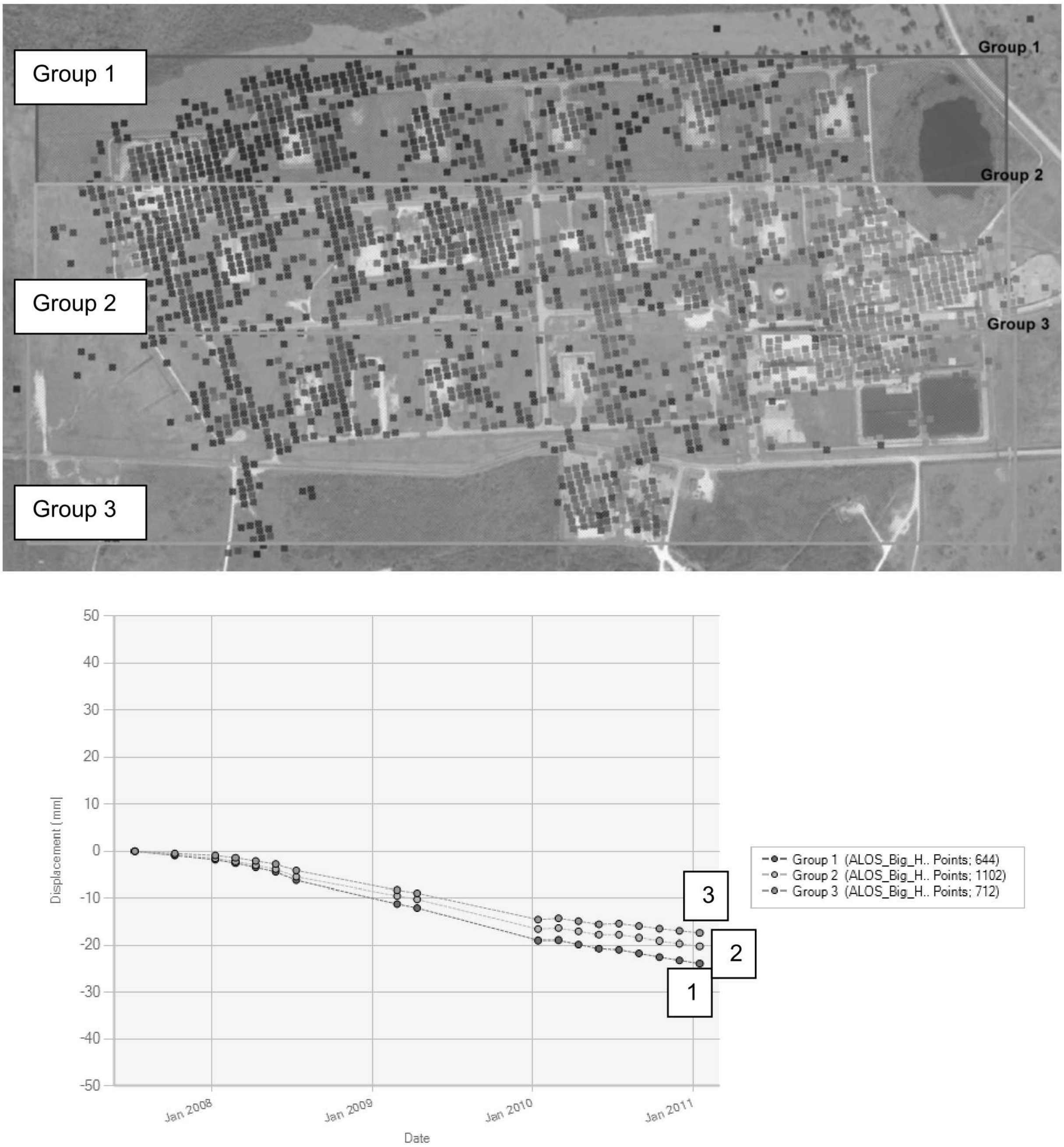

Figure 13. Horizontal sliced groupings of ALOS DS data along with a plot of the cumulative displacement average (mm) for each selected group.

Discussion

Land survey measurements indicate that uplift is occurring over portions of the Big Hill SPR site. Historic InSAR data was acquired to (1) confirm the surface uplift trend recorded by land survey, (2) understand the regional surface behavior, and (3) possibly understand the subsurface source causing the uplift.

The InSAR analysis confirms surface uplift is occurring over the Big Hill site, specifically over the eastern edge. However, the InSAR suggests uplift began in 2009 whereas the land surveys indicate uplift started as early as at least 2002. The fact is that the two data sets are hard to compare one to one because of the difference in (1) reference point, (2) data sets, (3) design of data collection, and

(4) sampling density. Either way, both sets of data support that surface is currently uplifting. The type of movement is applying strain to the cavern well bores, which will eventually cause the wells to lose integrity.

InSAR data collected and analyzed outside the immediate Big Hill area was not reliable; hence regional behavior could not be discerned. The data is deemed questionable because the region is covered in grasslands and marsh with low density of infrastructure present.

The source of the uplift is still not understood, but the addition of the information provided by the InSAR analysis certainly helps towards narrowing down the possible theories. The ALOS data indicates that since at least 2007 the rate of subsidence across the site decreases from a west to east direction. The subsidence behavior changes between 2009 and 2010 with a decrease in subsidence rates along the western half of the field and with a gradual uplift across the eastern half of the field and off the dome. The boundary between reduced subsidence rates and measured uplift occurs along the region of the mapped caprock graben fault. The current thought is that the uplift recorded at the surface is caused by rotational fault block movement. This current fault movement may have been initiated by salt moving up or perhaps by the waste injection into the caprock occurring south of the Big Hill site. The uplift measured off the dome to the east may be explained by the underlying fault system originally initiated by the growth of the salt dome at depth where a fault system can start at the apex of the salt dome and extend at angle up and out over the dome edge.

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