

# Detecting mining-induced ground deformation and associated hazards using spaceborne InSAR techniques

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## ABSTRACT

The Delaware Basin, an evaporite sequence spanning west Texas and southeast New Mexico, is well known for the mining of potassium salts, known as potash. Several companies operate mines in the region, primarily using room-and-pillar techniques. However, the region's karst topography is prone to ground subsidence and sinkhole development when triggered by anthropogenic activities. We explored a region of significant ground subsidence encompassing a potash mine. Incorporating synthetic aperture radar (SAR) images from the advanced land-observing satellite (ALOS) and Sentinel-1A sensors, we used interferometric SAR techniques to detect a significant amount of subsidence located in several distinct areas from 2007 to 2011 and from January to November 2016. To investigate the origin of this subsidence, we considered potash mining by analysing the mine operator's production records. We observed a strong correlation between the total subsidence rate in our area and the potash production rate during 2007–2011. Furthermore, we observed a considerable amount of continuous subsidence during 2016, despite the mine operator suspending potash production on 6 May 2016. As such, the observed subsidence could result in deleterious consequences throughout the region if further action is not taken.

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Potash mining; sinkhole precursors; InSAR; ground deformation

## 1. Introduction

### 1.1. Background

Under the barren desert of the Delaware Basin southeast of Carlsbad, New Mexico, large deposits of valuable mineral assets reside beneath layers of anhydrite, halite, sylvite, and other evaporite minerals (Barker and Austin 1993). As such, in the last few decades, the region has become a centre for mining activities, particularly for the extraction of potassium salts, including muriate of potash (KCl) and langbeinite ( $K_2Mg_2(SO_4)_3$ ) (Barker et al. 1996). Used primarily in the production of plant fertilizers, potassium salts are primarily extracted in the Carlsbad potash mines using conventional room-and-pillar mining techniques, in which continuous boring machines grind underground deposits into small chunks, which are then transported to potash mills on the surface (Austin 1980). There, the ore is ground into powder, crystallized, and processed into commercially usable forms, such as fertilizer (Austin 1980).

Naturally, these mining techniques carry an impact on local geologic formations. The removal of thousands of tons of rock no doubt creates vulnerabilities in the surrounding karst geologies. Several

prior instances of deleterious phenomena have been documented – both in the surrounding region and in similar environments across the world. In one example, a sinkhole near Jal, New Mexico could have been formed from the Salado dissolution related to an improperly-cased water well (Powers 2003). Another such publication details notable sinkhole collapses over abandoned brine wells (Class III injection wells) in 2008 just 30 km from our observed area. A 122-m wide collapse sinkhole (known as Jim’s Water Services sinkhole) opened on 16 July 2008 and a 111-m wide sinkhole (known as the ‘Loco Hills’ sinkhole) formed on 3 November 2008 (Land and Aster 2009; Richardson et al. 2009). Subsequent analysis determined the cause of the sinkhole to be anthropogenic due to improper construction of the brine well with regards to the surrounding geologic formations (Land 2013). On the same day, a nearby brine well owned by Jim’s Water Service collapsed into another anthropogenic sinkhole (Richardson et al. 2008). In a more recently studied case in the same region, significant amounts of ground deformation were observed in two sinkholes near Wink, Texas, thought to be the result of aqueous dissolution of underground cavities (Kim et al. 2016). Finally, in a much more serious incident, an improper implementation of room-and-pillar mining in the Berezniaki potash mine (BPM-3) of the Ural Mountains led to the subsequent flooding and collapse of one of the largest potash mines in the world (at the time of publication) (Malovichko et al. 2009; Kovin 2011). Even more striking was the fact that the collapse occurred in an area which was considered to be relatively safe (Andreichuk et al. 2000; Andreichuk 2002). Needless to say, the long-term geological consequences of potassium mining activities require further analysis to evaluate environmental and occupational hazards.

