Inventory and Analysis of hydraulically fractured wells in the Dutch on- and offshore.

Abstract:

Since 1954, 242 wells are hydraulically fractured in the Dutch on- and offshore. This report is focused on all fracced wells between 1995 and 2012. The aim of this research is to get a complete overview of all the frac operations and ultimately come up with a best practice for successful and safe fraccing in the Netherlands. An extensive data mining exercise is performed to create a thematic database with the most important parameters. The cumulative and monthly production history of the wells is used to determine if a frac operation is successful or not. Trends and relations between various parameters are analyzed with a data visualization program. 55% of the frac operations were defined as a production success. Tip screen-out designed frac jobs performed with a high amount of injected proppant (>100.000kg) and a high concentration of coarse grained proppant in the fracture (>10kg/m^2) show the highest probability to result in a production success. It is highly unrealistic for a frac to grow into the deepest Dutch drinking water aquifer (200 m TVD). The majority of the fracs operations are performed below 2000 meter TVD and the maximum frac height in all the described operations is calculated to be 185 meter. Future frac operations have to be more extensive and consequent in parameter computing and reporting. This is required to obtain a complete database and analysis.

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1. Introduction

1.1 The history of hydraulic fracturing in the Netherlands

The Netherlands has a long history of extracting and exporting natural gas. Since the discovery of the Groningen gas field in 1959, every Dutch household benefited from the economic contribution from this natural gas (Focus on Dutch Gas, 2012). With a declining amount of gas in conventional reservoirs, the challenge of the present and the near future is to invest in research on unconventional sources. Unconventional gas reservoirs include tight gas, coal bed methane, gas hydrates and shale gas.

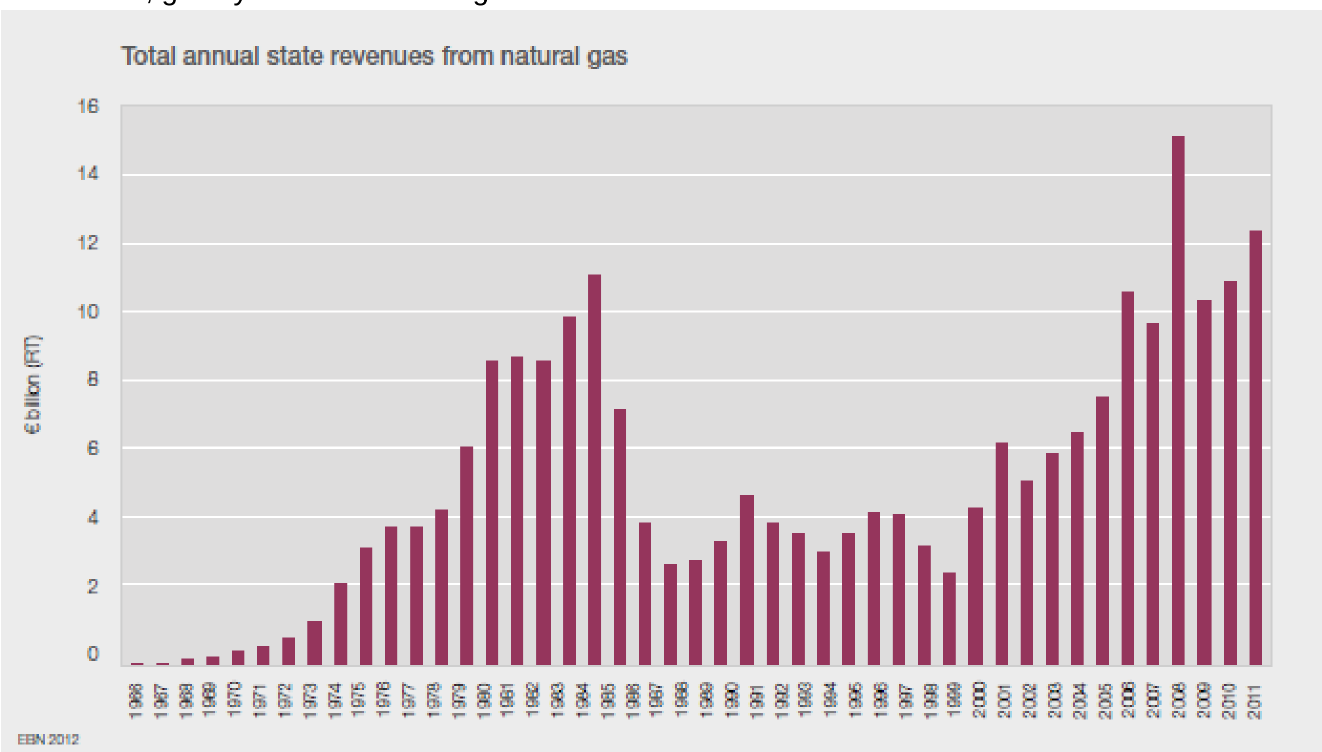


Figure 1 Dutch state revenues from natural gas

This reports is focused on the extraction of tight gas in the Netherlands. Tight gas is natural gas that is trapped in very low permeable sandstone reservoirs (<1 mD). To get this gas out, the reservoir has to be hydraulically fractured[1]. Fraccing is a technique to increase the productivity of a tight reservoir by creating fractures (see Section 2). The first onshore fracced well in the Netherlands originates from July 1954. From that time on 242 wells are fracced, on- and offshore (Figure 2).

[1] Hydraulically fractured will be called 'fracced' in the report. Hydraulic fracturing will be called 'fraccing'.

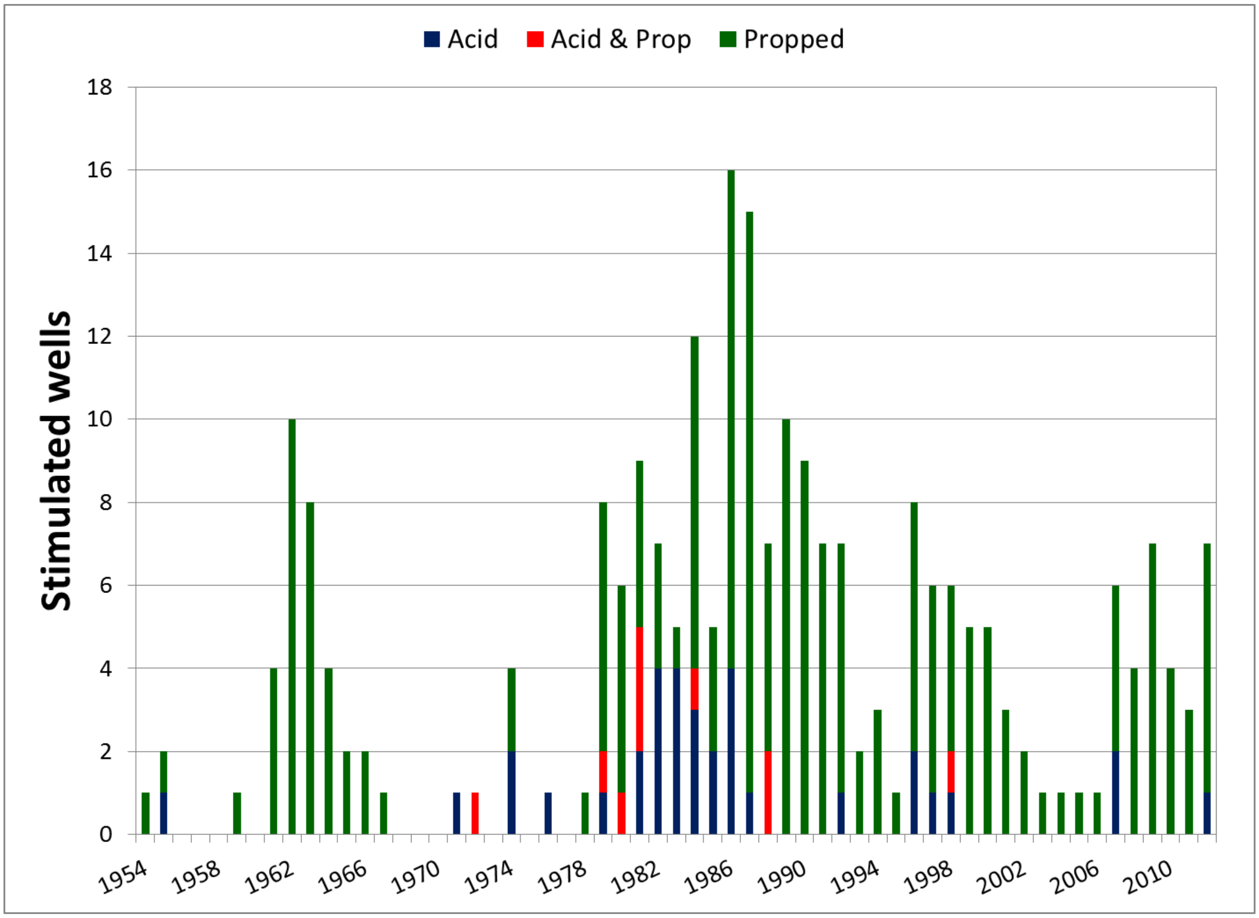


Figure 2 Fracced wells in the Dutch on- and off-hore

The technique and understanding of fraccing has evolved continuously over time, especially during the last decade when the shale revolution in the U.S.A. began. Shale gas and oil production in the U.S.A can be compared to tight gas extraction. The gas is trapped in a ultra-compacted and low permeable shale layer and is also being extracted by hydraulic fraccing. Horizontal drilling and multistage fraccing wells (Figure 3) could develop larger volumes compared to a frac made with a vertical well. U.S. shale gas extraction led to lower gas prices, a decrease of the domestic CO_2 emission (I.E.A. 2012) and an economic boost by the creation of 600.000 jobs, a contribution of $76 billion to GDP and a domestic total of 34% in natural gas production (HIS, 2011)

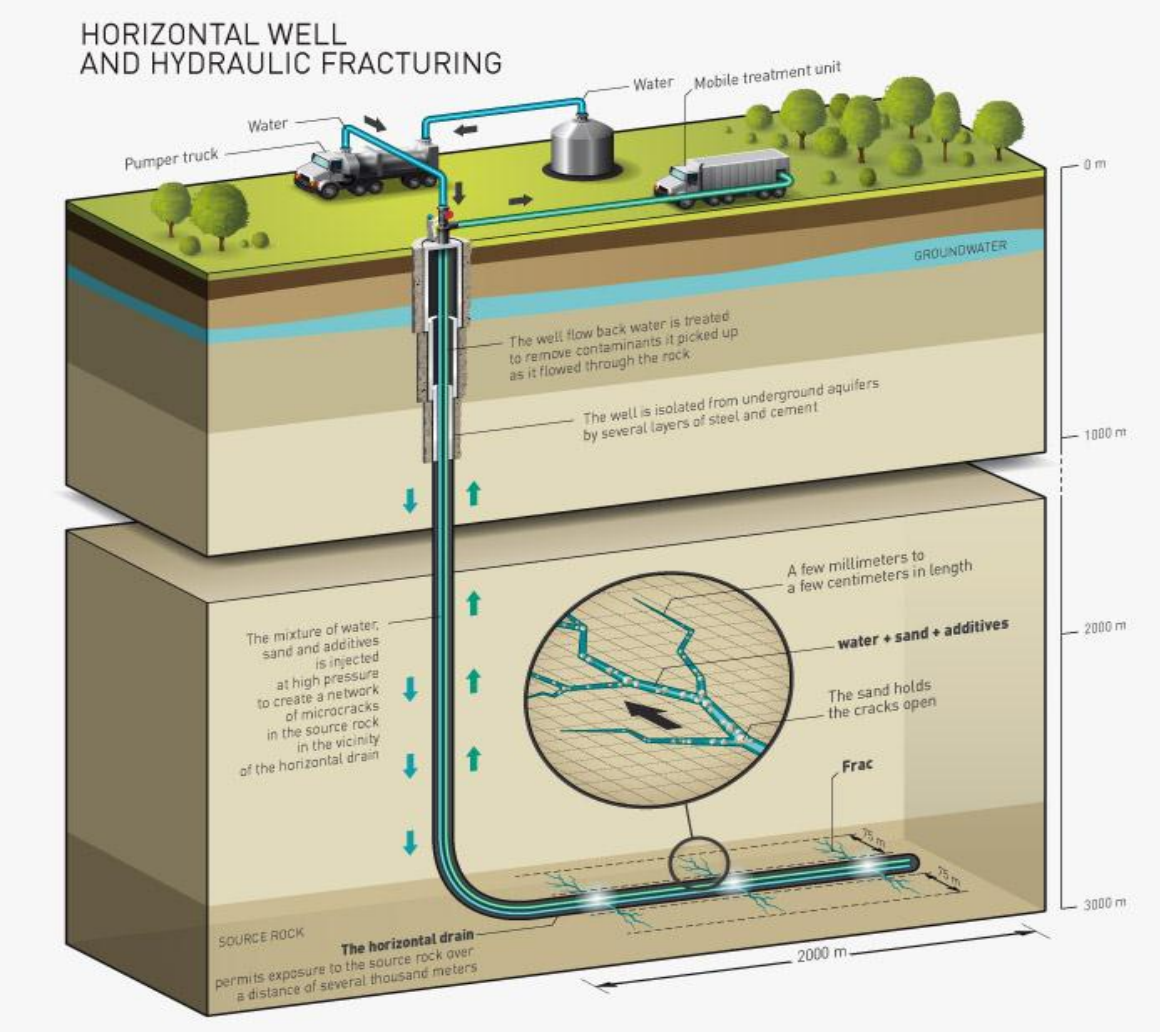


Figure 3 Horizontal drilling. Source: Total

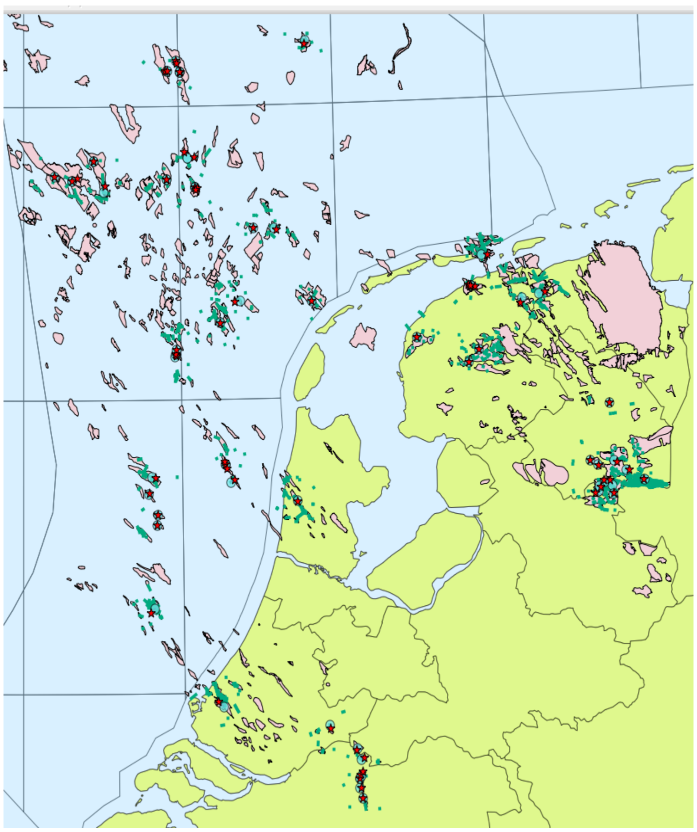
The technique of horizontal drilling and fraccing have also reached the Netherlands. A research is performed for the Ministry of Economic Affairs about the possibilities and potential risks of shale gas extraction in the Netherlands. Till then, it is prohibited to drill exploration wells in the potential shale layers; Posidonia shale and the Geverik Member (Bouw and Lutgert, 2012).

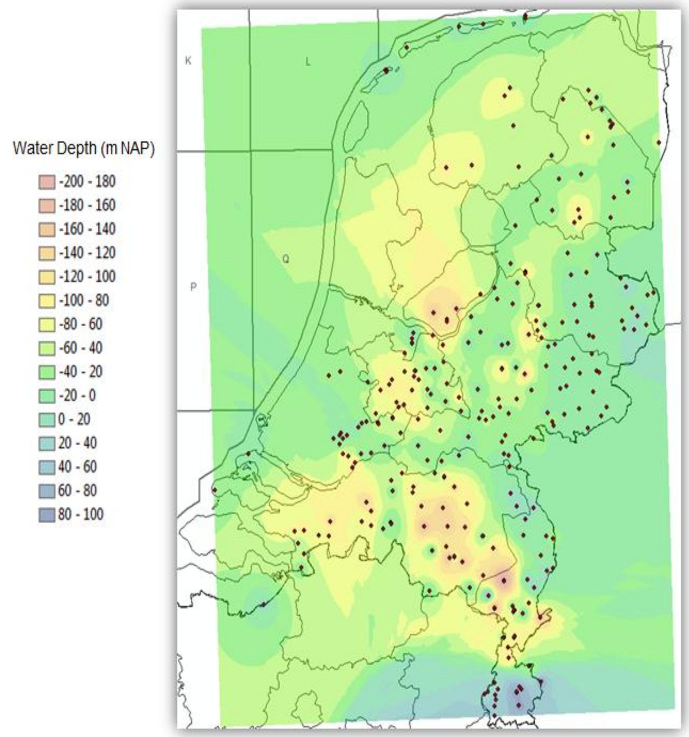
1.2 Hydraulic fraccing; A risk for the Dutch drinking water?

Hydraulic fraccing is often associated with ground and drinking water pollution. This paragraph is not focused on the environmental impact but reviews the onshore fraccing operations in the research period (1995-2012) and their potential impact on the Dutch drinking and groundwater quality.

Figure 4 and 5 show that it is highly unrealistic for an onshore frac to grow into a potential drinking water aquifer. The biggest calculated height growth in an onshore tight gas well in the Netherlands was calculated to have a height growth of 185 m. The deepest level in the Netherlands at which groundwater is being extracted for drinking water purposes is 200m. With the majority of the fracs situated beneath 2000m TVD (true vertical depth), the frac operations are performed at safe distance with respect to leaking from the created fractures .

