Comment on “Accelerated Fill-Up of the Arbuckle Group Aquifer and Links to U.S. Midcontinent Seismicity” by Ansari et al. (2019)

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Abstract

Spatiotemporal analysis of Arbuckle Group formation pressures and disposal volumes provides insight into contributing factors underlying the regional trends in formation pressure identified by Ansari et al. (2019, https://doi.org/10.1029/2018JB016926) using statistical analysis. Based on trends in bivariate correlation of reported values, Ansari et al. (2019) suggested that rising formation pressures were a result of fluid injection within 25 km. Our primary concern is that the correlation trends are most likely an artifact of the method used by Ansari et al. (2019), at least in part, and the conclusion that pressure diffusion is limited to within 25 km of the injection point does not necessarily follow from the analysis. We also note that estimated formation pressure depends on the depth of the pressure gauge, which, in some cases, varies from one measurement to the next and should be accounted for to accurately assess measured changes. The spatial relationship of formation pressure changes among wells provides valuable insight into the origin of those changes. For each well, we project pressure to a baseline depth to account for changes in gauge depth and reexamine trends in formation pressure. Spatiotemporal progression suggests post-2011 formation pressure changes originate from a spatially dense group of high-rate saltwater disposal wells near the Kansas-Oklahoma border well beyond 25 km (and as far as 90 km) away.

1. Introduction

Recent research (Ansari et al., 2019) examines trends in formation pressure (P*) reported for Underground Injection Control (UIC) Class I industrial and municipal wastewater disposal wells across Kansas completed in the Arbuckle Group. A significant increase in P* was observed in most wells beginning in 2012 and was attributed to an increase in saltwater disposal (SWD) in the Arbuckle Group associated with development of the Mississippian limestone play near the Kansas-Oklahoma border (Evans & Newell, 2013). Bivariate analysis was used to quantify the relationship between P* and disposal volumes in both UIC Class II SWD and Class I wells within various radii up to 50 km. The median correlation was largest between P* and cumulative disposal volumes within 25 km, beyond which correlation leveled off. Based on this observation, Ansari et al. (2019) suggested that pore pressure diffusion is limited to distances of up to 25 km from the injection point. Although we understand that this suggested radius was interpreted using multiple lines of evidence, our primary concern is with the method employed by the authors. While we limit the scope of our discussion to pressure, the following concerns apply to all trends identified using the bivariate correlation method outlined in Ansari et al. (2019).

The observed correlation behavior is likely, in part, an artifact of the analysis approach. As the radius around the P* measurement point increases, the successive combined injection volumes increasingly convey the same information and, therefore, yield similar correlations. A circle with a 20 km radius occupies 64% of the area of a surrounding 25 km circle, which in turn occupies 69% of the area of a surrounding 30 km circle, and so forth. This means that each consecutive 5 km ring contributes successively less variation to the resulting vector of injection volumes—an effect that, on its own, would lead to a leveling off of the correlation with increasing radius, regardless of the P* measurements and injection volume distributions. Thus, it is unclear whether the correlation trend accurately reflects the actual relationship between P*, injection volumes, and distance. Furthermore, the results are most likely influenced by a screening effect—the tendency for nearby observations to reduce the influence of more distant observations (Chilès & Delfiner, 1999; Journel & Huijbregts, 1978). Consequently, we question whether the leveling off of correlation with increased...
distance can be interpreted as evidence that pore pressure diffusion is limited to within 25 km of the injection point, as suggested by Ansari et al. (2019).

The connection between observed correlations and causal mechanisms is not always straightforward. One aspect of the P* data that may shed light on contributing factors is the spatial relationship of P* changes among the measured wells. In this comment article, reported P* values are corrected for changes in depth of the pressure gauge. Although Ansari et al. (2019) are able to identify general trends without this step, it is technically correct and the most appropriate way to accurately assess pressure. We reexamine trends in P* and interpolate between wells to produce regional maps. The spatiotemporal progression of change in formation pressure is used to infer the origin and geographical extent of these changes and assess contributing factors.

2. Correcting for Change in Gauge Depth

At most Class I facilities, P* is estimated from an annual pressure falloff (PFO) test (Environmental Protection Agency, 2002). A logging tool with a pressure gauge is placed deep in the well (usually, but not always, at the same depth each year). Fluid is injected at a constant rate until radial flow is achieved, then the well is shut in and the pressure transient is recorded. At the end of the test, pressure is measured at regular intervals as the logging tool is removed from the well. Horner analysis is used to estimate P*, and static fluid level (SFL) is determined by analyzing the pressure gradient with depth or by direct measure. In cases where there is no active disposal and the Arbuckle Group pressure and fluid level are essentially static, some facilities perform an alternate test where pressure is measured at regular depth intervals extending to the bottom of the well. The measured bottomhole pressure is assumed to be the formation pressure at that depth, and static fluid level is determined in the same manner as a PFO test. (Henceforth, we use P* to refer to formation pressure estimated from either type of test.) Numerous practical factors might impact the reported P*, one of which is discussed in detail in this section and illustrated with examples from the data set published by Ansari et al. (2019).

