

## Refracturing Activities in the United States — How Much Do We Know So Far?

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### Abstract

Refracturing old wells instead of drilling and stimulating new wells has become a new trend in the United States due to the oil prices falling in 2011. This work aims to disclose all refracturing activities in the most active shale play in the United States (Bakken, Niobrara, Marcellus, Permian, Eagle Ford, Barnett, and Haynesville) in terms of techniques, candidate selection, fracturing fluid types, and the number of refracs in one well. FracFocus was used to collect data on over 130,000 wells in the United States that were completed between 2013 to the end of 2019. The refractured wells were extracted from the database and the fracturing fluid types were classified as slickwater, linear gel, cross-linked gel, hybrid, and not reported treatments based on the presence of key chemical ingredients. After processing the data, there were over 1200 wells refractured across the most active shale plays in the United States. The results showed the most common fluid type used in refractured wells is hybrid. In terms of shale plays, Niobrara was the most active shale play with over 280 refractured wells followed by Bakken, Eagle Ford, Marcellus, Permian, Barnett, and Haynesville, respectively. Furthermore, the refracturing activities in each well were further analyzed and clustered into two groups; one or two refracs since some wells were refractured more than one time. However, over 95% of the wells were only refractured once. Moreover, refrac candidates can be identified based on the following factors; the original wells' cluster spacing, well spacing, proppant distribution, fracture orientation, production response from initial fracture, reservoir thickness, and permeability. The optimal ranges of the aforementioned parameters were provided to achieve the best results in terms of saving money and providing the best productivity. This will help optimize future refracturing operations in the United States and all across the world.

### Introduction

Refracturing is a process to re-stimulate a producing well after initially being hydraulically fractured to improve its production (Jacobs, 2015). Refracturing technology is not a new technology, and it has been known for a long time. Refracturing vertical wells have been active in the United States since the 1970s and they showed promising results in terms of productivity improvement. However, refracturing multi-stage

horizontal wells is a relatively new process across the United States as it started to emerge in 2011 (Dutta, 2017). Due to the oil prices falling in 2011, oil companies started to shift their focus on refracturing oil and gas wells instead of drilling and completing new ones. Another factor that shifted the industry back to refracturing activities is the reserve size of the unconventional resources and the focus of the industry on the unconventional technology of extraction (King, 2014). To further emphasize the economic benefits of refracturing, an Eagle ford well was used as an example to compare the cost of fracking a new well and refracturing the well, the economic forecast found that a new well would cost 2 to 4 million to frac; however, initiating a new frac in a preexistent fractured well would cost 1 to 1.5 million (Fu et al., 2017).

The refracturing operation can be highly challenging due to the lack of data on the surface and its success is determined and controlled by many factors (Yanfeng & Salehi, 2014). As a result, the industry started to study and create models to predict the success or the failure of refracturing jobs before initiating one. In fact, it is recommended to include the refrac plan in the initial stage of developing a field due to its efficiency in providing a high return on investment in a shorter time (Dutta, 2017). To predict the failure or success of refrac operations, it is important to understand the factors contributing to a successful refrac. Another complication to consider when it comes to refracturing operation is the formation of the fracs; depending on the pressure distribution created by the initial fractures and the cluster spacing between the fracture stages, a new fracture might be initiated reaching more sweet spots in the reservoir. In another case, the initial fracture would reopen and reorient in the producing section of the reservoir (Fu et al., 2017). This shows that the level of uncertainty in the refracturing operation could be a challenging case that needs to be considered before starting a refracturing operation.

The first part to consider is the completion strategy used to initiate the refrac. The use of a diversion tool is the first to consider when completing a well for a refrac. The diverter needs to remain in the initiated fracture to plug the perforated zones for at least two to four weeks (Cookson, 2020). Therefore, permanent diverters are usually used in refrac operations. Another factor to consider when completing a well for a refrac operation is the washed-out perforation due to

production from original completion for several years. To resolve this problem, customized pods based on the size and shape of the perforation are installed in the well to solve the problem of washed-out perforation. The use of pods to plug a fraction of the wells yielded a better result compared to other completion alternatives such as straddle packers or squeezed-type systems with a less expensive cost of operation (Cookson, 2020). The only drawback with the use of diverters is the level of uncertainty. When completing a refrac job with diverters, it is not easy to determine where the fracturing fluid would propagate the formation. However, using an expandable liner instead of a diverting agent gives a higher degree of certainty because it is possible to mechanically isolate the old zones to perforate new ones. Since 2009, Entventure Global Technology Company has used expandable liners for completing 15 wells in the Marcellus, Barnett, and Eagle Ford Basins (Jacobs, 2015). The process of installing expandable liners starts by installing milling tools into the cased hole to prepare for the expandable liner. The expandable liner is then installed and expanded to maximum diameter through the expansion cones sealing the old perforation and giving more space for the new perforation to be made. Although the use of a diversion agent is found to be much cheaper than the use of an expandable liner, the expandable liner completion in many cases yielded higher production and profit in refracture operations. **Figure A.1** (Appendix A) shows the production data of three wells produced in the Barnett shale using refrac technology; the figure shows that well 1 which was produced through an expandable liner showed production gains higher than the two offset wells (well 2 and well 3) which used diverter agent technology (Jacobs, 2015).

Another factor to consider in a refracturing operation is choosing the right candidate and the optimal time for refracturing. In a study conducted on the refractured-producing wells in the Barnett shale, the findings of the study showed that the production after the refracturing job in 171 studied wells increased 2 to 4 times of their initial production before refracturing. The study also found that it is better to restimulate the well at a relatively early stage of production instead of waiting for too long (Wang et al., 2013). **Table A.1** (Appendix A) is a literature summary of refracturing operations in the most active shale plays in the United States.

This work aims to understand the refracturing activities in the most active shale play in the United States in terms of state-of-the-art applications, candidate selection, and techniques. Furthermore, this work will disclose the refracturing activities over time and the fluid types used in each well.

### **Refracture Candidate Selection**

While refracturing is a successful operation that yields higher income by minimizing the cost of drilling a new well, not all wells can be considered good refracturing candidates (Hunter et al., 2015). Many studies have been conducted to determine the candidacy of a well to be refractured (Charry et al., 2016). Many factors need to be taken into consideration to determine if the well is a good candidate for refracturing

(McFall et al., 2017; Diakhate et al., 2015). The following subsections present the main refrac candidate parameters.

### **Cluster Spacing**

The initial completion design of the well plays an important role in determining the success rate for a refracturing operation. From a perforation standpoint, when the spacing between the perforated intervals is large, the probability of unstimulated zones of the reservoir rock is usually high, especially if the initial production of the well was lower than anticipated (McFall et al., 2017). Based on case studies on several wells, for a well to be a refracture candidate, the cluster spacing has to be larger than 500 ft/stage (French et al., 2014). Other approaches to selection suggest different values of cluster spacing; larger than 90 ft/stage (Hunter et al., 2015), and larger than 300 ft/stage (King, 2014).

