URTeC: 2813

Significance of Well Orientation on Cumulative Production From Wells in the Bakken Region

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This paper was prepared for presentation at the Unconventional Resources Technology Conference held in Denver, Colorado, USA, 20-22 July 2020.

Abstract

We conducted a comprehensive analysis of approximately 7000 horizontal wells drilled in the Middle Bakken formation between 2007 and 2016 to assess the impact of well orientation on cumulative production. While it is common practice to drill horizontal wells “on-azimuth”, that is, in the direction of the minimum horizontal stress (S_{hmin}), there is a diversity of well orientations in the Bakken. S_{hmin} is consistently oriented N42°W throughout the production area. Our analysis clearly demonstrates that wells drilled in the direction of S_{hmin} (“on-azimuth”) produce more barrels per foot than wells in other directions, both in the core area and across the entire Bakken play. However, the amount of uplift gained from drilling on-azimuth wells decreases as the field matures, which we hypothesize is due to depletion. We found that the relationship between production and well orientation is consistently observed, regardless of the amount of proppant used. An economic analysis indicated that for wells of equal length, it is clearly beneficial to drill wells in the direction of S_{hmin}. However, wells in the direction of S_{hmin} are consistently shorter in length than off-azimuth wells, and it is generally more efficient to drill longer laterals on a given leasehold. Nevertheless, using the average oil price at the time the wells we studied were drilled, we find that the shorter wells in the on-azimuth direction have a significant economic uplift of several million dollars per well relative to the longer wells drilled in the off-azimuth direction.

Introduction

Hydraulic fractures propagate in a plane perpendicular to the least principal stress (Hubbert and Willis, 1957) which normally means that hydraulic fractures propagate in vertical planes, normal to S_{hmin} in areas characterized by strike-slip or normal faulting. When exploiting unconventional oil and gas reservoirs, it is common to drill horizontal wells with multiple hydraulic fracturing stages in the direction of S_{hmin}. If the spacing between adjacent wells reflects the drainage area associated with the propped half-lengths of the hydraulic fractures of the wells, it would seem to result in optimal recovery. This said, in some areas wells are drilled in north-south or east-west directions regardless of the stress orientation to 1) optimally exploit available acreage with the highest number of wells and 2) take advantage of the fact that drilling longer wells decreases drilling and completion costs on a per foot basis.

In this paper we study the relationship between well orientation (relative to the stress field) in the Bakken play to assess its effect on production. The Bakken shale play is in the Williston Basin straddling a region of 200,000 square miles across western North Dakota, eastern Montana, Saskatchewan, and Manitoba. Unconventional oil production started in 2006 and peak oil production reached its maximum to date in 2019 with approximately 1.5 million barrels per day (EIA, 2020a). We have restricted this study to wells drilled in the Middle Bakken formation to avoid intermingling data from the less productive Three Forks.

Our initial analysis considered 176 wells from the core area of the Bakken (Figure 1). This area was chosen for two principal reasons. There are multiple wells of varied orientation in an area of uniform NE-SW maximum horizontal stress (Lund Snee and Zoback, 2020); and relatively uniform average well productivity (as indicated by the background shading in the figure). We then go on to extend our analysis to the entire Bakken field.