Leaking due to migration of methane or frac fluid trough a bad constructed well, without protective cementing intervals or poor well casings, is part of another discussion on pollution. Since every gas and oil well in the Dutch onshore penetrates trough a potential drinking water aquifer, this discussion has to be applied on all wells and not be specified to fracced wells only. Since the beginning of hydrocarbon extraction in the Netherlands, there was no reporting on pollution of the drinking water due to operational failures in the vicinity of producing drinking water wells.





Source: KWR watercycle institute

Figure 4 Fracced wells in the Netherlands compared with the maximum groundwater depth for drinking water extraction. The stars show the location of the fracced wells.

1.3 Internship objectives

For this research, an inventory is made of all fracced wells in the Dutch on- and offshore between 1995 and 2012. The time span is chosen to exclude early fracs with a totally different frac technique. A detailed analysis is made on the created database with a data visualization program. The goal is to discover trends and relations between the different frac operations that were performed and ultimately come up with a well-founded answer on the research question: Is there a best practice for successful and safe hydraulic fracturing of tight gas wells?

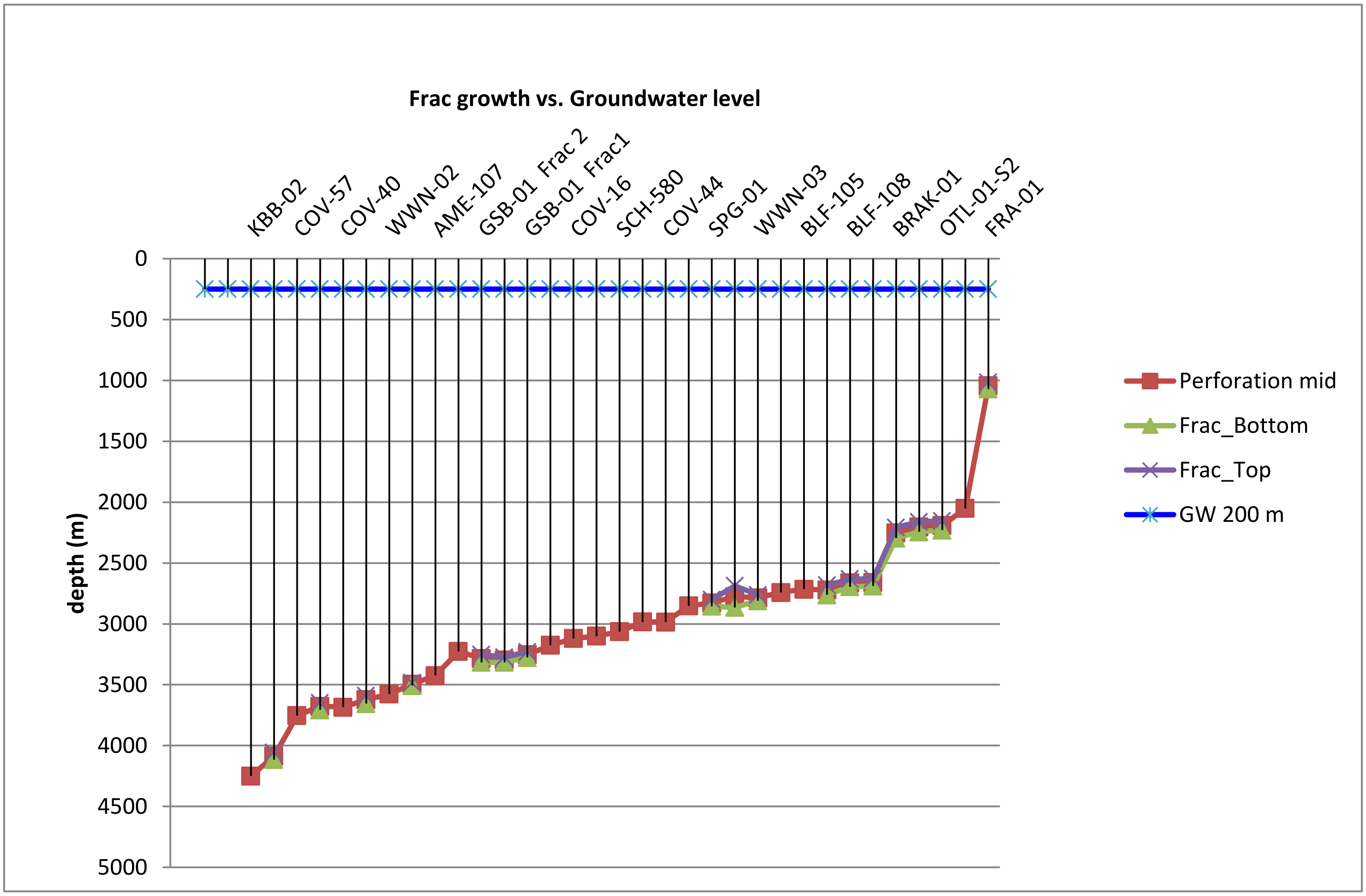


Figure 5 Groundwater level versus the calculated frac growth

2. Hydraulic Fraccing; a short summary

A lot of research is being performed on this topic. This chapter will give a very brief summary of some important features and nomenclature in fraccing being described in this research.

Hydraulic Fraccing is the process of creating fractures by pumping fracturing fluid at a high pressure down a wellbore into a tight rock formation. The fracturing fluid (Figure 6) typically consists of 90,5% of water, 9% of sand (proppant) and 0,5% of additives (J.Daniel Arthur).

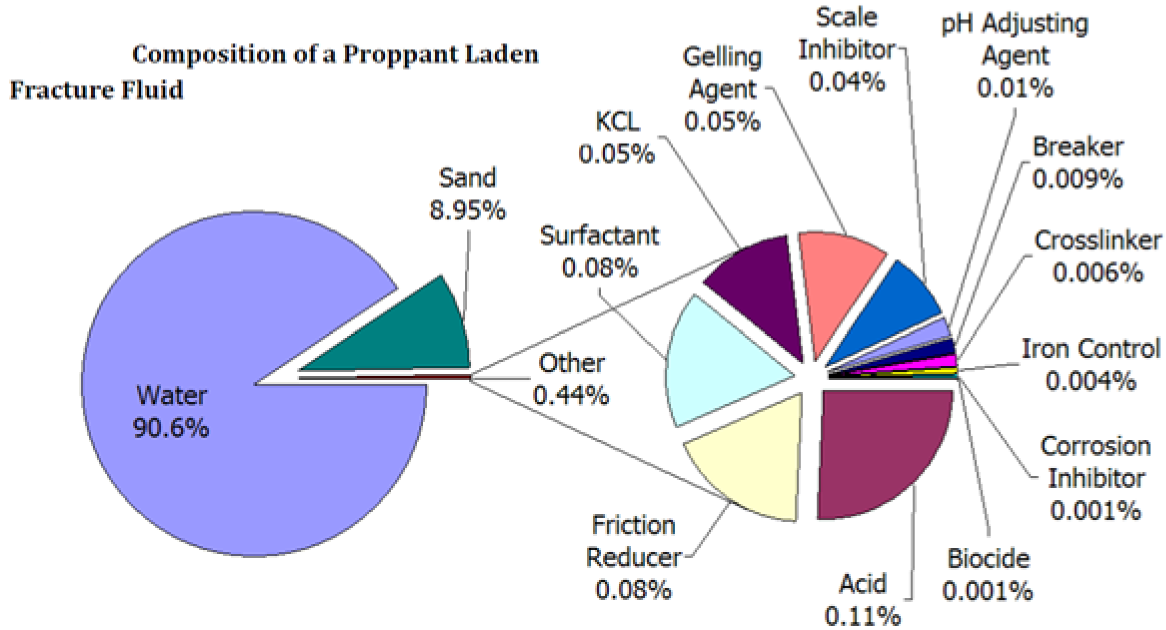


Figure 6 Fracture fluid composition

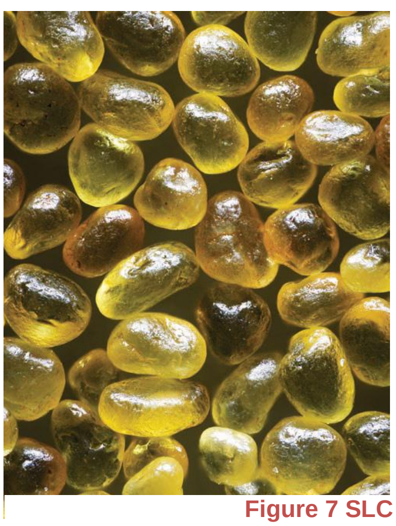


Figure 7 SLC resin-coated proppant sand

The proppant is an important part of the fracture fluid (Figure 7). Proppant is a granular material that is added to the fluid to keep the fracture open after it is being fracced. Well sorted resin-coated sand can be used as a proppant. Alternative proppants (non-sand) like ceramics, bauxite and zirconium oxide are also used. When a proppant is properly placed it creates local conductivities in the fracture in a range of 10-15000 mD-m under reservoir conditions.

To get the proppant into the fracture, a gelling agent and friction reducer are added to the fluid. The friction reducer allows the fracturing fluids and proppant to reach the target zone at a higher rate and reduced pressure. The gelling agent allows the proppant to stay in suspension while being pumped in the fracture. Other chemicals like Corrosion and Scale inhibitors, Acid, Biocide and pH Adjusting Agent are added to protect the tubing, casing and wellbore from damaging.

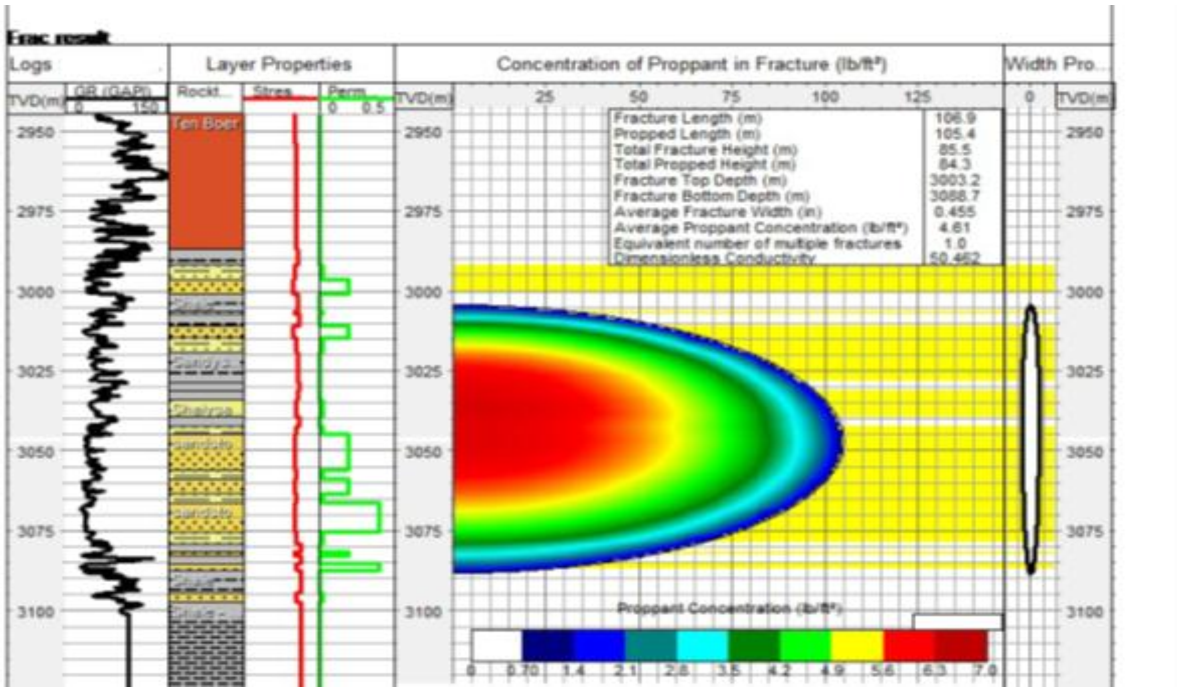


Figure 8 Fracture simulation

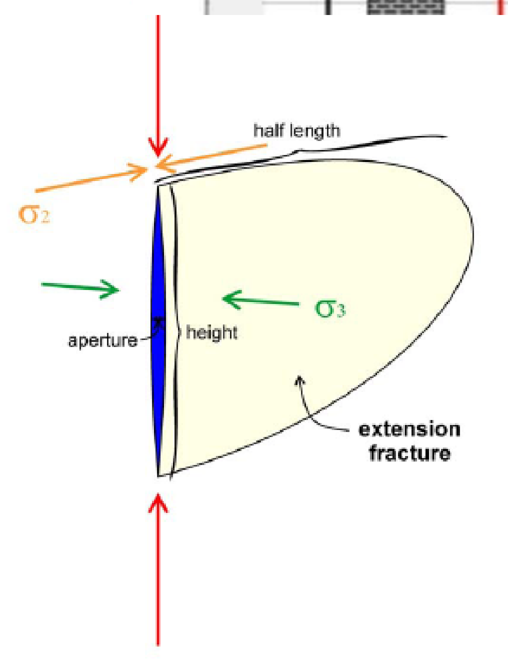


Figure 9 Frac dimensions

A fracture simulation program is used to quantify the growth of the fracture in three dimensions and gives numbers on typical parameters like fracture half length, height, proppant concentration and conductivity. Figure 8 shows the result of a frac simulation of one of the fracced wells described in the research. The targeted reservoir depth is shown in the layer properties. Besides the low permeability of the sandstone layers, the reservoir has a layered interval of impermeable shale layers alternating with sandstone layers. Fraccing in this operation is therefore also used to penetrate these layers and improve the vertical connectivity.

Figure 8 and 9 visualize the nomenclature that is used for the description of frac dimensions. The fracture half-length is the distance from the wellbore till the end of the propped fracture length. The aperture, or fracture width, shows the size of the crack that is made. The fracture height is the vertical growth of the frac into the reservoir. Many variations in the ratio between frac length, height and width are designed for all the frac operations, mainly adjusted to the geological situation of the reservoir.

A design technique called Tip Screen-out (TSO) is used to increase the fracture width by injecting a high concentration of proppant after the original fracture volume is filled. This will increase the volume of the fracture and allows higher amounts of proppant with a higher concentration to fill the fracture void. The effect of this technique will be discussed in the section 5.4: Database Analysis.

Simulations of the fracture growth will always remain an approximation to reality. Examples of fracture development in reality show that a growth of a fracture occurs more complex than is shown in the planar approximation in the simulations. Figure 10 shows an example of a fracturing experiment visualized with a mineback. The frac operation was performed and a mineback was excavated to expose the fracture growth path. Here it shows clearly that the growth of the fracture is not as homogeneous as models predict. Because the current models give the closest approximation to reality, that data is used when referring to fracture dimensions. More research is needed in the future when it comes to heterogeneous fracture modeling, that however is beyond the scope of this report.

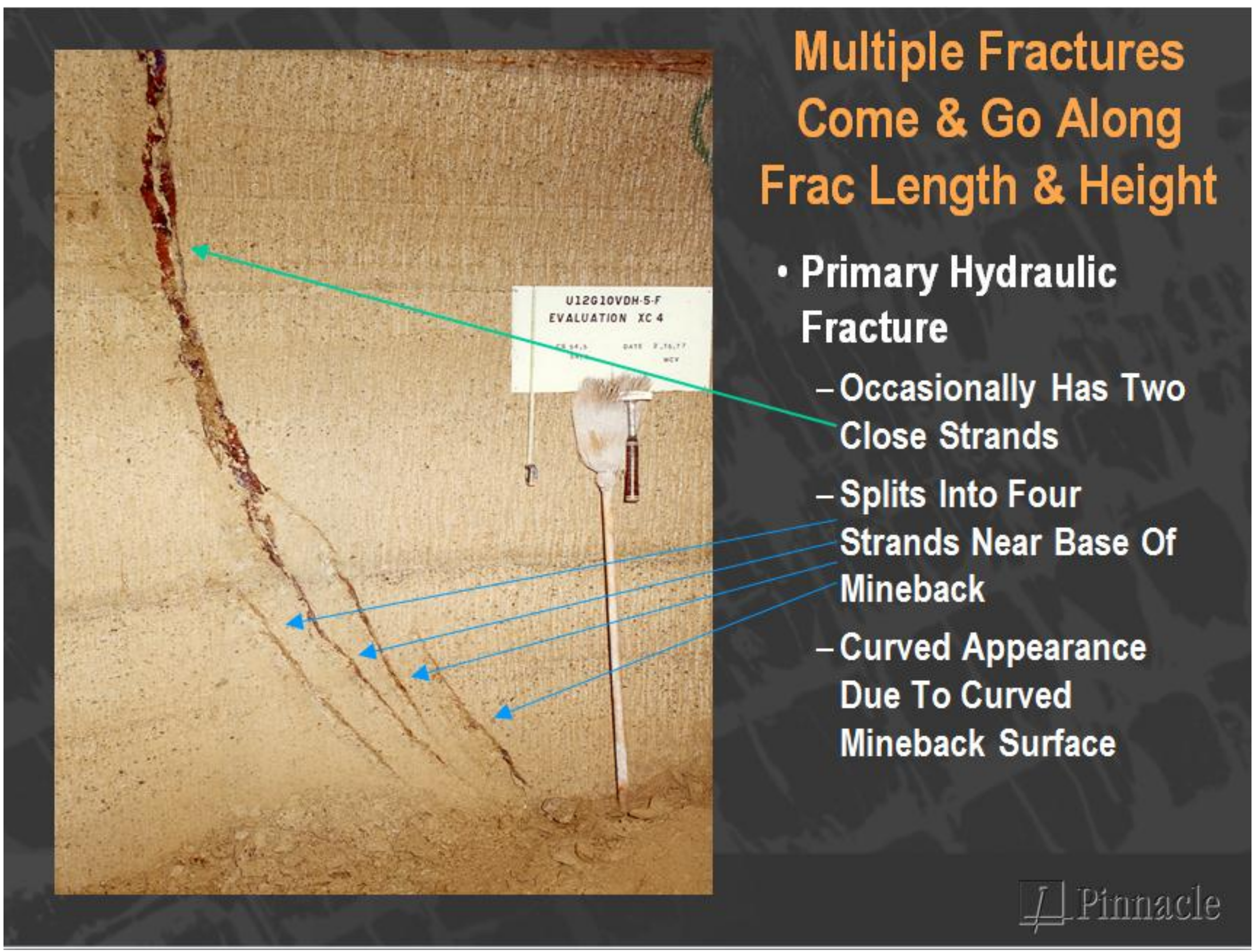


Figure 10 Fracture growth into a Mineback, Hans de Pater, Fenix Consulting Delft BV.