### **Well Spacing**

Well spacing is another important consideration that is related to the initial completion design. Closely spaced wells can lead to a decrease in production due to fracture interference and pressure communication induced by the fracture hits (Sinha & Ramakrishnan, 2011; McFall et al., 2017). Therefore, it is important to consider the initial well spacing when considering a refracture candidate. Producing wells spaced 500 ft, or more from infill wells can be a good candidate based on the well spacing criteria of selection (McFall et al., 2017). Another well spacing criteria of selection suggests that wells spaced less than 800 ft can be a good candidate, but certain completion techniques and proppant volume is required to ensure refracture success (Hunter et al., 2015).

### **Proppant Distribution**

Proppant distribution is an important factor that controls the efficiency of the first fracture operation which may lead to the necessity of another fracture operation to reach unstimulated areas in the reservoir (Asala et al., 2016). On the other hand, if the initial volume per lateral foot of the proppant was known, it can be a great additive to the selection of refrac candidates. Wells that have a proppant volume of less than 1000 lb/ft are under-stimulated. Therefore, these wells can be a good candidates for refracturing (Hunter et al., 2015). Another study suggests refracture wells when 30% or more of the original stages place minimal proppant (French et al., 2014).

### **Production Response from Initial Fracture**

Poor production from the initial fracture can occur due to different reasons. Fracture conductivity losses could occur due to chemical interaction with incompatible drilling or completion fluids leading to a sharp production decline in high-producing fracture wells (Rayson & Weaver, 2012). Poor production can also occur due to proppant pack damage as a result of poor production management such as opening the choke too aggressively, proppant crushing, or problems in proppant distribution through the initiated frack (Hunter et al., 2015; McFall et al., 2017). Based on case studies on several refractured gas wells, some refracturing candidate selection

techniques choose wells with a production gas rate of less than 700 mscf/d to be refractured (French et al. 2014). Most of the studies determine the amount of gas produced as a parameter of selection by comparing the production of the candidate well relative to the other fractured-producing wells with similar reservoir qualities (Moore & Ramakrishnan, 2006; Roussel & Sharma, 2013).

### **Reservoir Parameters**

Reservoir quality is one of the main parameters of success when considering a refracturing treatment to enhance productivity (Li et al., 2019). The key factors to consider reservoir quality for the refracturing job are; relatively high reservoir pressure after the fracturing operation indicating a high portion of unproduced gas in place, low productivity relative to other wells with the same properties, wells with high permeability and high skin value, the possibility of refracture orientation (Moore & Ramakrishnan, 2006). Other studies suggest other factors such as low water production below 25 bwpd, near a water source for fracturing fluid, and no perceived faults to avoid the risk of fracturing faulted formation (French et al., 2014).

## **Data and Methods**

### **FracFocus Data**

The main requirement for this study was to extract useful data from the accessible FracFocus database to study the refracturing activities in the United States in terms of the fluid types used and the number of refracturing activities in the U.S. major shale plays. To ensure a valid data analysis through the FracFocus database, it is important to have a wide understanding of unconventional well hydraulic fracturing to group the chemical given in chemical abstracts service (CAS) format based on their purpose in the hydraulic fracturing operation (Al-Alwani et al., 2019a). The analyzed data of FracFocus contains chemical data of wells completed after 2012, each well is named in API number format, and the chemical used is mentioned in the form of CAS number. For example, water is reported as CAS= 7732-18-5. The naming of the chemical used was not the only flaw in the reporting method of FracFocus, a high number of the reported wells in the database do not have complete data and some of the used chemicals were not reported, or reported with spelling errors (Al-Alwani et al., 2019b).

### **Combining FracFocus Data**

After downloading the chemical ingredients data from the FracFocus website, all the data were combined into one file for the data to be processed and analyzed. The next step was identifying the parameters to be included in the processed database such as; job start date, well API number, well location, and chemical CAS number. A file was created based on the required parameters and cleaned from white spaces and saved to be used in the next step of data processing. The purpose of this study is to analyze the data on the chemicals used in the refractured wells. Therefore, the next step was separating the

refractured wells from the created file. To separate the refractured wells from the data file, any well that had two different job start dates in the data file was separated from the rest of the wells to be processed in the next step of the analysis. The next step of processing the researched data was classifying the chemical used in the refractured wells into 18 groups based on the CAS number reported in the original file. The created chemical groups from the CAS number are; water, proppant, acetic acid, guar gum (gelling agent), biocide, clay control, ethanol, ethylene glycol, gel breakers, hydrochloric acids, isopropanol, methanol, naphthalene, phenolic resin, potassium hydroxide, sodium chloride, solvents. The reported percentage, mass, and volume for each of these chemicals were then aggregated under each well.

### **Treatment Classification**

The main purpose of grouping the used chemicals in the hydraulic refracturing operations reported in the FracFocus database is to study the fluid types based on the used chemicals. The fluid types of the refractured wells were divided into four main types of treatments; slickwater, linear gel, cross-linked gel, and hybrid treatments (Al-Hameedi et al., 2020). To ensure a valid classification of the hydraulic fracture fluid used in each of the refractured well, the fluids used in each operation were classified based on their chemical composition. For example, slickwater treatment is the treatment consisting of water, friction reducers, and some clay control agents. Linear gel treatment is for treatment consisting of water, and gelling agents (guar gum, or other chemicals). The cross-linked gel is the same as linear gel with adding some cross-linkers to increase the viscosity of the gel and hybrid treatments are a combination of the different fluid types (Al-Alwani et al., 2019c). Due to the reporting issues in the original file of FracFocus with some chemicals not being reported or being reported as “confidential”, some of the treatment types in the data analysis were denoted as “not reported”.

### **Refractured Data Classification**

FracFocus — a public chemical registry for hydraulic fracturing in the United States — was used to collect data on over 130,000 wells in the United States that were completed between 2013 to the end of 2019. As said earlier, the refractured wells were separated based on the job start date of the fracturing operations in the original database. To ensure the classification would only include the refracturing operations on the studied wells, the first reported treatment chemicals (the original frac) used in each well were excluded from the analysis, and each refracturing operation in a specific well was denoted by a number; number 1 for the first refracturing operation, and number 2 for the second refracturing operation to report each chemical treatment based on the refrac number for each refractured well. It is important to mention that there were some wells refractured more than two times, these wells were a very small sample compared to all refractured wells. Thus, these wells were eliminated from the database. A sample size of 1200 refractured wells was created based on the mentioned classification to study the refracturing operations in the United

States. The refractured wells are grouped based on their distribution among the most active shale plays in the United States which are Bakken, Niobrara, Marcellus, Permian, Eagle Ford, Barnett, and Haynesville as shown in **Figure A.2** (Appendix A).