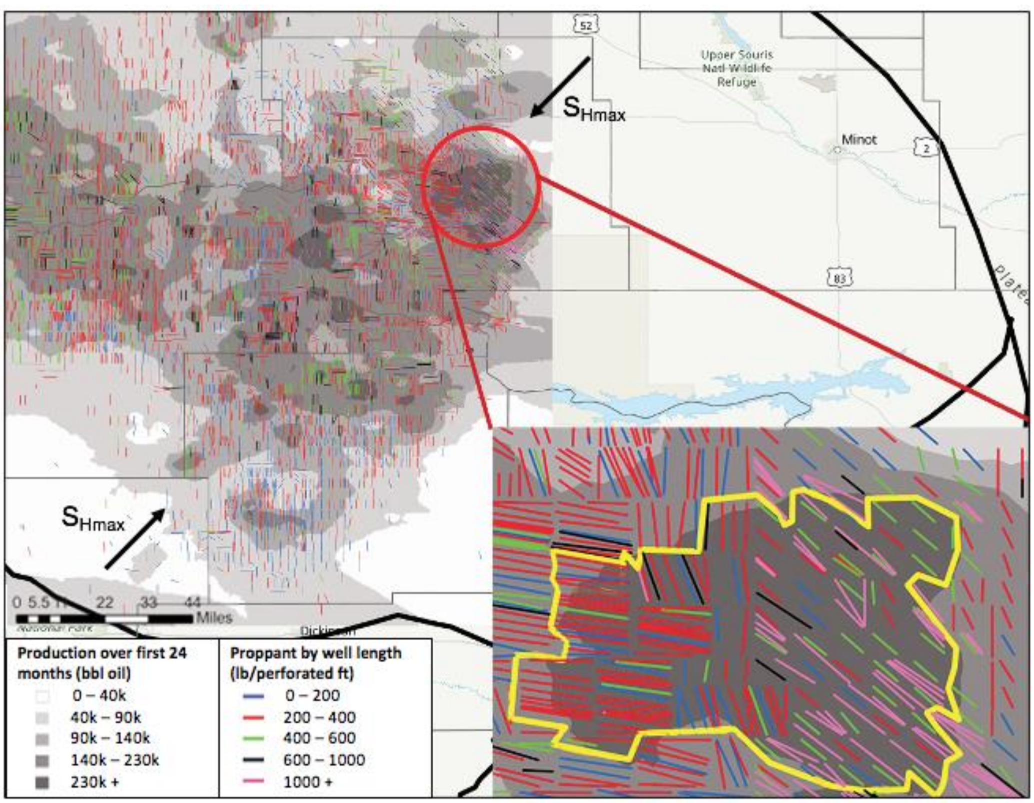


Figure 1. Study area in the Williston Basin chosen to examine the relationship between well orientation and well productivity in the Bakken Formation.

Methods

We retrieved our data from the publicly available Enverus (formerly Drillinginfo) database. Approximately 10,000 wells were drilled in the Middle Bakken between 2007 and 2016, but after filtering out wells with data, we analyzed a total of 7,198 wells across the entire play and 176 wells in the focus area shown in Figure 1. The time at which drilling and completion took place is an important factor in our analysis since the drilling and completion methodologies evolved over time and, as time went on, more in-fill wells were drilled which were less productive due to depletion associated with previously drilled wells. Following the work of Hakso and Zoback (2019), we binned the wells into two-year epochs (based on the year of their first date of production) with at least 24 months of production. At the time of this analysis, wells drilled after 2016 had not completed their 24 months span. Additionally, there is only a very limited number of wells for the 2005-2006 epoch (79 wells across the entire play), so we dropped this epoch in our analysis since it was not statistically significant.

To determine the orientation of the horizontal section of the wells, we used the full well trajectory and computed the direction from the well heel to the well toe. There were a few cases in which multiple horizontal wells were drilled from the same vertical well. These were removed as the production values were reported under the same API which made it ambiguous how much oil each well in different horizontal orientations produced.

In the focus area, wells were drilled in multiple directions (Figure 2a). About 44% of the wells were drilled on-azimuth, about 29% of wells were drilled almost E-W and the remainder of wells were drilled approximately N-S. In the Bakken as whole (Figure 2b) the vast majority (72%) of the wells were drilled in a N-S direction, 8% were drilled on-azimuth, 8% are E-W and about 6% are N-NW, with the remainder scattered.

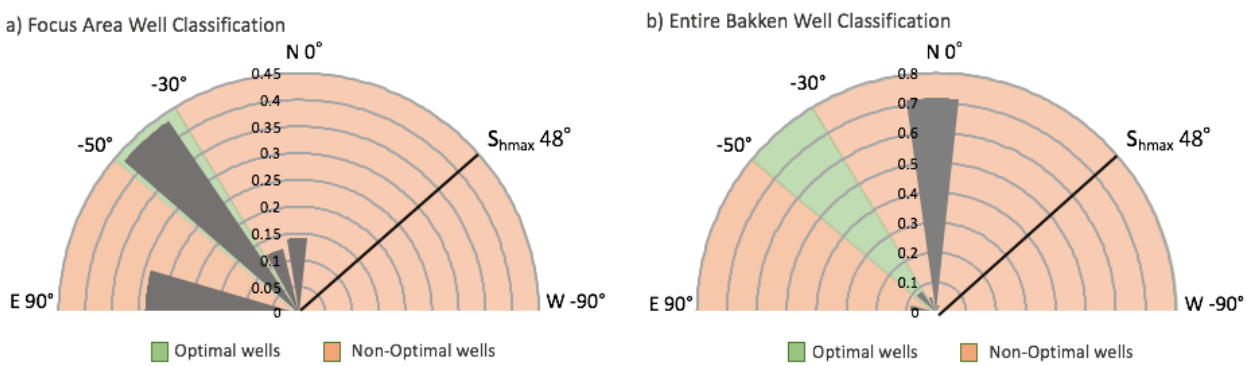
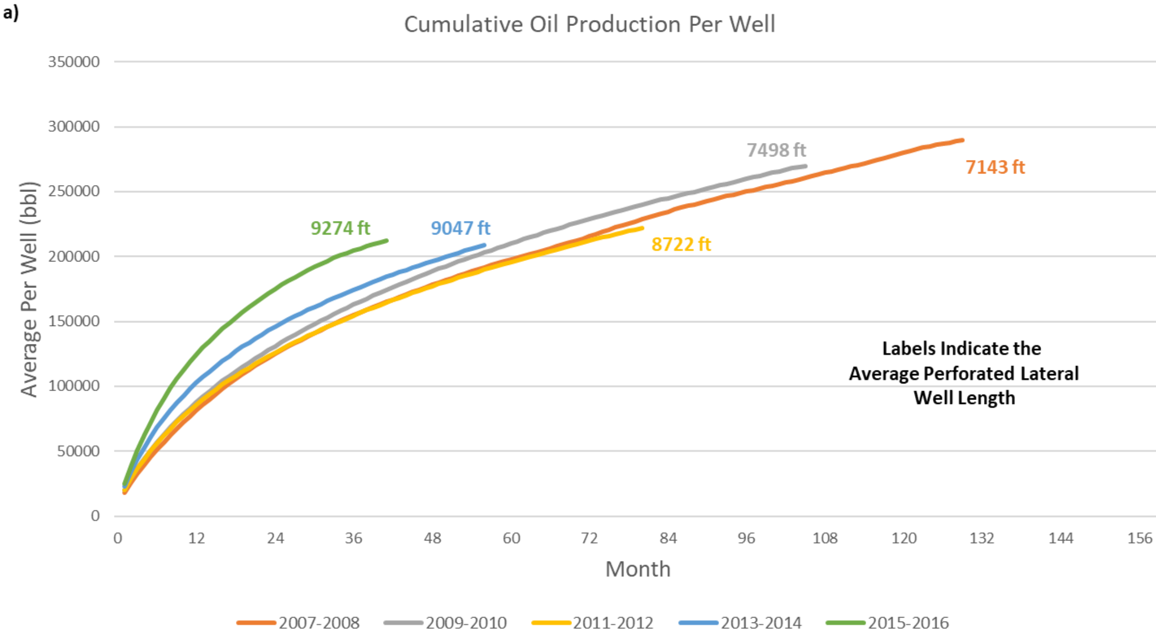