3. Methods

To get an answer on the research question it is important to construct a detailed database of all fracced operations between 1995-2012. This time interval is chosen to exclude very early fracs which are using different and out of date techniques. Table 1 gives an overview on the frac operations performed. The number of fracs is higher than the total amount of wells because some wells are designed to have multiple fracs. Slanted wells are included in the vertical wells column.

Frac operations (1995-2012)			
Operator	**# Fracs**	**#Vertical Wells**	**# Horizontal wells**
NAM	29	19	3
GDF Suez	2	2	0
Wintershall	25	18	2
Northern Petroleum	13	11	0
Vermilion	2	2	0
Total	23	15	1
TAQA	1	1	0
	95	68	6

Table 1 Fraccing operations between 1995 and 2012

The research is divided in multiple stages:

1. **Data gathering**: A data mining exercise is performed to get all available information on a frac operation. This consists of preliminary design studies, drilling reports, feasibility studies and most importantly the final fracturing treatment report. The latter gives information about the actual job volumes, materials used, pressure developments and frac dimensions. The data mining is firstly done in-house, on EBN owned data. Additional data is replenished in accordance with the operator.
2. **Construction of a thematic database**: The mining exercise gives a lot of data which has to be separated into several thematic categories. This will allow a better analysis of the impact of the different approaches in frac operations of the various operators in various reservoirs. The approach of dividing the database into categories can also be used to selectively choose parameters out of the bulk data that is gathered. The following categories are used to construct the database[2]:

    - Reservoir properties (e.g. Permeability-thickness, Porosity, Initial pressure, GIIP)
    - Well properties (e.g. Well orientation, Length of horizontal section)

[2] A complete overview of all the parameters gathered can be found in Appendix A

- Production rates (e.g. Best monthly production, Cumulative production after time)
- Frac design (e.g. Half length, Height, Width, Frac conductivity, Tip Screen-out)
- Proppant (e.g. Job volume, Injected proppant, Concentration, Proppant material)
- Chemicals used (e.g. Fraccing fluids, Additives)
- Viability (Production success, Technical Success)

3. **Production profiles:** To define whether the fraccing operation is a success or not, an important criterion is the production before and after the job. In some reservoirs the frac operation is performed after a considerable time of producing from an unfracced reservoir. These frac jobs are being conducted when a field is reaching its 'end of field life' and thereby cannot produce a viable amount of gas anymore. To give these fields a final boost, the reservoir is stimulated by fraccing. In this case the production rate and cumulative production before and after can be compared directly.
   The majority of frac jobs is conducted directly after the well is drilled. The wells productivity is tested and can be a reason for the operator to frac the well. An estimation is made for the productivity after the frac job. Additionally the production quantities of the frac job are compared to the unfracced wells in the same gas field, when applicable. It is possible for a frac job to be successful but still produce less than wells that aren't fracced. It is important to look into these cases and come up with a suitable explanation.
4. **Data analysis:** A data visualization program[3] is used to plot certain parameters in a 2 or 3-D graph. The benefit from the program lies in the possibility to add more dimensions in a 2-D plot. The color, size, range and shape of all the data points can be edited which gives a better insights in the data clustering, trends and relative importance of certain parameters. Together with the conclusions of the production improvement research this will result in a final package of information that can be used for interpretation. Finally the interpretation will give explanations why a frac is successful or not.

[3] ©TIBCO Spotfire

4. Production profiles

The production history of a well gives a lot of information about the well performance during its lifetime. In this section some typical examples are given where the influence of fraccing is visible in in the production profiles. In several cases the frac operation is performed after the well had produced for a certain period of time. In other cases the frac operation is performed immediately after the well was completed and indicated poor initial production. A distinction is made between the cumulative production and the actual production per month. When possible, a comparison is made between an unfracced well and a fracced well producing in the same field. All production amounts are given in Mm^3/month (Million m^3 gas/month).

4.1 Determination of a 'successful frac'

The determination if a well is a production success or not is dependent on three factors.

Definition of a Production Success:

1. Production rates before and after fraccing (PI factor increase of at least 2)
2. When there is no production history available because the well is fracced immediately after completion, the success is determined by the expected production increase compared to the realized production increase.
3. If the first two points do not lead to a definitive answer, the production rates of a fracced well will be compared with the production rates of an unfracced well in the same field. If a fracced well produces significantly better than an unfracced well, it is considered as a production success. (Only used when applicable; not every field has fracced and unfracced wells producing from the same reservoir)

4.2 Examples of successful fraccing operations.

A successful fraccing operation is characterized by a strong production increase after fraccing, or a better production performance compared to unfracced wells in the same field. The following examples show some typical production developments of successful fracs:

The wells L8-G4 and L8-A2 are fracced. L8-G4 is fracced in March 2007 and L8-A2 is fracced in May 2004. Both wells show a clear increase in their production rate after the frac operation. The unfracced wells show no visible production from 2006 onwards.

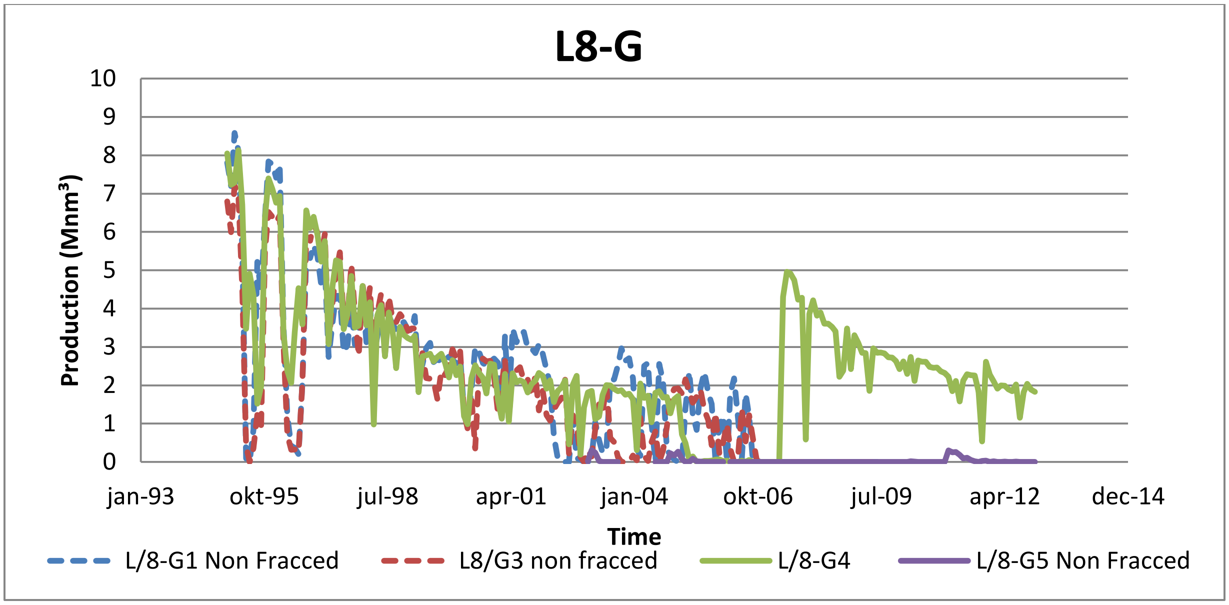


Figure 11 Production rates L8-G field

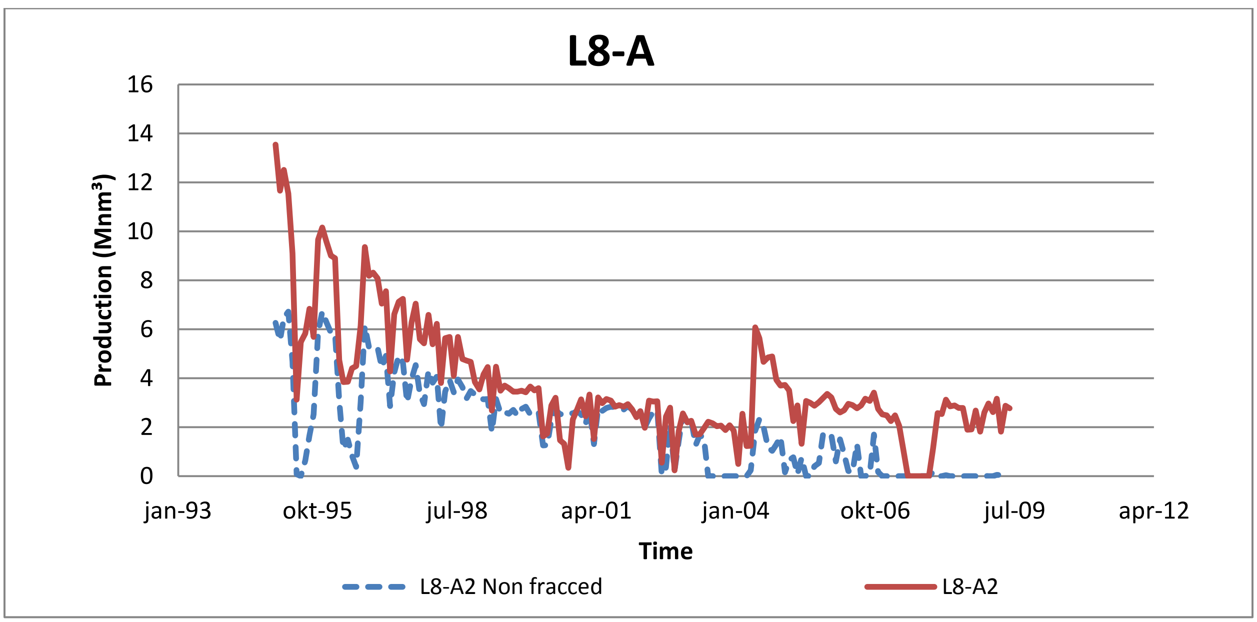


Figure 12 Production rates L8-A field

The cumulative productions from both the L8-G and L8-A field confirms the fraccing success. Without fraccing the wells didn't have any viable gas production anymore. Fraccing gave a boost to the production. An important observation from the Figures 11, 12 and 13, is the timing of the frac operation. Both wells are fracced in their so called 'end of field life', where the production rates of the well are dropped to a very low level. Without a stimulation method like fraccing, the well would have shut down and be taken out of production. The success of both operations led to an operator decision to also frac L8-G3 in 2013. This well produced 900.000m³ of gas in April 2013, indicating an initial production success.

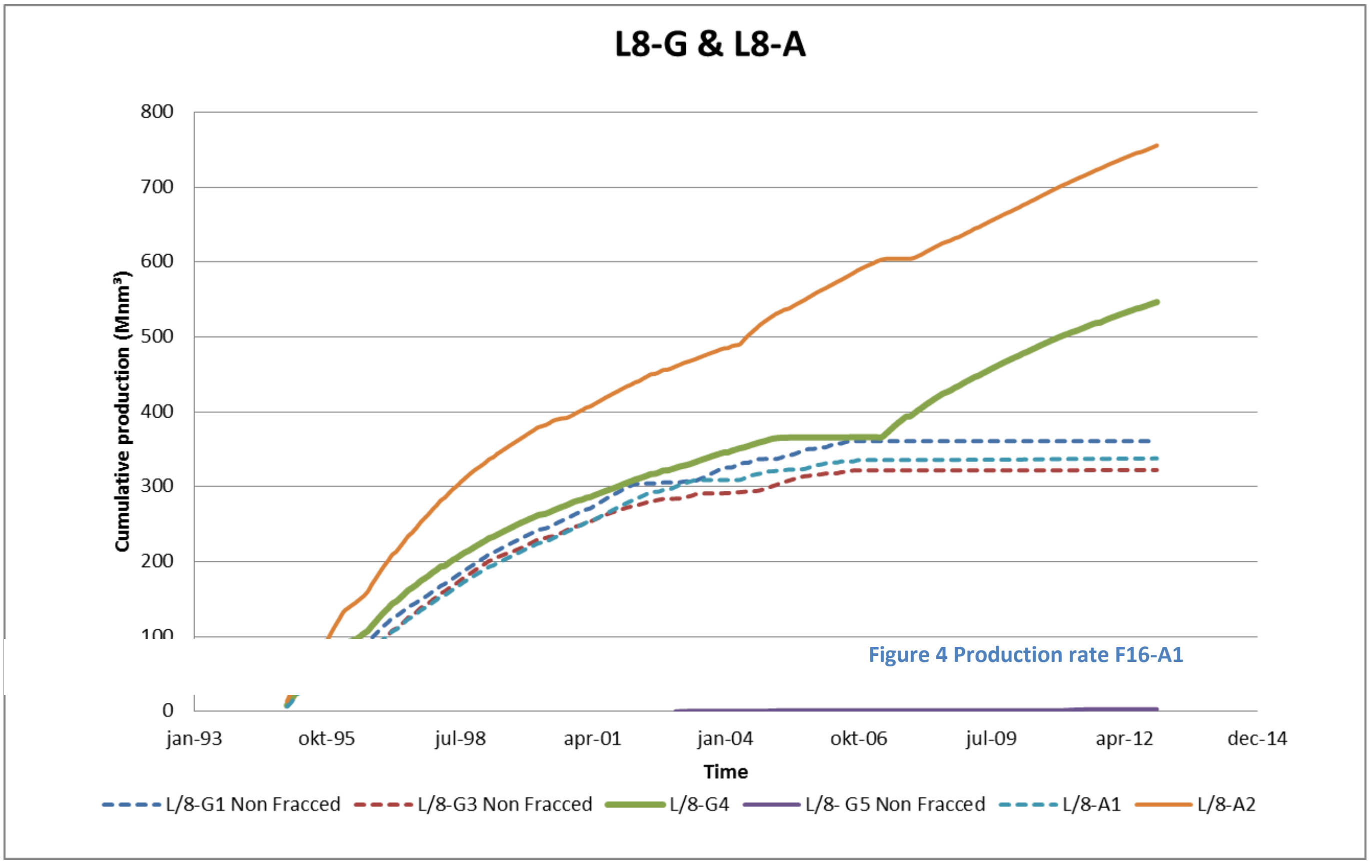


Figure 13 Cumulative production L8-G and L8-A fields

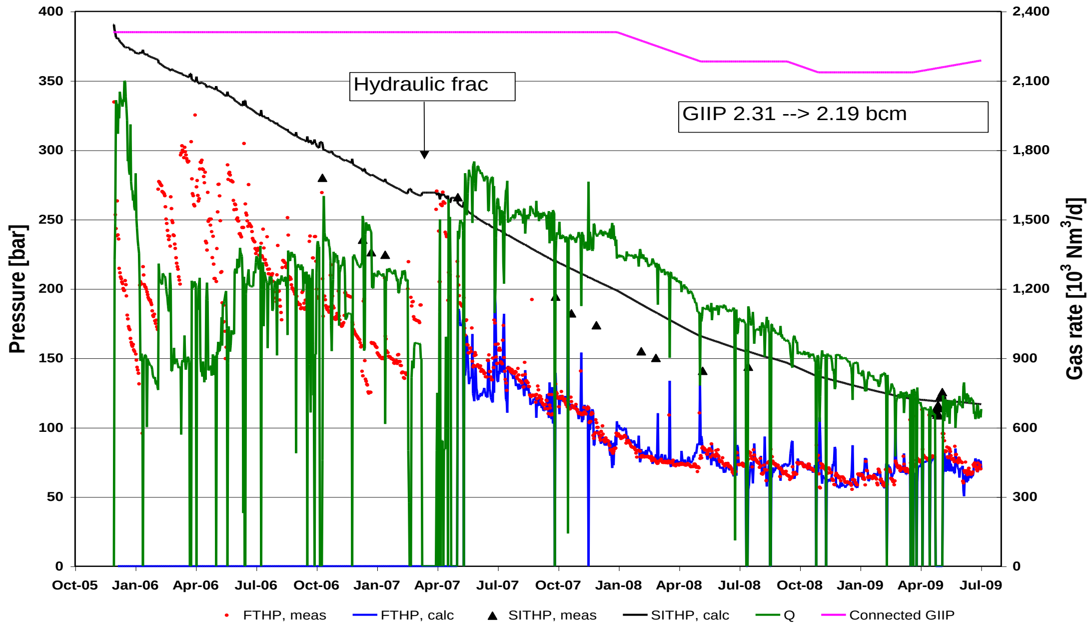


Figure 14 Production rates F16-A1

Similar frac timing is observed in wells F16-A1 and F16-A3. The wells were producing for a certain period of time before the frac operation took place. Well F16-A3 has been hydraulically fractured in October 2006, well F16-A1 in April 2007. Figure 14 and Figure 15 show the history matching plots of both wells. The improvement in flowrate (green lines) and the increase in wellhead pressure (red dots) after the frac are clearly visible. In the history match models, the post-frac pressure matches (blue lines) assume constant productivity, indicating the sustainability of the productivity improvement. A productivity index increase factor of 2 - 3 has been calculated for both wells.

