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Short Communication

Taking the pulse of aging oil wells in the Permian Basin from space

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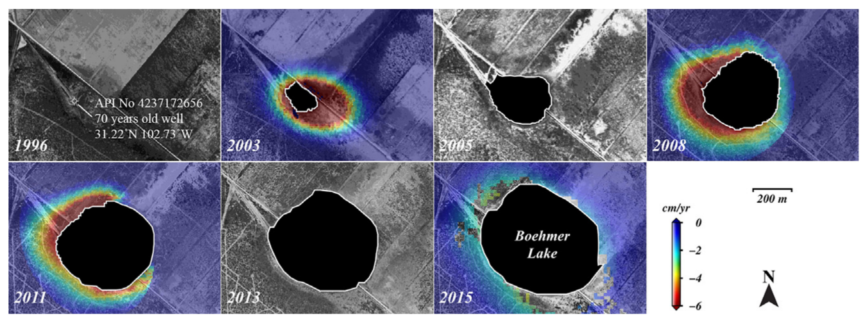
HIGHLIGHTS

- Hydrocarbon production has been conducted in the Permian Basin for decades.
- Geohazards (e.g., subsidence, sinkholes) emerged over mismanaged aging wells.
- Geohazards led to transformation of landscapes such as creation of Boehmer Lake.
- InSAR provides additional capability to monitor aging oil wells from space.

GRAPHICAL ABSTRACT



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ABSTRACT

Thousands of unplugged abandoned oil wells throughout the Permian Basin – one of world's leading oil plays – have potential to create ground instability and damage the environment due to aging facilities and instances of mismanagement. Satellite radar remote sensing technologies, capable of detecting subtle surface changes over time with broad geographic coverage, are a valuable tool for monitoring the health and integrity of aging oil wells by gauging the stability of the well and its surroundings.

1. Main

In recent years, the Permian Basin, encompassing west Texas and southeastern New Mexico (Fig. 1), has experienced yet another resurgence in activity with newly found massive oil and gas reserves (Gaswirth et al., 2018). Cost-reducing advances in hydraulic fracturing technology helped production soar to unprecedented levels and, in mid-2020, oil production reached 4.2 million barrels per day (BPD), moving the Permian into the top place among the world's leading oil plays (U.S. EIA, 2020). However, this is not the first boom the region has experienced: the Permian Basin has been developed since the early 1900s and has seen several cycles of booms followed by plummeting oil prices and great setbacks to the industry. This long history of cyclical oil and gas production means that a myriad of aging wells, including >40,000 wells older than 50 years (ENVERUS Drillinginfo, n.d.), exist in the Permian Basin. Of the Permian's four major basins (Delaware, Midland, Val Verde, and Central Basin Platform) the Central Basin Platform contains the highest percentage of aging oil wells, with 26% of the more than 68,000 oil wells older than 50 years (3; Fig. 2, Table 1). In contrast, the Midland Basin has the fewest, with only 4% of its oil wells older than 50 years, but still numbering over 3,000 wells (Table 1). Multiple geohazards related to the integrity of aging wells have been reported by residents and state and federal

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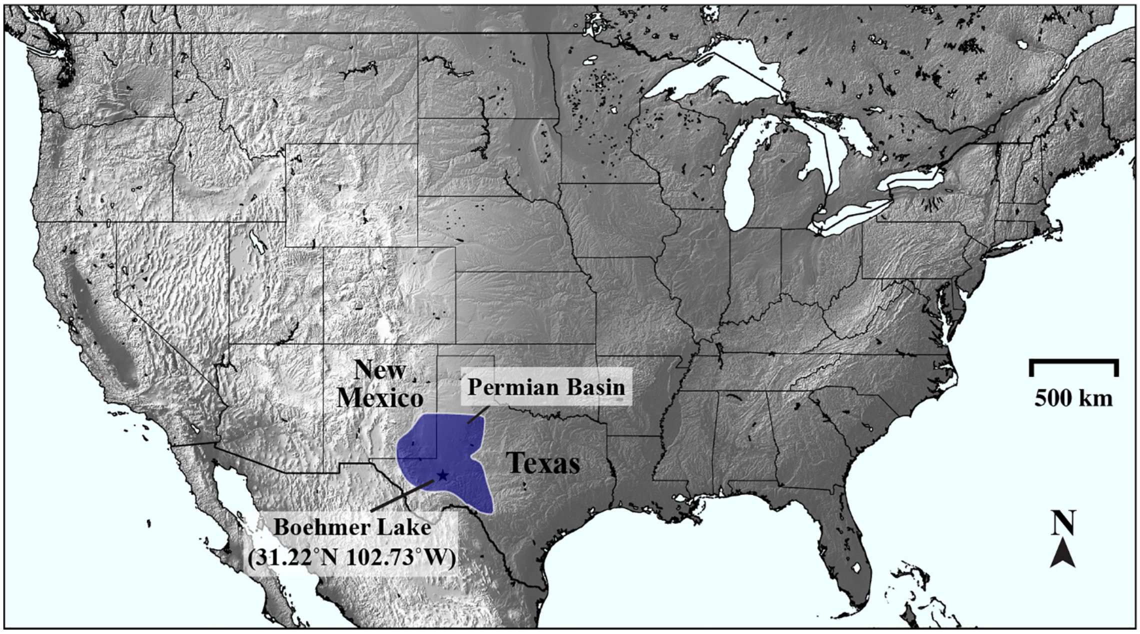

