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movement over Bryan Mound**

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InSAR for monitoring cavern integrity: 2D surface movement over Bryan Mound

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Abstract

Surface deformation is important to monitor above solution-mined caverns in order to help ensure the ongoing safety, and to track the long-term geomechanical stability, of these underground assets. InSAR is becoming an increasingly utilized technology within the solution mining industry to fulfill subsidence monitoring needs as this approach provides highly accurate and regular measurements of movement above storage facilities, salt domes and the surrounding area.

The Bryan Mound storage site in Texas is part of the Department of Energy's Strategic Petroleum Reserve (SPR), which contains the world's largest supply of emergency crude. As such, monitoring the health of the caverns located at this facility is of national interest.

Two stacks of radar imagery collected by the Cosmo-SkyMed constellation of X-band satellites are currently being used to monitor subsidence over the Bryan Mound site. The use of two separate stacks (acquired from ascending and descending polar orbits) is particularly advantageous as this allows signals from two viewing geometries to be identified and combined in order to isolate and decompose results into true vertical and east-west horizontal movement vectors.

In the case of Bryan Mound, vertical subsidence observed at this site is coupled with the presence of predominantly west-ward horizontal motion over much of the dome. An updated processing has been carried out in spring 2018, which more completely captures recent movement patterns occurring over the past 1.5 years.

This paper will describe the InSAR work that has been carried out over the Bryan Mound salt dome to date, with particular emphasis placed on the utility of 2D deformation results in helping to characterize the integrity of underground storage caverns. Future work on the integration of detailed ground movement results with other types of monitoring data (for instance with cavern pressure information) to provide a more complete picture of cavern and dome health will also be explored.

Key words: InSAR, Strategic Petroleum Reserves, Subsidence, Caverns, Instrumentation and Monitoring, Rock Mechanics, DOE (US Department of Energy), Bryan Mound

Introduction

The Bryan Mound storage facility is one of four salt domes that make up the U.S. Strategic Petroleum Reserve (SPR). Maintained by the United States DOE (US Department of Energy), these four sites provide the largest emergency supply of emergency crude anywhere in the world. As a result, these assets are of vital importance to monitor to ensure their continued integrity. Surface subsidence has long been used as an indicator of the health of underground assets, with any changes in surface elevation among one of the primary indicators relied upon for the identification of possible cavern integrity issues. In fact, subsidence monitoring over brine mining caverns is required on an annual or semi-annual basis in both the state of

Texas (Railroad Commission of Texas Oil and Gas Division “Statewide Rule 81”) and Louisiana (Statewide Order No. 29-M-3, 2014), where all four SPR sites are located.

As part of the cavern integrity monitoring program over Bryan Mound, subsidence surveys have been carried out using monuments since 1982 on either an annual (1982 – 1992, 2009 – present) or biennial (1992 – 2009) basis (Lord 2017). In 2010, a GPS and tiltmeter system was also established over abandoned Cavern 3, which has exhibited the highest rates of subsidence in the past (Lord 2009). However, ground surveys have faced numerous challenges over the years including loss/destruction of monuments and markers, inconsistencies and errors in readings between years of data collection, low spatiotemporal resolution of the monument grid, and instability of reference benchmarks due to natural subsidence trends all along the Gulf Coast.

In recent years, Interferometric Synthetic Aperture Radar (InSAR) has been introduced as a subsidence monitoring method to address some of the challenges associated with conventional ground-based surveying over Bryan Mound, particularly with respect to the spatial coverage of the data points and the frequency of measurement collection. Multiple stacks of imagery have been collected since 2015 over this site, with the latest InSAR analysis carried out in April 2018. Results were used to characterize subsidence trends over the salt dome and surrounding area to further understand subsurface dynamics, particularly over Cavern 3. This paper describes the results of this analysis, with both vertical and east-west horizontal surface trends highlighted, including a comparison to sub-surface cavern pressures.

Site

Located near Freeport, Texas the Bryan Mound salt dome is a cylindrical dome overlain by caprock up to 400 ft thick and contains 21 mined caverns (Figure 1). The first interception of salt occurs at approximately -1050 ft in elevation and contains a high concentration of anhydrite (up to 20%). Prior to the DOE’s purchase of the dome, five of the caverns were subject to uncontrolled leaching, resulting in large and odd shaped caverns (Lord 2017). Cavern 3 has since been abandoned, with the remaining four of the original five still in use. The more recent 16 caverns were leached by the DOE and are cylindrical in shape at depths of approximately 2,000 feet (610 meters). 20 caverns in total are used for the storage of oil.