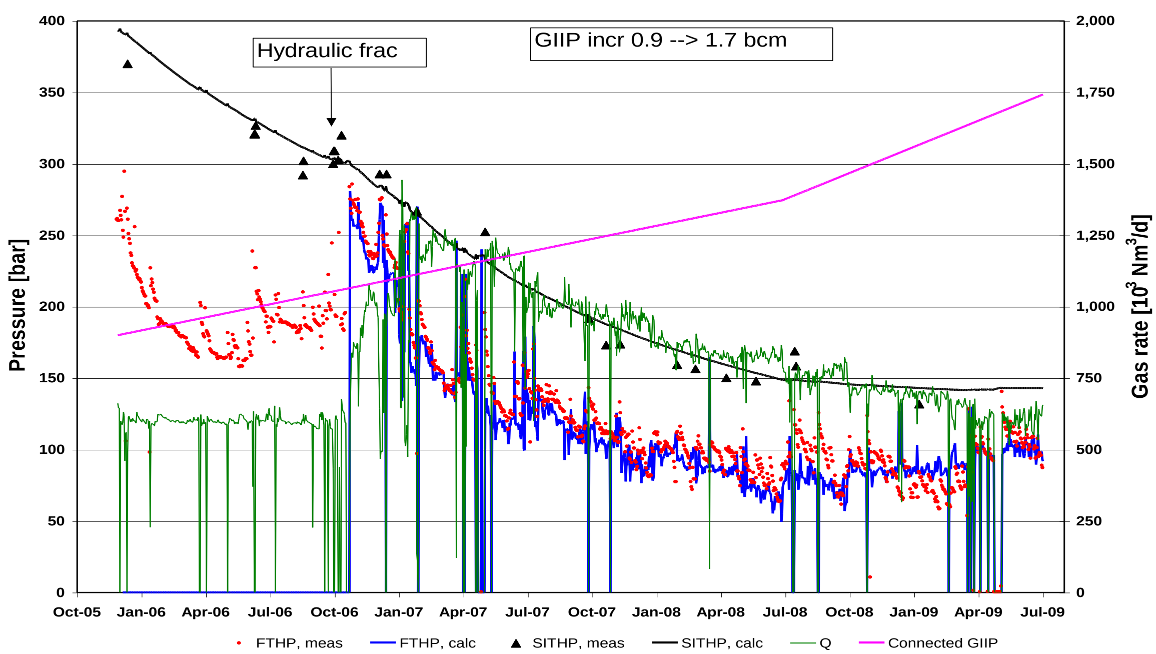


Figure 15 Production rates F16-A3

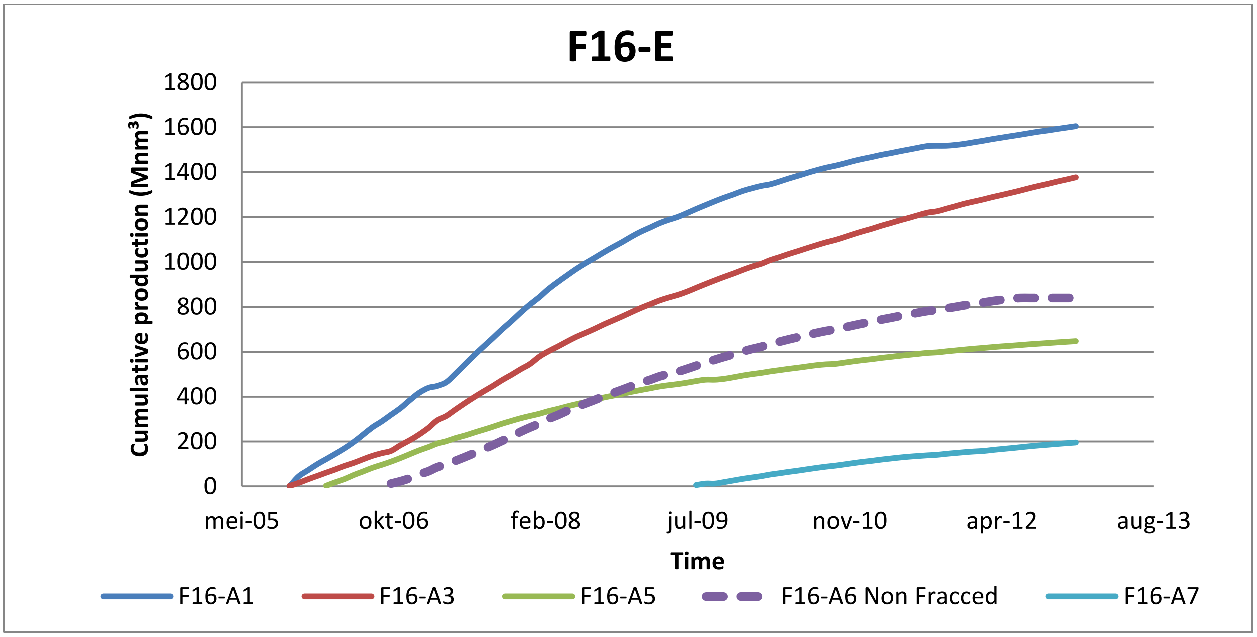


Figure 16 Cumulative production F16-E field

Figure 16 shows the cumulative production of all the wells in the F16-E field. F16-A1 and F16-A3 are producing more after their frac operation but also perform the best compared to all the other wells. F16-A1 is fracced in October 2006 where F16-A3 is fracced in March 2007. F16-A6 is the only unfracced well in the field and is performing worse than the two successfully fracced wells.

Although the wells F16-A5 and F16-A7 are fracced too, their production is lacking behind. The lack of production is due to technical failures of the frac operation. F16-A5 was terminated prior to proppant reaching the reservoir due to a reduction in rate and an increase in wellhead pressure. It is believed that scaling in the tubing has caused plugging. F16-A7 was terminated during the main frac after pumping 63.000 lbs. of proppant (planned 250.000 lbs.), due to gel pump failure; over displaced proppant into reservoir.

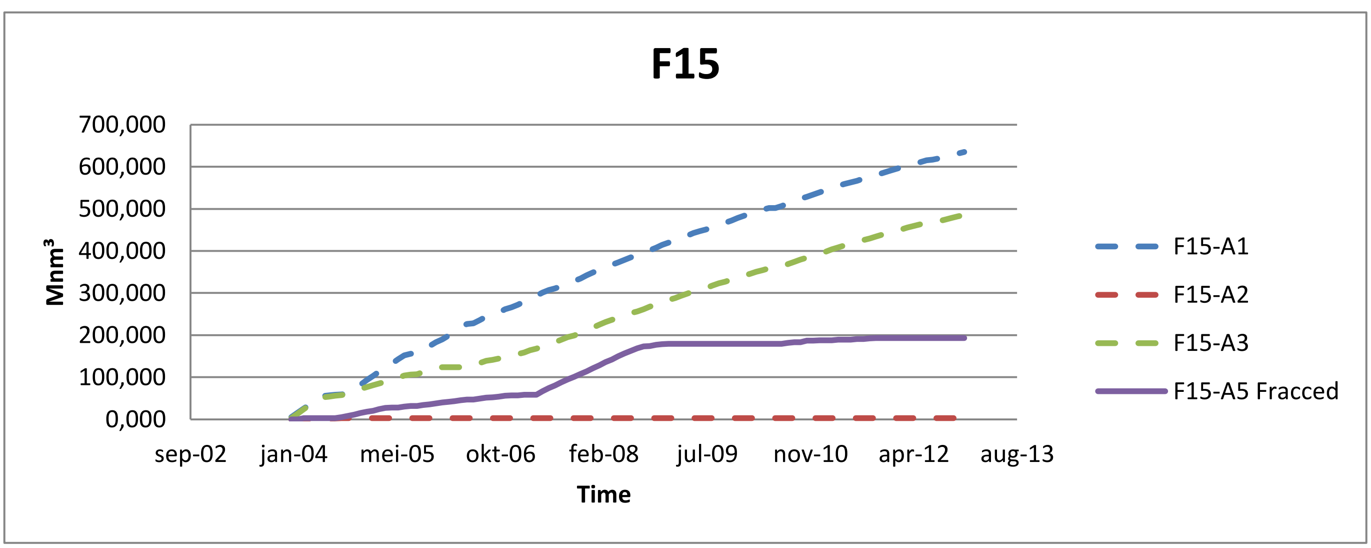


Figure 17 Cumulative production F15 field

Well F15-A5 was completed and perforated early January 2004. Expected production was in the range of 1.000.000 m^3/d but the production was only at 195.000 m^3/d. The reservoir quality was much poorer than expected. Only the upper layer from the Volpriehausen was producing gas.

Therefore well F15-A5 was fracced in the spring of 2007. Although the cumulative production of A5 is less than the two unfracced wells A1&A2, a clear increase in production is observed from 2007 (Figure 17, 18). The production rate increased to 350.000 Nm3/d in spite of the fact that only 60% of the planned amount of proppants could be pumped. The PI after fraccing is calculated to be 2.5 which makes the frac a production succes. After fraccing the well produces for two more years. As a remark, F15-A5 is initially producing less than other wells in the same field. The well has now stopped producing due to sand deposition.

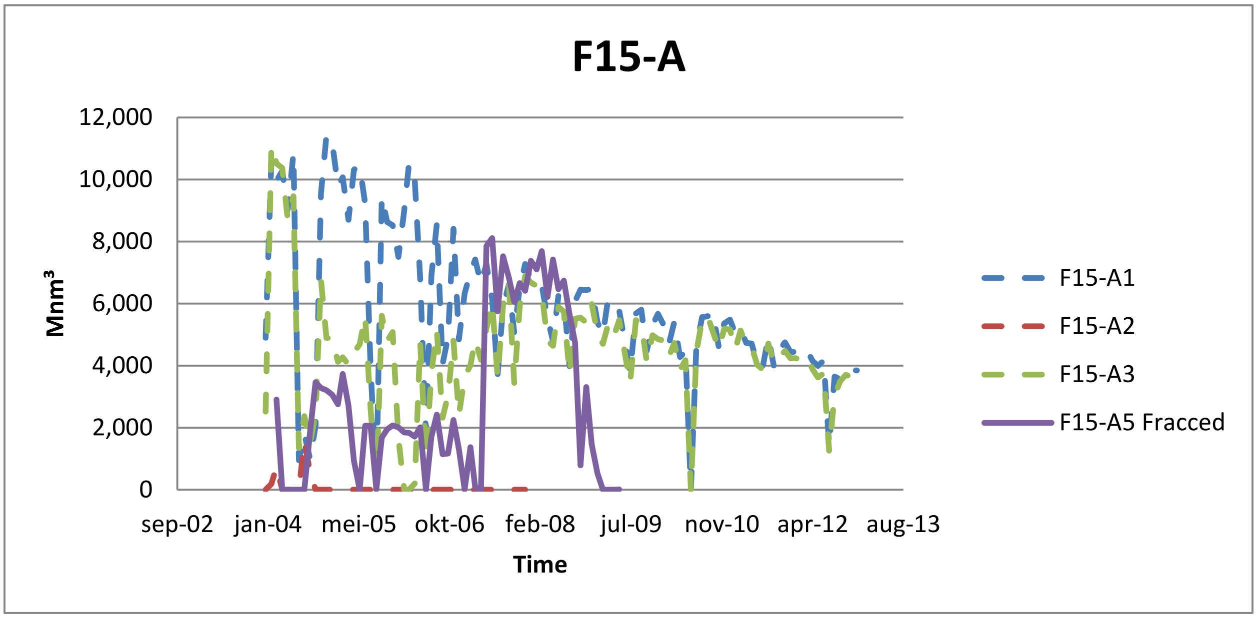


Figure 18 Production rates F15-A field

Figure 19 shows the cumulative production of all the wells in the L4-A field. L4-A2 is the only well that is not stimulated. L4-A1, L4-A4 and L4-A5 are propped fracs, where L4-A3 and L4-A6 are acid fracs. Acid fraccing is performed by injecting acid (usually hydrochloric acid) to dissolve the rock material and enable gas and fluid to flow into the well.

The wells are producing from 1983-1987 and thus the gas production starts before the research interval. The post frac productivity report from August 2000 gives more insights in the historical cumulative production and the production success. The stimulation campaign took place between October 1996 and April 1997. L4-A1 and L4-A3 are fracced in October 1996 and considered as the most successful fracs in the field. This is illustrated in the cumulative production (Figure 19) as well as the production rates (Figure 20). L4-A4, L4-A5 and L4-A6 do not show a significant increase in production after fraccing.

These fracs are therefore not mentioned as a production success. The only unfracced well in the field (L4-A2) is not producing any gas after 1996. The post frac productivity report indicates that all wells had serious self-killing problems before the stimulation program started. Although not every fracced well had a significant production improvement, every of those wells is still producing gas in the present. The only unfracced well is not producing anymore.

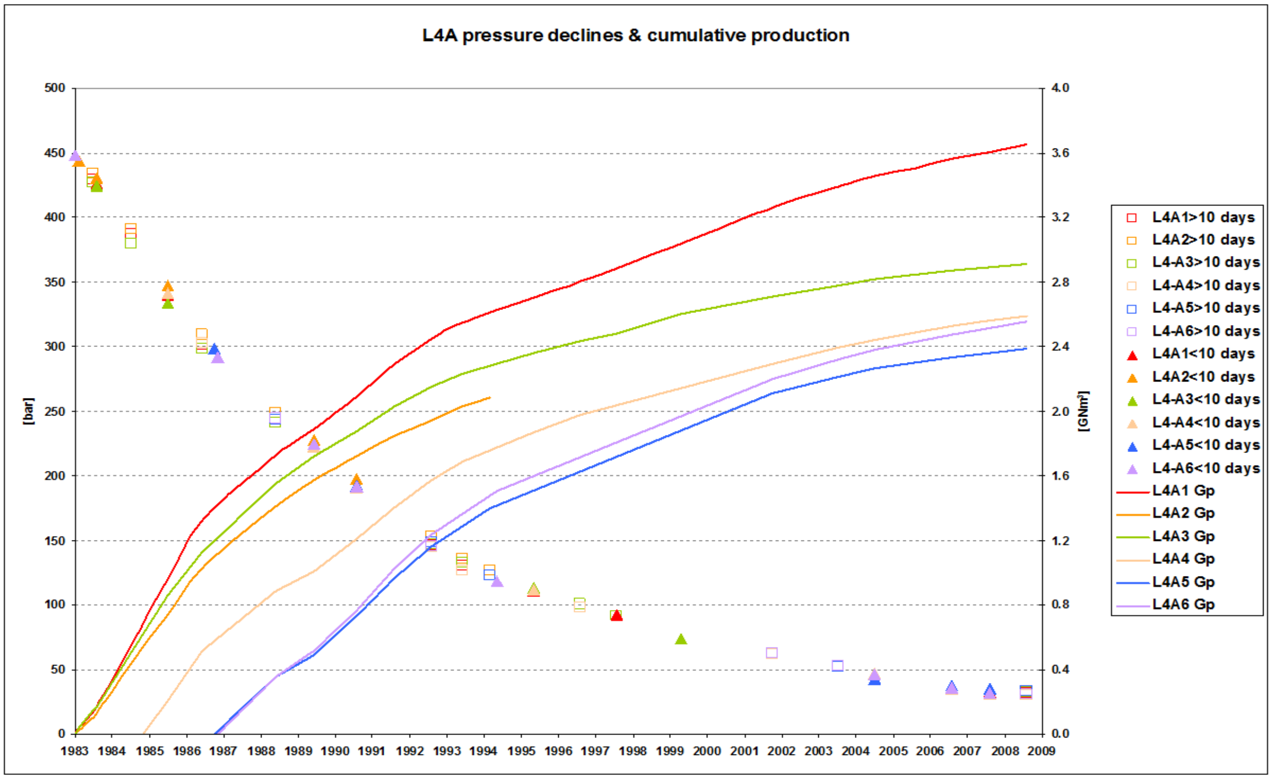


Figure 19 Cumulative production L4-A

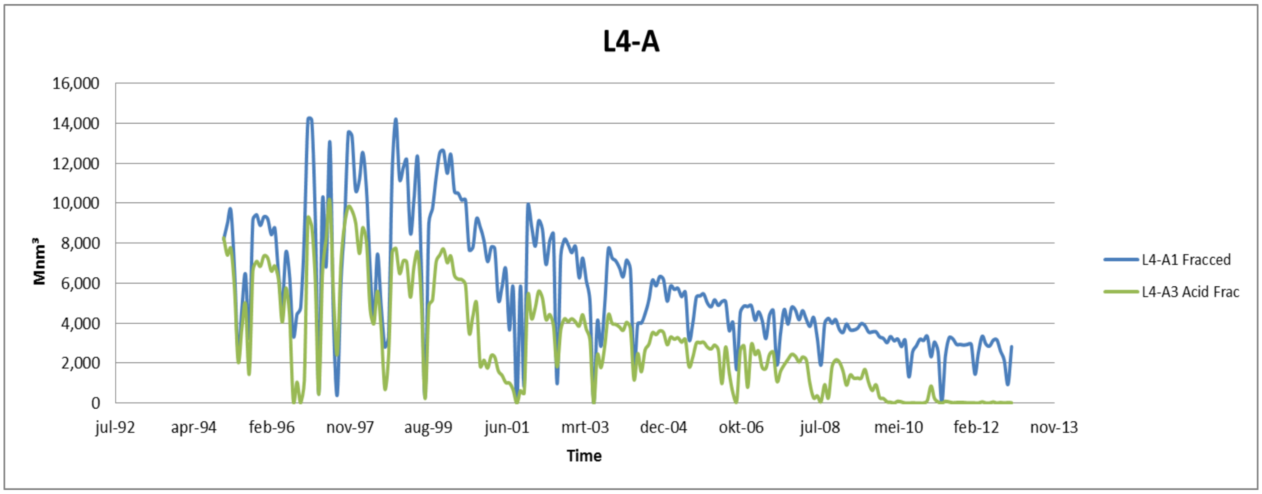


Figure 20 Production rates L4-A1 and L4-A3

WWN-3 (Figure 21) is an onshore well in the Waalwijk field and a good example of a successful onshore frac. With production rates around 150.000 m³ before fraccing and 600.000 m³ after, the PI is around 4.

