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**Abstract**

Earthquakes occurring naturally or induced by human activities can damage surface and subsurface infrastructure. Oil and gas wells represent a category of subsurface infrastructure that can act as leakage pathways connecting oil and gas reservoirs, groundwater aquifers, and the atmosphere. The integrity of these wells can be compromised through a wide range of processes and contribute to groundwater contamination, greenhouse gas emissions, and air quality degradation. We estimate the increase in such subsurface leakage potential due to seismic activity through geospatial analysis of 579,378 oil and gas well and 196,315 earthquake (magnitudes greater than 1.0) locations in Oklahoma, California, and British Columbia. We perform density-based clustering analysis and point density mapping using *ArcGIS*. We combine the well and earthquake point density maps to identify hot spots of joint high well and earthquake densities. We find that oil and gas wells and earthquakes are clustered in space, with densities reaching ~ 60 wells per km^2 and ~ 40 earthquakes per km^2 in California. There are at least two hot spots where these clusters overlap in each state/province. In Oklahoma and British Columbia, the hot spots are more correlated with earthquake densities; while, in California, the hot spots are more correlated with well densities. Our findings indicate the need to investigate the role of earthquakes on wellbore leakage through additional analysis of earthquake characteristics, wellbore attributes, improved data collection, and empirical field studies for all oil and gas wells, including those that are abandoned. In particular, large scale geospatial analysis establishing the scope of the problem and empirical field studies focusing on identified hot spots are needed to understand potential environmental impacts of earthquakes, especially those induced by oil and gas activities.

1. Introduction

Oil and gas wells can act as pathways for fluid leakage leading to groundwater contamination and emissions of greenhouse gases and air pollutants, thereby impacting climate, air quality, and water resources. Subsurface leakage via oil and gas wells are identified as a major concern in geologic storage of carbon dioxide projects and oil and gas production [1]. Failure in barriers to well leakage, or wellbore integrity issues, can occur due to thermal, chemical, and/or mechanical stresses during oil and gas production and other activities and create or enhance fluid leakage in and around wellbores [2–5]. Database analysis are used to estimate rates of wellbore integrity failures such as cement and casing impairment and to link these issues to well characteristics, spud date, well type and construction, production history, well location, geology, operator, abandonment method, oil price, and regulatory changes [6–11]. However, there remain uncertainties in the relative contribution of these factors to wellbore integrity, and a recent study shows that we are likely to be missing important controlling factors [12]. A particularly salient process that is yet to be studied in linkage with oil and gas well leakage is earthquakes.

Earthquakes or seismic events induced by oil and gas development activities is gaining scientific and media attention due to recent earthquakes of magnitude 4 and greater ($M \geq 4$) in central and eastern US [13] and

Western Canada [14, 15]. Although there is active research on mechanisms leading to induced seismicity, relatively few studies have looked at its role on creating or enhancing subsurface leakage and associated environmental impacts [16]. Although earthquakes and other tectonic activities are listed as geomechanical factors to consider in risk assessments for geologic storage of carbon dioxide [5] and oil and gas production [4], the level of risk that earthquakes pose to such engineering projects has not been quantified.

Fluids originating from an oil-and-gas reservoir or gas pockets in non-producing formations can migrate through a leakage pathway and contribute to (1) groundwater contamination and gas emissions to the atmosphere, (2) groundwater contamination only, or (3) gas emissions only. The oil and gas industry has developed standards for well integrity in drilling and operations [17, 18] so that any leakage can be quickly detected and mitigated. However, oil and gas well leaks continue to impact our environment. Furthermore, there are no standards or requirements to monitor oil and gas wells after they have been abandoned in any jurisdiction [19] and many leaks remain undetected. Monitoring can be costly, and leakage is difficult to detect and attribute [20]. Wellbore integrity studies using laboratory testing and modeling demonstrate the wide range of potential pathways and mechanisms through which a well can fail and cause leakage [2, 4, 5, 21]. The failure can lead to fluid migration ranging from small hard-to-detect leaks to catastrophic events [22], all of which can be caused by strong shaking or finite offset during earthquakes. Furthermore, small- and large-scale failures may not necessarily be independent and small failures accumulated over time may reduce the integrity of a wellbore barrier system to withstand earthquakes and other drivers of leakage. In addition to understanding wellbore integrity and the hydraulic characteristics of each leaky well, there is a need to define the geographic scope of the wellbore leakage problem, including smaller but more prevalent leaks.