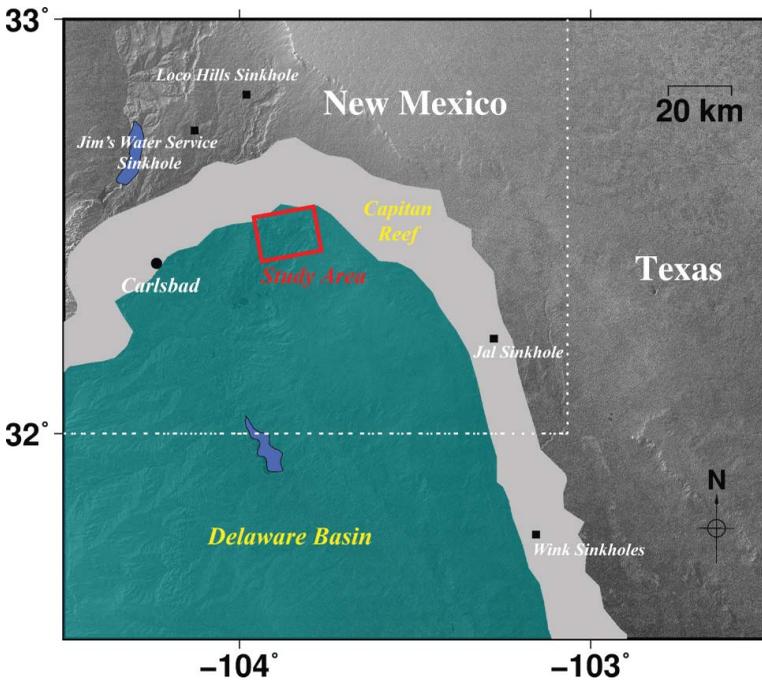
## 1.2. Location

The Delaware Basin from which the Carlsbad Potash District extracts its ores comprises 25,000 km<sup>2</sup> across New Mexico and Texas (Barker et al. 1996). Containing one of the greatest accumulations of evaporite salts in the United States, the area comprises over 80% of U.S domestic potash production (Barker and Austin 1993). The basin includes four relevant formations with significant evaporites: the Castile Formation, the Salado Formation, the Rustler Formation, and the Dewey Lake redbeds (Austin 1980; Barker et al. 1996). The Castile Formation, the oldest, contains halite interweaved with anhydrite and limestone (Lowenstein 1987). Below it, oil and gas are extracted (Barker and Austin 1993). Economically, the Castile and Rustler Formations are not particularly relevant. The potash ore that is extracted commercially occurs in several layers embedded in the Salado Formation, which also contains halite and anhydrite with high water solubility (Barker and Austin 1993). The younger Rustler and Dewey Lake Formations contain halite, anhydrite, limestone, mudstone, and sandstone (Lowenstein 1987).

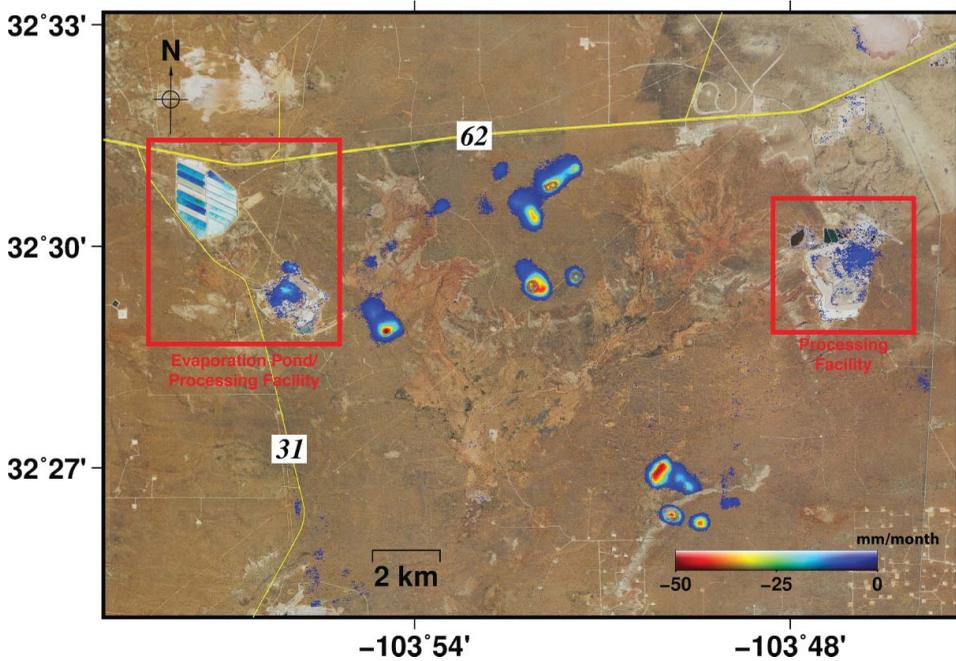
In this investigation, we observed an area 20 km east of Carlsbad, New Mexico (see Figure 1). Rich in mineral resources, the area has been used for potash mining for several decades, and is currently managed by a middle-market mine operator utilizing two shafts as well as a collection of nearby evaporation ponds and processing facilities. The locations of the observed subsiding areas can be seen in Figure 2, surrounded on both sides by evaporation ponds and processing facilities. The surface of the region is characterized by sandy and dry soils underlain by clay minerals (Barker et al. 1996). Vegetative growth is reduced to small shrubs and desert plants due to the semi-arid climate (Austin 1980).

