# Identification of Suppliers able to provide Hydraulic Fracturing Services in Unconventional Reservoirs and Risks associated with the Construction of these Wells.

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## Abstract

*According to the international agencies U.S. Energy Information Administration (EIA) and World Energy Council (WEC), Brazil is the 10th country in the world ranking of the largest holders of shale gas reserves, with 245 Tcf (trillion cubic feet) (6.9 Tcm – trillion cubic meters) of natural gas. Due to the low permeability of these formations, the so-called unconventional reservoirs, only become viable if stimulated through horizontal drilling and hydraulic fracturing techniques. These techniques, like any other ones, have associated risks that should be very well managed and mitigated. This article aims to show that the benefits, in terms of fostering the local economy, job creation and energy security, outweigh the risks since they are known and well managed. In addition, suppliers present in country, able to provide these services properly, with numerous successful cases around the world, are identified in the article as well.*

**Keywords:** hydraulic fracturing, fracking, unconventional resources, shale gas, risk management

## Introduction

Hydraulic Fracturing is a stimulation technique for oil and gas wells, already used in the world for more than seventy years and, in Brazil, since the 1960s. This technique basically consists of injecting a mixture of water, chemical additives and proppant (sand, ceramics or bauxite), from surface to the formation of interest, through the well. Due to high pressures achieved during injection, a fracture is induced inside the rock and filled with proppant. After relieving pressure, this fracture closes around the proppant, expelling back most of the fluid towards the surface and, therefore, maintaining a preferential channel of high conductivity, through which the oil or gas will flow.

Figures 1 to 3 exemplify the sequence of a Hydraulic Fracturing operation in its simplest configuration: vertical cemented well and perforated to the depth of a single pay zone.

As fossil resources became scarcer around the planet, new technologies emerged over time to extract these resources at previously unachievable depths, both onshore and offshore. Brazilian most classic example is the so-called Pre-Salt Layer, which had not even been discovered very short time ago and today is already responsible for 73.1% of Brazilian oil and gas production (ANP, 2021)[1]. Nowadays, Brazil is pioneer and world leader in ultra-deep water extraction technology thanks to the discovery of these huge accumulations in the carbonate reservoirs of the Brazilian Pre-Salt. By the way, the permeability of these carbonates can also be very low and these formations usually must be stimulated as well. However, through the acidizing technique since carbonate formations are soluble to Hydrochloric Acid. Otherwise, hydrocarbons simply wouldn't flow towards the surface.

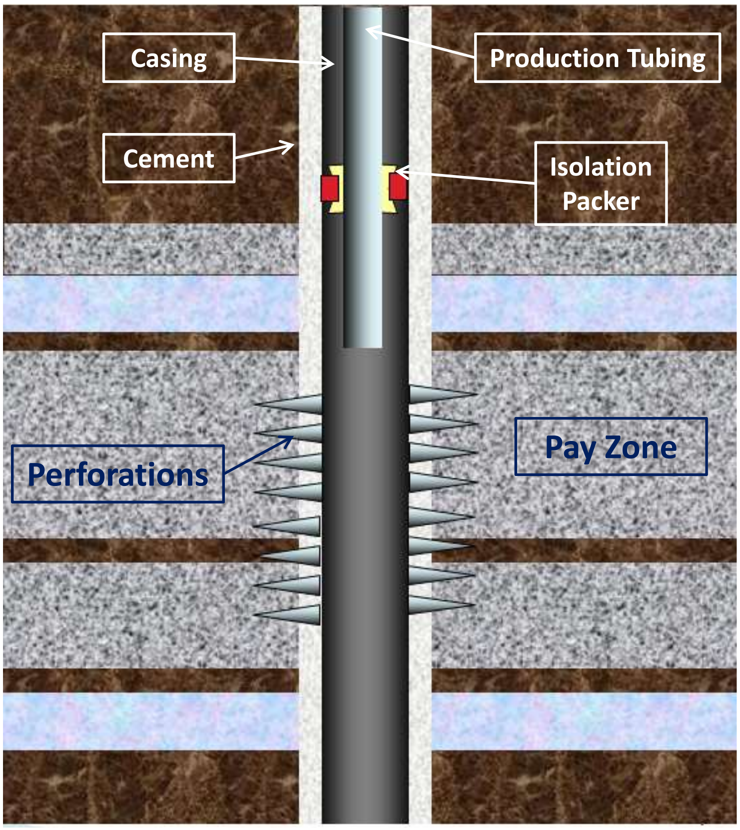


Figure 1 - Schematics of a conventional vertical well, ready to be fractured (Source: Elaborated by authors)

1 See: ANP. Available at: https://www.gov.br/anp/pt-br/centrais-de-conteudo/publicacoes/boletins-anp/bmp/2021/2021-03-boletim-pdf.pdf