Pressure (P) is related to height of the fluid column (h) in the hydrostatic equation:

\[ P = \rho gh, \]  

(1)

where \( \rho \) is the density of the wellbore fluid and \( g \) is the acceleration due to gravity. The height of the fluid column in the wellbore is the difference between the gauge depth and SFL. From Equation 1, it is clear that pressure increases with increasing gauge depth (i.e., increasing h). Although the gauge is typically placed at the same depth in a given well each year, it is not always consistent, which can lead to a large apparent change in pressure that does not represent a true change in P*. For example, P* reported for well KS-01-113-004 increased by more than 0.4 MPa between 2010 and 2011 (Figure S1a in the supporting information). However, the gauge depth also increased from 1,213 m below ground surface in 2010 to 1,250 m in 2011 (Table S1). The apparent pressure increase is, therefore, predominantly a result of a change in gauge depth rather than an actual change in P*. Because the reported gauge depth was inconsistent in more than half of the Class I wells, accounting for gauge depth is crucial to assess changes in P*.

The reported pressure can be projected to the baseline gauge depth using the following equation:

\[ P' = P + \frac{P}{h} \Delta h, \]  

(2)

where \( (P') \) is the formation pressure projected to the baseline gauge depth \((h')\), \( (P) \) is the reported formation pressure (i.e., P*) at the actual gauge depth \((h)\) during the pressure test, and \( \Delta h \) is the difference between \( h' \) and \( h \) (derived in Text S1). Because the pressure gradient is directly related to wellbore fluid density, density is accounted for in the pressure gradient term \((P/h)\), as explained in Text S1. About half of the facilities have reports dating to at least 2002; therefore, we selected 2002 (or the earliest reported year thereafter) as the baseline. We calculated depth-corrected P* values using Equation 2 and reported gauge depths (Table S1). The depth-corrected P* appear to more accurately represent true changes in formation pressure (e.g., well KS-01-113-004; Figure S1b). Although the general trend in formation pressure is more or less captured in the reported P*, failing to account for gauge depth changes would be
technically incorrect and contribute to artifacts in subsequent analysis. While we could have omitted what Ansari et al. (2019) describe as “random fluctuations” using an arbitrary threshold or a statistical approach, we opted to correct and retain these valuable data points in this already sparse data set using a physics-based approach.

3. Spatiotemporal Formation Pressure Changes

Although Class I well spacing varies across the state and is generally sparse outside of central Kansas (Figure S2), the spatial relationships of pressure change among wells can provide insight into large-scale regional trends. For each well, we normalized formation pressure by subtracting the depth-corrected baseline $P^*$ from each subsequent depth-corrected value. Thus, normalized $P^*$ represents the change in formation pressure relative to baseline. Normalized $P^*$ values were interpolated between wells and extrapolated outward to create statewide maps of formation pressure change. We omitted wells with more than 2 years between any two consecutive pressure tests (due to the inability to assess the overall annual trend), wells with a baseline year of 2012 or later, and well KS-01-173-009 because multiple high-rate disposal wells operating within 1 km during PFO testing could have affected $P^*$. For the remaining wells, pressure was interpolated from adjacent years to avoid time-lapse artifacts for any years with no pressure test.

Maps of Arbuckle Group formation pressure change were generated for 2010–2017. Prior to 2012, the Arbuckle Group $P^*$ was relatively consistent with little to no variation (less than ~0.1 MPa) at most locations (Figure 1a). A large increase in pressure began in southern Kansas in 2012 and progressed radially outward into surrounding counties over time (Figure 1b and Movie S1). By 2017, pressure changes occurred across central Kansas at least 90 km from the Kansas–Oklahoma border (Figure 1c). Because this area contains more than three quarters of the wells with pressure measurements, confidence in this regional trend is relatively high.

Pressure diffusion is a time-dependent process governed by the interaction of fluid flow and rock deformation, as described by the theory of poroelasticity (Biot, 1962). The time-dependent nature of this process is independent of the injection volume (except in the case of nonlinear diffusion and hydraulic fracturing of the medium) and directly related to hydraulic properties of the formation (Shapiro & Dinske, 2009). As such, the spatiotemporal progression of pressure is useful for estimating bulk fluid transport properties and serves as the basis for seismicity-based reservoir characterization (SBRC) (Rothert & Shapiro, 2003; Shapiro et al., 2002). In SBRC studies, earthquakes are used to track the “triggering front”—that is, to estimate the progression of the pressure change above the threshold that can trigger an earthquake (Shapiro et al., 1997).