## Results and Discussion

### *The Whole United States*

**Figure A.3** (Appendix A) shows the number of refractured wells in the most active shale plays in the United States. The refracturing jobs distribution indicates that the highest refracturing activities are located in the Niobrara and the Bakken shale plays, respectively. The refracturing activities around the region of the Niobrara shale play have shown major success in terms of production through contacting new reservoir regions, which yields higher gas recovery per well (Wolhart et al., 2007). The second highest shale play in terms of refracturing activities is the Bakken shale located in North Dakota which has witnessed a huge expansion in terms of oil production through fracturing activities in the past recent years (Rusyn, 2015). On the other hand, the Haynesville shale play has the lowest number of refracturing activities among the most active U.S. shale plays constituting 4% of the total number of refracturing activities in the studied shales. Based on the obtained results of the study, the years 2014 and 2018 were the most active years in terms of refracturing operations. The oil price drop in these years can be a valid reason for the industry to focus on refracturing instead of new wells' drilling activity.

From a fluid-type point of view, the most used fluid was the hybrid treatment covering 52% of the applied treatments on the refractured wells of the study. As mentioned before, hybrid fluid is the fluid type at which a combination of different fluid types (slickwater, linear gel, and cross-linked gel) is applied to the same well at different stages. The second highest fluid was the not-reported fluid, 31% of the studied fluids were not reported due to the reporting issues associated with the FracFocus database. The fluid type distribution is followed by slickwater, linear gel, and cross-linked gel fluid, respectively. Nonetheless, for the original fracture operations for the studied sample (1200 wells) across the major shale plays in the United States, hybrid fluid was also the most common fluid type. On the other hand, for the first and second refractures, the data have not shown a trend in the usage of a specific fluid type after the original refracs. In other words, fluid types of the original fractures are not a parameter in the candidate selection process (except proppant distribution which was discussed earlier). **Figure A.4** (Appendix A) summarizes the discussed findings of the study in terms of refracturing fluid over the past seven years (2013-2019).

For the wells refractured more than once, only 7% of the treated wells required a second refracture, indicating a high first treatment success rate. **Figure A.5** (Appendix A) shows the number of wells restimulated with either one or two refracture operations and the fluid types used for each of the reported wells.

### *Bakken and Niobrara Shale Plays*

**Figures A.6** and **A.7** (Appendix A) show the number of refracturing treatments over time for the Niobrara and Bakken shale plays. The most active shale plays around the United States in terms of hydraulic refracturing activities are the Niobrara and Bakken shale plays covering more than 40% of the refracturing activities in the most active shale plays around the U.S. In terms of refracturing treatment used, for both shale plays, the most common fluid type is the hybrid treatment covering more than 50% of the treatments used in the refracturing operations.

In 2018, the Bakken shale play has witnessed a high number of refracturing activities, which then went back to normal in 2019. However, for Niobrara, the years 2014, 2015, 2017, and 2019 were highly active in terms of refracturing operations per year. The Niobrara shale play had 21 second refracturing operations and the Bakken had 23 second refracturing operations, making the Bakken shale the shale with the highest number of second refracturing operations among the studied shale plays as shown in **Figure A.8** (Appendix A).

### *Eagle Ford and Marcellus Shale Plays*

30% of the refracturing activities are located in the Eagle Ford and Marcellus shale plays. In terms of size, the Marcellus shale play is bigger than the Eagle Ford shale play. However, they both have almost the same size of refracturing activities with almost 50% of the refracturing treatments being hybrid treatments. On the other hand, according to a study conducted by Al-Alwani et al. (2019b) for all original frac jobs (not including refractured wells) which used wells until the end of 2018 showed that the most common fracturing treatment in the Marcellus shale was slick water.

**Figure A.9** (Appendix A) shows that the Eagle Ford shale play witnessed very high hydraulic refracturing activities over the past three years (2017 to 2019). On the other hand, **Figure A.10** (Appendix A) shows that the most active time for the refracturing activities in the Marcellus was the year 2017 with 36 wells being refractured that year. The Marcellus shale play had a decline in refracturing operations between 2018 and 2019.

As shown in **Figure A.11** (Appendix A), both shale plays had a few second refracturing operations on their refractured wells with 15 wells in the Eagle Ford and 14 wells in the Marcellus, constituting a total number of 29 second refracturing operations over the past seven years in both shales plays.

### *Barnett, Haynesville, and Permian Shale Plays*

The other 30% of the refracturing activities are located in the Barnett, Haynesville, and Permian shale plays. The three shale plays have high fracturing activities. However, based on the refracturing operation size compared to the other studied shale plays, these shale plays have the lowest number of refracturing activities, with the Haynesville having only 57 refracturing operations over the past 7 years. The three shale plays along with the Eagle Ford together they represent 40 % of the refracturing activities in the United States. **Figure A.12** (Appendix A) shows the number of refracturing activities in the past seven years in the Barnett shale play. **Figure A.12**

(Appendix A) shows an increase in the refracturing activities over the past two years (2018 to 2019) in the Barnett shale play. However, for the Haynesville shale play, the year 2015 was the most active year in terms of refracturing operations as shown in **Figure A.13** (Appendix A). In the Permian shale play, the number of refracturing operations has increased in the year 2017 then it went back to normal by 2019 as shown in **Figure A.14** (Appendix A).

Only 19 wells from a total of 284 refractured wells in the three shale plays were refractured twice. Of these wells, 7 wells in the Barnett, and 6 wells in each the Haynesville and the Permian as shown in **Figure A.15** (Appendix A).

## Conclusions

Refracturing horizontal wells has been an active trend in the oil and gas industry over the past years due to economic challenges in the industry. In this work, data from 1200 wells were collected from the FracFocus database registry and utilized to study refracturing activities in the most active shale plays in the United States. Treatments types were classified based on key chemicals as slickwater, linear gel, cross-linked gel, hybrid, and not reported treatments. Original, first, and second refractures were also identified for each shale play. The following conclusions were made based on this study:

- 1200 wells were refractured across the major shale plays in the United States. Of these wells, 284 were in the Niobrara, 251 in the Bakken, 201 in the Eagle Ford, 179 in the Marcellus, 138 in the Permian, 89 in the Barnett, and 57 wells in the Haynesville.
- Over the past seven years across the major shale plays in the United States, the year 2018 was the most active year with 277 refracturing operations.
- The most common fluid type used in the refracturing operation is hybrid constituting 52% of the total number of treated wells followed by; not reported treatment (31%), slickwater (10%), linear gel (4%), cross-linked gel (3%).
- Due to the reporting and formatting issues with the FracFocus database in naming some of the chemicals, some of the treatment types were classified as “Not Reported” in the study.
- Approximately 9.6% of 1200 studied wells were refractured more than once. Most of these wells are in the Bakken shale play where more than 9 % of the wells were refractured more than once.
- Refrac candidate selection can be identified based on the following factors; cluster spacing, well spacing, proppant distribution, fracture reorientation, production response from initial fracture, and reservoir properties.
- Of the reported wells in the study, approximately 40 % of the wells are in Texas, which shows the major size of refracturing activities in the State of Texas.
- The refracturing operations were most active in the United States during the years 2014 and 2018. A valid

reason for the increase in the refracturing activity can be due to the oil price drop during that period.