Figure 2. Orientations of wells after the direction transformation process with the size of each "petal" proportional to number of wells, and classification of on-azimuth vs off-azimuth wells relative to S_{hmax} for **a)** 176 wells in the focus area; and **b)** 7198 wells across the entire play.

To assess relative production as a function of well orientation, we binned the wells in 20-degree bins, within the range from -90°W degrees to +90°E. Based on the average S_{hmax} direction in the region to be N48°E (Lund Snee and Zoback, 2020) we considered wells with orientation between -50° and -30° to be on-azimuth (parallel to S_{hmin}).

On a per well basis, cumulative oil production showed a steady increase in time (Figure 3a) as discussed by Hakso and Zoback (2019). However, if we consider average oil production per well on the basis of barrels per foot instead of total barrels (to normalize the effect of variable well length as indicated in Figure 3a), we show in Figure 3b that there was a decline in production per foot of well through time. The first epoch was the best, the second epoch was second best and the third and fourth epochs produced considerably less. While the fifth epoch produced more per foot of well than epochs 3 and 4, we show below that considerably more proppant was injected per well during that epoch.

a)



b)

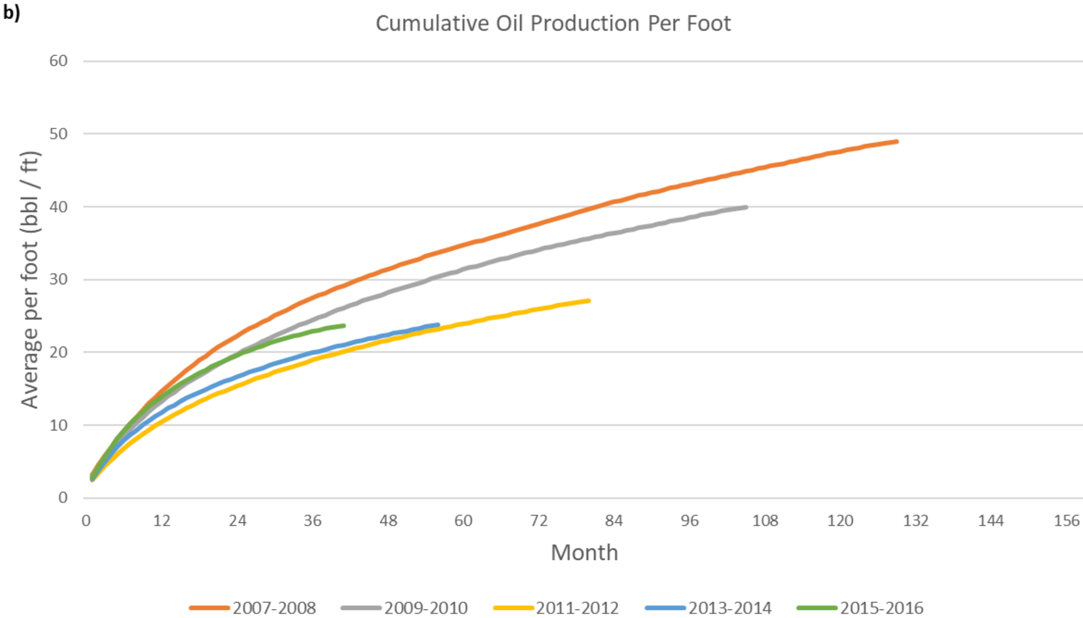


Figure 3. a) Average cumulative monthly oil production per well for each 2-year cohort across the entire play showing increasing production over time; and **b)** Average cumulative monthly oil production per perforated foot, normalized for well length, showing that oil production efficiency is actually decreasing over time. Data from Enverus Drillinginfo database (www.enverus.com).