The caprock is divided into two regions separated by a dominant northeast-to-southwest trending boundary shear zone, with additional shear zones present. The caprock has the greatest thickness over the northwest region, where an isolated region of salt is located which may correspond to the most recent movement of salt upward (Lord, 2007). Mining of sulphur took place at the Bryan Mound salt dome before being designated as an SPR site, creating voids in the caprock that correspond to areas of present-day subsidence. The Bryan Mound dome is also the most heterogeneous, with more impurities than the other SPR domes.

Historically, the highest rates of movement have been observed over Cavern 3, while the lowest have been measured over the northeast corner of the dome (Lord 2017). Subsidence rates identified from the ground survey carried out in 2016 were found to be -0.54 inches/year (-13.72 mm/year) on average.

Methodology

Synthetic Aperture Radar (SAR) satellites acquire images of the Earth’s surface by emitting electromagnetic waves and analyzing the reflected signal. A number of satellites are continuously circumnavigating the globe, collecting stacks of SAR images which have built up over time going as far back as 1992 over many parts of the world. From these images, changes in the reflected signal (phase change) are captured, and then analyzed to identify surface deformation and other changes in the Earth’s surface over time.

The most basic form of InSAR is Differential SAR Interferometry (DInSAR), which looks at comparing the changes in the returned phase values between two SAR images. Since the wavelength of the radar signal is known, changes in the reflected values between the two images are converted to ground movement. (This is done after any contributions to the phase signal by topography are accounted for with a DEM). The precision of the measurements obtained in the resulting DInSAR-derived displacement map is on the order of one centimeter.

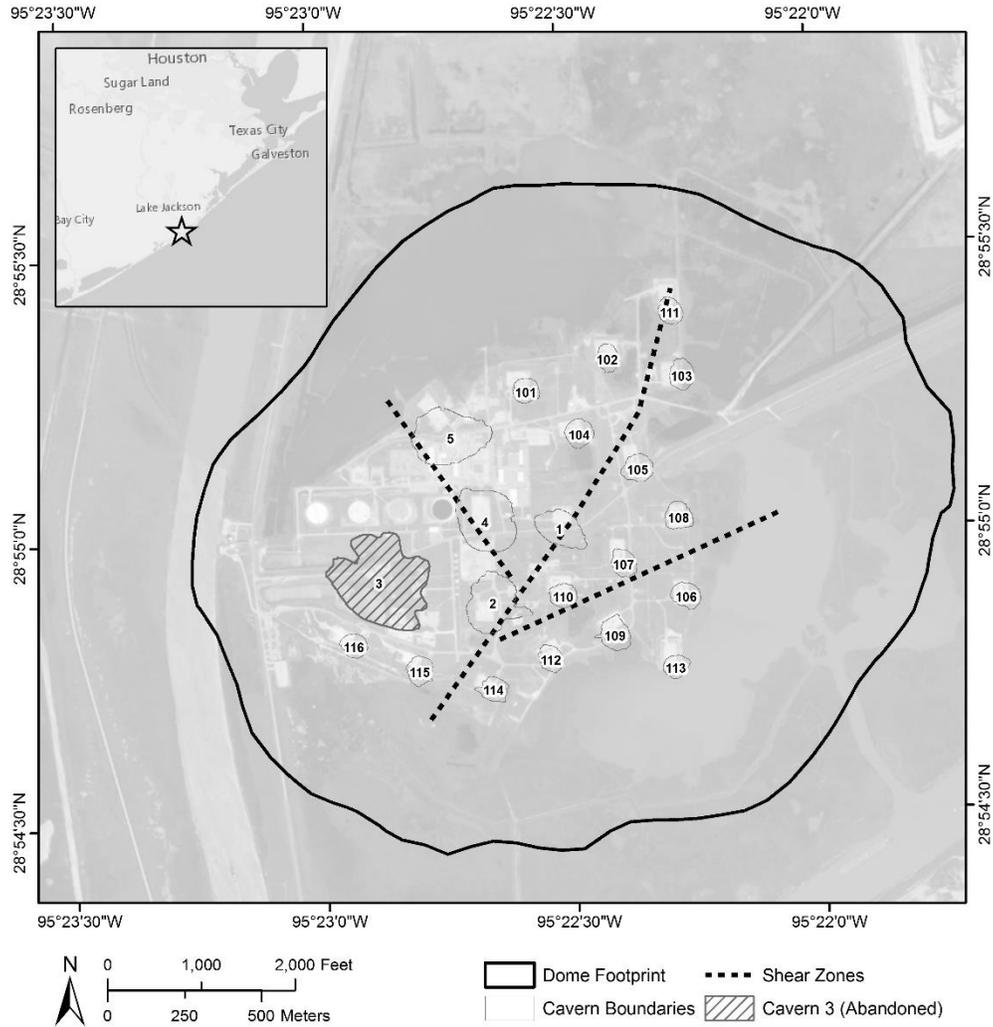


Figure 1: Bryan Mound location, orientation and cavern distribution.