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## Appendix A

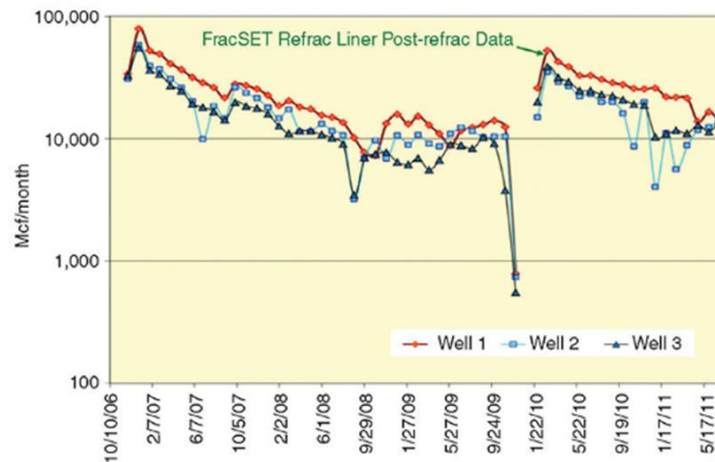


Figure A. 1- Production Gains from Refracture Operation in the Barnett Shale for three Wells (After Jacobs, 2015).

Table A.1- Refracturing Activities in the Most Active Shale Plays in the United States.

Shale Play	Reference	Goals/ Enhancement	Notes
Barnett	Senters et al. (2019)	This paper suggests the best refracturing technique in the Barnett Shale play	The evaluation of refracturing techniques was grouped into two parts; Bullhead refracturing techniques, where the refracturing operation is aimed to cover the stimulated interval, and the second group includes the mechanical isolation technique for refracturing.
	Tavassoli et al. (2013)	The study uses a numerical simulation technique to predict gas production from refractured wells along with sensitivity analysis to predict the shale horizontal wells suitable for refracturing and define the optimal time for refracturing	The suggested study was applied to 188 wells in the Barnett and found only 11 wells are suitable for refracturing and the optimum time for refracturing is in the period of 3 to 5 years after initial production.
	Potapenko et al. (2009)	Redirection of refracture to stimulate intervals that were not achieved during the first stimulation job in horizontal wells.	The study introduced a novel technique of fluid diversion without mechanical intervention.
	Wang et al. (2013)	Discover how refracturing improves production by studying treatment parameters that control production from refracture wells such as; proppant type and mass, surface shut-in pressure, pad volume, injection rate, and treatment fluid volume	Identifying fracture formation and initial completion type is important to get optimal production from refractured wells.
	Rath & Bielicki. (2018)	Using years of production from Barnett shale reservoir to understand the trends of production from refractured wells. The study showed that the number of refractured wells is around 2% of the number of new wells each year.	Based on the findings of the study; newer wells make a better candidate when choosing a well for refracturing operation, for a well to be refractured it has to have a relatively high initial production rate.
	Lio et al. (2017)	The paper provides evidence of an increase in production through refracture operation in two tight gas wells by reorienting deep initial fractures.	The technology of refracture reorientation can be applied to increase production in oil and gas-producing wells.

**Table A.1- Refracturing Activities in the Most Active Shale Plays in the United States ( Cont.)**

Shale Play	Reference	Goals/ Enhancement	Notes
Haynesville	Hunter et al. (2015)	Integrating multiple workflows for well candidate selection for refracturing operations and executing the type of refracturing treatment based on the selected parameters of the wells to be refractured either; completion parameter, or formation parameters.	The suggested screening technology for refrac candidate selection was applied to several basins around the US and the refracturing candidate class was divided into; superior, good, or fair based on the production potential from refracturing.
	Xu et al. (2017)	Implementing reservoir simulation techniques to model refracturing treatment in Haynesville to predict the performance of the refractured wells.	The suggested approach is validated by the history matching of real production data from the Haynesville shale.
	Krenger et al. (2015)	The paper discusses a different design consideration to increase production from under-stimulated wells through the use of a self-removing diverting agent.	In the study, different refracture diverting techniques in Haynesville was investigated to test their effectiveness. The chemical diversion technique was proven to be more effective in terms of full lateral coverage.
	Xu et al. (2019)	The study suggests a new method of modeling refracturing treatment in a numerical simulator with the usage of altered stresses caused by reservoir depletion.	The simulation study is validated through production history matching from refractured wells in the Haynesville shale.
Eagle Ford	Charry et al., (2016)	The main objective of the study is to identify the factors for a successful refracturing job based on real production data.	The research was based on real production data from 11 refractured wells located in the same field with different completion techniques.
	McFall et al. (2017); Diakhate et al. (2015)	These papers suggested a new solution for the process of candidate selection by analyzing each solution and ranking the candidate wells for refrac operation. The papers also discussed the results of the suggested solution when applied wells in the selected field for study.	Advanced diagnosis tools were used to monitor the effect of refracturing on the stimulated well and offset producers and evaluate the concept of diverting fluids in the horizontal wells.
	Nwabuoku & El Paso (2011)	The paper addressed the problem of initial completion requirements controlled by cluster spacing and suggested solutions to overcome the addressed problem.	The paper studied the improvement in the well productivity due to the suggested changes.
	Cadotte et al. (2018)	The paper studied the outcome of the new completion method of fluid diversion by the installation of a new casing string when refracturing in the Eagle Ford shale play.	The newly implemented completion technique proved to be efficient in a dataset of five wells by increasing the original EUR by 140%.
	Pankaj & Shukla (2018)	The paper showed the benefits of productivity gains through refracturing when using coiled tubing for the stimulation job.	When compared with the bullheading technique, the first generation of wells with 18 stages has shown 36% extra production through the initiated fractures.
Marcellus	Yi et al. (2019)	The study suggested a solution to mitigate the effect of the formation of “Hell dominated fractures” initiated in horizontal wells when refracturing.	The simulation study suggested that using small stages with more diverting agents can minimize the effect of overstimulating the dominant fracture.
	Rodvelt et al. (2015)	The paper discusses improving productivity EUR through the use of a new diversion technique to reduce cluster spacing.	Based on the analytical production simulator, the suggested solution proved to be efficient for 200 wells of the investigated wells.