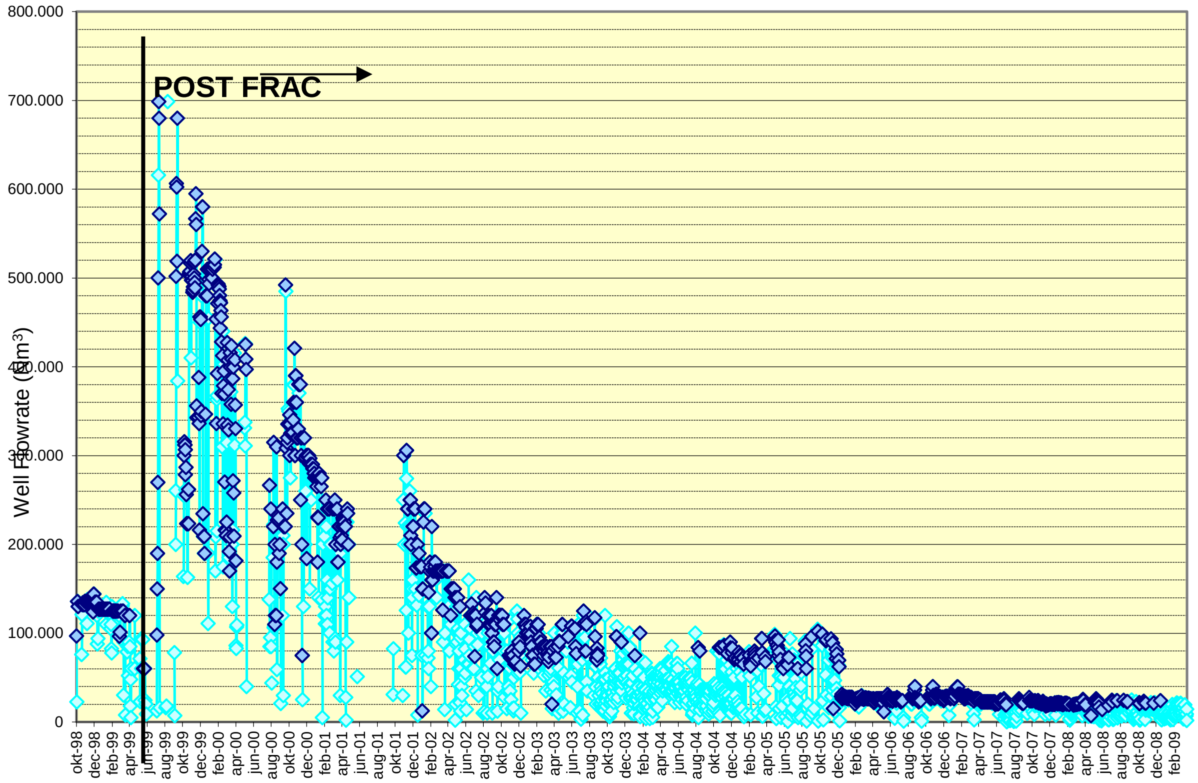


Figure 21 Production rates WWN-3

The previous described wells were fracced after a period of unfracced production. The following examples of successful fracs are wells that were fracced at the beginning of production. The wells are more effective than the unfracced wells, both in monthly and cumulative production.

The cumulative production of the wells in the E18-field are shown in Figure 22. E18-A2 is the only fracced well and also the most successful. Conspicuous is that despite the successful fracced well E18-A2, the operator chose to place an unfracced well E18-A3 in October 2008. From the production data this well is not a production success, with a cumulative production below 100 million m³ in the first year of production. The success of E18-A3 could be a drive to frac E18-A1 or E18-A3.

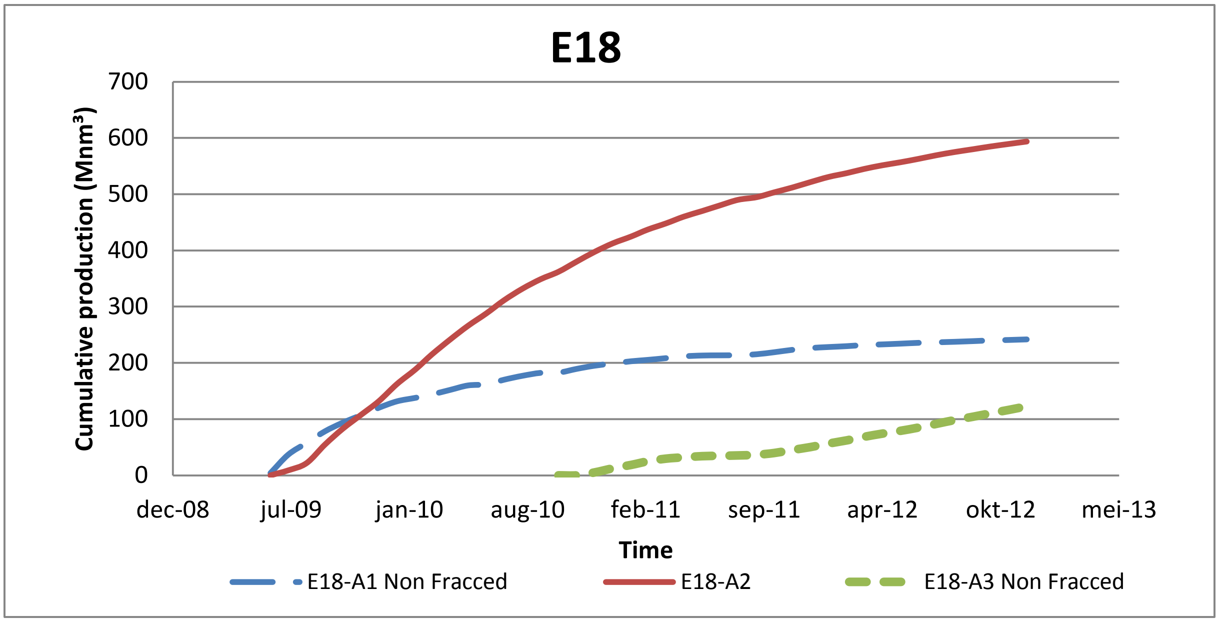


Figure 22 Cumulative production E18-A field

Well P6-S1 was scheduled for re-entry during 1997 after the discovery in 1990. An acid frac. treatment was planned to stimulate the reservoir and improve productivity. The treatment was designed to maximize the pumping rate, to ensure that the acid is placed in the reservoir under fracturing conditions. The frac is placed successful; the objective of placing the acid at frac conditions were met. The production of P6-S1 (Figure 23) is significantly higher than the unfracced well P6-S2. The fracture treatment report mentions that after the success of fraccing P6-S1, more wells in the P6-S field are considered to be fracced. Till now this did not happen.

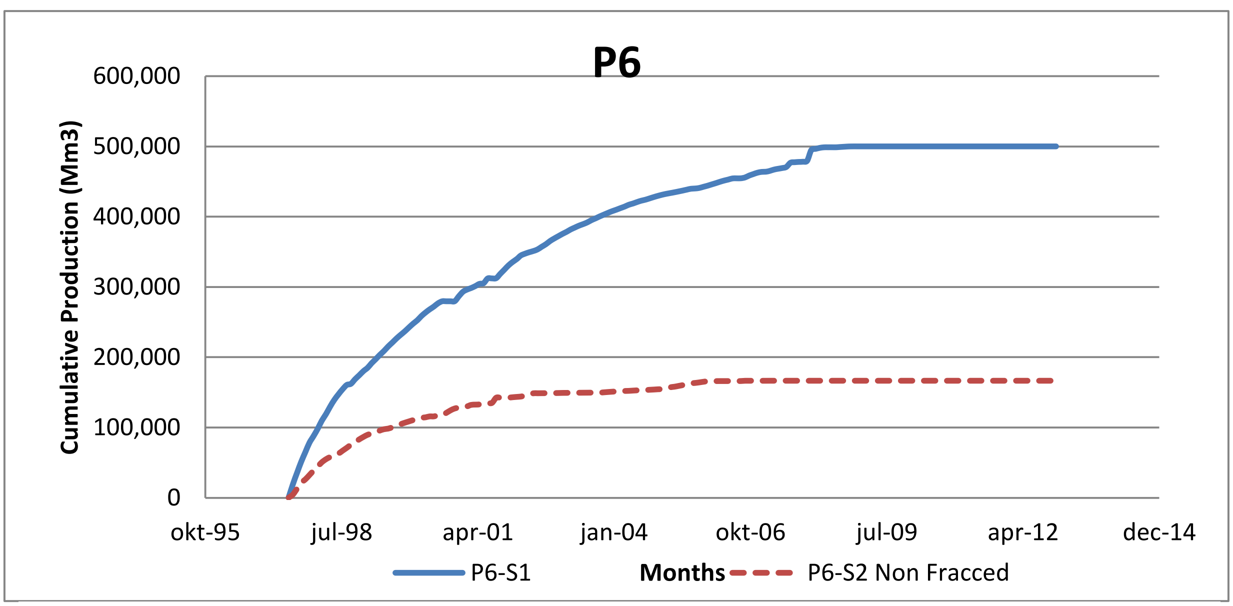


Figure 23 Cumulative production P6 field

4.3 Examples of unsuccessful frac operations

Although more successful fracs are placed than unsuccessful, there are some examples of failures. The cause of failure often lies in the technical failure of the frac operation, but it also happens that the expected production increase was not realized due to water production, or a deficit of gas present.

Well K4-BE3 (Figure 24) has started producing water in October 2005 and K4-BE1 has started producing formation water in February 2006. This was not expected because the wells are quite far from the GWC. Production logging has been performed and analysis shows water from the best producing zones. BE3, self-killing occurred rapidly due to water influx in the bottom-zone from which most of the gas production also came.

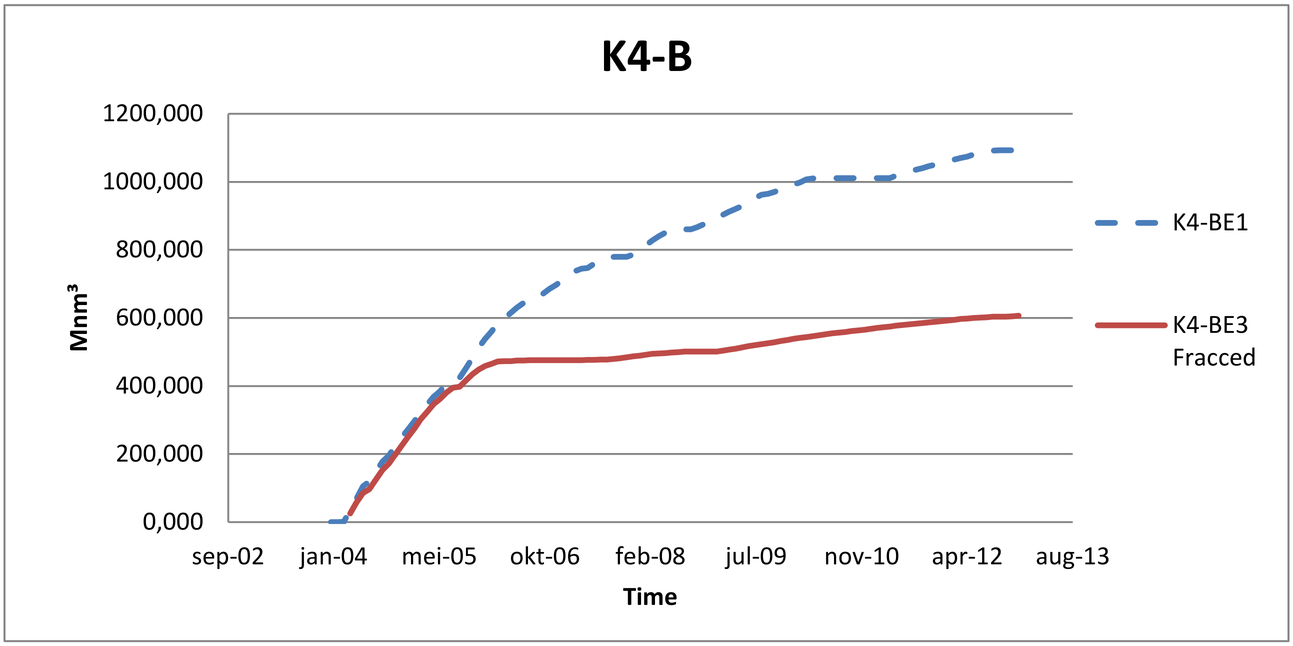


Figure 24 Cumulative production K4-B field

In 2008, the bottom zone was abandoned with a plug and a frac operation has been carried out on the Lower Slochteren and uppermost (low quality) U-Westphalian-C layer to improve productivity. This frac was not successful because less than 30% of the proppant could be pumped in due to problems with the surface equipment. After frac, the production rate increased by less than 25 KNM3/d, i.e. 15% of expectation. Furthermore, produced proppant remnants interacted with an emulsion of condensates and water resulting in complete clogging of the separator. The well has been stopped temporarily while remedial solutions are being investigated (filters, de-emulsifiers, etc). A re-frac of the well is still an option, once the clogging problem has been solved.

Both fracced wells K5-CU2 and K5-CU1 producing less than the unfracced well K5-CU3 (Figure 25). The fraccing operation on K5-CU1 give little improvement (10%). The high near wellbore friction caused a far lower proppant injection than planned; 25.500 lbs. are pumped instead of 169000lbs. planned (15% only). The frac operation on K5-CU2 was technically a success, all proppant was placed as designed. The lower Slochteren reservoir was absent, which originally was the targeted reservoir for the frac operation. Instead of fraccing the lower Slochteren, it was decided to frac the underlying Westphalian. After clean up, the well showed water production in a range of 69 to 120 m³/d. This water production caused the decline in gas production and finally lead to a non-viable situation.

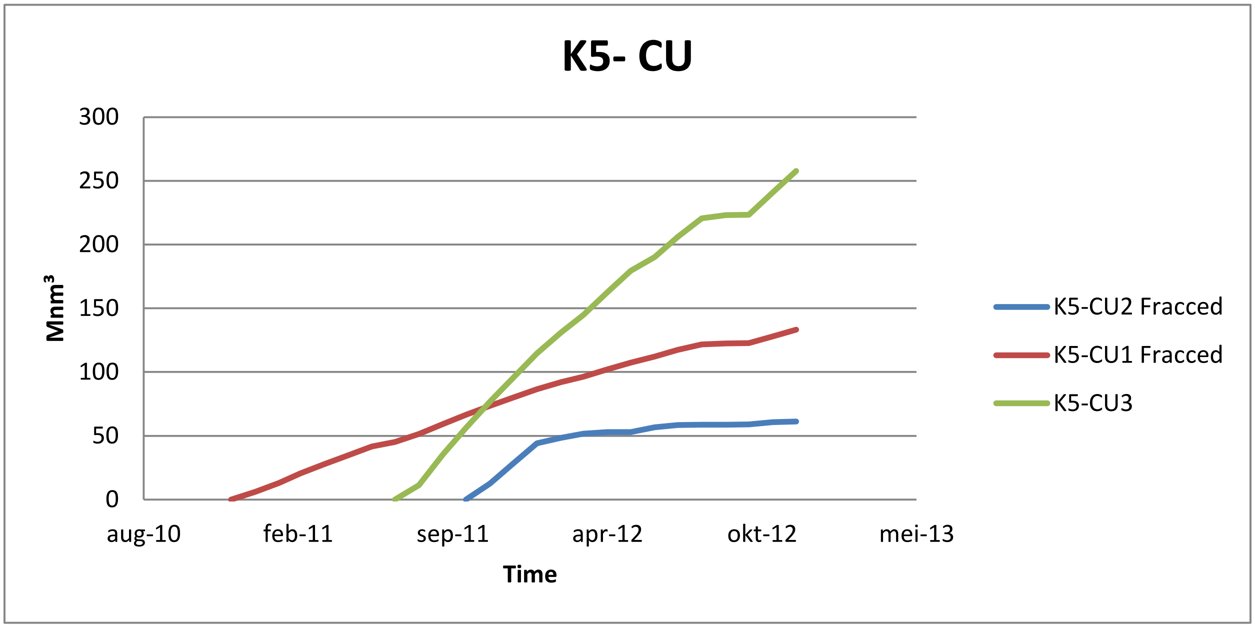


Figure 25 K5-CU cumulative production

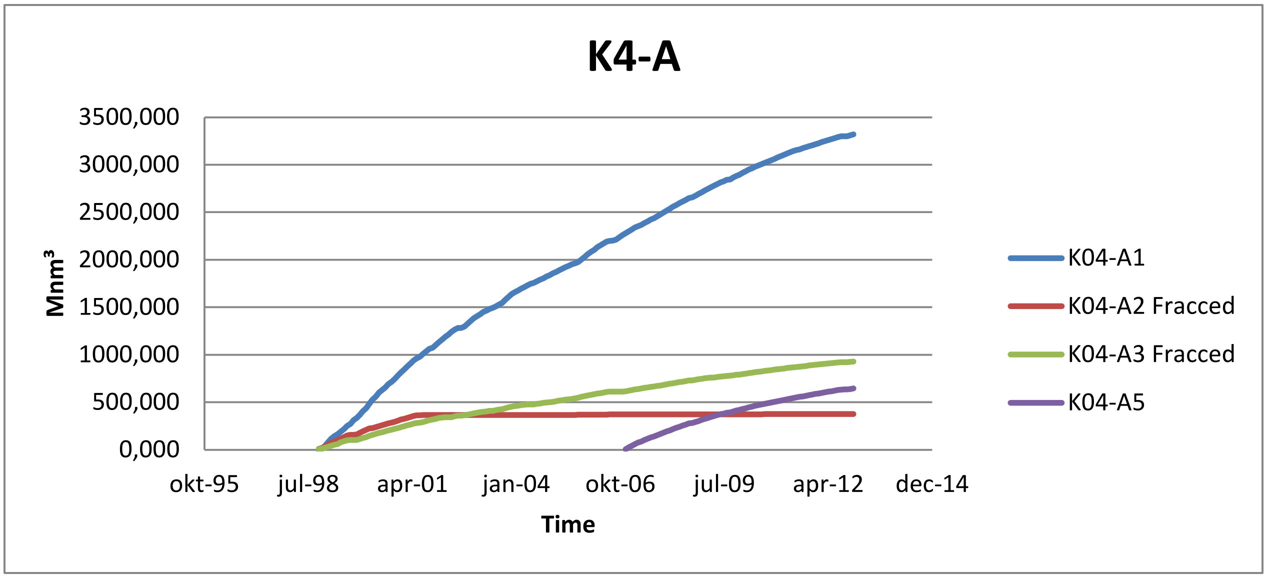


Figure 26 Cumulative production K4-A field

Hydraulic fracs were performed in K4-A2 and K4-A3. The fracs were technically successful because the mechanical skins decreased significantly in both wells, but the gain in production was very limited due to the fact that the connectivity of the Westphalian is rather poor away from the well bore and the higher production rates could be sustained for a very limited period of time (hours). Both wells have produced formation water within a few months after start-up. K4-A2 gave an immediate increase of production after fraccing, but after some time this gain seemed to fade out. The amount of water produced by K4-A3 is small and stable over time. K4-A2 produced a lot of water and it stopped producing in 2001.