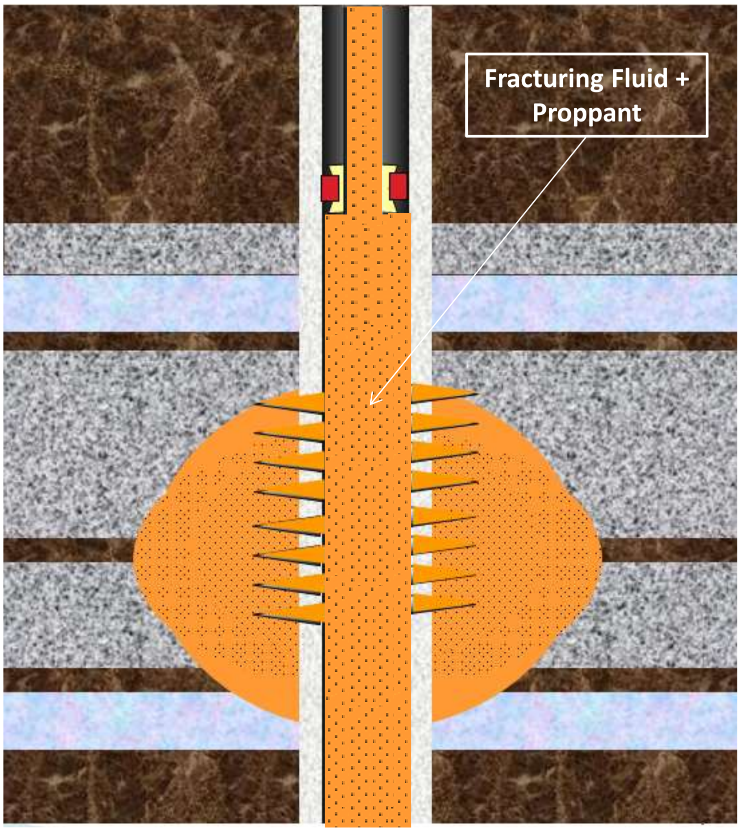


Figure 2 - Open fracture during pumping of the fracturing fluid plus proppant (Source: Elaborated by authors)

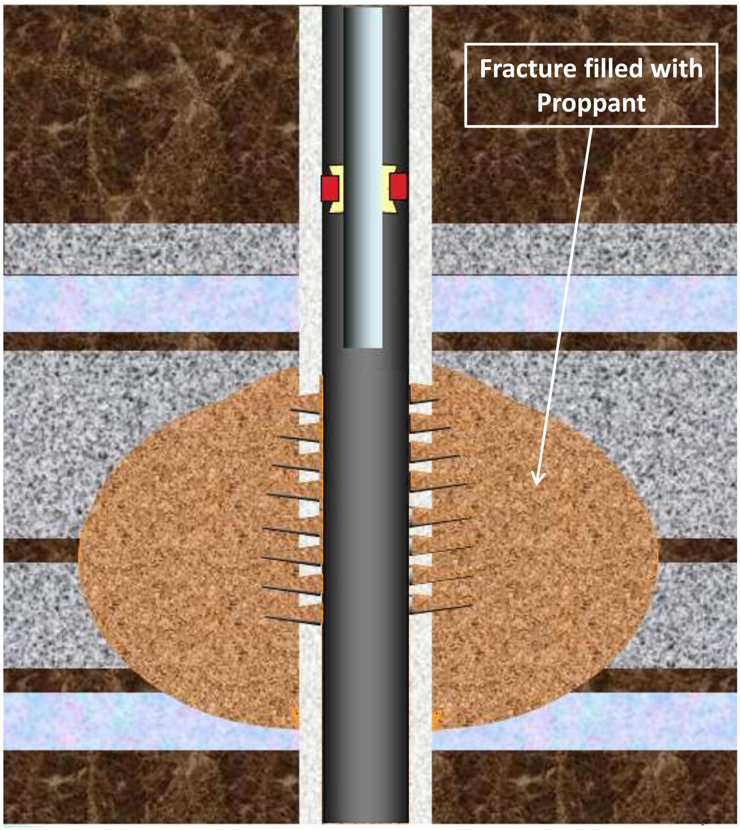


Figure 3 - Fracture filled by proppant after the end of the operation (Source: Elaborated by authors)

In the case of unconventional reservoirs, something very similar occurs. The source rock becomes the formation of interest, usually a shale rock, which is at much higher depths compared to conventional reservoirs, but also holds much more vigorous hydrocarbon accumulations. Figure 4 illustrates the comparison between the two types of reservoirs: conventional and unconventional.

Furthermore, this type of formation has very low permeabilities, in the range of micro-Darcies (µD)2. By the way, this is one of the criteria for the reservoir to be classified as unconventional (ANP, 2014)3. Due to the low permeability, this type of reservoir only becomes productive if stimulated through the Hydraulic Fracturing technique.

Usually, shale formations, due to the high pressures and hardness of the rock, also have natural fractures, but those are not interconnected for the hydrocarbon to flow. The result of Hydraulic Fracturing, in addition to the induction of new fractures, is the interconnection of these natural fractures, with consequent creation of a pathway to oil or gas.

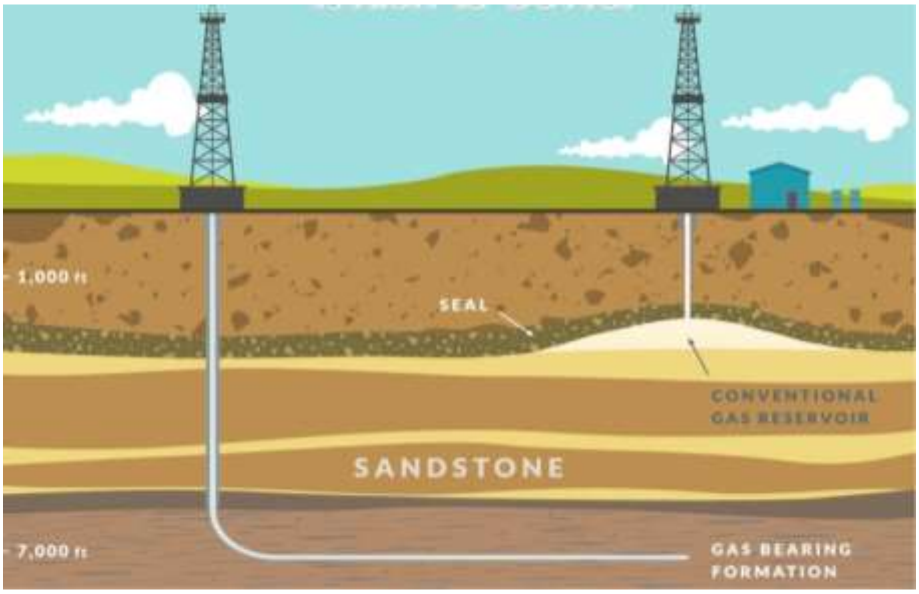


Figure 4 – Conventional vs unconventional reservoir (Source: https://www.slideshare.net/weboreit/difference-between-horizontal-directional-drilling)