**Table A.1- Refracturing Activities in the Most Active Shale Plays in the United States ( Cont.)**

Shale Play	Reference	Goals/ Enhancement	Notes
<b>Bakken</b>	Yao et al. (2007)	The papers studied the prediction of stress field redistribution due to production, which affects the formation of the new fracture in a refracturing operation.	To verify the validation of the software used to achieve the suggested conclusion, a tiltmeter was used to monitor the fracture initiation in the studied wells.
	Lantz et al. (2007)	The paper discussed the refracture operation success in the Bakken shale in Richland county by comparing reservoir production before and after the restimulation job.	Through the seven years of production, the treatment size has remained the same, but the pumping method has changed.
	Ruhle. (2016)	The paper used production data of refractured wells in the Bakken shale to predict the performance of future refractured wells based on their completion and types.	More than dozens of wells have been analyzed using microseismic monitoring tools.
	Indras & Blankenship (2015)	The paper addressed the economic performance of refracturing in Bakken shale.	The applied sensitivity analysis indicates that the generated net present value of refracturing is higher than drilling a new well in the Bakken shale.
<b>Permian</b>	Leonard et al. (2016)	The paper described certain diagnostic technology tools and re-completion designs used in North American basins to optimize refracturing.	To ensure viable results from the diagnoses, the study analyzed data on stimulation effectiveness and performance from 121 wells.
	Athavale et al. (2019)	The paper evaluated different refracturing technologies applied to under-stimulated wells in the Bone Spring formation.	Based on the outcome of the research, the use of an expandable liner for isolation is more effective and it showed promising results on the refractured wells at which it was applied.
	Han et al. (2018)	The paper investigated refracturing jobs in several wells in terms of production increments based on the completion technique used.	The study applied in the Delaware Basin suggests some solutions when refracturing wells in the area of study in terms of refracturing design and data gathering.
<b>Niobrara</b>	Wolhart et al. (2007)	The paper reported the findings of a study conducted to measure the frac orientation in the operations carried out in the Wattenberg field.	The results of the study indicated that the reason for the refracture operation's success in the area of study is due to the high probability of refracture orientation in the Wattenberg field.
	Miller et al. (2016)	The paper discussed the phenomenon of fracture interference when carrying out refracturing operations and whether it has a positive or negative effect on the initial production of the parent well.	The results showed that the initiated fracture interferences have a negative effect on the parent well production.
	Roussel & Sharma (2013)	The paper suggested a systematic approach for refracturing candidate selection based on production data and reservoir properties.	The selection method was successfully implemented on 300 tight gas wells in the Wattenberg field.

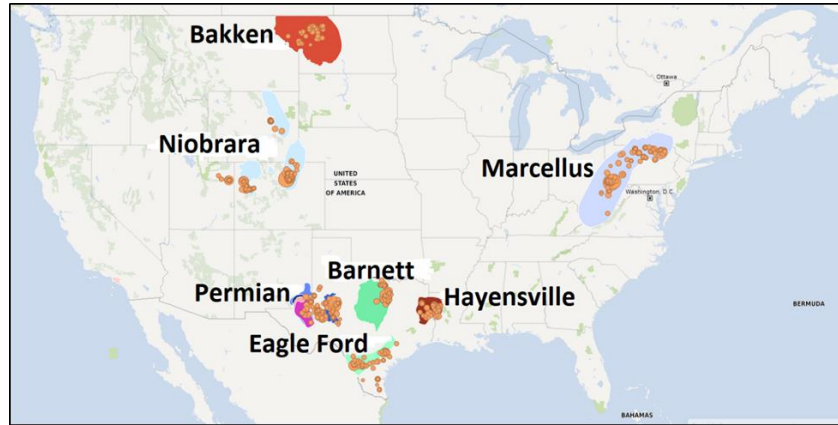


Figure A. 2- Refractured Wells Distribution in the Most Active Shale Plays in the United States.

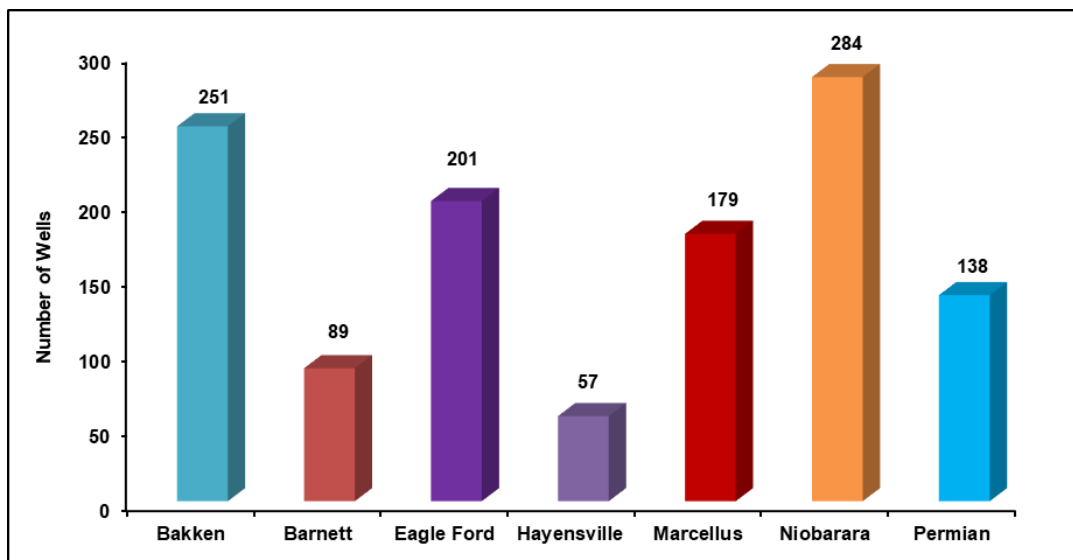


Figure A. 3- The Number of Refractured Wells Distribution in the Most Active Shale Plays in the United States.

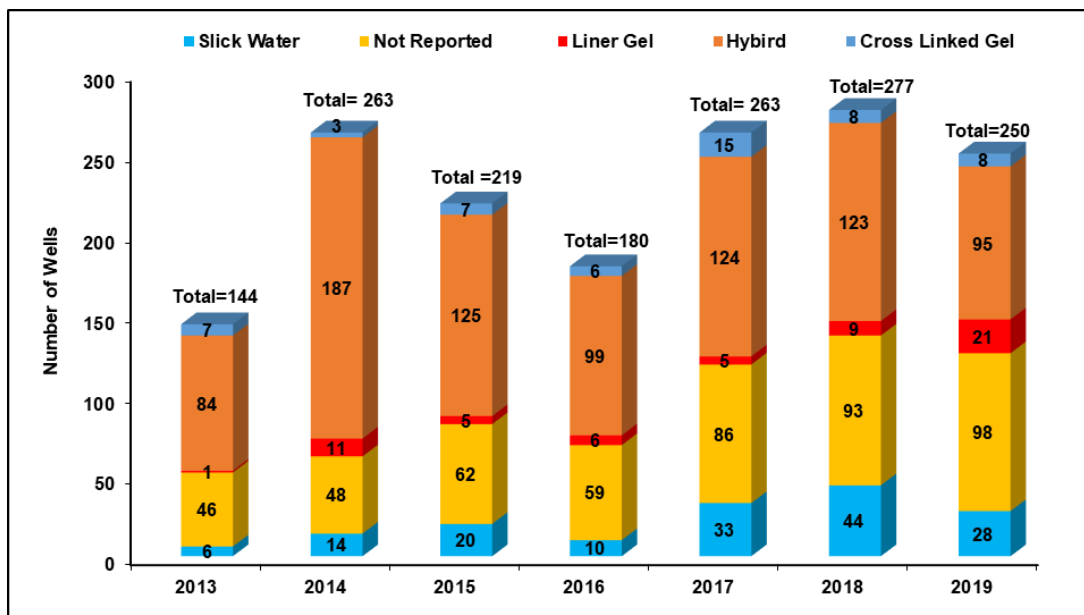


Figure A. 4- The Number of Refracturing Treatments Distribution over Time in the Most Active Shale Plays in the United States.