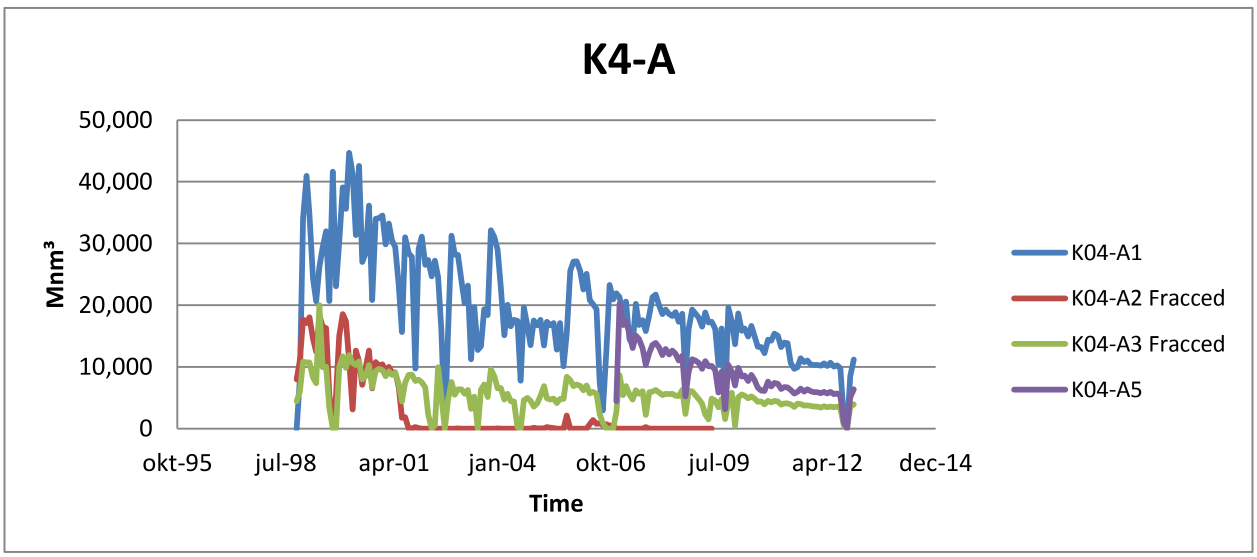


Figure 27 Production rates K4-A field

K4-A1 and K4-A5 are unfracced wells. K4-A1 is by far the best producing well in the field, where K4-A5 is the second best and most recent well (Figure 27). In this case, the unfracced wells are the better performing wells with respect to the fracced wells. Placing a frac in the close approximate of the GW contact is therefore a risk for producing from the water bearing part of the reservoir and can lead to an unsuccessful well.

5. Database analysis

After the creation of a thematic database, the challenge is to discover trends or relations between all the frac operations performed during the determined research interval. All parameters and units are listed in Appendix A. The data visualization program ©TIBCO Spotfire is used to create the figures in this chapter. The benefit of this program compared to Microsoft Excel lies in the multiple visualization methods and the reduced error rate. Not all the data could be obtained. There are multiple reasons for an incomplete dataset. Data was missing (from EBN as well as the Operators side) or was not reported.

Despite an incomplete dataset, there was a lot of data gathered to analyse. In some cases, conclusions are drawn on fewer data points as there were frac jobs but these still can show important differences between the frac jobs were the is data available. Table 2 gives an overview of the amount of successes, both technical and production, from all the executed jobs. It has to be noted that, due to an incomplete dataset, not all the fracs could be categorized.

Table 2 Success of fraccing

Frac operations	**total**	95
Technical succes	yes	71
	no	12
Production succes	yes	53
	no	35

When a frac is a technical success, it means that all proppant is placed as designed and the clean-up of the well is performed without any major operational difficulties. In most cases, if the frac is a technical failure, it is also a production failure. In one case, a frac was a technical failure (early screen-out), but the production increase was high enough to be a success.

The data points can vary in colour, size and shape to indicate more than one dimension in a 2-D plot. The figures described in this chapter are the ones which clearly indicates trends or relation between several data base parameters or the ones which clearly don't describe trends. It is not logical to plot every parameters against each other, so the pictures shows a logical infill of the axis and data filter. In some cases it is expected to find a relation between different parameters. If this relation is not found, it is worth mentioning because the parameter choice can be part of an operators design vision. If the analysis show no difference on the end result with that parameter value, it has to be communicated to the operating company to reduce the risk of failure and a possible reduction in operation costs.

5.1 Production rates

The previous chapter described the production behaviour of each individual fracced and unfracced well in a specific gas field. The scope of this analysis lies in the comparison between the fracs. Figure 28 plots the Best Monthly Production after fraccing against the Cumulative production over a certain time interval. The Best Monthly Production is usually observed in the first months after fraccing.

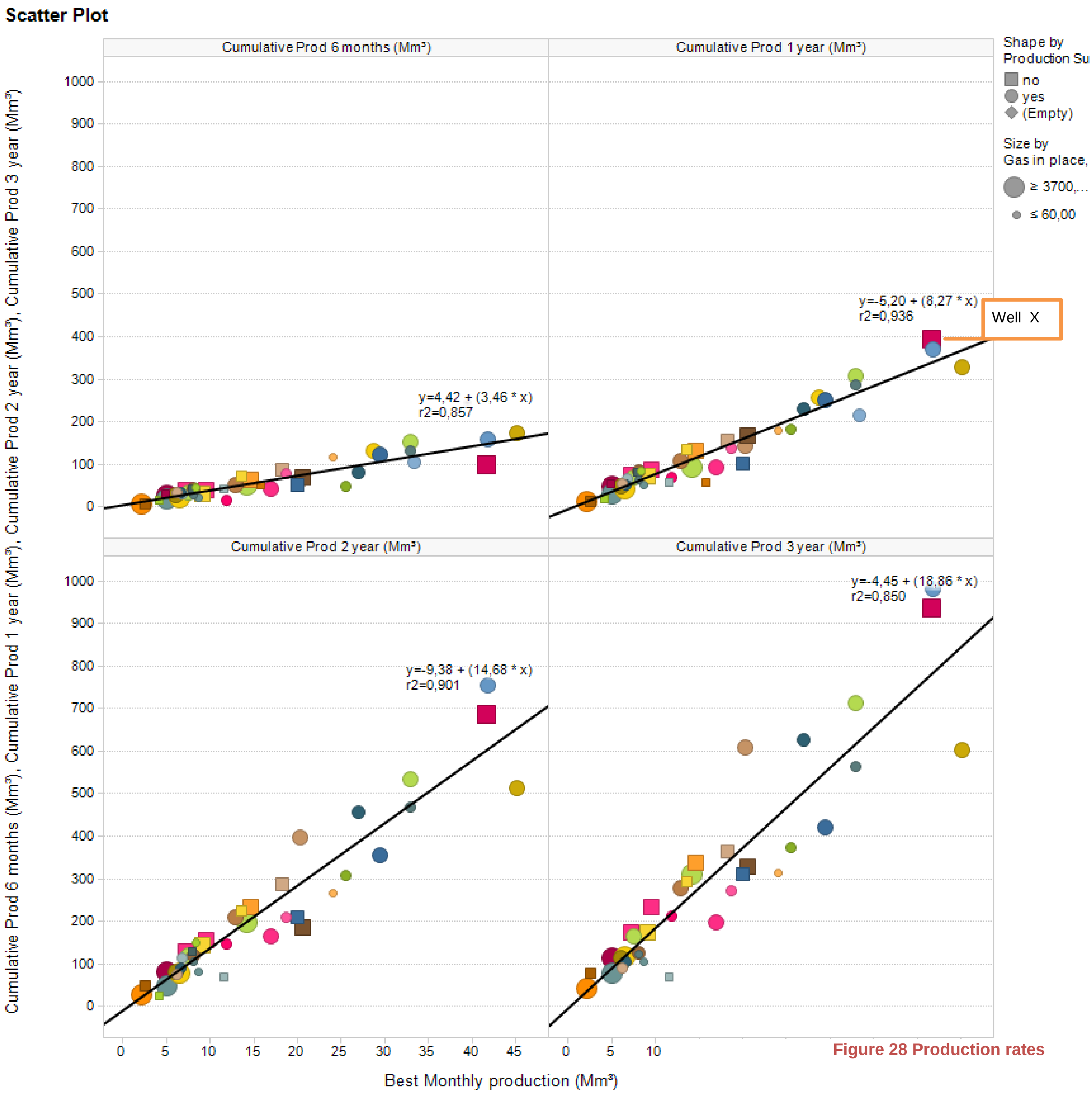


Figure 28 Production rates

The reason to plot this best month against a longer time interval is to make an accurate forecast in the beginning of the production stage. Figure 28 shows strong linear relations between the plotted data, with the best accuracy observed in the cumulative production after one year (R^2=0.936).

All the data points have different colours which depict the different fracced wells. The size of the data points shows a variation of the initial Gas in Place (GIIP); a bigger point depicts a larger GIIP. The shape of the data point represents the production success where a square stands for no and a circle stands for yes.

Some important observation can be made from Figure 28. The amount of GIIP is not a criterion for the amount of production in time. Fields with a small GIIP as well as fields with a large GIIP can be found in well with relatively high and low production rates. When the time interval is increased, the data points show a funnel shape distribution; wells with a high production rate tend to have a bigger deviation in time than wells with a low production rate. This implies when the production rates are higher, the well will faster encounter more factors that influence the cumulative production. The GIIP can be one of these factors. It can be expected that in a field with a low GIIP it is harder to produce the extrapolated amount of gas after a longer period of time; it is a common phenomenon for fields reaching their end of field live to produce less gas. The data points with a high GIIP tend to deviate positively from the linear relation; the well is producing more gas than expected. The opposite is observed in data points with a small GIIP, they tend to produce less gas than expected after a 2 or 3 years of production.

A notable aberration in the data points is the high producing purple square, for confidential reasons it is called well x. Despite its high production and GIIP it is not considered as a success. This can be explained by the production rates before and after fraccing. The well is situated in a field where 3 wells were successfully fracced. The success of these operation led to the decision to also frac well x. Well x was already producing a sufficient amount of gas (~1 million m^3/day) from a fairly good reservoir (up to an observed conductivity of 500mD.m). The production rates after fraccing were only increased for a very short period of time and fell back to the rates before fraccing.

5.2 Reservoir properties

Every fracced well is placed in its own targeted reservoir. In the Dutch on and off-shore there are several important reservoirs where a petroleum play caused a high probability of hydrocarbon accumulation. It is therefore common for a well to target a similar reservoir. Table 3 shows the reservoirs[4] in which the frac operations were performed. The bar diagrams (Figure 30) give a visualization of the success rate.

[4] Formation names are in some cases reported as the formation group e.g. Rotliegend, Upper and Lower Slochteren formation are part of the Rotliegend group.

Table 3 Targeted reservoir frac jobs

	All	Success	No Success
Cretaceous Chalk	3	3	0
Bundsandstein	16	12	4
Zechstein Platten Dolomite	1	1	0
Upper Slochteren	27	17	10
Lower Slochteren	23	17	6
Rotliegend	3	0	3
Lower Slochteren and Upper Westphalian	2	0	2
Limburg	1	1	0
Westphalian	8	1	7
Dalen	1	0	1
Hardenberg	1	1	0
Total	86	53	33

Figure 29 shows that the majority of wells are drilled in the Permian reservoirs, ~60% from the Rotliegend, Upper & Lower Slochteren and Zechstein formation. Remarkable is the high failure rate of the Westphalian fracs, 90% of those wells are being considered as a failure. The Westphalian in the Netherlands is characterized for its layered intervals and high permeability heterogeneity (Wong & de Jager, 2007) which can be a reason for the failure amount.