Fig. 1. Extent of the Permian Basin (blue-colored area) and location of the Boehmer Lake (black star). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

authorities. Moreover, recent advances in satellite remote sensing techniques have helped detect more widespread geohazards in the basin (Kim and Lu, 2018; Zheng et al., 2019). These geohazards include subsidence due to sinkhole formation centered on wells, ground deformation around oil extraction and fluid injection wells, subsurface wastewater leakage, and subsidence induced by solution mining.

It may not be coincidence that most geohazards have occurred at or near the older oil wells (Fig. 2). A series of federal environmental regulations, including Clean Water Act (1972), Safe Drinking Water Act (1974), and Resource Conservation and Recovery Act (1976) with Solid Waste Disposal Amendments of 1980, were enacted in 1970s to protect water resources from pollution and have been primarily administrated by U.S. Environmental Protection Agency (EPA) (US EPA, n.d.). As a result of these regulations to address the environmental impacts of oil and gas operations, current oil production has high standards that require the sealing of aquifer systems during drilling and oil production, careful management of fluids (e.g., wastewater, CO_2) to prevent contamination of water resources and maintain the stability of the surface and subsurface, and the use of advanced materials to avoid the corrosion of pipelines and casing damage (Alzahrani and Mohammad, 2014). However, many of these standards were not in place until rather recently. Past oil production standards did not prohibit injection of freshwater for waterflooding projects in this area (Martinez et al., 1998), even though the Permian Basin contains evaporite and carbonate formations above the oil producing formations (Baumgardner Jr. et al., 1982). When pressurized freshwater leaks through to water-soluble layers, the area can experience immediate geohazards, including subsidence and collapse sinkholes and ground fissures (Johnson, 2005; Kim et al., 2019). For example, Wink sinkholes (Fig. 2), near the boundary between the Central Basin Platform and the Delaware Basin, formed at the locations of 50-year-old abandoned producing and water-supply wells in 1980 and 2002, respectively, and were linked to salt dissolution through natural and induced fractures near the mismanaged boreholes (Baumgardner Jr. et al., 1982). The salt dissolution and thereby ground instability over the area neighboring the sinkholes is ongoing, and rapid subsidence exceeding 50 cm/year has been captured from spaceborne radar imagery (Kim et al., 2019). In addition to Wink sinkholes, Jal (also called Whitten ranch), Loco Hills, Denver City sinkholes in the Permian Basin have collapsed near or at oil wells and have threatened the nearby infrastructures and oil facilities (Kim et al., 2019). Along Pecos River, multiple places have experienced subsidence due to the salt dissolution around old wells (Fig. 2). The collapse sinkholes (yellow stars in Fig. 2) are main threats due to their immediate impacts on the surface and underground but subsidence has gradually made negative effects on roads and water quality.

Another example of growing geohazards over aging wells in the Permian Basin is the evolution of Boehmer Lake (Fig. 3). Wellbore American Petroleum Institute (API) Number 4237172656, drilled in October 1951 6.5 km southwest of Imperial, Texas, has no detailed production information after the initial drilling and is currently listed as a dry hole and an abandoned well in the Railroad Commission of Texas database. The lake that can be currently seen from maps and satellite images emerged in 1996 (Fig. 3). The lake is not purely natural, and high salinity of the lake water has been reported (Malewitz, 2016). The lake water has a toxic total dissolved solids (TDS) of 90,000–100,000 mg/L including salts and minerals, and its water quality is deteriorated much beyond that of freshwater (TDS <1,000 mg/L) or saline water (TDS of 10,000–35,000 mg/L) (Mulder, 2015; Scanlon et al., 2019). Similar to other major basins in the Permian, the Central Basin Platform is underlain by a thick salt layer, called the Salado Formation, at a depth of 300–500 m (Stueber et al., 1998). Although we were unable to determine the volume of produced oil and/or the well's depth due to its age, it is certain that the well has been left subject to cracks and corrosion without appropriate plugging. Based on optical images (Fig. 3), the area around the abandoned well has continued to experience subsidence, and the sinking surface has been gradually submerged by saline water upward from brackish San Andres aquifer at the depth of ~800 m and salt deposits through the underground cracks and corroded pipelines. The TDS of the San Andres aquifer is less than 10,000 mg/L (Malewitz, 2016) but that of lake water surged to ~100,000 mg/L. The once-flat surface has transformed into a lake exceeding 200,000 m^2 in area. Using contemporary satellite technology, interferometric synthetic aperture radar (InSAR), to measure the surface deformation from multiple repetitive radar image acquisitions, we now have the capability to capture surface changes at meter-scale spatial resolution over large areas (Lu and Dzurisin, 2014) with temporal, forensic investigations (Kim and Lu, 2018). Based on recent analysis of multi-sensor spaceborne InSAR observations first recorded in 2003, the area