A pressure change of 0.2 MPa has been documented to trigger earthquakes on critically stressed basement faults (Hornbach et al., 2015; Stein, 1999). Although formation pressures were measured in the Arbuckle Group and not the underlying basement rocks where earthquakes are occurring, this is a reasonable choice for examining how quickly the pressure change was transmitted. The 0.2 MPa pressure change propagated to the north and northeast at 14–18 km/yr, on average, and appeared to decelerate with time. In general, this rate is consistent with the 16 km/yr rate observed for the progression of earthquakes in south central Kansas (Peterie et al., 2018).

4. Discussion

The regional change in $P^*$ observed in Kansas is approximately centered on a spatially dense group of high-rate SWD wells located within an area about the size of two or three counties (~5,000 km$^2$) that spans both sides of the Kansas-Oklahoma border (Figures S3). The majority of these Arbuckle disposal wells were drilled in 2011 or later, during development of the Mississippian limestone play. Most of these wells were permitted to inject at rates much higher than in the past (Peterie et al., 2018). Between 2010 and 2015, the annual disposal volume near the border dramatically increased from less than 50 MMbbl to nearly 500 MMbbl. Injection volumes remained relatively consistent elsewhere during this time (Figure S4). Annual disposal volumes reached a maximum in 2015, after which volumes slightly decreased following injection restrictions imposed by regulatory agencies in Kansas and Oklahoma, as well as declining oil prices (and, thus, declining production and associated SWD).

Although disposal volumes began declining by 2016, pressure continued to incrementally rise in south central Kansas in 2016 and 2017. As noted in the previous section, pressure diffusion is a time-dependent...
poroelastic deformation process. Numerous studies indicate that pressure changes (including pressure decrease) will lag changes in disposal volume, especially at distance (e.g., Langenbruch et al., 2018; Langenbruch & Zoback, 2016). Paroditis et al. (2004) explicitly noted that the peak pore pressure lags shut in away from the injection point, and the time lag increases with increasing distance. It is, therefore, expected that pressure would continue to rise, especially considering that the southernmost pressure

Figure 1. Change in Arbuckle Group formation pressure (relative to baseline) in (a) 2011, (b) 2014, and (c) 2017. The box indicates the primary area under consideration, where more than three quarters of Class I wells are located and confidence in the regional trend is high. Beyond the area bounded by measurement points, pressure change is extrapolated and confidence is lower.
measurement is more than 25 km from the nearest high-rate disposal well (injecting at a rate of 10,000 bbl/day or more) near the southern Kansas border. This observation further supports that local disposal (<25 km) is likely not the primary driver of measured pressure changes.

Most cases of injection-induced seismicity involved just one or a few wells injecting at a rate of ~10,000 bbl/day (Ake et al., 2005; Deichmann & Giardini, 2009; Healy et al., 1968; Horton, 2012; King et al., 2014; Hornbach et al., 2015). In 2015, when disposal rates were at their highest, the total disposal volume near the Kansas-Oklahoma border was equivalent to more than 100 wells injecting at a rate of 10,000 bbl/day (Peterie et al., 2018). It is, therefore, unsurprising that this volume of fluid could produce a large additive pressure change that propagated to unprecedented distances of 90 km or more. Some authors have suggested that pore pressure changes will primarily be limited to near injection wells, and poroelastically induced Coulomb stress change is the likely triggering mechanism beyond ~15 km (Goebel et al., 2017; Goebel & Brodsky, 2018). This suggestion is largely based on patterns of seismicity and a comparison of results from uncoupled pore pressure diffusion modeling (in which solid stresses do not change, neglecting important poroelastic effects) and fully coupled analytical solutions for poroelastic stress.

It is important to note that Goebel et al. (2017) and Goebel and Brodsky (2018) do not specify a maximum distance for coupled pore pressure diffusion. Although poroelastic coupling affects pore pressure change (Segall & Lu, 2015), Goebel et al. (2017) and Goebel and Brodsky (2018) did not evaluate pore pressure changes in the case of fully coupled poroelasticity. Given the significant poroelastic stress change calculated as far as 100 km away (Figure 7 in Goebel et al., 2017), it is likely there are coupled changes in strain and pore pressure at these distances as well. The observed spatiotemporal changes in Arbuckle Group formation pressure strongly suggest that coupled poroelastic changes in stress and strain influenced pore pressure diffusion to distances of at least 90 km from the causal wells near the Kansas-Oklahoma border.

5. Conclusions

A spatially dense group of high-rate SWD wells near the Kansas-Oklahoma border are at the geographic focus of a regional increase in Arbuckle Group formation pressure. Increasing formation pressures propagating away from the geographical focus since 2012 strongly suggests that the large increase in SWD volumes is the primary source of poroelastically driven pore pressure diffusion into central Kansas 90 km or more away. Accounting for change in gauge depth and accurately assessing spatial changes in formation pressure are essential for identifying the primary cause driving the observed changes.

Data Availability Statement

Disposal volumes for wells in Oklahoma can be found at http://www.occceweb.com/og/ogdatafiles2.htm website. Reported gauge depths and disposal volumes used in this comment article are provided in the supporting information.
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