## 2. Methodology

Due to the dangers of potash mining, numerous attempts have been made to observe its environmental and geological effects on surrounding topographies, using global positioning system (GPS) monitoring (Mousavi et al. 2001), geodetic surveys (Szczerbowski 2004), and ground-penetrating radar (Kovin 2011). Unfortunately, limitations of these previous technologies inhibit a comprehensive evaluation due to factors of cost, resolution, and method of observation (Lanari et al. 2004;



**Figure 1.** The location of our observed area (in a red box). The mine is located 50 km east of Carlsbad, New Mexico. The surrounding terrain is flat desert scrublands, underlain by carbonate and evaporite rocks. The ground surface in the arid area is covered by short shrubs and sparse trees.



**Figure 2.** Locations of the subsiding areas as observed by ALOS PALSAR InSAR processing, relative to nearby thoroughfares and mining facilities (labelled in red). The deformation rate was calculated by stacking interferograms with high coherence. However, because the subsiding areas varied spatially and appeared intermittently throughout our study period, this map can only give a glimpse of the unstable areas of the potash mine.

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Gourmelen et al. 2007). With its low cost, high resolution, and robust application, Satellite Interferometric Synthetic Aperture Radar (InSAR) becomes a prime candidate in mapping ground surface deformation at a spatial resolution of metres and measurement accuracy of centimetres to sub-centimetres (Lu and Dzurisin 2014; Lu and Zhang 2014). InSAR technology has been used previously to observe sinkholes in the surrounding region (Paine et al. 2009; Rucker et al. 2013).

In this study, we used two data-sets of satellite radar images. The first 13 ascending L-band radar images taken by the Advanced Land Observing Satellite's Phased Array-Type L-band Synthetic Aperture Radar (ALOS PALSAR) sensor, spanned from December 2007 to March 2011. To evaluate the continuing effects of mining activities in more recent years, we obtained a second data-set – nine descending C-band images taken by the European Space Agency (ESA) Sentinel-1A satellite during 2016. The ALOS PALSAR and Sentinel-1A sensors have revisit times of 46 and 12 days, respectively. Using Sentinel-1A and 1B sensors in tandem would allow for observation intervals as low as 6 days, but most U.S regions are only observed every 12 or 24 days due to the ESA's global acquisition plans. The L-band ( $\sim 23.6$  cm wavelength) ALOS PALSAR sensor has the benefit of maintaining high coherence over the vegetated areas, while the C-band ( $\sim 5.6$  cm wavelength) Sentinel-1A sensor has the advantage of heightened sensitivity to small subsidences due to the relatively short wavelength and thereby phase changes in interferograms. However, it is important to note that the potash mine in question within this study is located in New Mexico, an arid, loosely-vegetated region, and the land cover does not significantly influence the coherence of interferograms. Moreover, the rapid subsidence rates found in mining operations are sensitive to both short and long-wavelength radar sensors. As such, the choice of data sources was made simply due to convenience and familiarity. The interferogram represents the phase changes of two SAR images over the same locations, or in other words the difference of distances from the SAR satellite to the ground surface. After removing the effects of topography, orbital configurations, and noise, the phase values in interferograms can be used to retrieve the ground displacement (uplift, subsidence).

In order to observe the relatively small areas of subsidence with sufficient detail, it was crucial to maintain the appropriate resolution of the SAR images. The 10 and 20 m resolutions of the ALOS PALSAR and Sentinel-1A sensors, respectively, were not ideal for detecting the precise amount of subsidence in our study area. We therefore applied small multi-look factors to increase the accuracy of our observations. Data from the Shuttle Radar Topography Mission was used to remove topographic signatures from our interferograms. Although the digital elevation model was acquired in 2000, the effect of topographic artefacts was negligible due to the relatively flat surface of the region. Because we processed small areas cut from the original coverage, we did not consider the influence of tropospheric and ionosphere artefacts with relatively low spatial frequency. In contrast to the InSAR processing of the ALOS PALSAR data, which followed a more conventional procedure (as described in Lu and Dzurisin 2014), processing the Sentinel-1A data required extremely high precision (better than 0.001 pixel) as well as iterative coregistration of master and slave images. Thus, we employed the enhanced spectral diversity method to meet the requirements for high-precision coregistration (see Prats-Iraola et al. 2012).

After generating the interferograms, we observed the rate of deformation in each of the subsiding areas. Although a volumetric analysis would have been preferable, loss of coherence necessitated that our observations rely on the maximum rate of subsidence at each deforming area during each interval of observation. Also, because we could not calculate the horizontal and vertical deformation through combining the ascending and descending track, we assumed that the observed line-of-sight (LOS) deformation heavily relies on the vertical components. This assumption is plausible in most mining-related situations because a relatively small horizontal deformation generally occurs near the edge of subsiding areas; vertical formation in the peak of each bowl of subsidence is not heavily influenced by marginal horizontal deformation. As a consequence, we converted all observed LOS deformation to vertical deformation through the consideration of an incidence angle. As the physical shape of each subsiding area is generally Gaussian with lateral and vertical symmetry (e.g. Zhao et al. 2013), using the maximum at each site should suffice as a relatively accurate estimate of the

actual amount of deformation. In later comparisons, we summed all of the maximums in order to view the entire subsiding area as a cohesive unit. As we could not obtain production records for each subsiding area, we decided to take the average of the rates of subsidence across all 10 sites in order to draw connections between potash production rates and rates of subsidence. We are able to treat all subsiding areas as one unit because all of the mineral rights in our entire area belonged to the single mine operator.