## Logistics

The deeper the area of interest, obviously the more expensive the well will become. Since they are found at great depths, new techniques that brought more efficiency to the growth of unconventional fields in the United States had to be developed. Thus, horizontal drilling, combined to hydraulic fracturing and other technological innovations of perforating and completion, resulted in the Plug & Perf technique, which consists in performing a sequence of multiple fractures along a horizontal well that can reach more than 2,000 m of extension only in the horizontal section. Then, in order to further increase efficiency, two wells began to be completed at the same time: while one is being fractured, the other is being perforated and vice versa, until the entire horizontal section of the wells has been stimulated. This technique is called Zipper Frac.

2 Darcy and micro-Darcy (D and mD) are units of permeability measurement, named after Henry Darcy. Although they are not known to be official units in the International System of Units (Is), they are widely used in the oil and gas industry. Permeability measures the ability of a fluid to be transmitted through a rock (or other porous medium).

3 Resolution ANP nº 21/2014. Available at: <https://www.legisweb.com.br/legislacao/?id=269028>

That demands a great effort in terms of logistics that, if not well planned and managed, can hinder the development of unconventional resources. The logistics network for the construction of these wells is extensive and complex, especially during the hydraulic fracturing phase, involving constant and large-scale replenishment of supplies for the operation to be successful. The pad is the area that will receive all infrastructure of two or more production wells and their activities. Figure 5 compares hydraulic fracturing operations on a single, conventional well lease and a pad containing four unconventional wells.

Despite the need for a much larger area compared to conventional leases, the work is quite similar. Both require embankment around wells and opening access roads to support heavy machinery traffic (much more intense for unconventionals).


Figure 5 – Conventional vs Unconventional Fracturing (Source: Elaborated by authors)

The drilling phase changes only in terms of depth and degree of inclination. Typically, wells that reach shale layers are deeper than conventional ones that are drilled only down to sandstone or carbonate. However, the drilling rig will be basically the same as a conventional directional well.

A drilling rig with greater capacity is required as well as the volumes of drilling fluid, cement and completion fluid will be larger because of the depth. The number of casing and drill pipe sections also increases. Such modifications do not have a significant impact on logistics during the drilling phase, but rather on the completion phase, which will involve the perforating and fracturing phases at the same time, coiled tubing intervention for well conditioning and subsequent well production testing.

So, the construction of the pad occurs simultaneously to the advance of drilling. After drilling the two or four wells of the pad, the rig will be ready to be demobilized from the lease, which will receive all the equipment of the completion site. For safety reasons, mobilization of equipment for the hydraulic fracturing operation is not normally initiated meanwhile the rig is still on the pad.

Another need of unconventional wells is the construction of at least two water pits: one for water storage, base of the fracturing fluid, and another one for receiving flowback fluids after fracturing. These pits are usually excavated straight into the ground and covered by waterproof canvases which, in the water storage pit, serve to prevent loss of the resource to permeable soil and, in the one receiving the flowback fluids, to avoid contamination of the soil with chemicals and/or hydrocarbons.

Therefore, a constant and reliable water supply is crucial for the efficiency of the operation and, therefore, its economic viability. Whether this is done through water producing wells, direct connection to the distribution network or watercourses near the pad. The use of water trucks should be avoided to the maximum because, if the water supply is done exclusively in this way, the demand for water per day can reach the equivalent of up to eighty trucks. When the Zipper Frac technique (two wells being fractured at the same time) is being used, it is possible to perform up to six stages of fracturing every twenty-four hours. In addition to the high cost of these trucks, the need to maintain the access roads to the pad will be much greater as well. It is also very common for the water supply to take place in two or three different ways, being only complemented by water trucks.

Figure 6 shows part of a pad in the Desert of Saudi Arabia during the hydraulic fracturing phase. In addition to the equipment shown in the picture, it is still necessary: accommodation containers, which should include first-aid clinic and cafeteria, parking area for stand-by equipment and trucks suppliers of water and sand, Diesel supply and several other materials necessary for the operation in general.