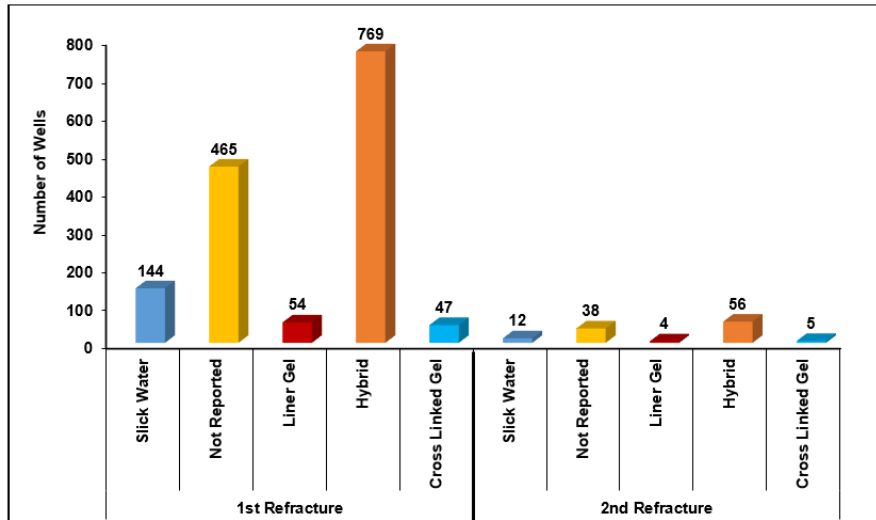


Figure A. 5- The Number of Refracturing Operations on the Studied Wells.

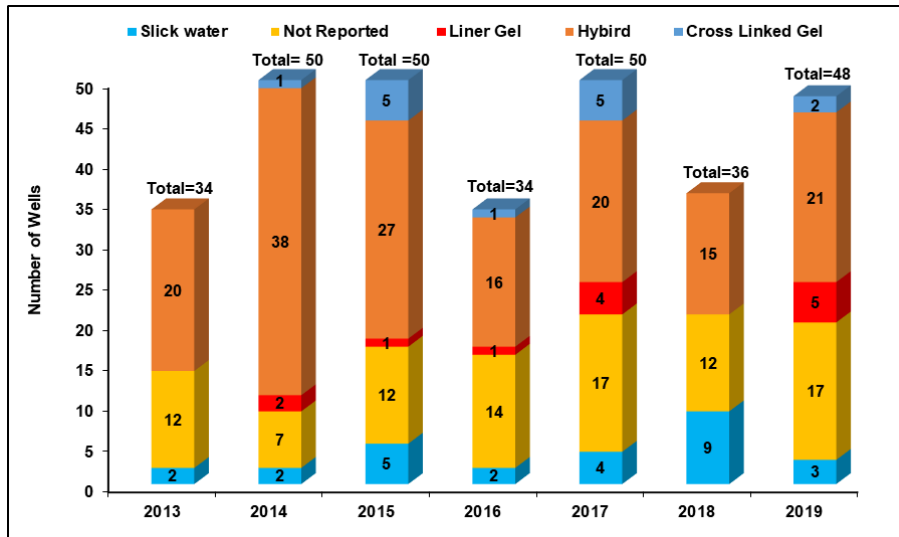


Figure A. 6- The Number of Refracturing Treatments Distribution over Time in the Niobrara Shale.

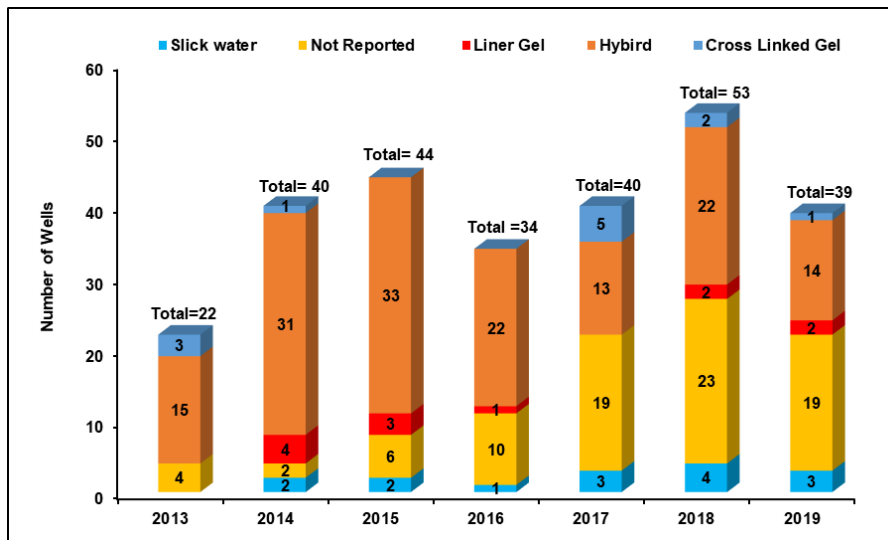


Figure A. 7- The Number of Refracturing Treatments Distribution over Time in the Bakken Shale.

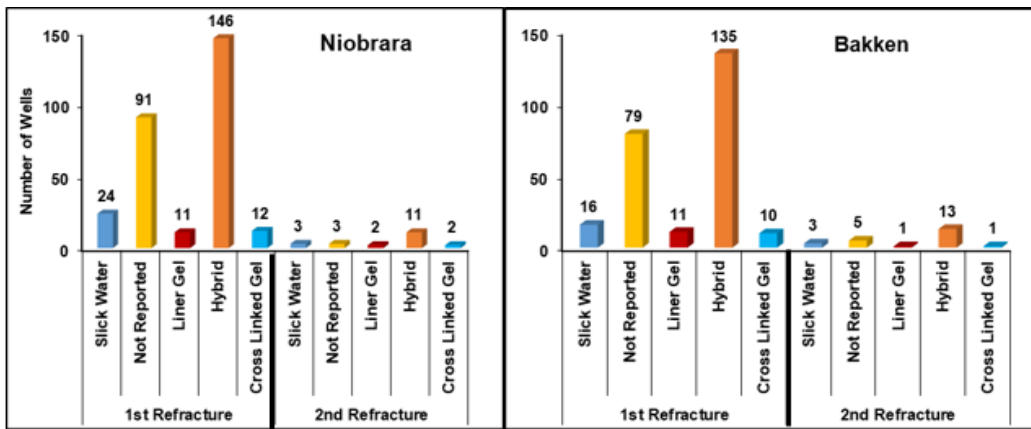


Figure A. 8- The Number of Refracturing Operations on Niobrara & Bakken Wells.