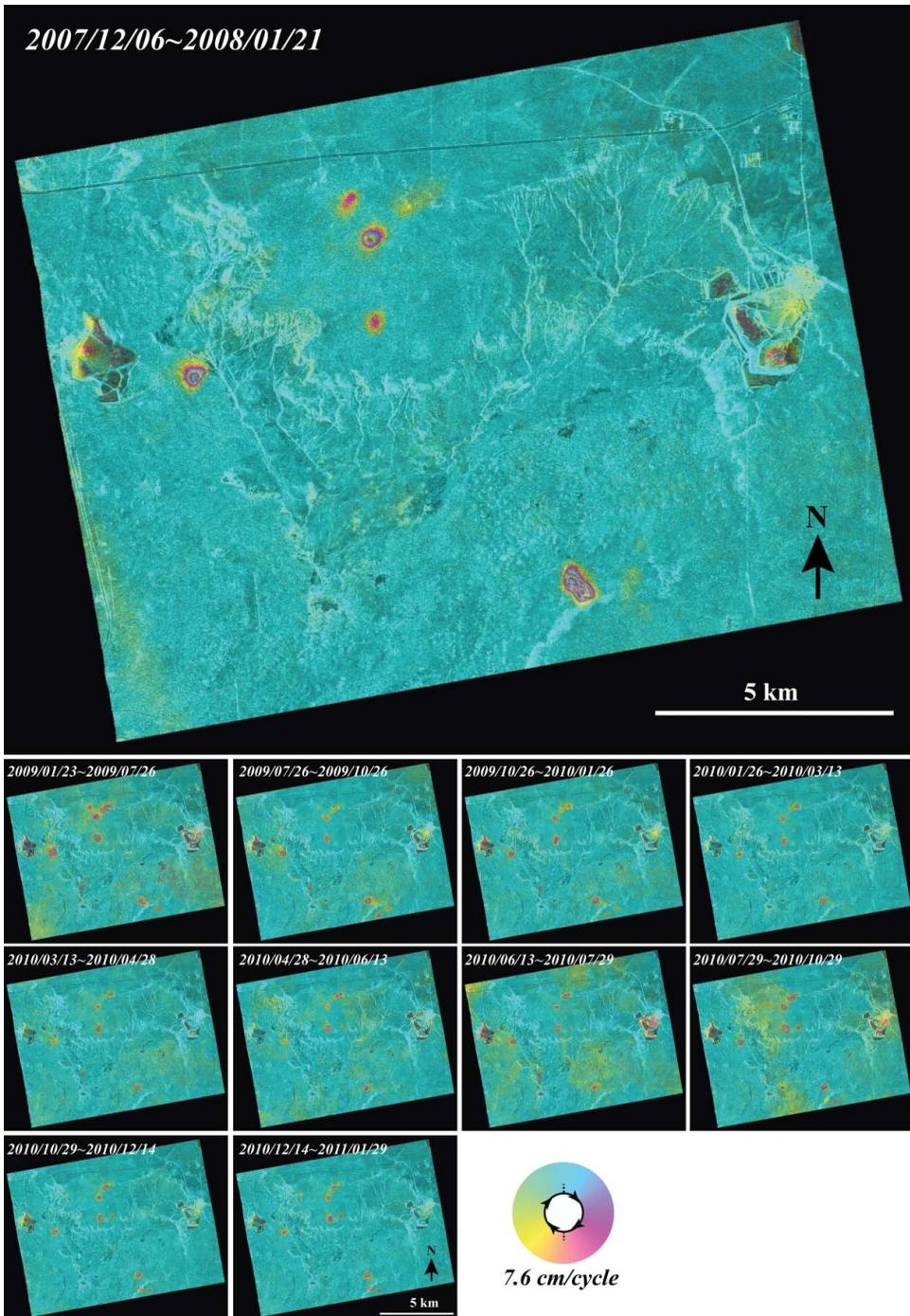
In order to develop a comprehensive analysis of the situation in Carlsbad, New Mexico, we then supplemented our remote observations with groundwater-level records from the United States Geological Survey (USGS) National Water Information System (available at [waterdata.usgs.gov/nwis](http://waterdata.usgs.gov/nwis)), historical precipitation records from the National Oceanic and Atmospheric Administration National Centers for Environmental Information (available at [ncdc.noaa.gov](http://ncdc.noaa.gov)), and seismic records from the USGS National Earthquake Information Center (available at [earthquake.usgs.gov/earthquakes](http://earthquake.usgs.gov/earthquakes)). To gauge the amount of mining activity occurring in the region, we recorded the quarterly financial reports of the company behind the potash mines in our study area. Each report (available at [investors.intrepidpotash.com](http://investors.intrepidpotash.com)) documented the amount of potash extracted during each financial quarter. By analysing a myriad of potential factors that could have played a role in causing the observed subsidence, we were able to construct a multifaceted evaluation of the Carlsbad Potash District's predicament.