Advanced forms of InSAR build upon this premise by analyzing changes in the reflected phase values over stacks of radar images (15 – 20) that are built up over time. The latest generation of algorithms improve the precision of the deformation measurements by modelling and removing any atmospheric contributions to the signal phase. This approach yields clouds of measurement points that are identified from the reflected signals of naturally occurring features on the ground. Both point-wise radar targets (individual features such as buildings, well heads or rocky outcrops) and area-based radar targets (sparsely vegetated areas or uncultivated fields) are exploited with this latest generation of multi-interferometric approaches. This analysis over Bryan Mound utilizes TRE Altamira’s proprietary SqueeSAR™ algorithm (Ferretti et al. 2011).

Due to the combination of the Earth’s rotation and the satellites sun synchronous orbits, an area can be imaged during satellite transit from both North-South (descending acquisition geometry) and South-North (ascending acquisition geometry). As a result, the same area can be analyzed from two different acquisition geometries since SAR satellites acquire imagery on an angle that deviates from the vertical known as the Line-of-Sight (LOS). The main benefit is that the two data sets can be combined and decomposed using vector geometry to estimate true vertical and east-west horizontal vectors of movement. (LOS sensitivity to possible motion in the N-S direction is negligible as this direction corresponds approximately to the flying direction of the satellites.)

InSAR has already been established as a methodology for monitoring the health of underground assets including seasonal gas storage in depleted reservoirs (Teatini et al., 2011), underground CO₂ storage in geologic formations (Ringrose et al., 2009), geothermal production areas (Eneva et al., 2013) and as a method to monitor aquifer depletion (Hernández-Espriú et al., 2014). This technology has also been employed over solution mined caverns, including Bryan Mound and Big Hill of the SPR, as well as the high-profile case of the Napoleonville salt dome in the area of Bayou Corne, LA.

Results

SAR imagery has been collected over Bryan Mound using the Cosmo-SkyMed constellation of satellites since October 2015 (Table 1). TRE Altamira's SqueeSAR data processing algorithm was applied to identify stable radar scatterers, yielding point densities between 5,079 to 8,677 measurement points per square mile (1,958 to 3,345 measurement points per square kilometer). The use of two different satellite geometries allowed for the decomposition of measurements into precise estimations of the vertical (Figure 2) and (east-west) horizontal (Figure 3) components of motion.

Table 1: Summary of the radar data sets collected for InSAR monitoring over Bryan Mound.

Satellite	Geometry	No. of Images	Repeat Interval	Acquisition Period
CSK	Ascending	81	8/16-Days	17 Oct 2015 – 12 April 2018
CSK	Descending	37	16-Days	15 Oct 2016 – 20 April 2018