We perform geospatial analysis of earthquakes and oil and gas well data in California (CA), Oklahoma (OK), and British Columbia (BC) to make the first evaluation of enhanced subsurface leakage potential due to earthquakes. The three different regions are chosen based on oil and gas production history and seismic activity. CA is the fourth-largest oil producer (174,107 thousand barrels in 2017) by state in the US and is well-known for natural and induced earthquakes [23]. OK is the sixth-largest crude oil (165,920 thousand barrels in 2017) and fourth-largest natural gas (8518 million cubic feet per day in December 2018) producing state and has recently experienced numerous earthquakes due to oil-and-gas-related wastewater injection. BC has limited oil production but is the second-largest natural gas (5018 million cubic feet per day in December 2018) producing province in Canada with increasing use of hydraulic fracturing, which has been linked to recent $M \geq 4$ earthquakes [14]. Due to the range in oil and gas development and seismic activity, the analysis of these three states/province can provide broad insights on the potential link between earthquakes and well leakage.

2. Methods

We analyze 27,679 permitted well records from the BC Oil and Gas Commission (downloaded in February 2019), 229,561 wells in the CA Division of Oil, Gas, and Geothermal Resources Well Records (downloaded in February 2019), and 534,662 oil and gas well data for OK from the National Oil & Gas Gateway (downloaded in September 2019). Wells in the CA database were drilled from 1887 to 2018 and 10% of the wells were drilled in 2009 to 2018. Wells in the BC databases were drilled from 1912 to 2018, with most (77%) being drilled from 2009 to 2018. Wells in the OK database were completed from 1894 to 2019 with only 5% of the wells drilled from 2009 to 2018. These date ranges are based on available drilling, completion, or spud dates, which are not available for all well records. For BC and CA, we neglect ‘cancelled’ wells because we assume that these wells were never drilled and cannot act as leakage pathways. For OK, we do not analyze wells with the status ‘Expired Permit Not Drilled’ for the same reason. Table 1 describes the data used to represent all oil and gas wells and abandoned oil and gas wells in our analysis.

We analyze 196,315 seismic events with $M \geq 1.0$ in the US Geological Survey (USGS) catalog from 2009 to 2018. Most of the data (179,969 or 92%) is for CA. There are 10,109 and 6237 events for OK and BC respectively. The completion magnitudes are 1.1, 2.5, and 1.6 for CA, OK, and BC respectively (figure S7). We include all earthquake data with $M \geq 1.0$ to evaluate the role of frequently-occurring small-magnitude seismic events. We also map major fault traces from the USGS fault and fold database for CA and OK [24] and the BC Geological Survey’s Geology Faults database for BC [25]. Faults can be a conduit, a barrier, or a conduit-barrier system, and the impact of faults on leakage can be highly variable. However, there is no available database, to our knowledge, that we can use to characterize the mapped major faults as conduits or barriers.

We perform two different spatial analysis using tools in *ArcGIS* to (1) identify clusters of wells and earthquakes and (2) combine point density distributions to determine hot spots where high well and earthquake densities overlap. First, we use the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm [26] in the *ArcGIS Density-Based Clustering Analysis* tool to identify the number of clusters in each state/province for cell sizes of 5 km and 10 km and with 10 as the minimum number of wells or earthquakes. The

Table 1. Description of all and abandoned oil and gas well data by state/province with sufficient location and status information (as of February 2019 for BC and CA and October 2019 for OK).

	Source(s)	All wells		Abandoned wells	
		Count	Description	Count	Description
BC	BCOGC permitted well records	27,679	All well activity statuses, except cancelled	12,195	Well activity statuses: suspended ('SUSP'), abandoned ('ABAN')
CA	DOGGR well search	229,561	All well status codes, except cancelled	153,308	Well status codes: B (Buried-Idle), I (Idle), U (Unknown), P (Plugged and Abandoned)
OK	National Oil and Gas Gateway	322,138	All standard well status, except expired permit, not drilled	70,341	Standard well status: Abandoned, Inactive