### 3. Observations

After obtaining and processing images from the ALOS PALSAR sensor, we generated 11 differential interferograms (Figure 3). As shown, we identified 10 distinct areas of subsidence, ranging up to a maximum average of 62 mm/month per site across all 10 sites. Because of the rapid subsidence rate spanning several years, only a few interferograms that maintained high coherence could be used. As such, we carefully implemented phase unwrapping to maintain coherence and avoid phase jumps in the subsiding areas. One particularly interesting aspect of these sites was the continuously changing locations and intensities of subsidence (Figure 4). Not only did the subsiding areas vary in their rate of subsidence, but each moved a significant amount across the study period, up to 800 m in some locations. Furthermore, some sites seemed to spontaneously appear, disappear, and even branch into multiple independent sites. The rates of subsidence changed significantly throughout the duration of our observations, as shown in Figures 3 and 4. The average subsidence across all 10 sites ranged from a maximum of 62 mm/month between December and January 2008 to a minimum of 30 mm/month between July and October 2009.

With regards to possible environmental factors leading to the subsidence, we considered precipitation, groundwater, and seismic records. In terms of seismic activity, no significant events were recorded within 50 km of our study area during the duration of our observations. Looking at precipitation, we gathered data from a weather station 8 km to the south of the study area. During winter months, from November to approximately March, little to no rainfall was received. In the summer, from May until October, monthly precipitation peaked at approximately 110 mm. To analyse the effect of groundwater levels on the rate of subsidence, we gathered data from two wells within 30 km of the study area. In both locations, groundwater levels remained fairly constant during the entire observation (Figure 5).

Finally, we generated eight differential interferograms (not shown) from the Sentinel-1A C-Band sensor detailing the same area from January to November 2016. However, the observed deformation patterns were much different from that of the ALOS images. Although several distinct sites of subsidence remained and continued to vary in intensity of subsidence, their locations did not vary significantly throughout the duration of our observations. Unlike the ALOS images, during which the rates of subsidence increased and decreased repeatedly, the rates of subsidence in 2016 exhibited a much different pattern (shown later in Figure 6). Up until May 2016, the rate of subsidence remained relatively constant, with small deviations from an average mean subsidence rate (across all 10 sites) of



**Figure 3.** Time-series vertical deformation from December 2007 to January 2011, estimated by ALOS PALSAR InSAR processing. The colour of each figure uses a cyclical colour scheme to clearly depict the rapid subsidence during the period of each observation. One complete fringe represents half of a LOS phase ( $\pi$ ), or 7.56 cm in the vertical direction. Notice the continuous changes in both deformation location and intensity.

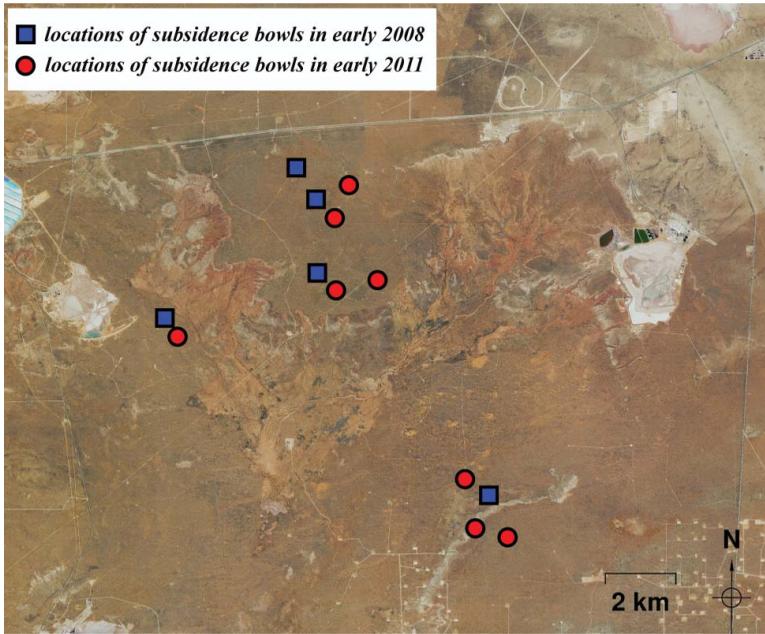


Figure 4. Locations of subsidence bowls as observed from the initial (blue squares) and final (red circles) interferograms (Figure 3) during our study period. This figure clarifies the spatial movements of subsiding areas from early 2008 to early 2011.