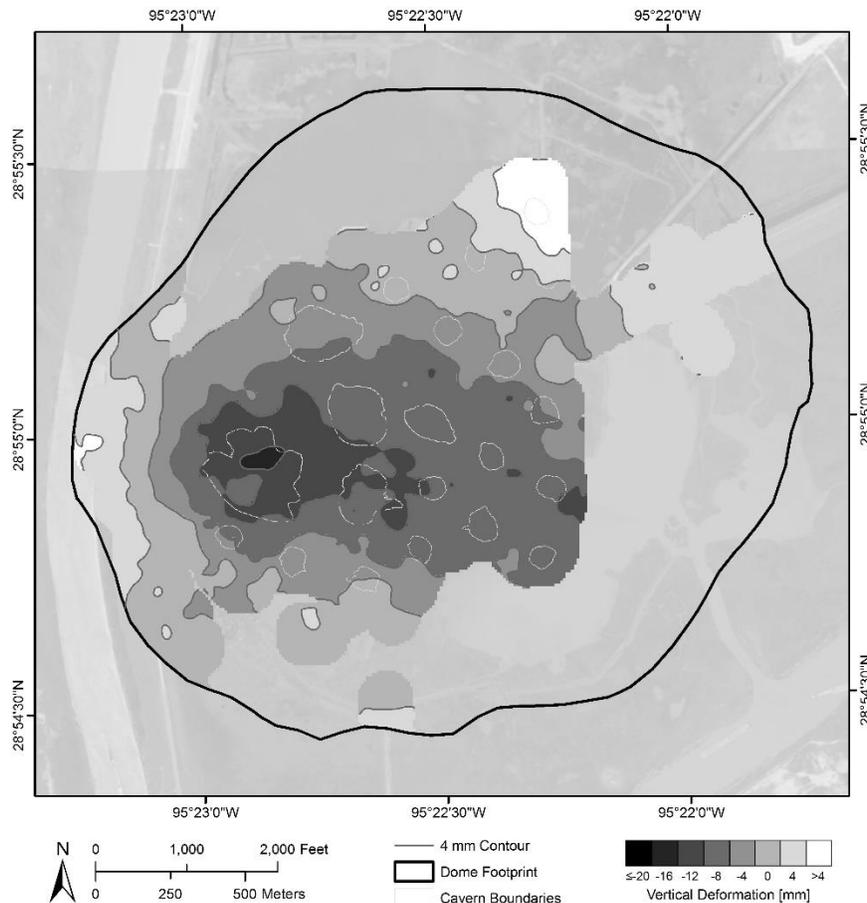


Figure 2: Vertical deformation occurring since October 2016 (period of overlap between both data sets), interpolated from measurement point identified with the SqueeSAR algorithm and clipped to the dome footprint.

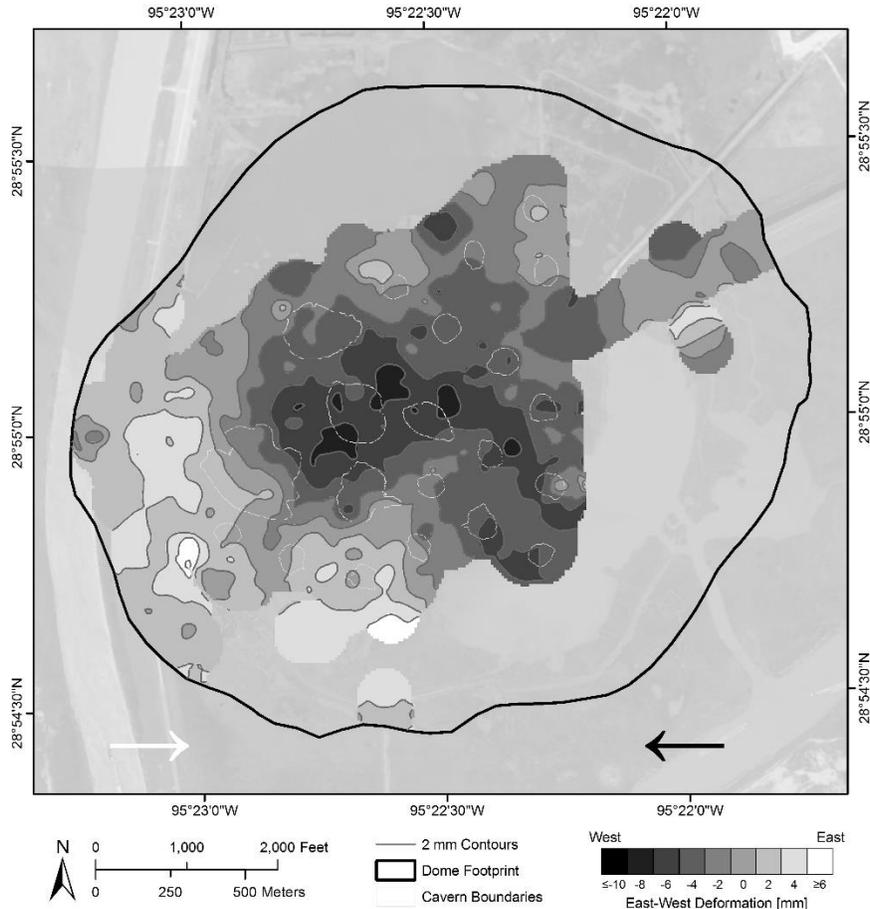


Figure 3: East-west horizontal deformation occurring since October 2016 (period of overlap between both data sets), interpolated from measurement point identified with the SqueeSAR algorithm and clipped to the dome footprint.

Deformation identified from the SqueeSAR analysis carried out over Bryan Mound yielded vertical deformation rates ranging between -0.74 inches (-18.7 mm) to +0.28 inches (+7.0 mm). The highest rates of subsidence were identified over Cavern 3, which is consistent with historical records. Strong subsidence rates were also identified over Caverns 1, 2, 4, 109, 110, 113, 107 and 106 (see Figure 1), all of which are located in the southeastern part of the salt dome (Table 2). Uplift was primarily identified from measurement points located along the outer edges of the salt dome, with only cavern 111 in the northeastern corner of the dome exhibiting uplift over the dome itself.

East-west movement trends were strong over much of the salt dome, with horizontal movement occurring in both directions towards the area of maximum vertical subsidence. As a result, a strong gradient of differential displacement can be identified over Cavern 3 and directly west of this location, particularly when viewing a surface profile cross section over this area (Figure 4).