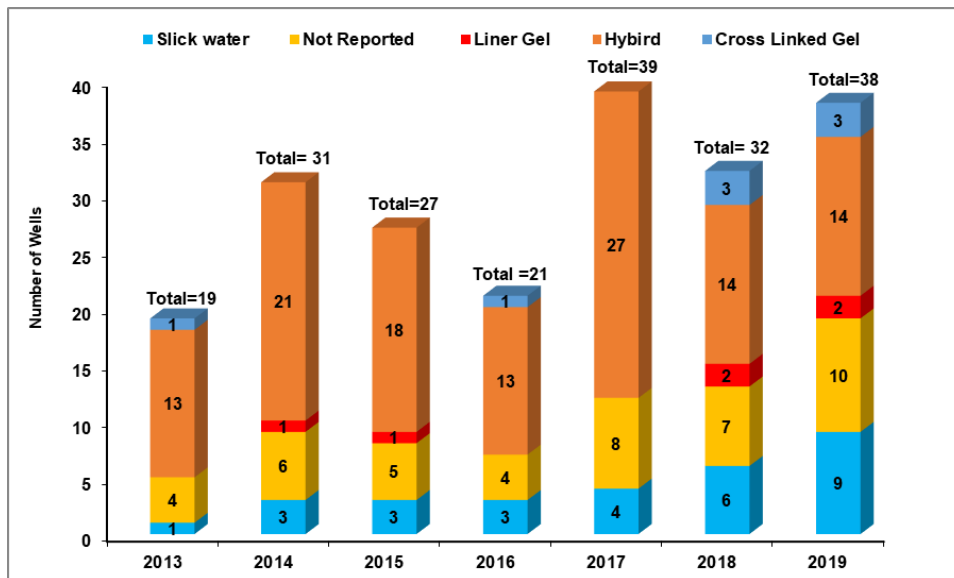


Figure A. 9- The Number of Refracturing Treatments Distribution over Time in the Eagle Ford Shale.

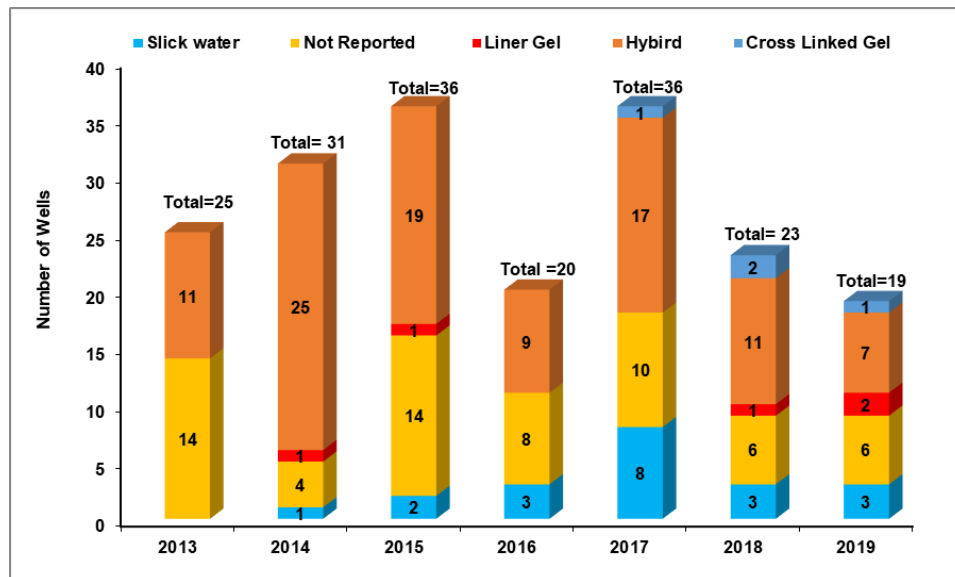


Figure A. 10- The Number of Refracturing Treatments Distribution over Time in The Marcellus Shale.

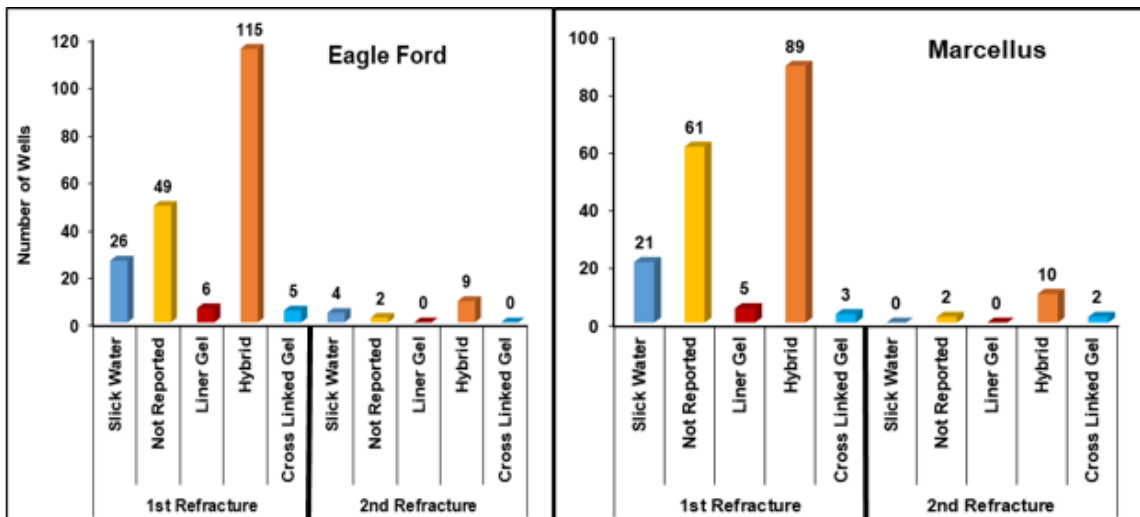


Figure A. 11- The Number of Refracturing Operations on Eagle Ford & Marcellus Wells.