Results

As shown in Figure 4a, in the first epoch (2007-2008) 34 on-azimuth wells and 10 off-azimuth wells were drilled. The on-azimuth wells were 33% more productive on average for the first two years of production. In the second epoch (2009-2010), 8 on-azimuth wells and 30 off-azimuth wells were drilled. During this epoch, the on-azimuth wells produced more than twice as much per foot as the off-azimuth wells. In both epochs 1 and 2, relatively small amounts of proppant/ft were used during hydraulic fracturing. No meaningful comparison could be made for the third epoch as only 1 on-azimuth well was drilled during that epoch. However, during the fourth epoch (2013-2014) comparable numbers of on-azimuth and off-azimuth wells were drilled but the on-azimuth wells produced about twice as much per foot as did the off-azimuth wells, although it should be noted that the on azimuth wells used considerably more proppant (Figure 4b). The average production efficiency for on-azimuth wells in the last epoch is lower than the earlier epochs which is likely due to depletion through time, and the fact that a greater proportion of wells are in-fill wells. The fact that the average of the on-azimuth wells in the last epoch is lower than the off-azimuth wells may be due to the fact that there are only 4 on-azimuth wells and 8 off-azimuth wells considered, including one off-azimuth well with unusually high production.

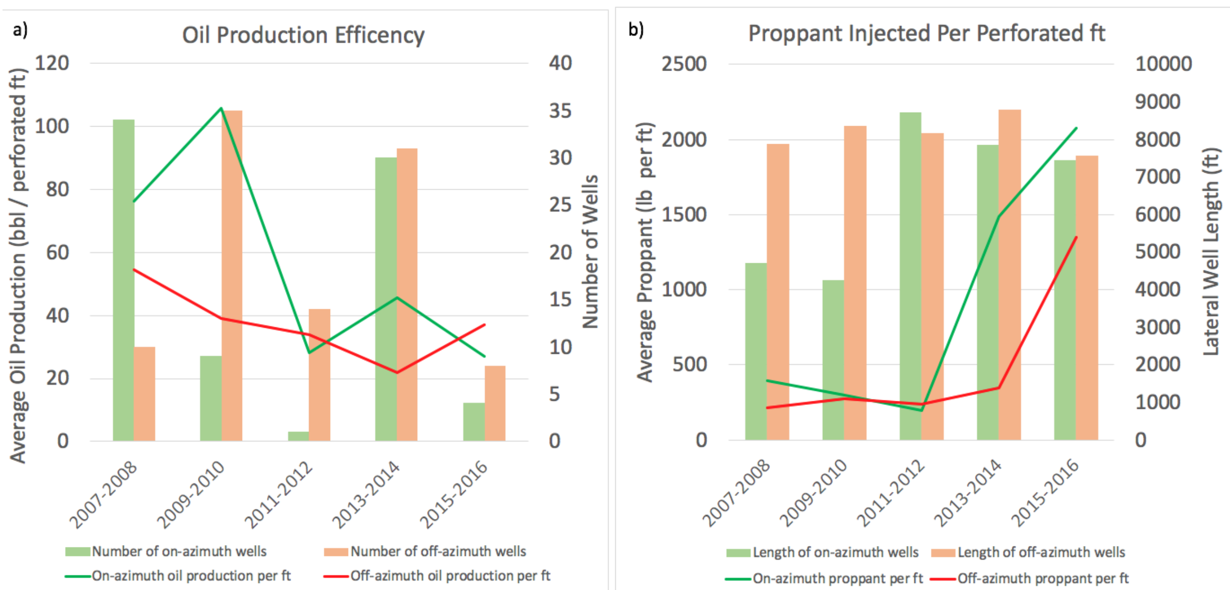


Figure 4. Results for 176 wells in the focus study area. a) Average cumulative oil production efficiency after 24 months for on-azimuth and off-azimuth wells, and the number of on-azimuth and off-azimuth wells; **b)** Proppant injected per perforated foot in the on-azimuth and off-azimuth wells, and the lateral length of on-azimuth and off-azimuth wells.

As shown in Figure 4b, the amount of proppant used increased markedly in the last two epochs. However, binning the wells based on the amount of proppant per foot, we see that regardless of how much proppant was injected, the wells in the on-azimuth direction have much higher production (Figure 5).