Westward motion was found to be predominant over most of Bryan Mound, especially over the central part of the dome and in the direction of Cavern 3. The strongest rates of western motion were identified over shallow Caverns 1, 2 and 4, as well as 104, 105, 107, 108 and 113. These caverns are located primarily in the center and outer eastern perimeters of the salt dome. Up to 0.46 inches (11.6 mm) of western motion was identified. Movement in an eastward direction was primarily observed over the western portion of the salt dome, in the direction of Cavern 3 and towards the center of the salt dome. Only three caverns (114, 115 and 116) exhibited eastward horizontal motion, all of which are located along the southwestern border of the cavern field. Up to 0.38 inches (9.6 mm) of eastward movement was observed immediately west of Cavern 116.

Table 2: Summary of average vertical and east-west horizontal motion identified from measurement points identified within cavern surface footprints. (Note for horizontal movement, western motion is represented with negative values)

Cavern	Average Vertical		Average Horizontal		Cavern	Average Vertical		Average Horizontal	
	[in/yr]	[mm/yr]	[in/yr]	[mm/yr]		[in/yr]	[mm/yr]	[in/yr]	[mm/yr]
1	-0.26	-6.5	-0.16	-4.1	107	-0.30	-7.5	-0.09	-2.2
2	-0.32	-8.2	-0.13	-3.3	108	-0.22	-5.5	-0.13	-3.4
3	-0.40	-10.2	-0.06	-1.7	109	-0.27	-6.9	-0.04	-1.1
4	-0.28	-7.1	-0.12	-3.1	110	-0.30	-7.5	-0.07	-1.7
5	-0.21	-5.3	-0.10	-2.6	111	0.09	2.2	-0.03	-0.8
101	-0.15	-3.9	-0.10	-2.5	112	-0.25	-6.4	-0.02	-0.6
102	-0.07	-1.7	-0.09	-2.2	113	-0.29	-7.4	-0.12	-3.0
103	-0.04	-0.9	-0.06	-1.5	114	-0.17	-4.4	0.02	0.4
104	-0.16	-4.0	-0.08	-2.1	115	-0.20	-5.2	0.00	0.1
105	-0.17	-4.2	-0.11	-2.7	116	-0.24	-6.1	0.01	0.4
106	-0.28	-7.2	-0.07	-1.7					