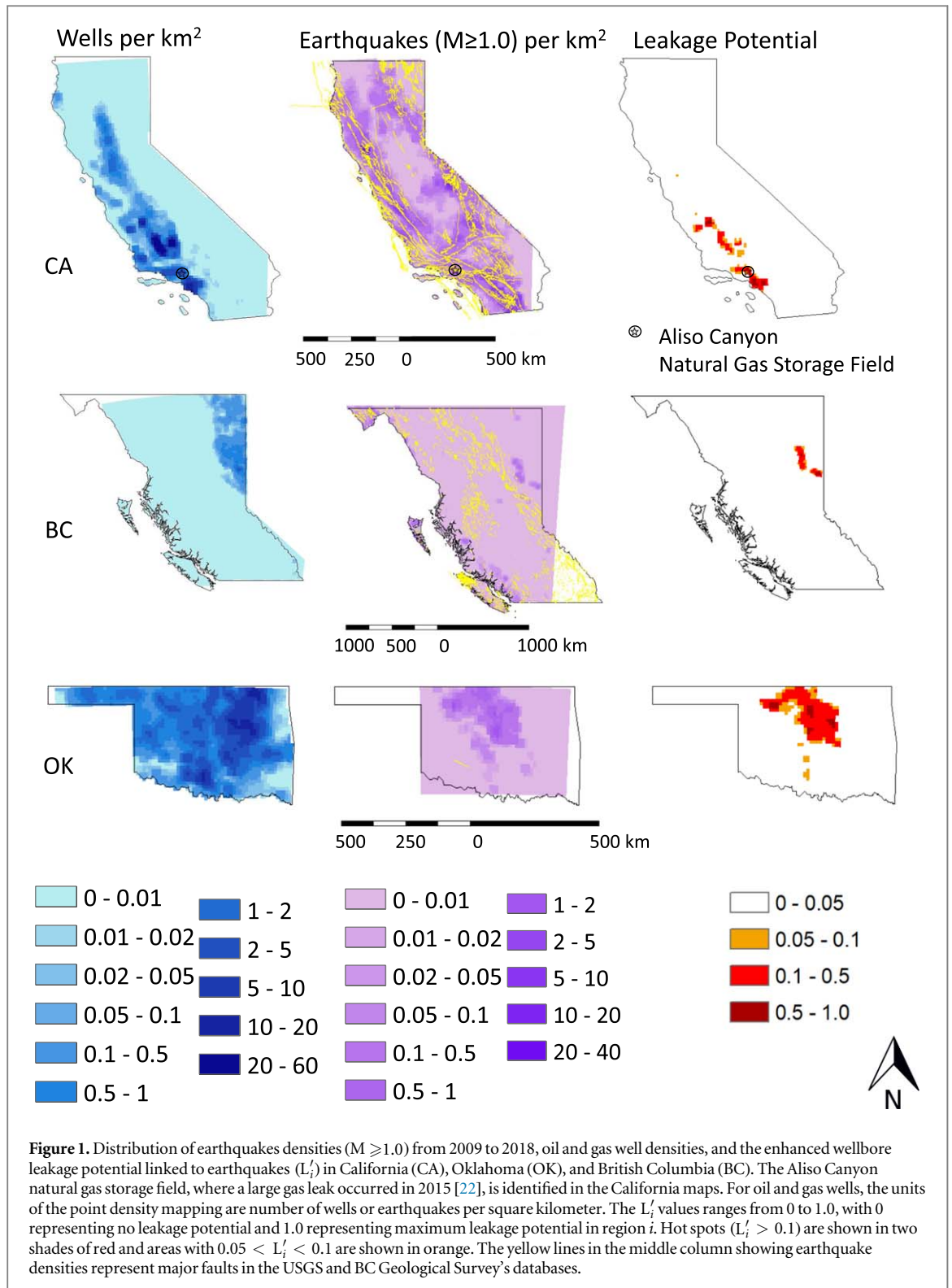
resulting density-based clusters are used to evaluate spatial clustering in each dataset and how the number, shape, size, and distribution of clusters vary between regions. The second analysis is used to determine hot spots of high well and earthquake densities within a region and employs a two-step approach. First, we use the *Point Density* tool with a cell size of 10 km and a rectangular neighborhood to develop maps of well and earthquake densities, $w_i(x, y)$ and $e_i(x, y)$, where i denotes the state/province and x and y are the geographical coordinates. Then, using the *ArcMap Spatial Analyst Map Algebra Operators*, we normalize $w_i(x, y)$ and $e_i(x, y)$ by the maximum point density in each province/state, w_i^{\max} and e_i^{\max} , and estimate the enhanced leakage potential in region i , $L_i(x, y) = (w_i(x, y)/w_i^{\max}) \times (e_i(x, y)/e_i^{\max})$. In other words, the leakage potential ($L_i(x, y)$) represents the combination of normalized well and earthquake densities for a given state/province i . We then normalize the leakage potentials in each region by the maximum leakage potential in that region and map $L'_i(x, y) = L_i(x, y)/L_i^{\max}$. We define 'hot spots' of joint high well and earthquake densities as $L'_i(x, y) \geq 0.1$ but also present $0.05 < L'_i(x, y) < 0.1$ (figure 1).