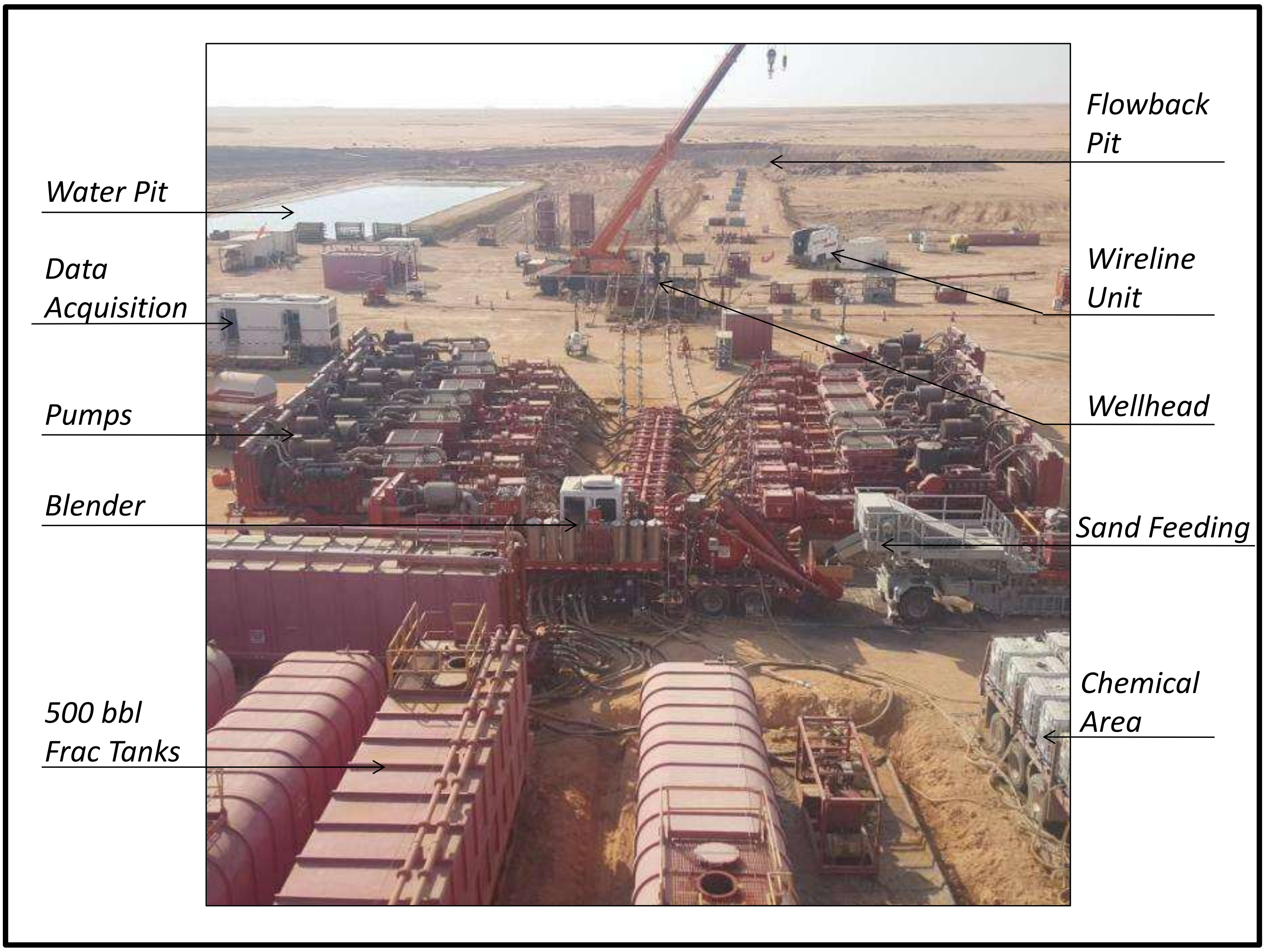


Figure 6 – Pad located in the Desert of Saudi Arabia (Source: Personal File)

After the demobilization of the drilling rig from the pad, the installation of the completion site is started. Usually, the rig will leave the well free of drilling mud, conditioned with completion brine and closed through the Christmas tree, which will later be replaced by a fracturing head (frac head). This frac head is made to withstand high pressures and flow rates (15,000 psi; 92 bpm[4]) and has multiple side inlets, where the iron lines (3-inch pipes) will be connected to. The pumps will inject fracturing fluid into the well through these lines and there is also a superior inlet through which the E-Line cable is run in hole.

4 1 bpm (barrels per minute) corresponds to 159 liters per minute.

It is via electric signal through this cable that the perforation of the zones to be fractured will be carried out. Figure 7 shows a fracturing head and its connections.

The frac head also has remotely driven hydraulic valves and manual wheel valves for opening and closing the well. These valves are not only activated regularly during plug & perf fracturing operations, but also can be required in a possible incident to seal the well in case of any unwanted flow of hydrocarbons towards the surface. Therefore, it is necessary to regularly inspect and maintain all components of the frac head, performed by accredited technicians and according to the schedule established by the manufacturer, for example every ten stages of fracturing.