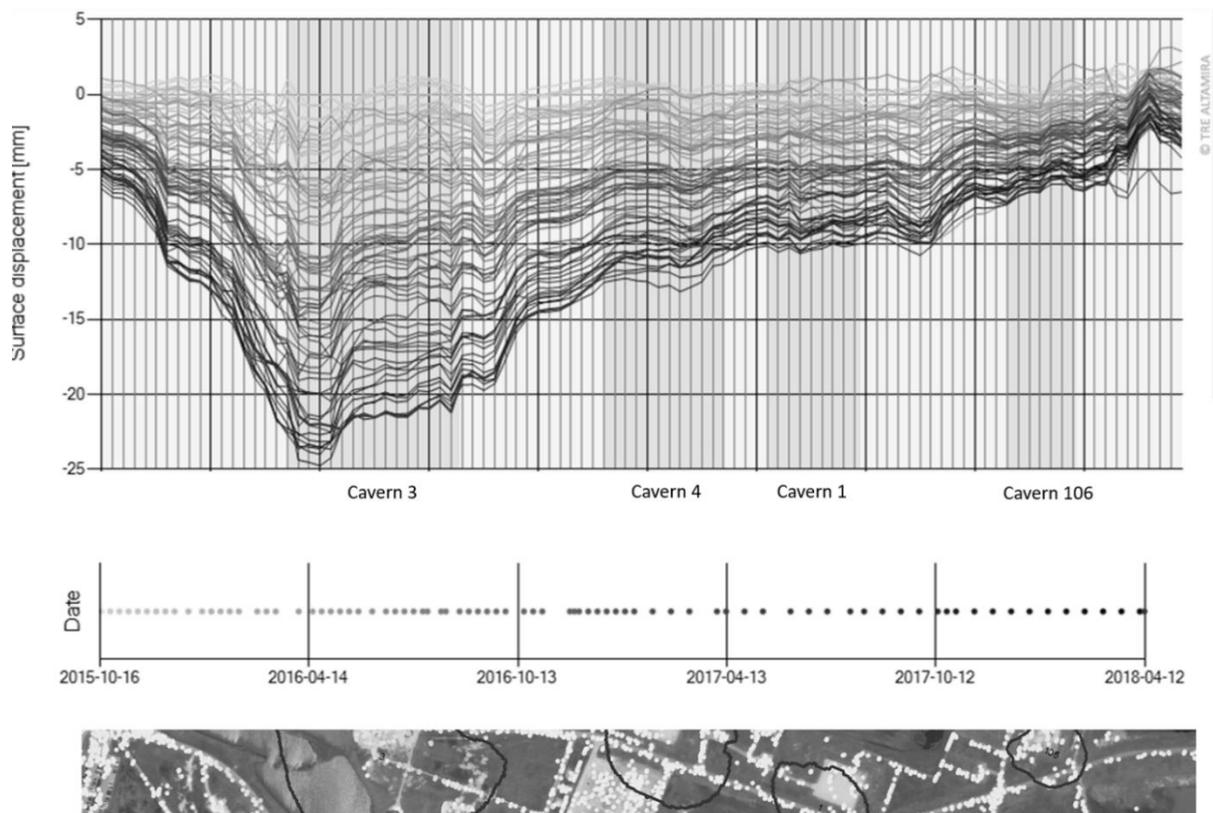


Figure 4: Surface profile cross section over the indicated caverns, illustrating the evolution of the ground surface over time (lighter traces represent the beginning of the data stack).

Discussion

InSAR results were found to yield detailed information on patterns of ground movement over the time period covered by the satellite imagery. In order to explore potential linkages between surface measurements and sub-surface dynamics, the InSAR results obtained from this analysis were examined in comparison with several additional site-specific parameters. The primary objective of these comparisons was to look for surface movement patterns that may be used going forward as potential indicators of cavern integrity.

Cavern 3 and Dome Geology

The geology of the Bryan Mound salt dome is heterogeneous, making for varied and complex interactions between the caverns and the dome itself. Cavern 3 in particular, is subject to several influencing factors, not all of which are adequately characterized as historical production records are incomplete and the cavern itself abandoned. Cavern 3 is known to extend fairly fair horizontally and is relatively shallow compared to the other caverns (Lord 2017). Furthermore, a void has been identified in the caprock over Cavern 3 and there is evidence that some of the caprock has been collapsing into this cavity, making this area of the dome unstable. Surface subsidence rates are the highest at this location, and any accelerations in movement dynamics would be a key indicator of threatened cavern integrity. As of now, displacement rates identified from the InSAR analysis are strongest over this area, but rates are consistent over time in both the vertical and horizontal direction.

Shear zones are zones of impurities and/or compositional change that separate salt spines. Bryan Mound is dominated by three main shear zones (Figure 1), with more possibly present. As these zones represent areas vulnerable to higher creep rates, salt falls and preferential leaching, these locations were examined in relation to rates of surface deformation. While vertical and horizontal motion trends did not appear to follow shear boundary zones with any regularity, this may be due to the wide variability in the composition of these features.

Creep Rates and Salt Fall Occurrences

The highest salt creep rates have been identified within Caverns 106, 114 and 115, and to a slightly lesser extent Caverns 103 and 113 (Lord 2017). These caverns are all located close to the border of the salt dome. While the displacement rates identified over these caverns are not among the highest recorded in either the vertical or the horizontal direction (with the exception of Cavern 106) it is possible that these locations are subject to greater differential movement due to their proximity to the edge of the dome. This would not be accounted for when looking solely at average deformation values.

Over the deeper, cylindrical wells drilled by the DOE, many of the caverns with higher rates of vertical subsidence were also observed to coincide with high number of recorded salt falls. For instance, Caverns 106, 107 and 109 had a recorded 10, 8 and 7 number of salt fall events, and also exhibit some of the largest vertical surface subsidence rates.

Historic Sulphur Mining Impacts

While initially being explored for oil, large deposits of sulphur varying from a few inches to 7 ft thick, were discovered on the Bryan Mound dome (Kirby and Lord 2015) These areas were mined in the early 1900's using the Frasch process, which created large voids in the mined limestone as the sulphur was withdrawn. As the remaining limestone often is unable to support the weight of the overburden, it can later collapse and cause subsidence on the surface. The mining of flat lying sulphur deposits, like those generally found on Bryan Mound, typically results in broad subsidence bowls with strong horizontal movement (Kirby and Lord 2015).

Figure 5 displays the salt dome boundary and storage caverns, along with the 1935 mapped sulphur ore reserves. It can be inferred that the locations of mapped sulphur correspond to the some of the most heavily mined regions of the dome. Caverns 1, 2, 4, 104 and 105, fall both within shallower caprock elevations and over ore reserve zones. These caverns may therefore be located within some of the more fractured and

cavernous regions of caprock, where greater trends of subsidence would be expected. However, while some of the fastest deformation occurring on the dome both vertically and horizontally were identified over Caverns 2, 4 and 1, significant sulphur mining also took place over the northeastern part of the dome and subsidence rates are low in this area (Table 2).