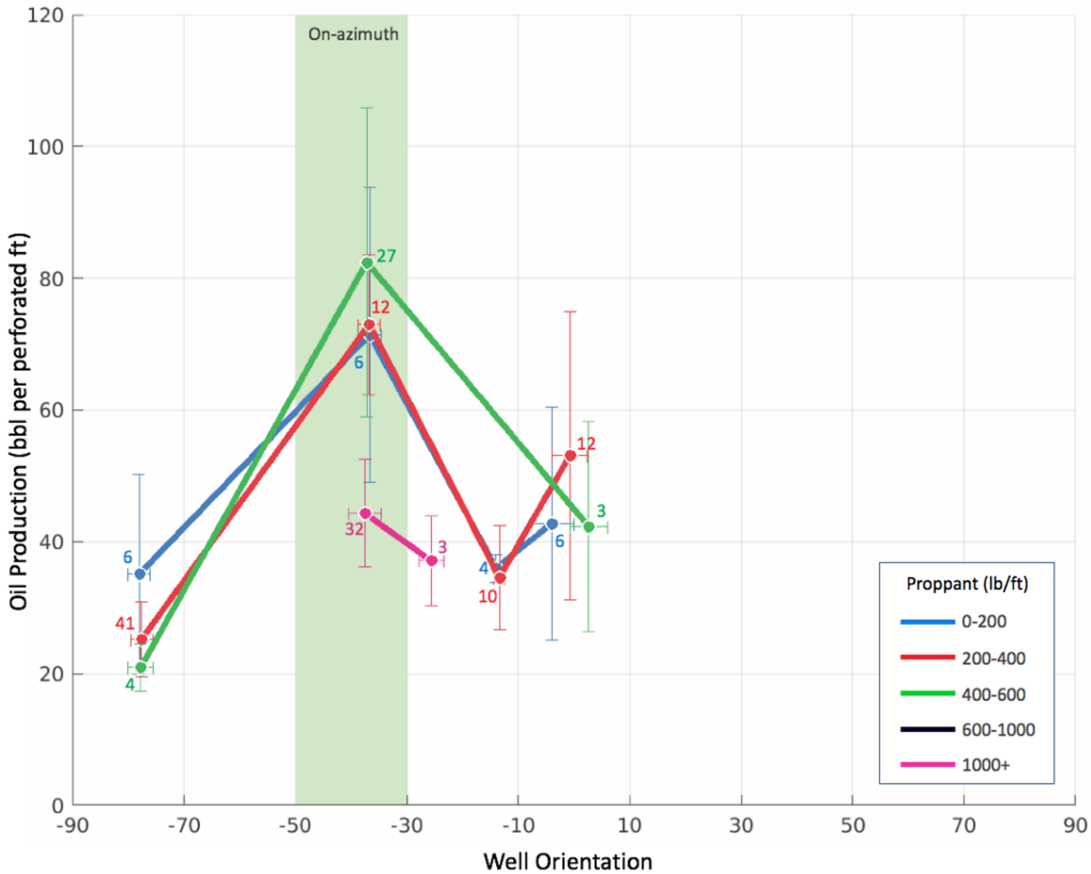


Figure 5. Average cumulative oil production per perforated foot after 24 months for wells with different amounts of proppant in all epochs relative to their orientation within the focus area. Error bars depict the range of 25th and 75th quartile orientations and oil production around the average of each orientation bin. The number of wells used to determine each average are shown and bins with less than three data points were discarded to ensure meaningful averages.

In extending our analysis to the whole field, we find that the oil production efficiency is clearly higher for on-azimuth wells in all epochs (Figure 6a). On-azimuth wells are consistently more efficient than off-azimuth wells in all epochs, from 116% more efficient in epoch 1 (2007-2008) to 4% more efficient in epoch 5 (2015-2016). Meanwhile the production efficiency of off-azimuth wells remains fairly consistent through time. This supports our hypothesis that the decreasing production from on-azimuth wells is caused by depletion. The off-azimuth wells are not as impacted by depletion because the hydraulic fractures are not extending as far from the borehole where the oil has already been produced.