3. Results

Oil and gas wells and earthquakes are clustered in space in all three study areas (figure 1 and S1–S6). In CA, oil and gas wells are densely clustered in highly productive oil and gas regions, specifically the southern portion of the Central Valley of CA and the southern coastal region (Los Angeles, Ventura, and Santa Barbara Counties). Earthquakes in CA are clustered in the vicinity of the San Andreas Fault and the Eastern California Shear Zone. Oil and gas production in BC is confined to the gas-bearing Montney Basin and Horn River Basin in the northeastern portion of the province. The increase in seismicity in this northeastern BC area over the past decade is mainly attributed to hydraulic fracturing activities [14], while the earthquake clusters along the coast are mostly due to plate tectonics. Oil and gas production is prevalent throughout OK. However, earthquakes in OK are clustered in the north-central portion of the state.

California has the highest maximum densities of oil and gas wells and earthquakes with $M \geq 1.0$, reaching 60 wells per km^2 and 40 earthquakes per km^2 (figure 1). State-wide average earthquake densities are also highest in CA at 0.42 earthquakes per km^2 (table 3). However, OK has the highest state-wide well densities of 1.8 wells per km^2 (table 2) but with a maximum well density of 15 wells per km^2 (figure 1). BC has the smallest region-wide density of oil and gas wells at 0.03 wells per km^2 and the lowest density of earthquakes at 0.007 earthquakes per km^2 (tables 2 and 3). Correspondingly, the maximum point densities of wells and earthquakes are the lowest in BC at 3 wells per km^2 and 3 earthquakes per km^2 (figure 1).

Spatial clusters of wells are found throughout OK, whereas in BC and CA, the well clusters are concentrated in a few regions (see supporting information and figures S1–S6 available online at stacks.iop.org/ERC/1/121004/mmedia). There are 0.2 to 1.2 clusters of all wells per 1000 wells in CA and BC and 0.028 to 0.084 clusters of all wells per 1000 wells in OK (table 2) with the number of clusters increasing by a factor of 2.9 to 4.9 when the search radius is decreased from 10 km to 5 km. The well clusters in CA clearly delineate the Central Valley and southern coastal regions where oil and gas development is prevalent (figure S1). A decrease in the search radius from 10 km to 5 km separates northern and southern Central Valley into two separate clusters with the divide occurring around the Delta and the southern coastal area is separated into clusters for Los Angeles, Ventura, and Santa Barbara (figure S1). For BC, the 10-km search radius identifies the entire northeastern oil and gas-producing region as a single cluster, with a few small clusters in the northern portion (figure S2). The



5-km search radius divides the large cluster into one large cluster in the southern portion of the oil and gas region, representing the Montney Basin, and many small clusters in the northern region. However, these small clusters do not obviously follow boundaries of the Horn River or Liard Basin. In OK, there are 1.1 and 3.2 well clusters per 1000 wells when using a search radius of 10 km and 5 km respectively, both producing one large cluster in the middle and several small clusters around the fringes of the state (figure S3). The earthquake clusters also show that both 5-km and 10-km search radiuses produce meaningful clusters, some of which can be linked to tectonic activities (figures S4–S6).

Abandoned wells generally follow the same distribution as all wells in CA and BC (figures S1 and S2). This is in line with the expectation that wells are clustered in oil and gas basins, which is likely to have both abandoned

Table 2. Average state/province-wide densities of oil and gas well locations and numbers of well clusters per 1000 earthquakes using the DBSCAN algorithm with two search radiuses, 10 km and 5 km, for all wells and only abandoned wells. The well data is described in table 1.