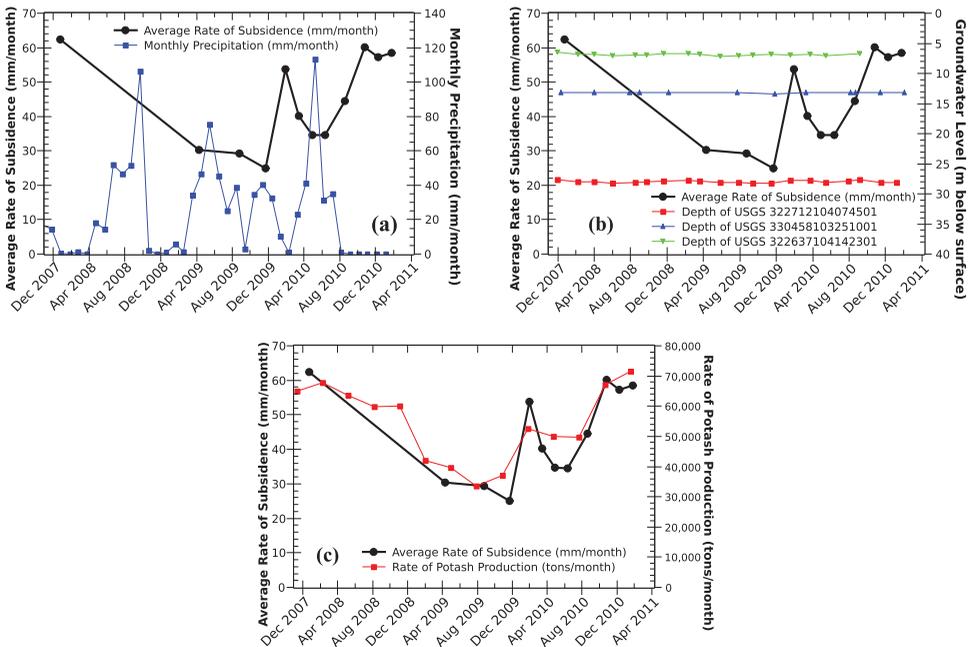
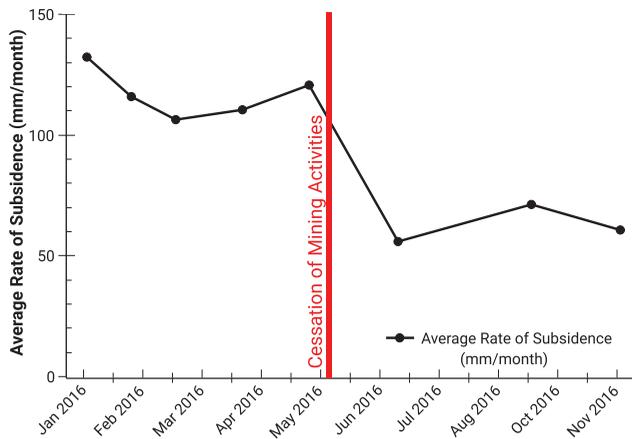


Figure 5. Comparing the average rate of subsidence across all 10 areas (in mm/month) as observed by the ALOS PALSAR sensor with (a) precipitation (cm), (b) groundwater levels (m below surface), and (c) monthly potash production (in metric tons), from December 2007 to April 2011. As shown, the rate of subsidence best correlates with the rate of potash production.

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**Figure 6.** The average rate of subsidence across all 10 areas (in mm/month), as observed by the Sentinel-1A satellite from January to November 2016. Notice the sharp decrease in subsidence between May and June 2016, concurrent with the suspension of mining activities in our study area.

about 115 mm/month. Between May and June 2016, however, the average rate of subsidence across all 10 sites more than halved, from over 120 to 55 mm/month. After the sudden decrease, the mean subsidence rate across all 10 sites steadied, averaging around 60 mm/month for the remainder of the observation.

## 4. Discussion

### 4.1. Cause of the subsidence

Ground deformation can be caused by numerous environmental factors. Prior publications have detailed many common sources, from changes in groundwater levels (Kim et al. 2015; Kim et al. 2017) to precipitation (Hu et al. 2016) to seismic activity (Lu and Wicks 2010). However, as shown in Figure 5(a,b), we found little correlation between the rate of subsidence and groundwater levels or precipitation. The cyclical nature of monthly precipitation levels remains in stark contrast to the pattern of subsidence, and the minimal variation in groundwater levels is not consistent with the large amounts of subsidence. If natural surface water did flow into the water-soluble Salado Formation, the subsidence should accelerate during wet seasons (winter in New Mexico and Texas) and the temporal pattern of deformation should exhibit seasonal variations. Our comparisons (Figure 5 (a,b)) show none of the seasonal fluctuations that would be expected if the subsidence was influenced by natural perturbations. The low correlation of the subsidence with groundwater levels and precipitation records between 2007 and 2011 therefore suggests that the instability of the ground surface is not induced by natural occurrence.