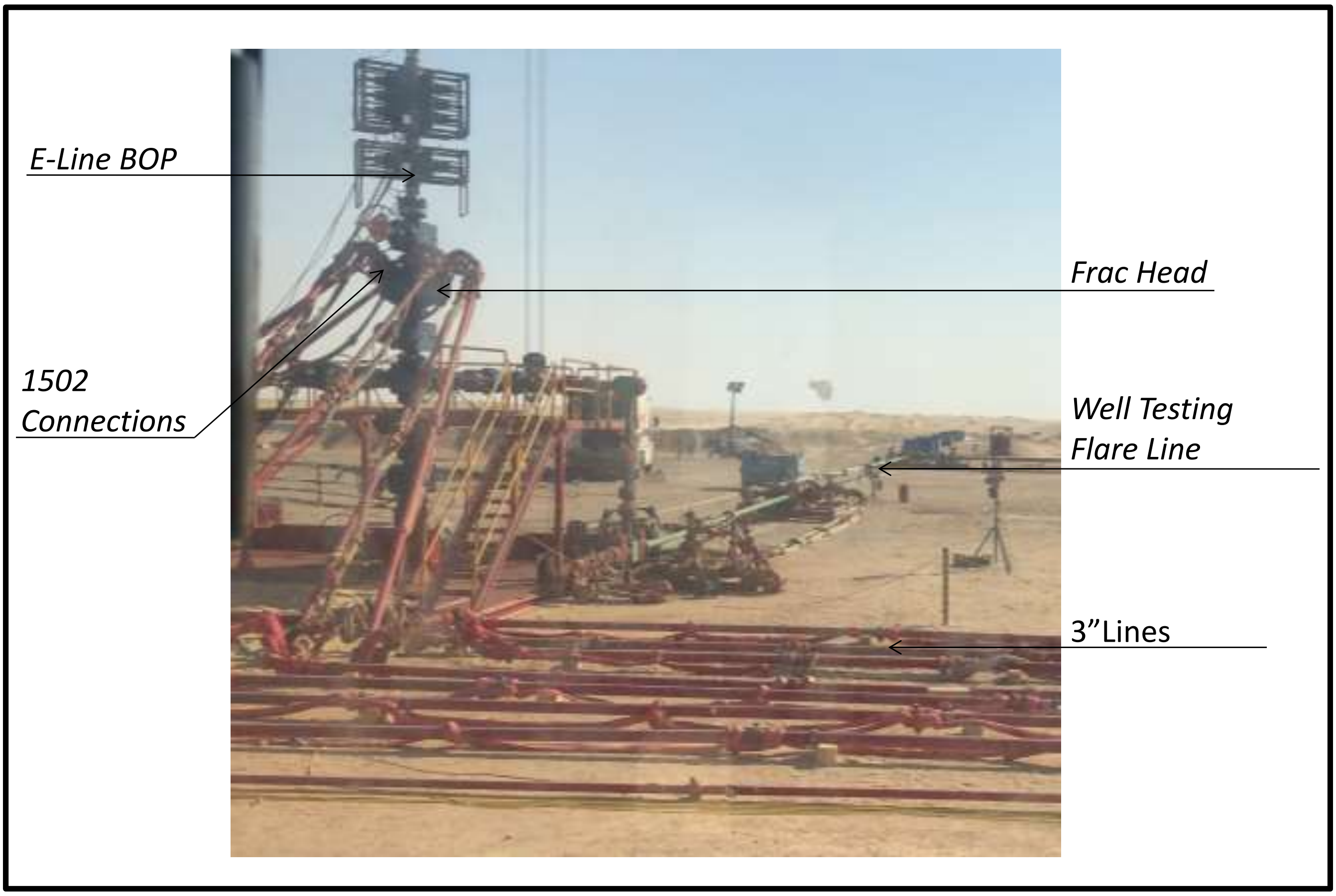


Figure 7: Frac Head (Source: Personal File)

After positioning the containers of the camp on the completion site (offices, dormitories, toilets, cafeteria and clinic), installed the frac head and pipes that will take the water from the pit to the frac tanks, begins the mobilization and rig up of heavy equipment for fracturing operations, perforating and well testing. All this machinery will be positioned according to a previously defined layout, such as this one shown in Figure 8, which is a pad containing two gas wells, where a 33-stage zipper frac was performed in each well.

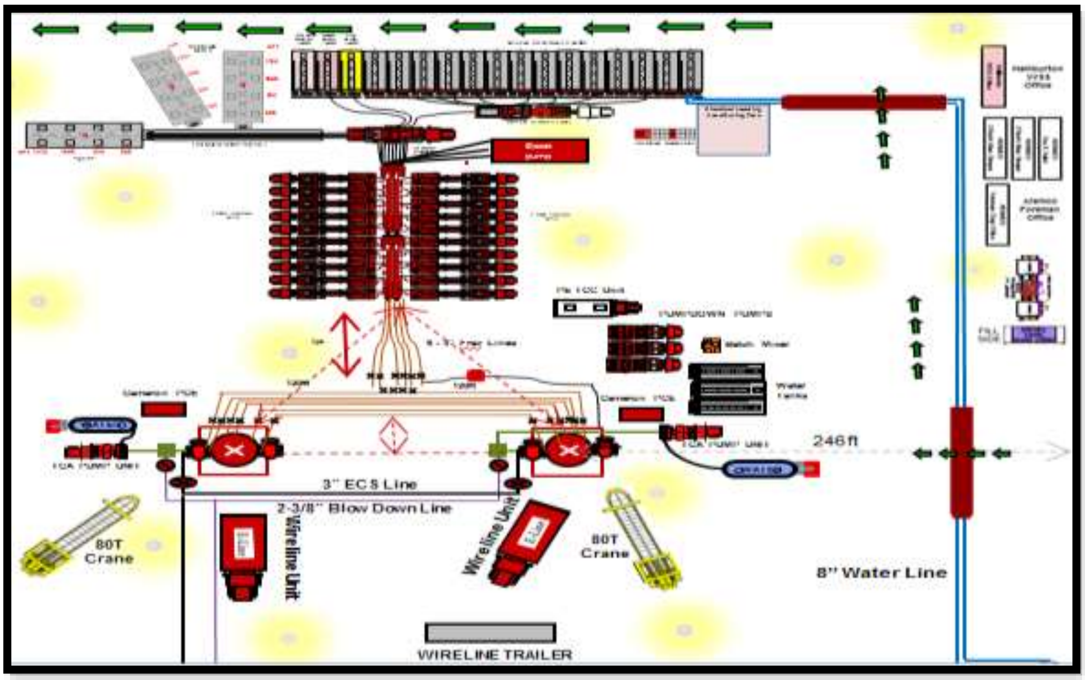


Figure 8: Zipper Frac Layout (Source: Personal File)

All this movement must be done in a safe, intelligent way and within a logical sequence, in order to minimize idle times. Simultaneous operations can and shall happen, since they compromise neither the safety of workers, nor the preservation of the environment and goods.

## Brazilian Sedimentary Basins with Potential for Shale Gas

Even with data limitation, it is well known that Brazil has a considerable volume of shale gas to be explored. However, despite this potential, to date this resource has not been explored in the country, even in the current scenario of great dependence on the import of natural gas to meet the national demand. This absence of activity is the result of Brazilian conditions, which are way different from the North American reality and end up barring the beginning of the unconventional exploration. Among them, it is possible to mention the low number of oil companies and the absence of policies to encourage the development of unconventional gas (SUÁREZ, 2016 apud FGV ENERGIA, 2021).