	All wells			Abandoned wells		
	Density $\left(\frac{\text{Wells}}{\text{km}^2}\right)$	Number of clusters per 1000 wells		Density $\left(\frac{\text{Wells}}{\text{km}^2}\right)$	Number of clusters per 1000 wells	
		10 km	5 km		10 km	5 km
CA	5.4×10^{-1}	8.7×10^{-2}	2.5×10^{-1}	3.6×10^{-1}	1.3×10^{-1}	3.8×10^{-1}
OK	1.8×10^0	2.8×10^{-2}	8.4×10^{-2}	3.9×10^{-1}	1.3×10^{-1}	1.4×10^0
BC	2.9×10^{-2}	2.5×10^{-1}	1.2×10^0	1.3×10^{-2}	5.7×10^{-1}	4.5×10^0

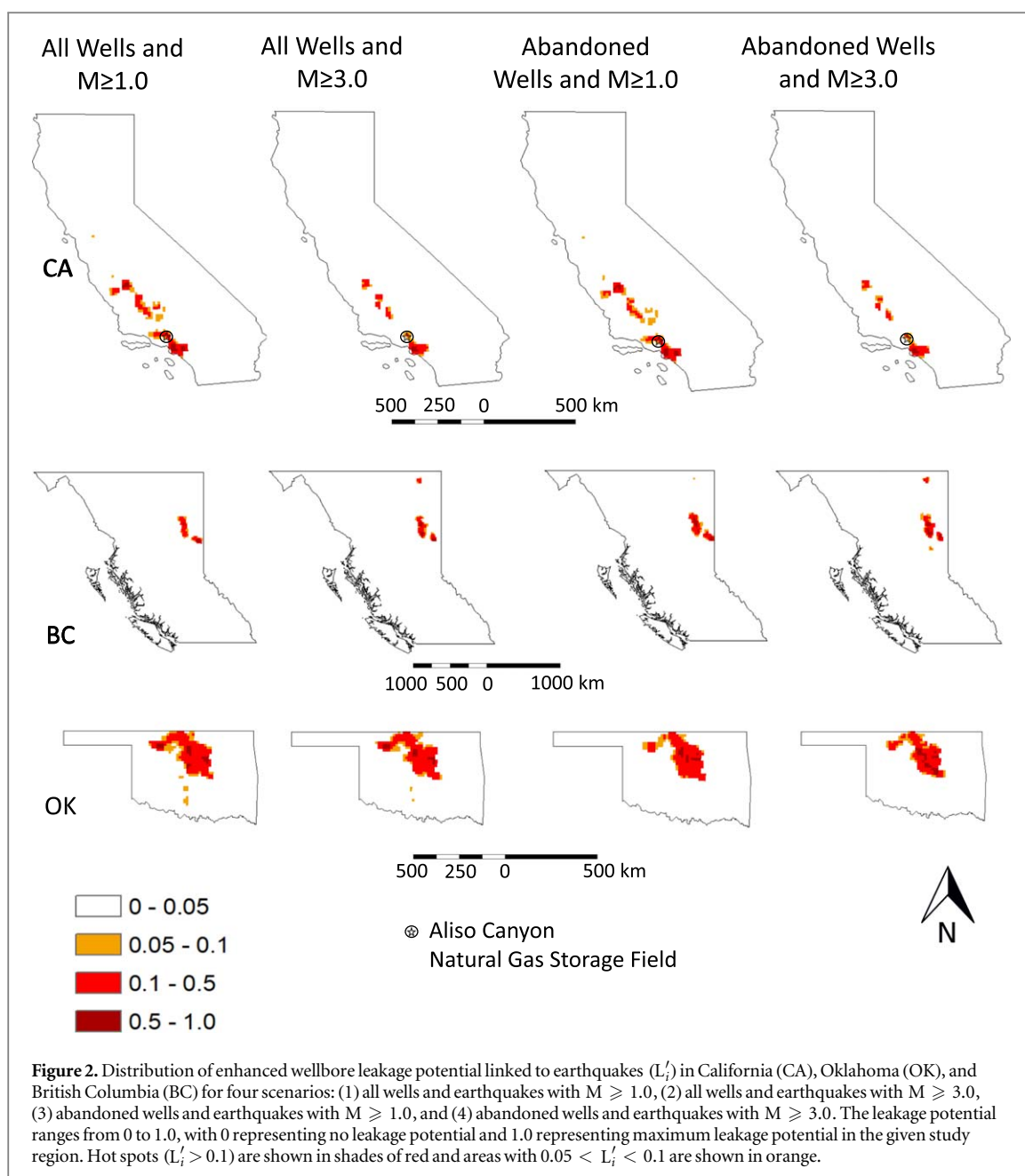
Table 3. Average state/province-wide densities of earthquakes and numbers of earthquake clusters per 1000 earthquakes using the DBSCAN algorithm with two search radiuses, 10 km and 5 km, for earthquakes with $M > 1.0$ and $M > 3.0$. The earthquake data includes earthquakes that occurred from 2009–2018.