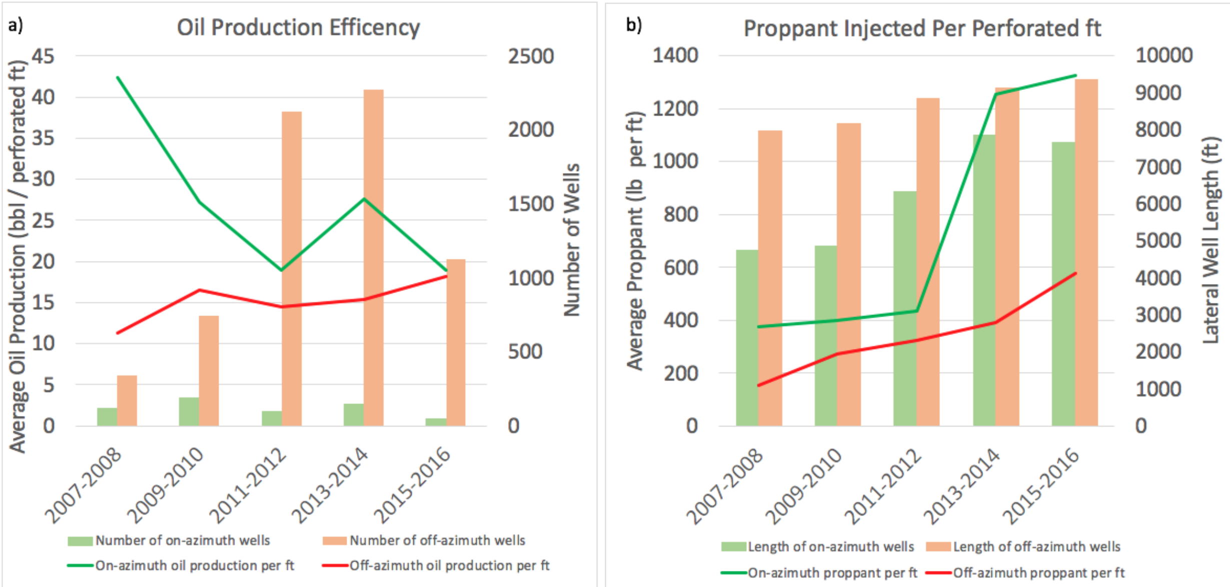


Figure 6. Results for 7198 wells across the entire Bakken play. a) Average cumulative oil production efficiency after 24 months for on-azimuth and off-azimuth wells, and the number of on-azimuth and off-azimuth wells; **b)** Proppant injected per perforated foot in the on-azimuth and off-azimuth wells, and the lateral length of on-azimuth and off-azimuth wells.

We can see for the 3 lower bins of proppant (Figure 7), the on-azimuth direction in the whole play is performing better than other directions. However, for higher amounts of proppant above 600 lb/ft (Figure 8), we do not see on-azimuth wells significantly performing better. This is possibly due to the impact from depletion as 88% of wells in the higher proppant volumes are in the two last epochs (2013-2016).

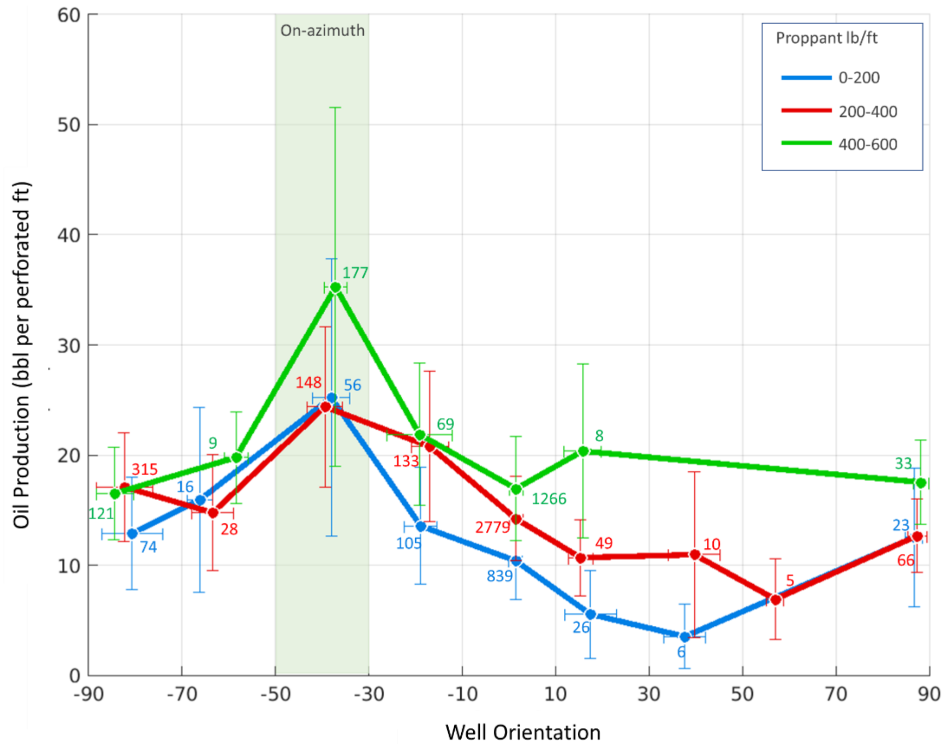


Figure 7. Average cumulative oil production per perforated foot after 24 months for wells with lower amounts of proppant show a good correlation between on-azimuth well orientation and higher production for the entire Bakken. Error bars depict the range of 25th and 75th quartile orientations and oil production around the average of each orientation bin. The number of wells used to determine each average are shown and bins with less than three data points were discarded to ensure meaningful averages.