Instead, we found that the rate of subsidence exhibits a strong correlation with the rate of potash production, as seen in Figure 5(c). Throughout the entire study period, the rate of subsidence exhibited a consistent relationship with the rate of potash production. This continuous correlation offers convincing evidence that the root cause of our observed subsidence may be linked to the potassium extraction activities of nearby mines. Logically, potash production would corroborate many of the unique characteristics of the deforming areas. We hypothesize that the numerous distinct locations of subsidence directly indicate the locations of active mining sites. The movement of the various subsiding areas, for instance, can possibly be explained by the expansion of mine workings in pursuit of ores. Likewise, the ramification of a subsiding area may indicate a tunnel splitting into two. Figure 5 further suggests that there is a direct relationship between the amount of potash extracted from each site and subsidence thereof. As the amount of potash extracted from a certain site varies

(perhaps due to economic fluctuations or technical considerations), the rate of subsidence at that site appears to be affected directly. Extrapolating from our data, we estimate that for each 1000 metric tons of potash produced, a subsidence of approximately 8.8 mm is observed. While we cannot be sure of the exact mechanism of this subsidence, several processes are possible. For instance, it is possible that the overburden stress overlying the producing formation (Salado Formation) may be a consequence of the extraction of potash ores, causing growing pressure and thereby settlement on the ground surface. Likewise, the dissolution of water-soluble rocks due to freshwater leakage or impoundment during mining operations cannot be disregarded (although we could not obtain more detailed information regarding mining operations). Finally, a recent Securities and Exchange Commission filing by the mining operator revealed that the operator may be injecting freshwater solutions into previously mined rooms to dissolve the remaining support pillars for more ore. Although this process is normal in room-and-pillar mining, an improper implementation of this procedure could hazardously emulate processes that have caused ground deformation in the past (Johnson 2005; Onuma and Ohkawa 2009; Land 2013). Moreover, mining operations generally require special attention in maintaining proper control of water within active mines. Previous sink-holes (e.g. Wink, Jal, Loco Hills, and Jim's Water Service) were possibly caused by the improper management of old oil and active water wells that did not effectively prevent the flow of freshwater down the Salado Formation, either through corroded (not fully cemented) pipelines in the aquifer system, or deliberate but careless water injection. Therefore, although the mining operations and subsidence are planned and controlled, any improper management that would allow freshwater to flow into the Salado could cause a serious disaster. Overall, our analysis of spaceborne InSAR observations made in conjunction with production records strongly suggests that the subsidence during 2007–2011 was a consequence of the mining activities below the ground surface.

#### 4.2. Recent developments

Although the rapid subsidence (up to tens of centimetres per year) has the potential to pose a threat on the ground surface to nearby infrastructure and mining facilities, the large amount of deformation may not result in a severe catastrophe if the subsidence is well controlled by the mine operator. A lack of significant incidents in the potash mine since 2011 (the last year of ALOS PALSAR observations) demonstrates this may indeed be the case, and that the surface and underground stability of the mine may be well controlled by the operator through the use of pillars and other instruments in the mining caverns. However, the long-lasting, careful management of a potash mine is a much more difficult task. If the mining operation were to be suspended or abandoned, the existing mining facility may be vulnerable to continuous subsidence and possible collapse events without comprehensive management.

After examining the cause of the subsidence observed from 2007 to 2011, we began analysing the long-term ramifications of the subsiding areas. Using the eight Sentinel-1A interferograms from 2016, we generated the temporal subsidence (Figure 6). Compared to the ALOS PALSAR data from 2007 to 2011, many attributes of the subsiding area remained the same. There were still numerous sites of subsidence, and each continued to vary in rate. Likewise, almost all of the sites continued to migrate at a similar rate, around 200 m per year (note: the 200 m per year subsidence is the estimate added up from all subsiding areas around a potash mine). The most striking aspect of the Sentinel-1A data, however, was the large amount of subsidence we observed. As seen in Figure 6, we detected an average of over 100 mm/month of subsidence (mean average of 117 mm/month) across all 10 sites in early 2016 (in this context, 'mean average' refers to the temporal mean of the spatial average of the subsidence rates). This is almost double the maximum amount observed from 2007 to 2011. Initially, we could not explain this large increase in subsidence. After all, the amount of potash production remained relatively consistent ( $\approx 65,000$  metric tons/month in the first quarter of 2016 compared to  $\approx 63,200$  tons/month in the second quarter of 2011). Assuming all of the observed subsidence originated from potash production, the data would indicate that the production of