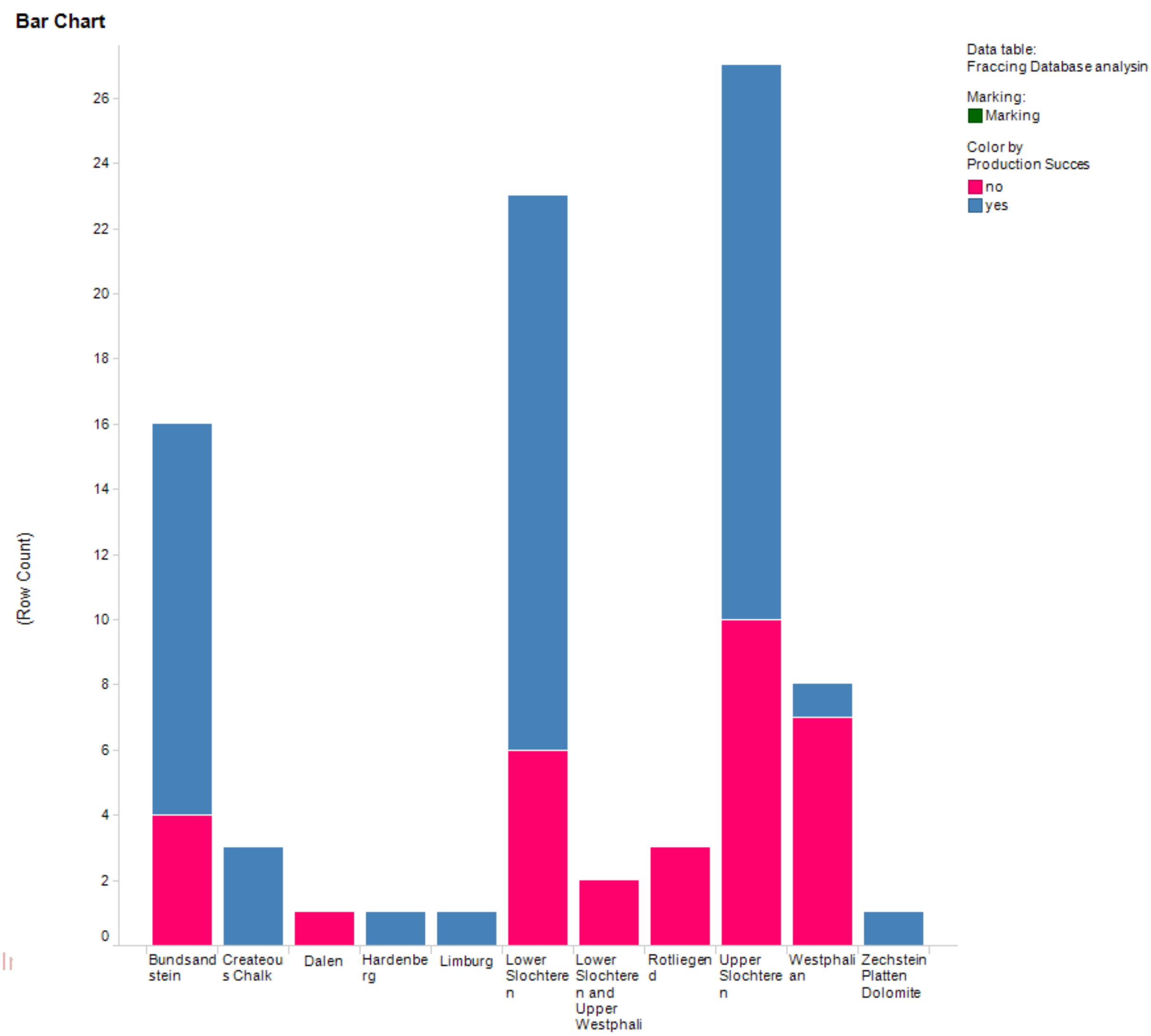


Figure 29 Bar diagrams of the success rate from all targeted reservoirs

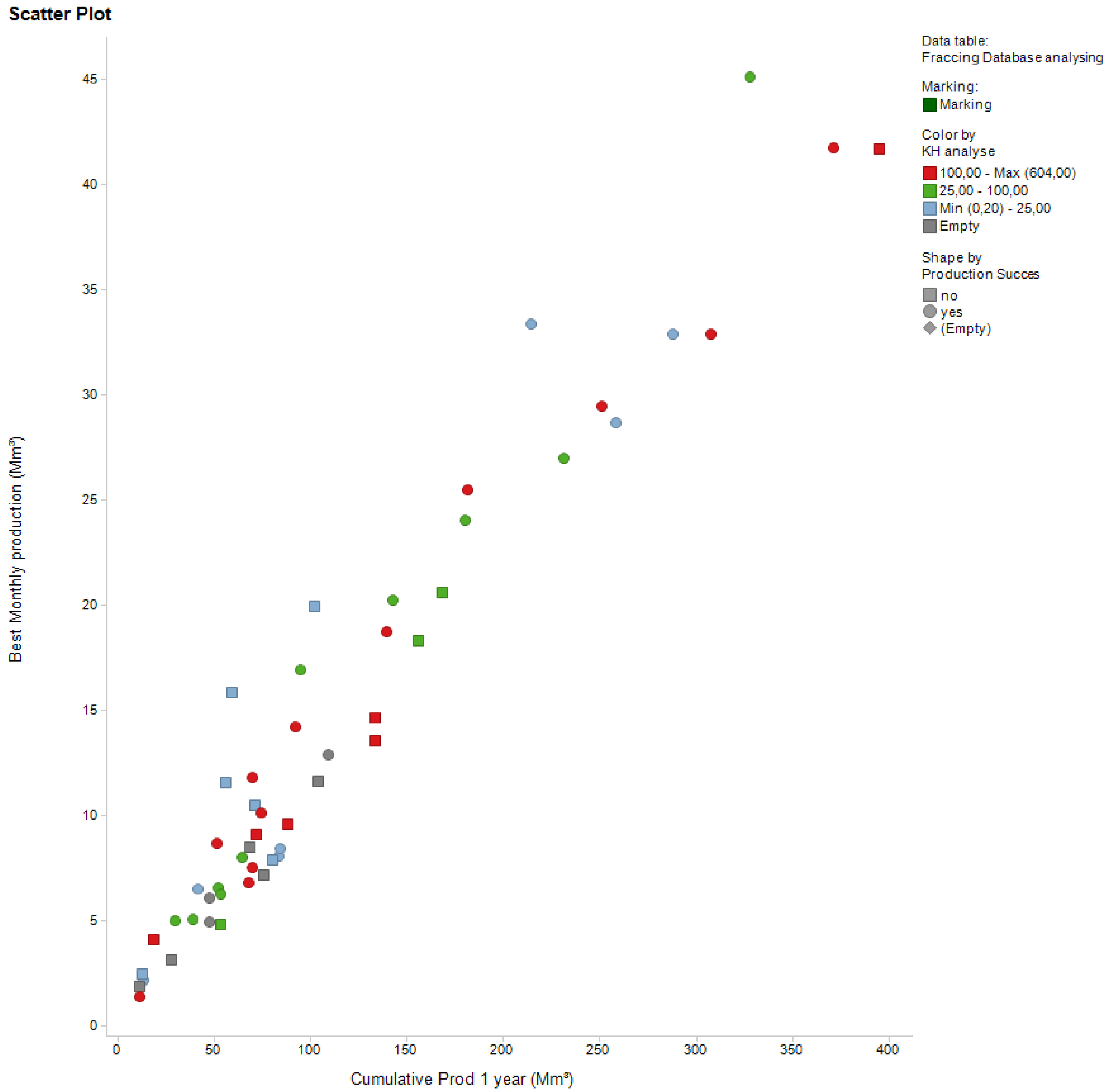


Figure 30 Permeability-thickness dependence

Figure 30 plots the similar relation as Figure 28 but has a different colour index. The goal is to discover if the permeability-thickness (KH = mD * m) has influence on the performance of the well. A 3-category distinction is made between wells with a very low, intermediate and high KH value (Figure 30). Where conventional wells usually produce more hydrocarbons for a higher KH value, this is not seen in fracced wells. Low, intermediate and high KH values are spread throughout the whole production interval. A more important parameter with respect to the conductivity is often not reported: the frac conductivity or F_{cd}. F_{cd} is a dimensionless parameter for the frac conductivity and is given by :

$$F_{cd} = \frac{k_f\, w}{k\, x_f}$$

where k_f w (md * m) is the fracture conductivity, k is the reservoir permeability and x_f is the fracture half length.

Operators often chose to only report the proppant concentration in the fracture, which indicates a certain frac conductivity. Every proppant comes with a certain conductivity range, which is tested in the laboratories of the manufactures (Halliburton,2005). Since laboratory experiments do not give the exact values for frac conductivities at reservoir conditions, the comparison between proppant concentration and frac conductivity cannot be related directly.

5.3 Proppant and job volumes

Fracture treatment reports and design studies have a high data availability on proppant and fluid volumes that are used during the jobs. Throughout time, there have been developments to improve the modeling of the distribution of proppant inside the fracture. This paragraph describes the importance of the job volumes, concentration of proppant in the fracture, injected fracturing fluid and proppant size.

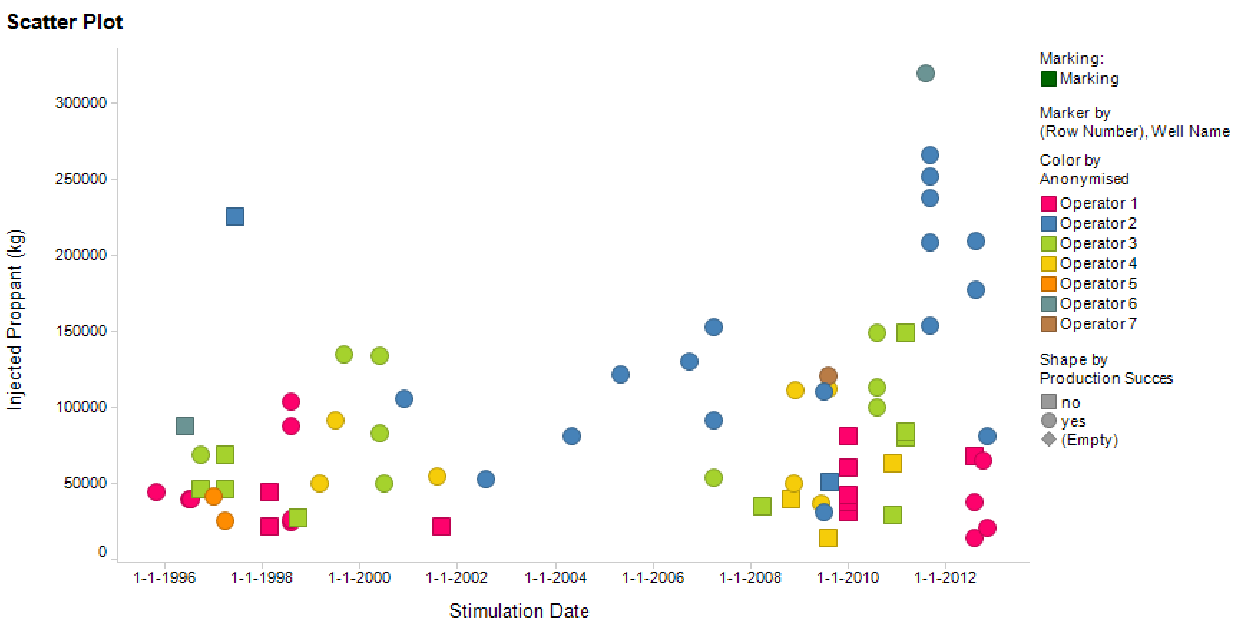


Figure 31 Injected proppant between 1995-2012

Figure 31 and 32 give an overview of the changes in time between 1995 and 2012 looking to the amount of proppant injected and the concentration inside the fracture. The colour of the data points shows the different operators that executed the frac operations. The name of the operators are anonymised for this research. There is a slightly increasing trend visible in the concentration and amount of proppant injected. The colours however show that the increasing trend is mainly caused by Operator 2. The increase can be explained by the developed techniques of injecting proppant into the fracture and a different vision on fraccing between the different operators.

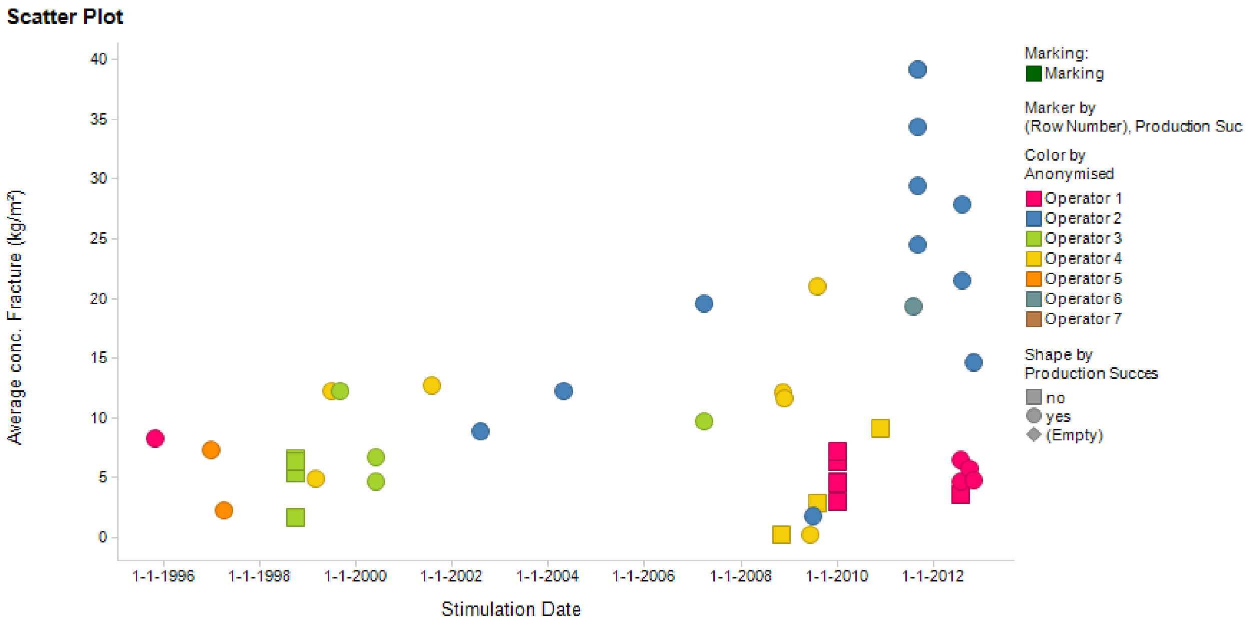


Figure 32 Concentration proppant between 1995-2012

Figure 31 and 32 also show a trend which is better visible in Figure 33. Fracs with a higher concentration of proppant in the fracture as well as fracs with a higher injected proppant amount have a higher probability to be a production success. All the fracs with a maximum concentration above 20kg/m³ are marked as a production success. The area in Figure 33 where the average concentration is lower than 10 kg/m³ and 100.000 kg of proppant contains the highest amount of production failures (45%).

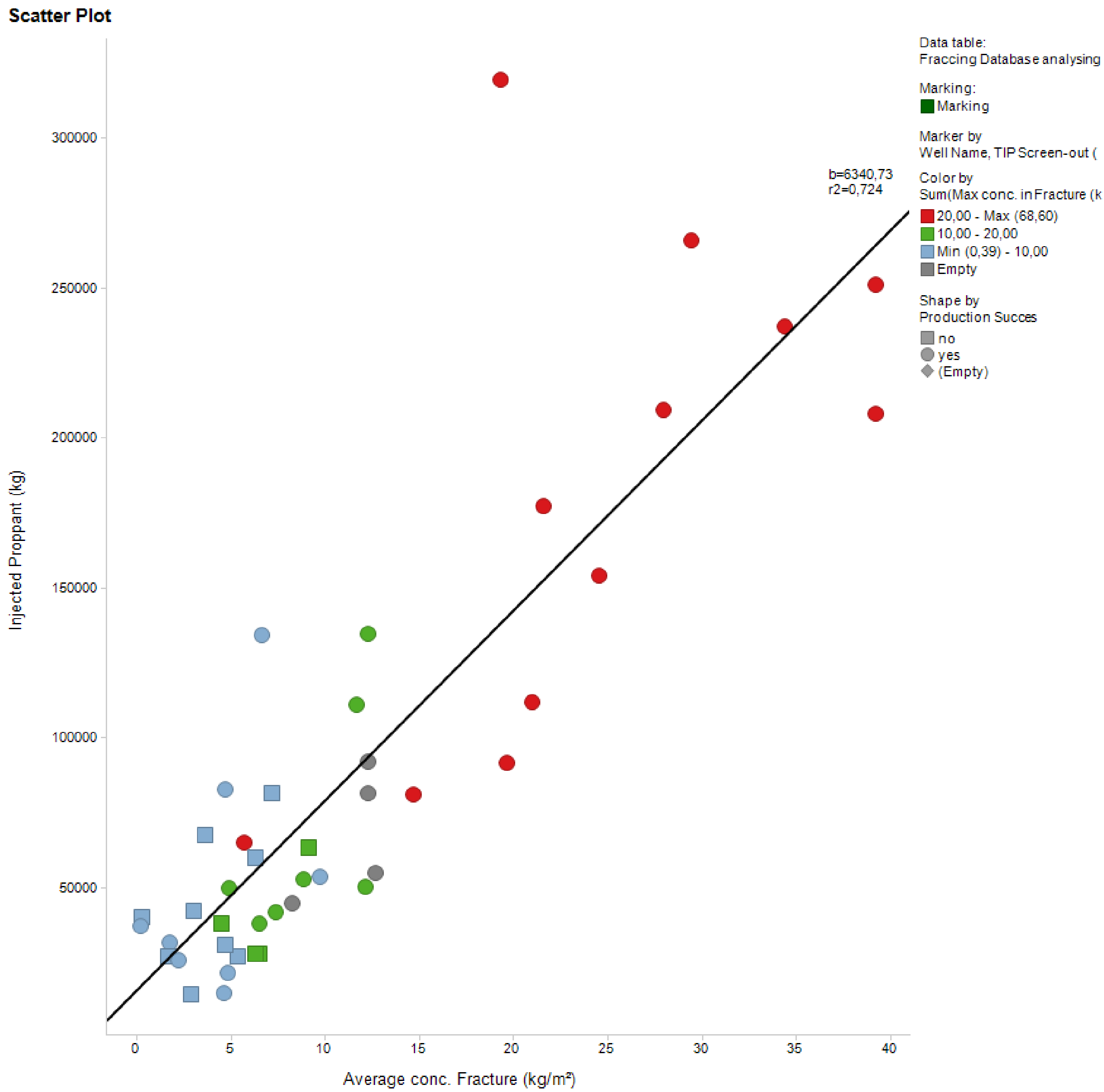


Figure 33 Concentration of proppant in the fracture

The concentration of proppant is not measured in every frac job but seems to be an important parameter to report. A parameter which is reported more frequently is the proppant size. Each proppant type has different characteristics like conductivity, shape, strength and size. Proppant sizes are represented as fractions, e.g. 12/18, 20/40, 16/30, which gives information about the mesh sizes of the grains. A 16/30 proppant is sieved to have at least 90% between 16-30 mesh size (600-1180 µm). The smallest fraction stands for the highest mesh size. Generally, coarser proppant allows for higher flow capacity due to the larger pore spaces between the grains. On the contrary, a larger pore space can give a higher chance of break down or crush under stress due to the relatively fewer grain-to-grain contact points.

Figure 34 shows the importance of the proppant size for the production success. Similar to the previous figures , Figure 34 depicts that the amount of proppant injected is strongly related to the production success. 91% of the jobs with >100.000kg of injected proppant results in a production success. 51 % of the jobs <100.000kg results in a failure. There is also a difference visible between the used proppant sizes. All the jobs with a big proppant diameter (12/18), result in a production success. The highest amount of failures is observed on proppants with a smaller grain size (20/40) or proppants mixtures, consisting of two types of proppants. Despite the higher expected risk of proppant crushing when using 12/18 or 16/20 proppant, the only frac job which mentions crushed proppants used a size of 20/40. Two notable aberrations of production failure with a high injected amount of proppant can be explained. One of the cases is already described as well x in section 5.1. The second case (well y) was a technical frac success, but the well started to produce water just after the operation.