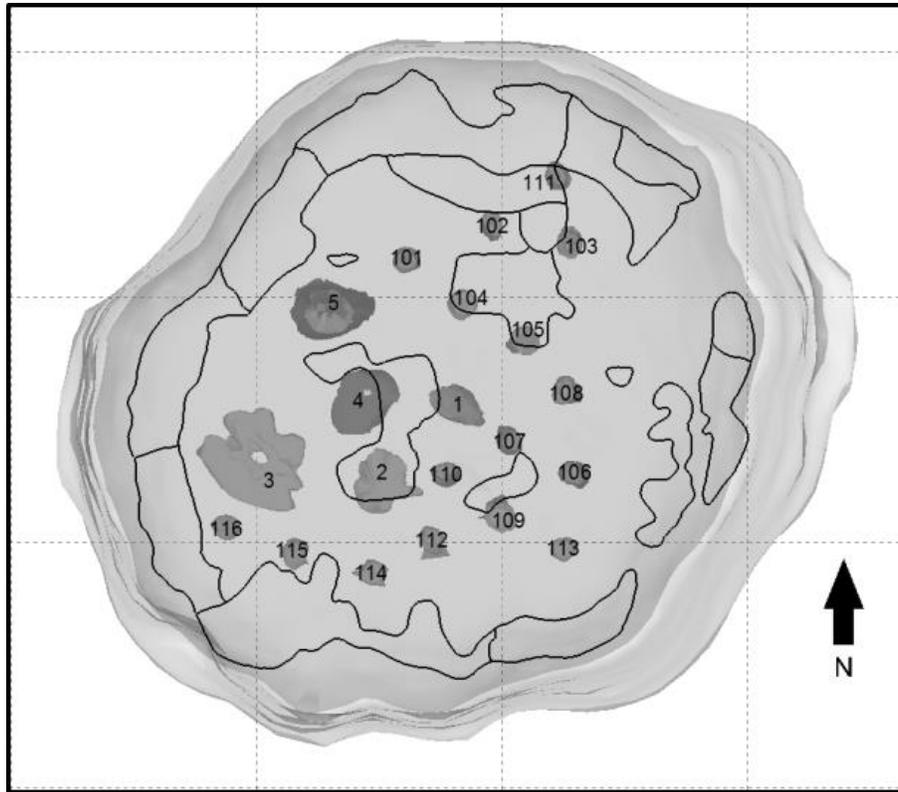


Figure 5: Map of the 1935 sulphur ore reserves and the Bryan Mound SPR caverns. Modified from Kirby and Lord 2015.

Cavern Pressure History

Observations of storage caverns have indicated that pressure fluctuations, often as a response to injection and withdrawal, induce expansion and compression of the cavern. Depending on a variety of factors, including cavern depth, magnitude of pressure changes and the geomechanics of the overburden, these fluctuations can be communicated on the surface, either in real time or with a temporal lag. Historical surface deformation data at Bryan Mound was compared with cavern oil pressures to try and understand how subsurface dynamics relate to the surface.

The pressure histories of all caverns were examined and compared to surface movement behavior to look for possible correlations. Figure 6 shows average vertical and horizontal components of motion over Cavern 108, together with the changes in cavern pressure versus time. When examining movement trends alongside fluctuations in cavern pressures, it was found that by introducing a time lag of 24 days to the surface deformation, possible linkages became more obvious. Arrows indicating changes in pressure trends appear to correspond to changes in movement dynamics in both the vertical and east-west horizontal direction.

Further work comparing cavern pressure histories with surface dynamics will be undertaken. Cavern 108 was highlighted in this paper as this comparison yielded one of the strongest potential correlations between cavern pressure histories and surface movement dynamics (with the introduction of a temporal lag). This

cavern was also observed to have one of the highest levels of anhydrite concentrations based on readings from cavern well logs (up to 19%).