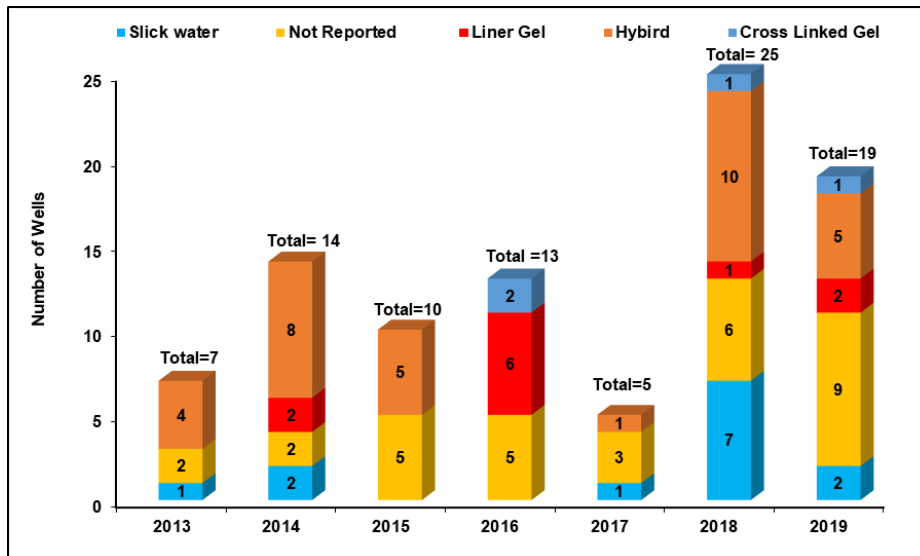


Figure A. 12- The Number of Refracturing Treatments Distribution over Time in the Barnett Shale.

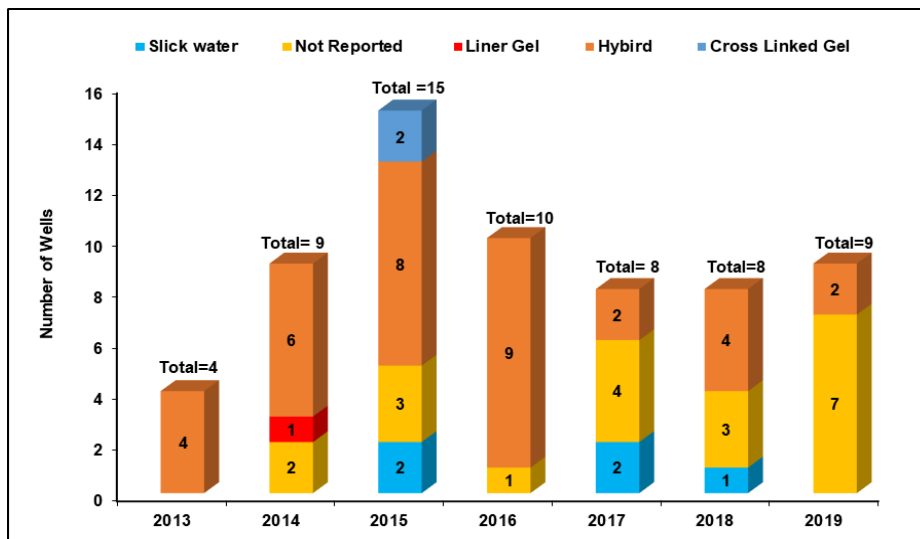


Figure A. 13- The Number of Refracturing Treatments Distribution over Time in the Haynesville Shale.

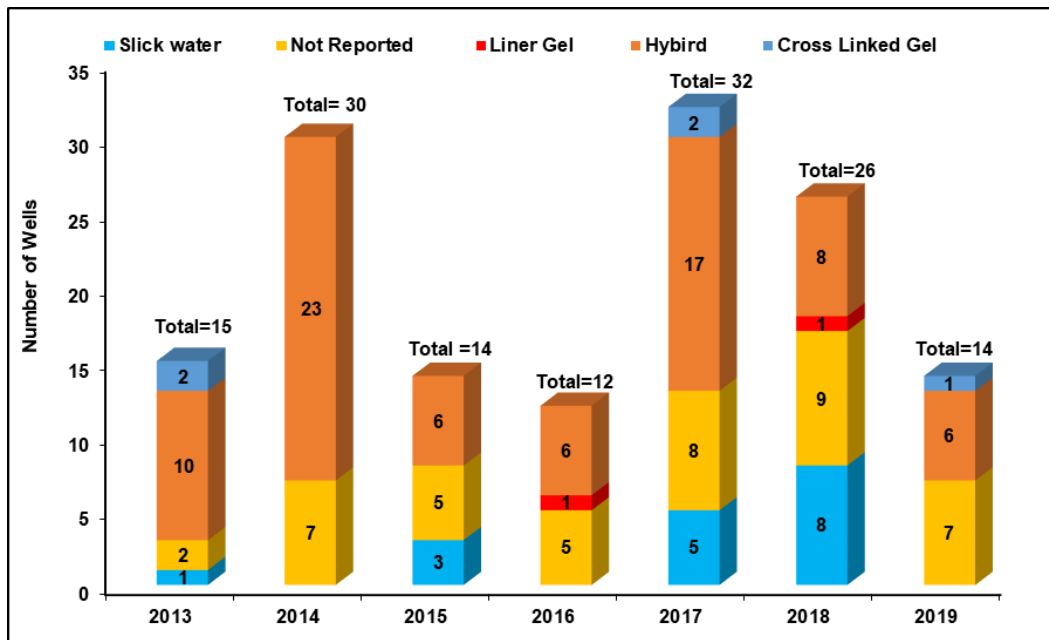


Figure A. 14- The Number of Refracturing Treatments Distribution over Time in the Permian Shale.

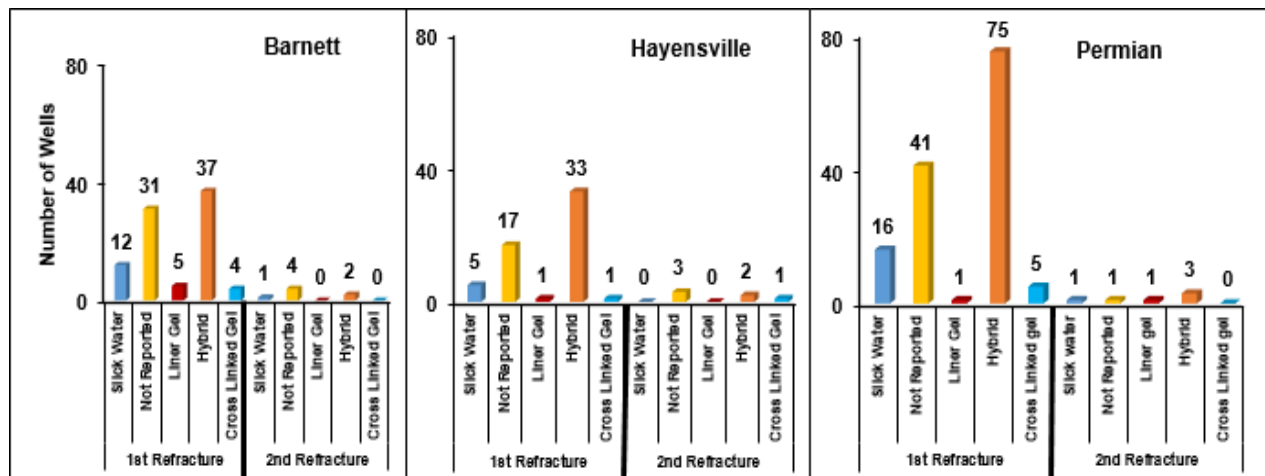


Figure A. 15- The Number of Refracturing Operations on Barnett, Haynesville, and Permian Wells.