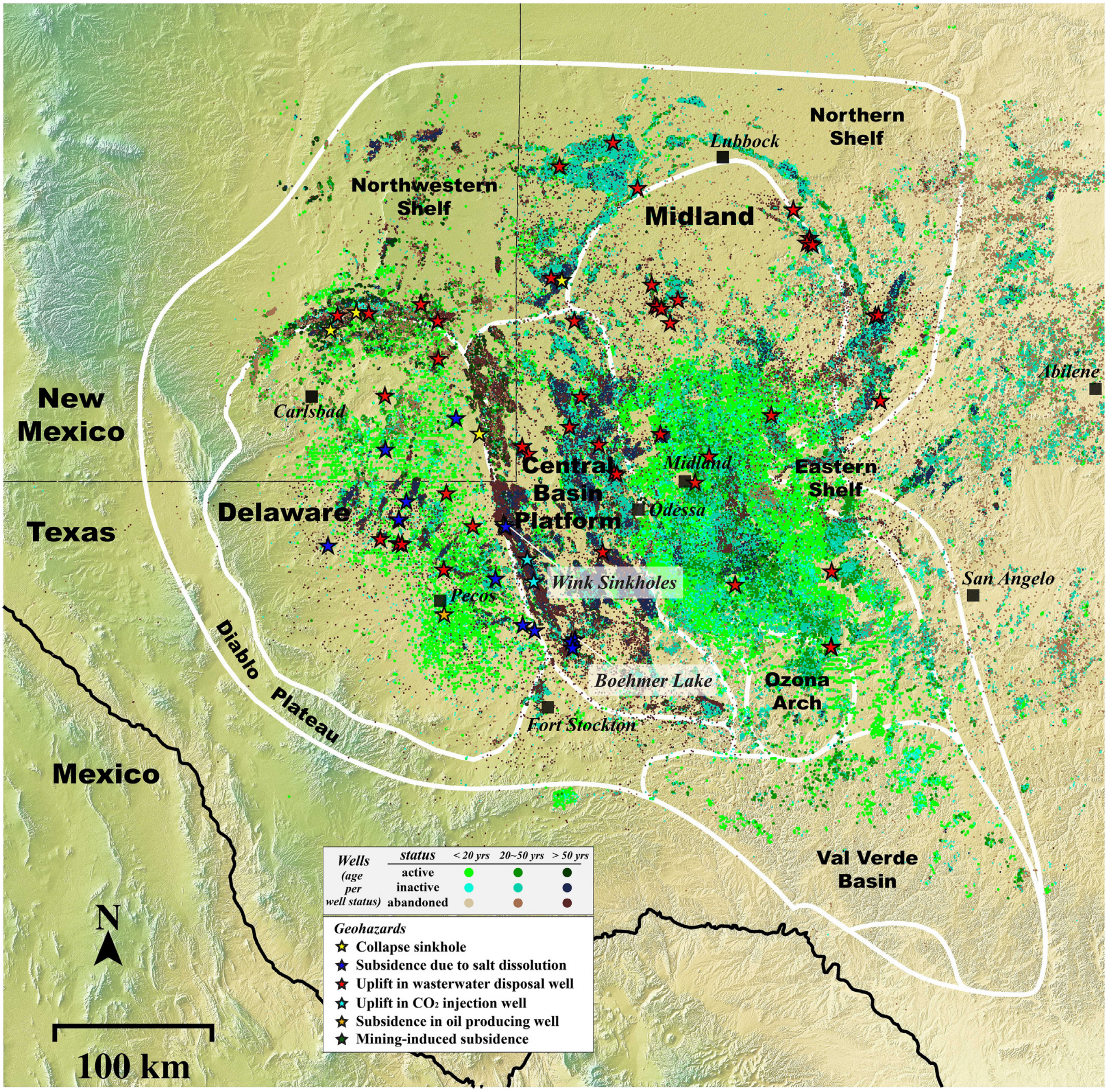

Fig. 2. Ages of oil wells in the Permian Basin and location of geohazards observed from satellites and reports.

neighboring the abandoned well subsided ~6 cm in 2003. This subsidence rate of ~6 cm/year continued throughout 2008 and 2011 and greatly contributed to growth of Boehmer Lake. In 2015, the vicinity of the lake was still subsiding at a rate of ~2 cm/year. Across the basin, there is localized deformation near other aging wells (Fig. 2). Applying the satellite InSAR technique, deployed as continuous monitoring, rather than as 'snapshots' in time, it is possible to identify and categorize many areas of concern in the basin (Kim and Lu, 2018). In the case of Boehmer Lake, we do not have InSAR data available from before lake formation in 1996, but it is likely that there were precursory landscape changes.