	$M > 1.0$			$M > 3.0$		
	Density $\left(\frac{\text{Earthquakes}}{\text{km}^2}\right)$	Number of clusters per 1000 earthquakes		Density	Number of clusters per 1000 earthquakes	
		10 km	5 km		10 km	5 km
CA	4.2×10^{-1}	2.2×10^{-1}	9.5×10^{-1}	5.5×10^{-3}	1.6×10^1	1.2×10^1
OK	5.6×10^{-2}	1.1×10^0	3.2×10^0	1.5×10^{-2}	1.5×10^0	1.4×10^1
BC	6.6×10^{-3}	6.3×10^0	9.3×10^0	3.3×10^{-4}	1.9×10^1	3.2×10^0

and active wells. Because of the general lower number of abandoned well densities, there are more abandoned well clusters per 1000 abandoned wells than all oil and gas well clusters per 1000 all oil and gas wells, differing by factors of 1.5(CA) to 17 (OK). This is because we use the same DBSCAN parameters for all wells, causing points to no longer be density-reachable and density-connected.

A larger number of clusters per 1000 earthquakes are found when using earthquakes with $M \geq 3.0$, than $M \geq 1.0$ (figures S4–S6). As with all and abandoned well clusters, this is because of the lower density of higher-magnitude earthquakes and the use of the same DBSCAN parameters. For $M \geq 1.0$, there are 0.22 to 9.3 clusters of earthquake events per 1000 earthquakes; and for $M \geq 3.0$, there are 1.5 to 19 earthquake clusters per 1000 earthquakes. The number of earthquake clusters consistently increase with decreasing search radius (10 km to 5 km) for $M \geq 1.0$ but not for $M \geq 3.0$. In CA and BC, the number of $M \geq 3.0$ -earthquakes per 1000 earthquakes decrease from 16 to 12 clusters per 1000 earthquakes in CA and from 19 to 3.2 clusters per 1000 earthquakes in BC because of the minimum points criteria. In other words, many $M \geq 3.0$ -earthquake clusters defined with a 10-km search radius become noise rather than multiple smaller clusters when a 5-km search radius is used. In OK, the number of earthquake clusters increase almost 10-fold from 1.5 to 14 clusters per 1000 earthquakes for $M \geq 3.0$ -earthquakes. A comparison of the major fault locations and earthquakes shows that there are regions in each province/state where a major fault is not mapped but an earthquake cluster exists (figure 1). In all three regions, the $M \geq 3.0$ clusters are captured in the $M \geq 1.0$ clusters but there are numerous $M \geq 1.0$ clusters that are not co-located with $M \geq 3.0$ clusters (figures S4–S6).

Overlapping oil and gas well and earthquake locations shows that there are at least two hot spots with increased potential ($L' > 0.1$) for earthquakes to create or enhance leakage pathways in and around wellbores in each province/state (last column in figure 1). In CA, the hot spots are in the southern portion of the Central Valley and Los Angeles County, which are regions with large oil and gas production. The Aliso Canyon natural gas storage facility, which experienced one of the largest methane leakages in US history in 2015 [22], is located in this seismically active area with high well densities. However, other oil and gas well clusters such as those in coastal regions around Santa Barbara and southwestern Central Valley are not found to be hot spots due to lower earthquake densities. In BC, the hot spots are in the northeastern region, where all wells and a major cluster of earthquakes are located. Because there is no oil and gas activity in western BC, there are no hot spots, despite numerous earthquake clusters along the coast of BC (figure S5). In OK, because oil and gas distribution is distributed throughout the state, the hot spots are in the southern portion of the earthquake cluster, where well



densities are larger. Overall, hot spots are more correlated with well locations in CA and earthquake locations in BC and OK but with important local-scale differences.