According to Suárez, the limited number of oil companies is the result of the restriction on exploration areas, accessed only through rounds of bids promoted by the federal government, and also of the size, market power, and monopolistic tradition of Petrobras, in addition to financing difficulties for small and medium-sized independent companies. However, today, the Petrobras' disinvestment process, the new Gas Law5 and initiatives such as the Program REATE 20206 have been helping to change this scenario, encouraging the entry of new small and medium-sized oil companies into onshore areas.

In a development perspective of unconventional resources in Brazil, the uniqueness of each basin where shale gas is found does not simply allow the replication of the same technique in other formations. That is, to achieve exploratory success, it is not only necessary to import equipment and services, but also a process of customization, aiming to adapt it to local conditions and geological knowledge that will be

5 Law number 14,134 from April 8th, 2021.

6 Revitalization of the Activity of Exploration and Production of Oil and Gas in Onshore Areas Program.

generated from the application of these techniques. These adjustments foreshadow an intense exploratory activity with longstanding utilization of services and equipment.

According to the international agencies U.S. Energy Information Administration (EIA) and World Energy Council (WEC), Brazil is the 10th country in the world ranking of the largest holders of shale gas reserves, with 245 Tcf (trillion cubic feet) (6.9 Tcm – trillion cubic meters) of gas (EIA, 2013; WEC, 2016). (TONG et al, 2018 apud FGV ENERGIA, 2021) place Brazil in 7th place in volume of recoverable unconventional oil (208.1x108 tons or 156 trillion barrels), and 72.1% of this volume corresponds to shale oil; and in 9th place in recoverable gas volume (6.5 x1012 m3 or 229.55 Tcf), 99.7% of which is shale gas.

In terms of unconventional gas, estimates from the ANP (Oil & Gas National Agency) and the EIA indicate that, together, the Parecis, Parnaíba, Recôncavo and São Francisco basins would have a shale gas volume of 533 Tcf, which would correspond to approximately 15.1 trillion $m^3$ (ANP, 2013; ARAUJO; ALAMADA; COSTA, 2016 apud FGV ENERGIA, 2021).

According to (EPE, 2019), as presented in Figure 9, there is the possibility of shale gas occurrence, mainly in the Devonian[7] Age shales of the Amazonas Basin (states of Amazonas, Pará and Amapá), Solimões Basin (State of Amazonas), Parnaíba Basin (states of Pará, Tocantins, Maranhão and Piauí) and Paraná Basin (between the states of Santa Catarina and southern Goiás), as well as in the Cretaceous[8] Age shales of the Recôncavo Basin (state of Bahia). The hatched area in the Recôncavo Basin corresponds to the portion of most generating potential.

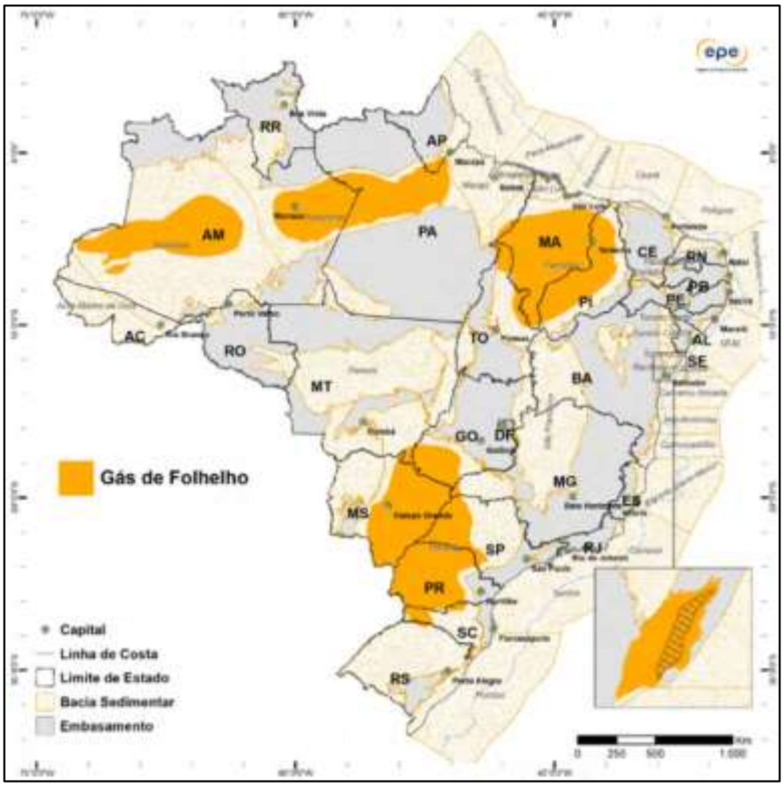


Figure 9: Estimated occurrence area of shale gas deposits in Brazilian basins. (Source: EPE)

7 The Devonian Age corresponds to the period of the Geological Time Scale that began, approximately, about 416 MY (Millions of years) and ended close to 359 MY. It corresponds to a global event characterized by the accumulation of organic matter in several sedimentary basins around the world, such as in the Appalachian Basin, through the Marcellus Formation (USA), which resulted in significant reserves of oil and gas. The Geological Time Scale, with descriptions and definitions of all ages is available at: https:\\stratigraphy.org/ICSchart/ChronostratChart2020-003.pdf

8 Within the Geological Time Scale, the Cretaceous Age is the Mesozoic Era period that is between 145 million and 66 million years old. Its name owes to limestone rocks (from greek crete = chalk = limestone) found mainly in Europe dating back to that time.