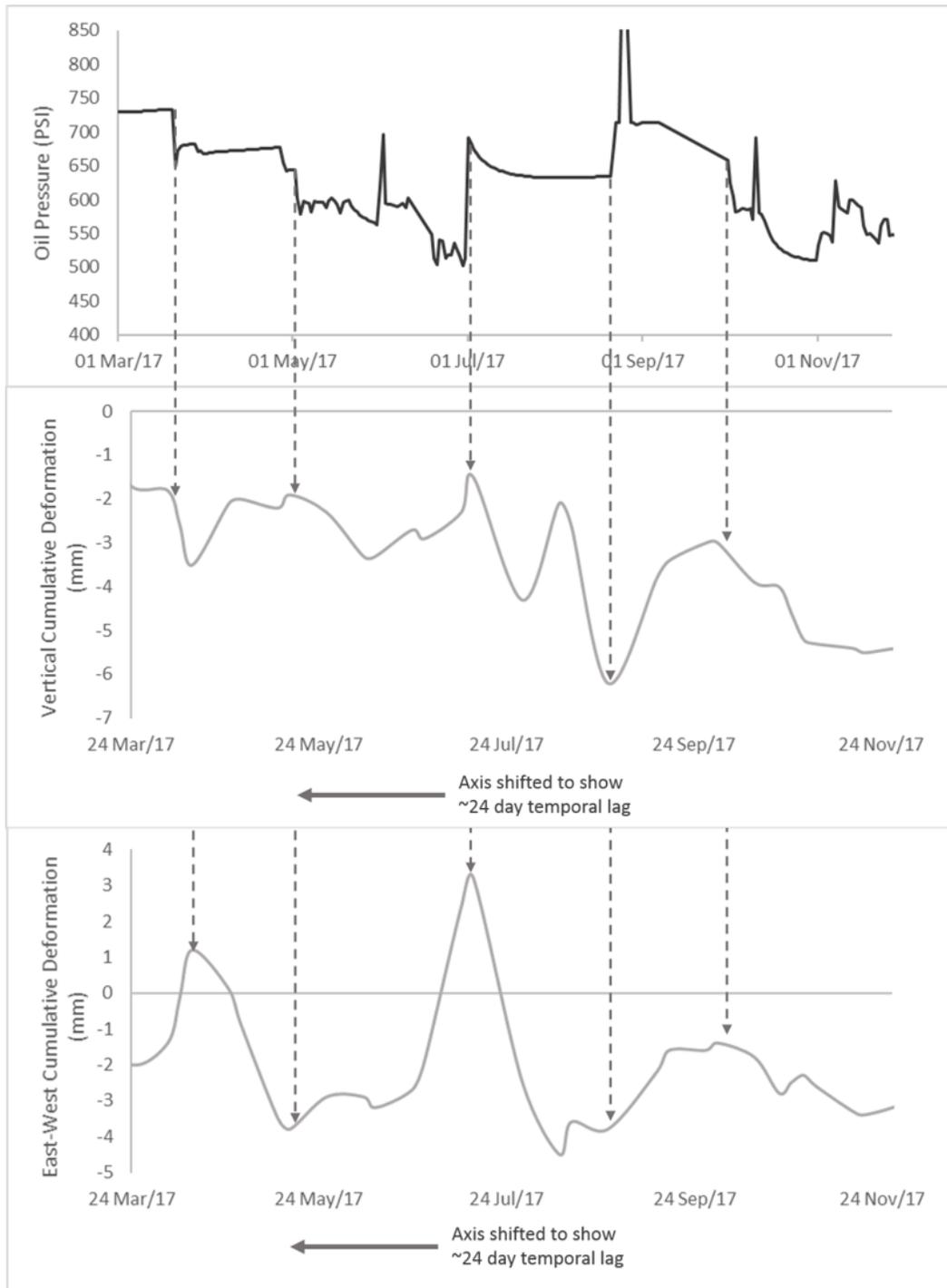


Figure 6: Cavern 108 pressure history (top) with average vertical (middle) and horizontal (bottom) time series of surface measurement points identified within the cavern footprint. Note the axis of the displacement data has been shifted by 24 days. (Cavern pressures exceeding 800 PSI represent MITs and therefore represent well, not cavern pressure.)

Conclusion

Two stacks of radar imagery were analyzed with advanced InSAR techniques to characterize movement trends occurring over the past year and half over the Bryan Mound dome. The main objective of this work was to use surface displacement dynamics as a means to capture information indicative of cavern safety and integrity, particularly over abandoned Cavern 3. With vertical and horizontal movement histories available from stacks of radar imagery collected for the past 1.5 years, possible linkages between surface trends and sub-surface behaviors were examined along with existing information on site geology and cavern storage/production histories.

Over Bryan Mound, the highest rates of vertical movement were observed over Cavern 3, with strong horizontal motion identified as occurring both east and west of this area, going in the direction of maximum subsidence. While vertical displacement trends identified over Bryan Mound are consistent with those reported in the past, the additional characterization of a strong gradient of horizontal motion over the western portion of the dome highlights movement dynamics that were not captured as clearly in the past.

Surface subsidence patterns are an important indicator of sub-surface cavern health, especially when monitoring caverns where structural integrity is a concern such as Cavern 3 over Bryan Mound. The use of InSAR for this purpose is especially promising, since subsidence information is regularly updated on a time scale that allows for non-linear behavior and possible accelerations to be captured. Ongoing work examining the deformation results over this site will be undertaken in an effort to continuously refine data interpretation and integration with other forms of monitoring information and provide a more complete picture of cavern health.

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