The general trends in increased leakage potential do not change substantially if we consider earthquakes with magnitudes greater than 3.0, rather than 1.0, and if we consider only abandoned wells, rather than all wells (figure 2). However, there are few small but important changes. Looking only at larger-magnitude earthquakes creates new hot spots, with the most prominent one being in northeastern BC. Most notably, the Aliso Canyon Natural Gas Storage Field is no longer in a hot spot ($L'_i > 0.1$) when only earthquakes with $M \geq 3.0$ are considered. Therefore, if any leakage is enhanced by earthquakes in this region, it is due to frequent low magnitude ($M \leq 3.0$) events.

4. Discussion

Earthquakes and the presence of vulnerable subsurface structures such as oil and gas wells can potentially enhance or create subsurface leakage. Our geospatial analysis points to hot spots where leakage can be enhanced by earthquakes and how low magnitude but frequent seismic events may be as important as few large events. This is in line with previous findings that show earthquake magnitudes poorly predict local damages and consequences [27]. Therefore, our findings indicate the need to investigate the role of earthquakes on wellbore

leakage through analysis of different earthquake characteristics (e.g. peak ground velocity or peak ground acceleration) and wellbore attributes (e.g. age, operational status, type), demonstrate how geospatial and temporal analysis may be used to quantify the scope of the leakage problem, and identify hot spots where future measurement efforts can be focused.

There are no studies, to our knowledge, focusing on the relationship between wellbore integrity and earthquakes. There is only one study, that we know of, with air and groundwater monitoring at one unconventional well site in Poland [16], where they found elevated atmospheric methane concentrations following an earthquake of $M = 0.5$ [16]. However, the authors were not able to attribute the elevated methane concentrations to seismic activity because methane emissions associated with normal production activities on site were not characterized. They were also unable to observe any correlations between injected volumes, seismicity, and groundwater parameters [16]. Even for natural earthquakes, the relationship between groundwater contamination/gas emissions and earthquakes remain poorly defined due to the difficulty of differentiating between the wide range of anthropogenic and natural processes governing groundwater quality and methane emissions [28]. Nonetheless, methane and other gas emissions are linked to natural earthquakes and are suggested as potential warning signals for earthquake risk [29]. Groundwater contamination due to brine and seawater intrusion through leakage pathways created by natural earthquakes are also documented [30]. Impacts of earthquakes on buildings and pipelines, including those that are buried, have long been an active area of civil engineering research. There are many empirical estimates of pipeline damage that relate the number of repairs to peak ground acceleration, peak ground velocity, maximum ground strain, and other factors [31, 32]. There is great potential to extend this existing body of research to subsurface wellbore leakage caused by earthquakes. However, there are key differences between these previous studies and the wellbore leakage problem presented here such as those related to fluid and geologic formation properties at deeper depths and to wellbore construction, use, and abandonment.

4.1. The detection problem

The limited empirical evidence linking earthquakes to leakage is due to the difficulty of detecting leakage in the first place. Environmental degradation associated with subsurface leakage appears in a subset of measurements and is not easy to detect [33, 34]. In one study across the Marcellus shale basin in Pennsylvania, where there is widespread unconventional gas production, 12 household wells out of 141 had methane concentrations exceeding the US Department of the Interior's threshold for immediate remediation, while little to no methane was found in many of the sampled wells [33]. A study synthesizing numerous studies on methane emissions from natural gas systems found that emissions follow extreme distributions with only 5% of emitters accounting for more than 50% of emissions [34]. This is also in line with government data analysis studies that show only a small percentage of wells have compromised cement and/or casing integrity (e.g. 0.7 to 9.5% in Pennsylvania [7]). Furthermore, many studies and industry risk assessment procedures focus on large, catastrophic events, ignoring smaller but more prevalent leaks. As a result, the vast majority of subsurface leakage, including those enhanced or created by earthquakes, are likely to go undetected.

The scope of the subsurface leakage problem may be substantial but is also difficult to quantify. Large differences in areal size of the province/state, the level and history of oil and gas production, and earthquake frequency, magnitudes, and distribution make comparison of leakage potential between regions difficult. The leakage potential values presented here are not designed to be used for direct comparison between states/province because they are normalized by the maximum number of earthquakes or wells in the state/province. Although the DBSCAN clusters are aimed at inter-region comparisons of the distribution of wells and earthquakes, we do not use them to provide quantitative information for leakage potential estimates. Therefore, there is a need for a generalized framework to quantify leakage potential that includes local information but also allows for inter-region comparisons.