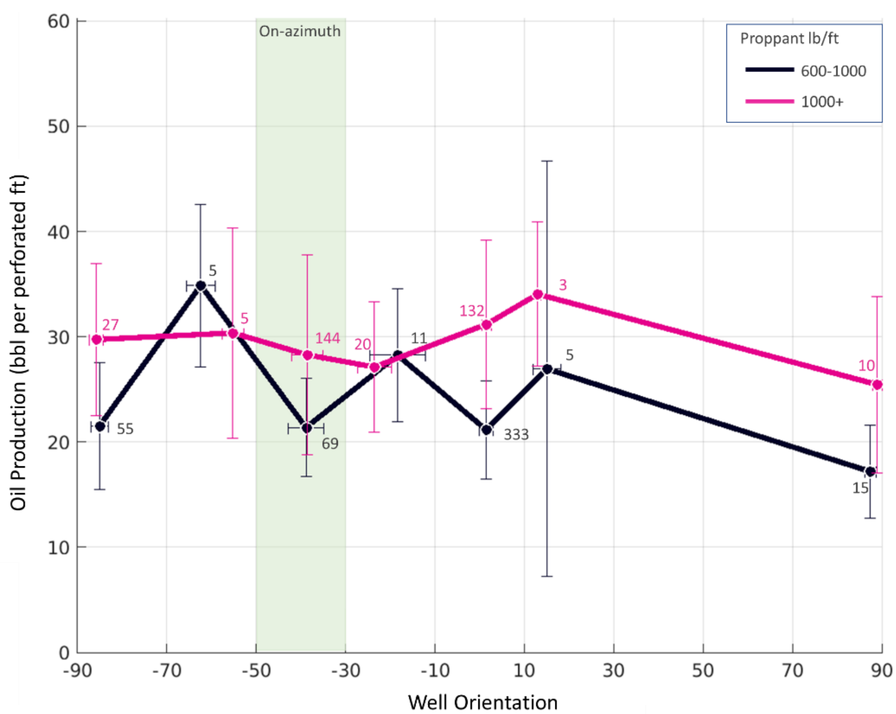


Figure 8. Average cumulative oil production per perforated foot after 24 months for wells with higher amounts of proppant show no correlation between on-azimuth well orientation and production for the entire Bakken. The higher proppant amounts were mostly used in later epochs to arrest field decline. Error bars depict the range of 25th and 75th quartile orientations and oil production around the average of each orientation bin. The number of wells used to determine each average are shown and bins with less than three data points were discarded to ensure meaningful averages.

Discussion

Our analysis shows that the orientation of a well in the Bakken has a correlation with production efficiency. In a case study in the Duvernay play in Alberta an "on-azimuth" well drilled in a NW-SW direction parallel to S_{hmin} produced considerably more than an "off-azimuth" well drilled in a N-S direction (Stephenson et al., 2018). In the Bakken, off-azimuth wells tend to be longer and often produce more total oil than on-azimuth wells. Drilling longer wells increases the total drilling and completion costs for a well but lowers the drilling and completion costs per foot. To investigate the economic impact of production efficiency from drilling on-azimuth vs. off-azimuth wells, we have developed an economic model that considers production, cost of wells (based on well length and amount of proppant used), and oil price (Figure 9). Wells in the on-azimuth direction are significantly shorter in length than off-azimuth wells, presumably because of the acreage constraints on drilling at an angle, so in the first part of this analysis, we normalize for length by calculating the economics on a per foot basis. We conclude our analysis by calculating the absolute economics for the off-azimuth wells (longer length, lower production efficiency) vs. on-azimuth wells (shorter length, higher production efficiency).

Figure 9. Economic analysis data and results. **a)** Well Production; **b)** Average well cost; **c)** Calculated net earnings per ft; **d)** Net earnings per well demonstrating that even though the on-azimuth wells are typically shorter, there is still a clear economic benefit from the improved production efficiency.

We evaluated the cost of each well based on the Capital Cost (CAPEX) since this portion of the cost changes based on well design. We largely ignored Lease Operating Expenses (LOE) because it mostly includes the maintenance cost after drilling and completion, and the cost is highly variable and complex based on location and operator. We consider the drilling cost per foot to be a fixed cost, while the completion cost per foot varies based on the volume of injected proppant. We adjusted the completion cost relative to how much the injected volume of proppant varied from the average amount of proppant for all wells in Bakken. The on-azimuth wells cost an average of $41/ft more than off-azimuth wells (Figure 9b) for two reasons: 1) the fixed costs for drilling a well are distributed over the shorter length, and 2) the volume of proppant injected is higher increasing the completion costs.

However, the oil sales value (which is the amount of money operators receive for selling their product) is higher on a per foot basis for on-azimuth wells due to their better production efficiency, which results in significantly higher net earnings per foot after deducting the costs from sales value (Figure 9c). It should be noted that in the last epoch, the sales value for on-azimuth and off-azimuth wells is almost identical and low, reflecting the declining production rate and the lower oil price.