Table 1 summarizes the characteristics of Brazilian sedimentary basins with potential for unconventional gas.

| Basin | | Amazonas | Parnaíba | Solimões | Paraná | Recôncavo |
|---|---|---|---|---|---|---|
| Geographic Situation | | Onshore | Onshore | Onshore | Onshore | Onshore |
| Deposit | Lithoestratigraphic Unity | Barreirinha Formation | Pimenteiras Formation | Jandiatuba Formation | Ponta Grossa Formation | Gomo Member, Candeias Formation |
| | Chronoestratigraphic Unity | Superior Devonian | Medium Devonian | Medium-Superior Devonian | Devonian | Inferior Cretacious (Neocomian) |
| | Lithology | Shale | | | | |
| | TOC (%) | 4-6 | 2-3 | 2-4 | 1-4 | 1-2 (peak 10) |
| | Avg Depth | 2,300 | 2,500 | 3,200 | ? | 3,000 |
| | Max Thickness (m) | 350 | 400 | 420 | 600 | 400 |
| | Area ($km^2$) | 370,000 | 390,000 | 270,000 | 640,000 | 2,000 |
| Technology for Production | | Hydraulic Fracturing | | | | |

Table 1: Brazilian sedimentary basins with potential for unconventional gas (Source: FGV ENERGIA, 2021)

From the five basins with potential, Paraná has the least exploratory activity in progress and, therefore, is not justified as a good location for the debut of the unconventional exploration in the country. Amazonas and Solimões, although their conventional resources are already being successfully exploited today, these are regions with very complicated logistics, even for conventional exploitation. Larger equipment needs to be transported by helicopters and, therefore, massive hydraulic fracturing operations, so necessary for the exploration of unconventional reservoirs, become unfeasible. As for the Parnaíba basin, although it already has some onshore exploration, including gas production (conventional) and generation of thermoelectric power of the type reservoir to wire (R2W9), it could also not be the best candidate when compared to the Recôncavo basin, which has much more tradition in hydraulic fracturing operations.

At Recôncavo Basin, gas occurs in the fractured shales of Candeias Formation (Members Gomo and Tauá). These are natural fractures that improve the permeability of reservoirs, having already recorded production of almost one million barrels of oil in a fractured reservoir, in only one well, in a period of 28 years (SARZENSKI; SOUZA CRUZ, 1986 apud FGV ENERGIA, 2021). Also mentioned, fields Riacho Quiricó and Rio Una have as main reservoirs the fractured shales of the Candeias Formation (CARNEIRO, 2005 apud FGV ENERGIA, 2021). These shales have Total Organic Carbon (or Total Organic Content - TOC10) ranging from 1 to 10%, lying at depths between 3,500 and 5,500 m, and net pay thicknesses between 1,500 and 1,850 m (BONGIOLO; KALKREUTH, 2008; MATOS, 2013; MIRANDA, 2014; PESSOA, 2013 apud FGV ENERGIA, 2021). The highest levels of TOC occur in the flexural edge of the basin

9 The reservoir to wire model consists of thermal generation in the vicinity of gas producing fields on land. The energy produced is sent to the transmission network that passes nearby.

10 Oil or gas has, as its basic raw material, organic compounds derived from living beings. Since any organic compound has carbon as an essential element, one of the ways to estimate the richness of the organic content of a rock is by measuring its carbon content, commonly known as TOC (Total Organic Carbon) (MCCARTHY ET AL, 2011 apud FGV ENERGIA, 2021).

(area of greatest potential), and these levels vary according to the geometry of the rift11 (COUTINHO, 2008 apud FGV ENERGIA, 2021).

In addition to favorable geological conditions, Bahia is one of the states that most performs hydraulic fracturing jobs in Brazil, along with the state of Sergipe (Sergipe-Alagoas Basin). Therefore, the local population is used to traffic of pumps and other heavy equipment, there is already an entire infrastructure focused on conventional activity and training for the local workforce would become just a complement, which is basically the change of scale between the two types of service.

## Identification of Suppliers able to provide Services and Products aimed at the Exploitation of Unconventional Reserves

From data obtained at both the website of the Association of Independent Oil and Gas Producers (ABPIP) and the Bulletin of Petroleum and Natural Gas Production of the ANP, a survey was carried out regarding the operator companies and suppliers of products and services in Brazil that can be directly benefited by the development of shale gas exploration activity in the country. Table 2 below lists these companies and details their areas of expertise.

| Company | Category | Activity |
|---|---|---|
| **Recôncavo E&P** | E&P | Exploration & production of oil and gas |
| **Eneva** | E&P | Exploration & production of oil and gas |
| **Alvopetro** | E&P | Exploration & production of oil and gas |
| **Great Energy** | E&P | Exploration & production of oil and gas |
| **Enauta** | E&P | Exploration & production of oil and gas |
| **Karoon Energy** | E&P | Exploration & production of oil and gas |
| **Geopark** | E&P | Exploration & production of oil and gas |
| **Energizzi** | E&P | Exploration & production of oil and gas |
| **Maha Energy** | E&P | Exploration & production of oil and gas |
| **Imetame** | E&P | Exploration & production of oil and gas |
| **3R Petroleum** | E&P | Exploration & production of oil and gas |
| **Petrosynergy** | E&P | Exploration & production of oil and gas |
| **Perbras** | Service Company | Rig rental, peripherals, operation services and maintenance of onshore rigs. |
| **Braserv** | Service Company | Rig rental, peripherals, operation services and maintenance of onshore rigs. |
| **Conterp** | Service Company | Rig rental, peripherals, operation services and maintenance of onshore rigs. |
| **Great Oil** | Service Company | Rig rental, peripherals, operation services and maintenance of onshore rigs. |

11 Rift, in geology, is the designation given to the zones of the globe, where the earth's crust and associated lithosphere are suffering a fracture accompanied by a clearance in opposite directions from neighboring parts of the earth's surface.

| | | |
|---|---|---|
| **Halliburton** | Service Company | Hydrocarbon localization, geological data management, drilling, formation evaluation, well construction, completion and production optimization. |
| **Schlumberger** | Service Company | Hydrocarbon localization, geological data management, drilling, formation evaluation, well construction, completion and production optimization. |
| **Baker Hughes** | Service Company | Hydrocarbon localization, geological data management, drilling, formation evaluation, well construction, completion and production optimization. |
| **Cameron** | Product Supplier | Frac Head manufacturing |
| **Mineração Curimbaba** | Product Supplier | Proppant supply |
| **Sulatlanitca** | Product Supplier | Chemical supply |
| **Carboflex** | Product Supplier | Proppant & Chemical supply |

Table 2: Suppliers (Source: ABPIP, ANP)

Besides those listed in Table 2, the development of unconventional reservoirs would benefit many other companies that will be subcontracted by this main chain. For example, catering companies, lodging, transportation of personnel and equipment, support machinery (generators, cranes, forklifts), earthworks, road opening, functional containers, internet providers, etc.