Database analysis with oil and gas industry and government data have provided many new insights on possible controls of leakage. However, they are unable to predict leakage and leakage pathway formation remains a largely random process [12]. For example, predictive modeling using logistic regression models, support vector machines, random forests, and back-propagation neural networks with data on Alberta wells show that the database is missing important predictors of leakage [12]. This is especially true for abandoned wells, for which the number of available measurements are small and information on wellbore integrity, location, and other critical factors are lacking. For example, there are approximately ~ 500 measurements of methane emissions from abandoned wells, yet there are at least five million abandoned wells in North America alone [35]. To better understand subsurface leakage and to identify the role of earthquakes on subsurface leakage, the current gap in data and empirical studies needs to be addressed through efficient use of, often limited, monitoring funds, especially for abandoned wells.

4.2. Wellbore integrity

There is a large body of literature on wellbore integrity, in addition to oil and gas industry standards [17, 18], considering environmental impacts of oil and gas development [3, 4, 35–37] and potential leakage in geologic storage of carbon dioxide projects [2, 5, 6, 38]. These studies show that wellbore integrity failures can occur due to a wide range of chemical and mechanical alterations or defects that could be caused by existing or injected fluids, oil and gas operations, and existing or induced geomechanical stresses [4]. Tectonic or seismic activities are listed as one of the many ways in which mechanical alterations, which involve fracture initiation and propagation, can occur. Chemical alterations may also be promoted by earthquakes as changes in pore fluid pressure drive fluids with corrosive substances to the wellbore. To avoid leakage, wellbores typically contain numerous barriers including multiple layers of steel casing and cementing [3]. Nevertheless, leakage along a wellbore can occur within cemented zones, between cement and steel casing, and between cement and the neighboring rock formation [2, 5]. The initiation and evolution of leakage pathways often involve a combination of a wide range of chemical, mechanical, and physical factors, including corrosion and dissolution of cement in acidic environments, thread leaks, poor cementing operations, pressure changes, and thermal stresses.

It is difficult to attribute wellbore leakage to earthquakes because there typically are other contributing factors and because of the detection problem. There are many factors that influence leakage with or without earthquakes that can be broadly categorized into technical degradation of the system, human intervention, process disturbance, inherent design errors, and external events, as identified to assess leakage risk on offshore petroleum installations [39]. Although advanced wireline downhole methods for determining well casing and cementing issues exist, they are not frequently done due to high cost and intrusiveness. In response, low-cost, non-intrusive, and fast monitoring system are being developed to obtain spatiotemporal data that can better detect wellbore integrity issues [40]. However, such systems are not yet available and are not widely deployed at scales needed to evaluate the large range of wellbore integrity failures and impacts. This is particularly true at abandoned wells, where measurements and data are lacking the most. Meanwhile, abandoned wells may be more prone to leakage due to their age and lack of management once the wells are abandoned. To investigate the potential link between earthquakes and subsurface-based leakage, new low-cost, non-intrusive, and fast monitoring methods [40], database analysis [6, 7, 10] and targeted field studies are needed at active and abandoned well sites. The results in this paper provide the first step to conducting additional database analysis and designing effective field studies for leakage along all and abandoned oil and gas wells.

5. Conclusions

Hotspots with frequent earthquakes and large well counts exist in CA, BC, and OK. One well-documented catastrophic leakage (Aliso Canyon Natural Gas Storage Field) is located in one of the CA hot spots. There may be many smaller leaks that remain undetected, especially in the hot spots. Furthermore, low magnitude ($M \leq 3.0$) but frequent seismic activity may play an important role in subsurface leakage. However, there are many gaps in oil and gas well databases and a lack of empirical field studies of all wells, especially those that are abandoned, to make a clear link. In parallel to overcoming the detection problem and improving our understanding of leakage mechanisms, geospatial analysis such as those performed in this study provide valuable insight into developing effective empirical field studies.

There are likely many oil-and-gas-producing regions outside of CA, BC, and OK, where wellbore leakage are being or have been created or enhanced by earthquakes. Although natural earthquakes are difficult to predict, there are many opportunities to minimize anthropogenic earthquakes and associated environmental impacts. Millions of wells have been and will continue to be drilled to meet growing oil and gas demands. Efforts to estimate the scale of the problem and minimize impacts of oil and gas development are needed. This need is becoming increasingly urgent as groundwater resources are depleted and contaminated and as atmospheric greenhouse gas emissions continue to grow.

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