1000 metric tons of potash in 2016 would cause 18.0 mm of subsidence – a significant increase from the 8.8 mm/ton observed during 2007–2011. However, a press release by the mine operator announcing the suspension of mining operations in Carlsbad offered an explanation (Jornayvaz 2016). As the mine operator announced on 9 May 2016, ‘While the transition of [the Carlsbad] facility to a care-and-maintenance mode [...] reduces our potash production capacity, this move, in combination with the transition of the East facility to Trio<sup>1</sup>-only production, removes [...] potash facilities from production during this period of low potash prices’. The mine operator followed its statements by explaining, ‘These two transitions [...] allow us to focus on our lower cost solar production’.<sup>2</sup> As seen in Figure 6, this suspension of mining activities coincided with an abrupt decrease in the observed rate of subsidence from May to June 2016. By our initial theory, if the rate of subsidence is directly related to the rate of potash production, then the suspension of mining activities should eliminate any observed subsidence. However, the rate of subsidence instead stabilized at a cumulative peak average of 63 mm/month. As such, this information combined with the abnormally large rates of subsidence earlier in the year leads us to suspect that a ‘baseline’ level of subsidence may have formed at approximately 60 mm/month of average subsidence across all 10 sites. We speculate that an incident between 2011 and 2016 caused the formation of this ‘baseline’. As the locations of the baseline subsidence were the same as those of the mining-induced subsidence, we surmise that the incident was related to mining activities. When potash production ceased in May 2016, only the baseline subsidence remained. Furthermore, this would explain the relatively high rate of subsidence observed during early (January–May) 2016. Subtracting the baseline mean average of 63 mm/month subsidence, the remaining subsidence of approximately 55 mm/month indicates a much more reasonable value of 8.4 mm subsidence per 1000 metric tons of potash produced, further corroborating our conclusion that only a portion of the subsidence observed in 2016 was directly caused by potash extraction. Thus, we believe that subsidence during mining operations, as observed by ALOS PALSAR InSAR, may be a consequence of the potash production, which in turn may cause an overburden on the subsurface tunnels or voids, thereby inducing surface settlement. However, the reasons behind the continuous, elevated subsidence that is observed by Sentinel-1A InSAR after the suspension of mining operations remain unclear. One possible theory would be that the subsidence could be induced by the inappropriate management of pillars and supports; however, without additional evidence support for this, the theory remains unclear. Overall, however, this two-factor theory remains the best explanation for our observations in 2016, allowing us to interpret both the relatively high rate of subsidence and the continuation of the subsidence even after the cessation of mining activities.

## 5. Conclusions

Needless to say, our observations reflect a serious issue. While the exact mechanism of the observed deformation is not yet known and could very well be benign, previous literature does suggest several possibilities. In Colorado, for example, ground deformation is well documented over abandoned coal mines which used the room-and-pillar method (Turney 1985). In many instances, the sheer weight of the overburden (possibly accelerated by groundwater intrusions) caused the formation of underground cavities. Over time, these deficiencies have led to sags, troughs, and even the formation of sinkholes up to 100 years after the cessation of mining activities.

In particular, prior literature has documented that ground subsidence can often be a precursor to sinkhole formation in addition to other environmental hazards. In numerous instances, in mines from Wyoming (Goodspeed and Skinner 1995) to Louisiana (Bauer et al. 1997) to Russia (Dyagilev et al. 2013), topographical collapse and subsequent sinkhole formation have followed ground deformation. Often, the process is similar: a catastrophic collapse occurs, the area is monitored, subsidence is observed, and secondary collapses continue.

Unfortunately, none of these locations were monitored before the initial collapse, preventing prior notice of the disaster and endangering lives. Remote sensing technologies such as InSAR can

alleviate these dangers. With its low cost and high availability, InSAR allows a topographical analysis of at-risk areas before catastrophe strikes. Despite being physically located over 650 km away from our study area, we were able to quickly identify areas of concern at almost no cost. Following our investigation, we alerted the mining operator regarding our concerns, and we expect the company to conduct an investigation into the safety of its mines.

In this specific case, we were additionally able to observe the long-term ramifications of potash production. Even though active potash production has been suspended in our study area, we continue to observe significant subsidence, totalling an average of over 60 mm/month across all 10 sites. Unfortunately, this is a significant area of concern. From our observations, we raise the possibility that an incident or series of incidents between 2011 and 2016 has led to the development of permanent subsidence in areas previously occupied solely by mining-induced subsidence. Considering the geology of the region and intensity of the observed subsidence, this could represent a serious threat. A failure or collapse in the mine workings would endanger hundreds of people and cost thousands of dollars. Without further action, this continuing subsidence represents a serious long-term threat to the entire region.

## Notes

1. Trio® refers to a proprietary langbeinite product,  $K_2Mg_2(SO_4)_3$ .
2. The mine operator utilizes solar production facilities in Moab and Wendover, Utah, but not in Carlsbad, NM.

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## Disclosure statement

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