When we incorporate the length of the wells in the economic analysis, we find that off-azimuth wells cost on average $837,000 more than on-azimuth wells because of their longer length (Figure 9b). Even though the off-azimuth wells might have higher total production due to their longer length, the on-azimuth wells have higher net earnings per well than off-azimuth wells (up to $9.7MM more) because of their superior production efficiency (Figure 9d). The only epoch this is not true for is the last one, 2015-2016, when the low production efficiency of the on-azimuth wells combined with a low average oil price results in on-azimuth net earnings that are marginally lower than the off-azimuth wells.

Finally, to normalize the effect of oil price, we calculated the net earnings for a consistent oil price of $75 per barrel for wells of the same length (7500 ft) in on-azimuth vs. off-azimuth orientations. Under these normalized conditions, the economic uplift of a well drilled in the on-azimuth direction of S_{hmin} is approximately $6.3 million more over the first two years of production relative to an off-azimuth well.

Conclusion

Our analysis clearly demonstrates that for wells drilled in the Bakken unconventional play between 2007 and 2016, those in an on-azimuth direction (parallel to S_{hmin}) have superior production on a per foot basis. On-azimuth wells are typically shorter than off-azimuth wells, presumably due to the constraints of drilling in a diagonal pattern on north-south square acreage. The off-azimuth wells therefore cost more on an absolute basis (but less per foot), with total greater production (but less per foot). We find that it is economically beneficial to drill shorter on-azimuth wells than longer off-azimuth wells, particularly at the beginning of field development before the effects of depletion are reflected in the production volumes.

Acknowledgments

This research was funded by the Summer Undergraduate Program on Energy Research at Stanford (SUPER) and the Stanford Natural Gas Initiative (NGI). Special thanks to Jens Lunde Snee, Kevin McCormack, and Ankush Singh for their assistance in the analysis.

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Appendix

	2007-2008	2009-2010	2011-2012	2013-2014	2015-2016
Oil production of on-azimuth wells (bbl/ft)	76.1	105.6	28.1	45.5	26.9
Oil production of off-azimuth wells (bbl/ft)	54.5	39.0	34	21.7	37
% production efficiency difference between on-azimuth and off-azimuth wells*	33%	92%	-19%	71%	-32%
Number of on-azimuth wells	34	9	1	30	4
Number of off-azimuth wells	10	35	14	31	8
% of on-azimuth wells	77%	20%	7%	49%	33%
Proppant volume for on-azimuth wells (lb/ft)	392	297	196	1487	2077
Proppant volume for off-azimuth wells (lb/ft)	216	275	241	344	1352
Perforated length of on-azimuth wells (ft)	4711	4260	8715	7862	7456
Perforated length of off-azimuth wells (ft)	7892	8372	8182	8803	7563

Table A. Tabulated results for 176 wells in the focus area of this study.
*The percentage difference was calculated by the subtraction of off-azimuth well's production efficiency from the on-azimuth well's production efficiency, divided by the average of both numbers. Positive values indicate that on-azimuth wells have a higher production efficiency, and negative values indicate that off-azimuth wells have a higher production efficiency.

	2007-2008	2009-2010	2011-2012	2013-2014	2015-2016
Oil production of on-azimuth wells (bbl/ft)	42.4	27.2	18.9	27.6	19
Oil production of off-azimuth wells (bbl/ft)	11.3	16.5	14.5	15.3	18.2
% production efficiency difference between on-azimuth and off-azimuth wells*	116%	49%	26%	57%	4%
Number of on-azimuth wells	117	186	94	148	49
Number of off-azimuth wells	343	745	2122	2270	1124
% of on-azimuth wells	25%	20%	4%	6%	4%
Proppant volume for on-azimuth wells (lb/ft)	374	399	435	1255	1325
Proppant volume for off-azimuth wells (lb/ft)	154	273	323	392	575
Perforated length of on-azimuth wells (ft)	4737	4858	6337	7849	7656
Perforated length of off-azimuth wells (ft)	7964	8157	8828	9125	9345

Table B. Tabulated results for 7,198 wells across the entire Bakken play.
*The percentage difference was calculated by the subtraction of off-azimuth well's production efficiency from the on-azimuth well's production efficiency, divided by the average of both numbers. Positive values indicate that on-azimuth wells have a higher production efficiency.

	2007-2008	**2009-2010**	**2011-2012**	**2013-2014**	**2015-2016**
Oil price ($/bbl)	76.99	62.00	86.40	86.55	38.96
Average drilling costs for total length of all wells ($/ft)	100	100	130	120	100
Average completion cost for lateral length of on-azimuth wells ($/ft)	421	404	454	502	441
Average completion cost for lateral length of off-Azimuth wells ($/ft)	377	386	439	425	398

Table C. North Dakota crude oil first purchase price (EIA, 2020b), completion and drilling cost from EIA (2016) adjusted for average proppant injected in on-azimuth and off-azimuth wells.