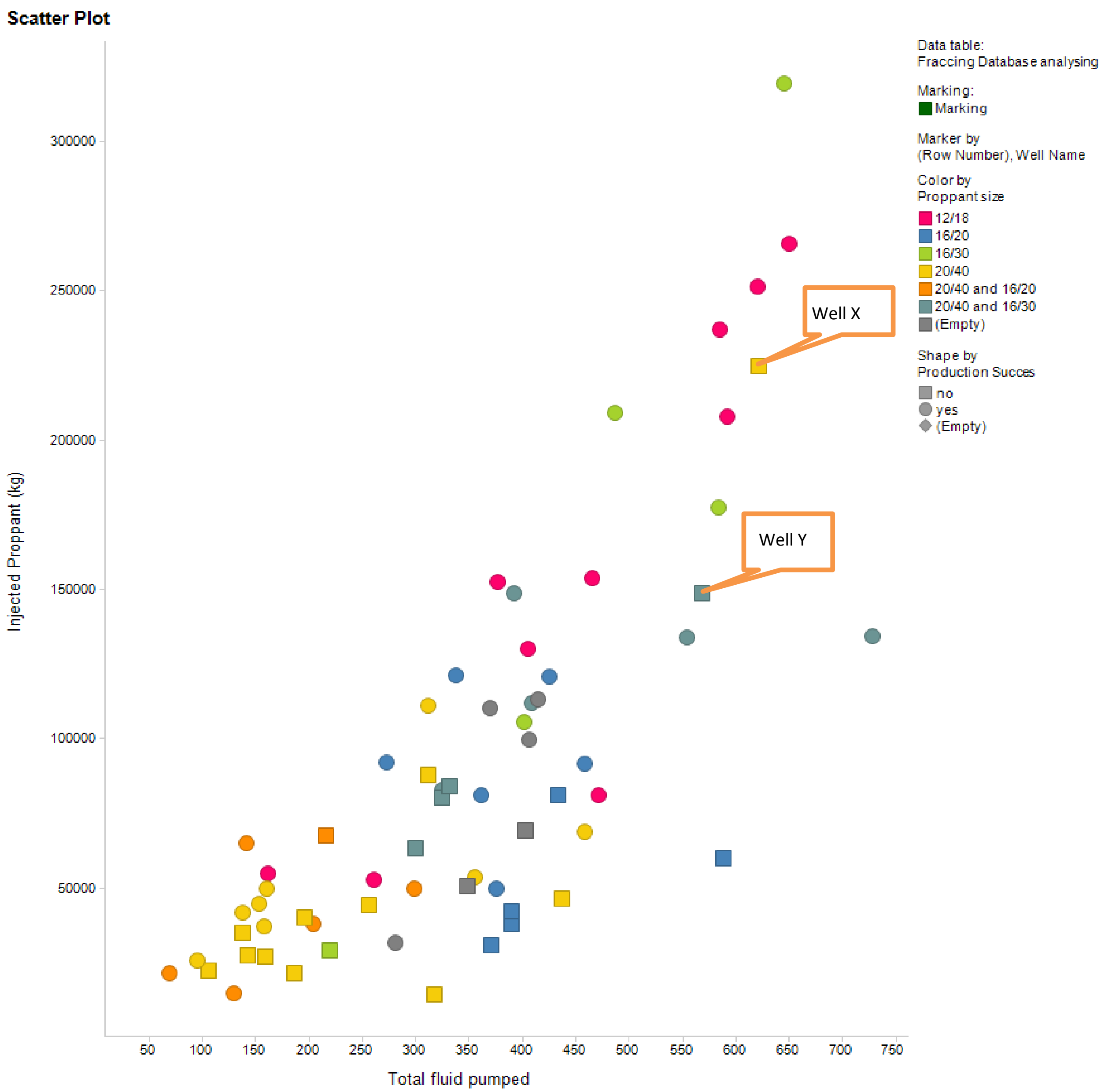


Figure 34 Proppant size vs job volume

5.4 Frac Dimensions and design

Designing a frac job is still a matter of debate in the industry. Section 2 described the most recent status of the current simulation programs available. Although a frac may grow more complex, the estimations of the frac dimensions are a good approximation of the reality. Micro-seismic monitoring is not used till now in the Netherlands. This would give a more detailed view on the frac dimensions but also quantify the micro-seismic events taking place when executing a frac job.

Figure 35 shows the simulated frac dimensions made during the post-frac analysis.

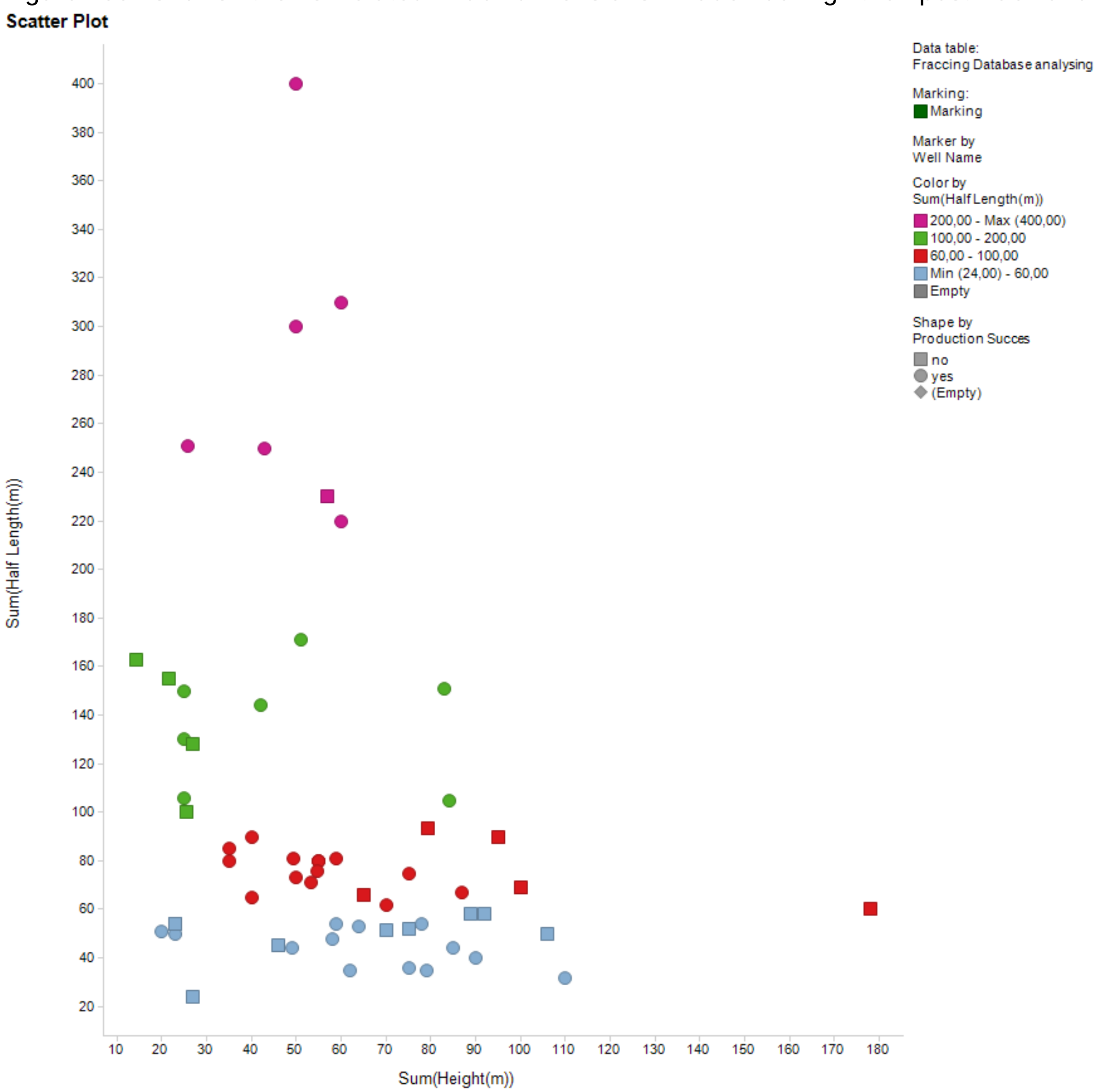


Figure 35 Frac dimensions

The colour scheme is used to categorize the half lengths of the fracs. In all the categories, production failures do occur. It seems that more factors are contributors to these failed operations. It requires an individual well analyze to determine the possible factors. This however is beyond the scope of this research and therefore it cannot be stated if there is a relation between the frac dimensions and the probability of success.

A more important design parameter is visible in Figure 36. Wells designed to show a tip screen-out behavior (TSO), are shown in green, where wells without this TSO design are coloured blue. TSO is observed when the frac job is designed to inject more proppant after the fracture void is already filled. If the injection is continued, this will be visible as an increase of the net pressure at the final stage of injection. The consequence of this design is a growth in fracture width without increasing the propped frac half-length and thus results in a bigger propped frac with higher proppant concentrations. The latter being an important observed parameter for the production success. 82% of the wells with TSO resulted in a production success.

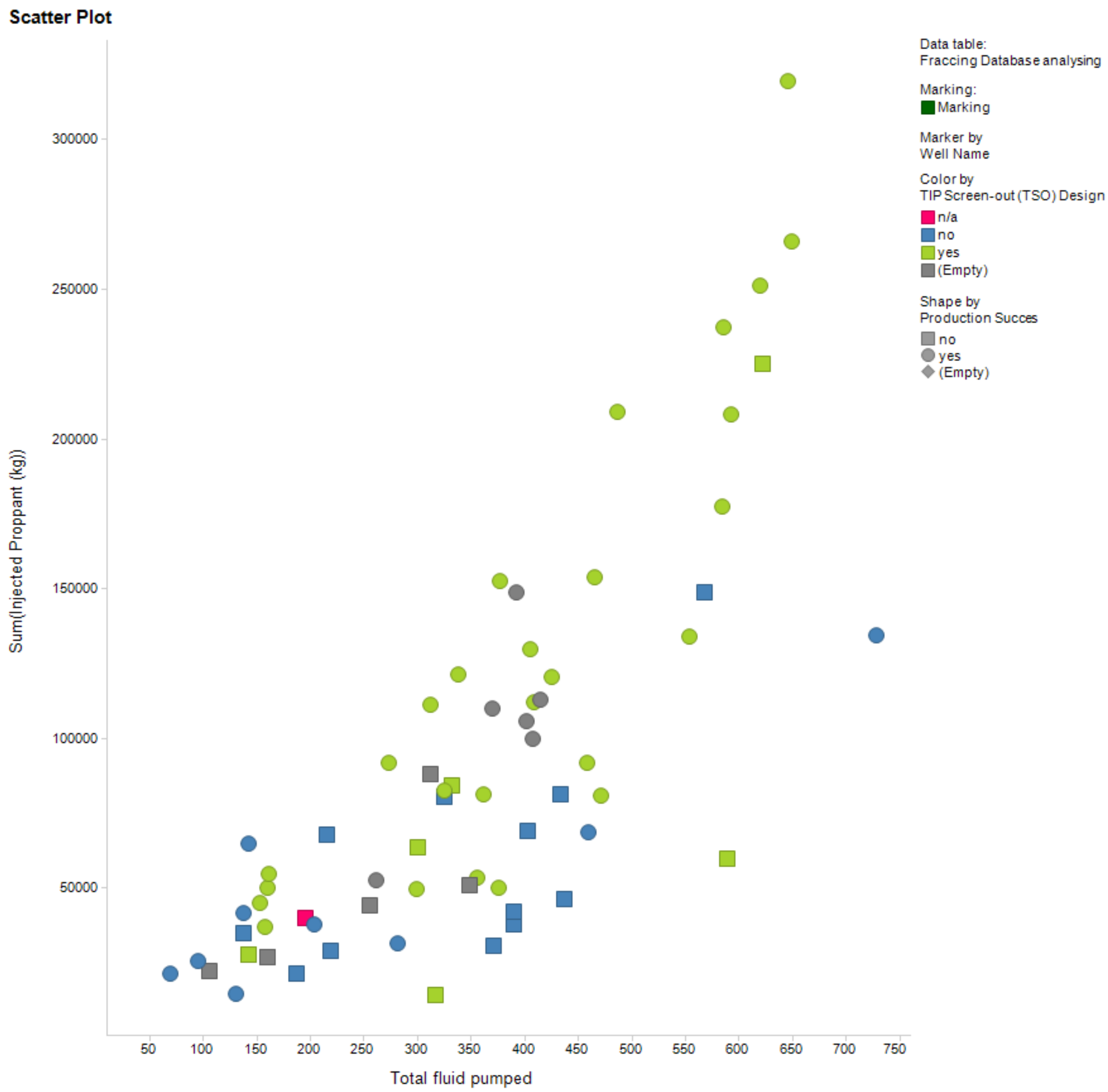


Figure 36 Tip Screen-out Design

Tip Screen-out design increases the fracture width. It is expected that wide fracs performing better than narrow fracs. Figure 38 shows the relation between the production success, TSO and fracture width. From Figure 38 it becomes clear that the wide fracs (>0,5cm) are more successful than narrow fracs. 39% of fracs <0,5 cm resulted in a production failure. The majority of wide fracs are TSO fracs; this confirms the width growth assumption that is accompanied with tip screen-out design.

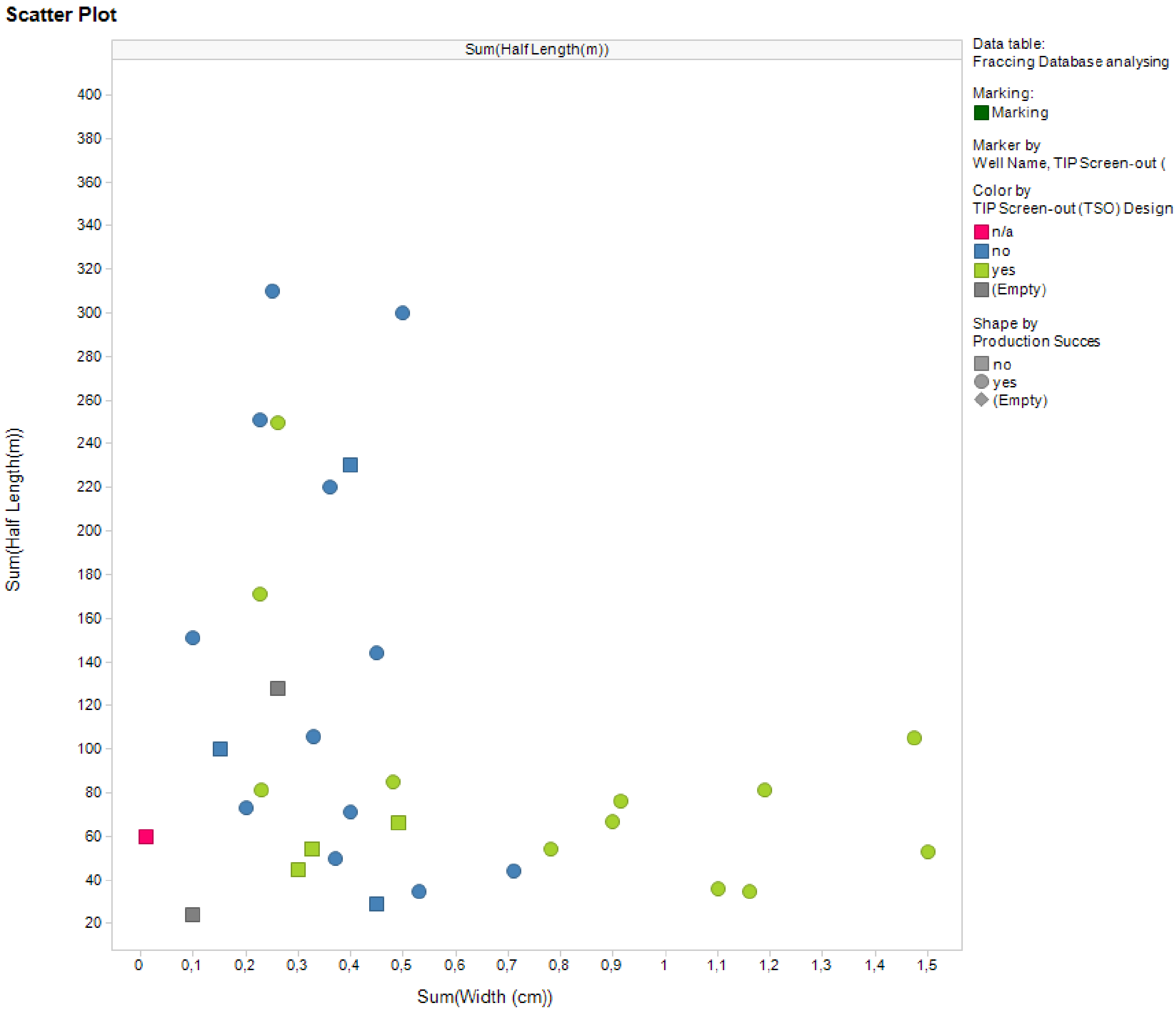


Figure 38 Relation between fracture width, tso and production success

Conclusions

- Frac growth into the Dutch drinking water reservoirs is highly unrealistic. Due to relatively small frac heigths (maximum of 185 meter) versus the distance between the frac and the drinking water reservoir (generally 2 kilometer or more).
- 55% of the fracs in the Netherlands, in the period 1995-2012, are determined as a production success.
- Big frac jobs with high amounts of injected proppant (>100.000kg) and proppant concentration (>10kg/m²) show the highest rate of production success. 91% of jobs with >100.000kg of injected proppant resulted in a success. 100% of jobs with a reported proppant concentration >10kg/m² resulted in a production success.
- 45% of the jobs with injected proppant <100.000kg and <10kg/m² resulted in a production failure.
- Proppants with biggest diameters give the best results for production.
- Tip screen-out is an effective design for creating wide fracs containing proppant with a higher concentration. 82% of the operations results in a production success.
- All wide fracs (>0,5cm) resulted in a production success. Narrow fracs (<0,5cm) resulted in 39% of production failure.
- Frac operations in the vicinity of water bearing parts of the reservoir can lead to production failures due to extensive water production. 6% of the fracs resulted in excessive water production.
- Frac operations can be successful in tight reservoirs with a variety of conductivities, ranging from very low (0-25 mD.m) to high (100-600 mD.m).

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Appendix A:

Parameters used to construct the Database.

Operator
Stimulation Date
Well Name
Technical success (yes or no)
Production Success (yes or no)
Best Monthly production (Mm³)
Cumulative Production after 6 month (Mm³)
Cumulative Production after 1 year (Mm³)
Cumulative Production after 2 years (Mm³)
Cumulative Production after 3 years (Mm³)
Formation Name
Porosiy (%)
KH (mD x m)
Permeability(mD)
G/W contact (TVD (m))
Temperature (ºC)
Gas in place, Connected GIIP (Mm³)
ISIP gradient (bar/m)
Closure stress gradient (bar/m)
Frac Gradient (bar/m)
Initial Reservoir Pressure (bar)
Gas column length(m)
Poisson ratio
Young's Modulus (Mpsi)
Geological sequence
Well profile (vertical, slanted or horizontal)
Angle (º)
Length of horizontal section (m)
Number of fracks
Spacing between fracs (m)
Half length(m) design
Half Length(m)
Height(m)design
Height(m)
Ratio Length/Height
Width (cm)
Frac conductivity (mD x m)
Effective conductivity (FcD)

Perforation depth top (TVD (m))
Perforation depth bottom (TVD (m))
Perforation interval (m)
Height containment of frac developing (m)
TIP Screen-out (TSO) Design (yes or no)
TSO increase (bar)
Injection rate (m^3/min)
Injected Proppant (kg)
Proppant type
Average conc. Fracture (kg/m^2)
Max conc. in Fracture (kg/m^2)
PAD Volume (m^3)
Total fluid pumped (m^3)
Total conc. in fluid (kg/m^3)
Proppant size
Service Company
Expected Production Increase
Realized Production Increase