Capturing the ground subsidence associated with aging wells from space can provide an alerting signal before a geohazard matures. Continuous localized subsidence over the Permian Basin signals that the aging wells might be deteriorated by salt dissolution in underlying evaporite layers and/or upflow of groundwater, and consequently can pollute groundwater and fracture roads and pipelines. Given the dense network of pipelines, oil facilities, infrastructure, and residential areas in the Permian Basin, monitoring the warning signals is worthwhile, as it provides an opportunity to mitigate the outcomes of the geohazards. With currently operating spaceborne synthetic aperture radar (SAR) sensors combined with the planned launch of the US NASA and India ISRO SAR (NISAR) mission in 2022, the resulting advanced radar imaging system will enable weekly observation of the entire Permian Basin, identifying the harbinger of subsidence and taking the pulse of aging oil wells to ensure a sustainable future for the petroleum industry.

Table 1
Ages of oil/gas wells in the Permian Basin.

Basin	Age	Number of oil/gas wells	Percent (%)
Delaware	>50 yrs	7,952	19
	20–50 yrs	12,361	30
	<20 yrs	21,529	51
	Total	41,842	
Central Basin Platform	>50 yrs	17,981	26
	20–50 yrs	24,687	36
	<20 yrs	25,995	38
	Total	68,663	
Midland	>50 yrs	3,346	4
	20–50 yrs	28,106	37
	<20 yrs	44,278	58
	Total	75,730	
Others	>50 yrs	4,097	8
	20–50 yrs	32,114	61
	<20 yrs	16,415	31
	Total	52,626	
All	>50 yrs	33,376	14
	20–50 yrs	97,268	41
	<20 yrs	108,217	45
	Total	238,861	

CRediT authorship contribution statement

Zhong Lu and Jin Woo Kim designed the project. Jin Woo Kim collected and processed data. Jin Woo Kim and Zhong Lu analyzed the results and wrote the manuscript.

Declaration of competing interest

The authors declare no competing interests.

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Data and materials availability

All data is available.

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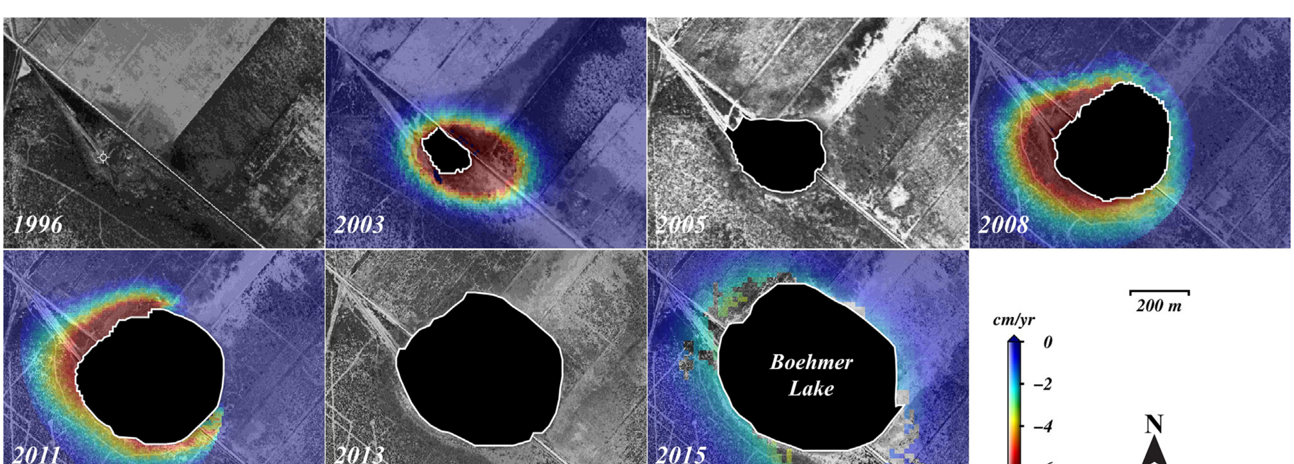

Fig. 3. Evolution of Boehmer Lake around an abandoned well (marked by a white cross) and vertical land subsidence throughout years observed by InSAR.