## Risks associated with the Development of Unconventional Reservoirs

There are representatives of society who express doubts as to the safety of hydraulic fracturing operations. The casualties associated with the fracturing technique are the most diverse, the main ones being problems with water (water scarcity or contamination of water courses), induced seismic activities and greenhouse gas emission (ADGATE; GOLDSTEIN; MCKENZIE, 2014). Around the world, some incidents have been catalogued, such as the gas leak at Marcellus formation in the United States, and the tremors recorded in Lancashire, United Kingdom. By carefully analyzing such incidents, in the strict light of science, Brazil can appropriate the lessons learned, in order to prevent similar events from occurring if hydraulic fracturing of unconventional reservoirs is employed in the country.

In addition to the inherent risks to conventional exploration and, therefore, already very well-known and mapped, two major concerns stand out: seismic shocks and water contamination. However, serious studies conducted in the United States and Canada show that seismic shocks are much more related to the injection of water into disposal wells than to the hydraulic fracturing operation itself. This water to be injected may really be a result of the return of the fracturing fluid after the job (flowback), but there are also other ways to dispose of this water. Water injection is also associated with secondary recovery methods when pumping water into the reservoir in order to maintain pore pressure. As for the risks of contamination of groundwater and watercourses through the unwanted migration of hydrocarbons, these can be mitigated through a good cementing project and respecting minimum limits of vertical distance between areas to be fractured and water zones.

**Seismic Shocks**

Seismic shocks, mostly, are caused by natural causes (tectonism), but in some situations, these earthquakes can be caused by anthropic actions, such as: injection of fluids into subsurface, extraction of oil and gas, impoundment of large water bodies, geothermal projects, extraction of minerals, civil works, among others (NICHOLSON; WESSON, 1992).

In the case of oil industry, the induced earthquakes are mostly from two major classification groups (NICHOLSON; WESSON, 1992): those related to fluid injection and consequent increase in pore pressure, as in secondary or tertiary recovery methods and, more recently, to hydraulic fracturing (HEALY et al., 1968); or related to the phenomenon of subsidence, in fields where there has already been a large production of fluid (DOSER; BAKER; MASON, 1991; PENNINGTON et al., 1986). It is noteworthy that the number of earthquakes recorded and related to hydraulic fracturing has a much lower frequency when compared to the others mentioned (KIM, 2013).

Addressing earthquakes induced only by injection of fluids into the subsurface, there is an intimate relationship with the propagation of failures. During injection, occasionally the fluid introduced at high pressures migrates through the pores of the rocks, generating fractures or reactivating existing ones (BC OIL AND GAS COMMISION, 2012). In this disturbed system, there is a great increase in pore pressure that, added to in-situ stresses, can cause a slippage of the faults, generating minor earthquakes.

To illustrate the frequency and impact of an earthquake, Table 3 is presented, which exposes the magnitude of an earthquake as well as its effects and occurrence around the world (BC OIL AND GAS COMMISION, 2012). The scale used in the table is that of local magnitude (ML) or popularly known as the 'Richter Scale', which is a logarithmic scale that considers only the maximum amplitude of the earthquake, without considering which seismic waves were responsible for the shakes. It is noteworthy that the scale goes up to values of 8 or more, however, as the study objective is the earthquakes associated with fluid injection, only the lower range of values was recovered.

To better evaluate this phenomenon and its impacts, one can take as an example the United States, where the United States Geological Survey (USGS), a U.S. government agency, has, as one of its duties, to monitor earthquakes through its measurement stations and relies on extensive historical data. In Figure 10, there is a map of the United States showing seismic activities with an ML≥3 within a period of approximately 50 years. Since 2009, there is a rapid growth in the number of earthquakes in the central North American part, represented in red.

The number of earthquakes grew from an average of 24 (ML≥3) per year within the period 1973-2008, to an average of 193 from 2009 to 2014 and peaking at more than 1,000 in 2015 (RUBINSTEIN; MAHANI, 2015).

| Magnitude ($M_L$) | Description | Earthquake Effects | Natural Seismicity Occurrences Worldwide |
|---|---|---|---|
| **-3.0 to 0.5** | Micro-Seismicity | Micro events created when hydraulic fracturing breaks rock, including micro shear movement and tensile fracturing, not felt. | Very frequent. Detection reliability extremely varied. Frequency estimated at many millions of events per year. |
| **0.5 to 2.0** | Micro earthquake | Very small earthquakes, not felt. | Very frequent. Detection reliability extremely varied. Frequency estimated at many millions of events per year. |
| **2.0 to 2.9** | Minor | Generally not felt, but recorded. (Not felt in Horn River Basin) | 1,300,000 |
| **3.0 to 3.9** | Minor | Often felt, but rarely cause damage. | 130,000 |
| **4.0 to 4.9** | Light | Noticeable shaking of indoor items, rattling noises. Significant damage unlikely. | 13,000 |

Table 3: Practical information associating earthquakes, their degrees in the Richter scale, surface implications and frequency in which they occur in the world. (Source: BC OIL AND GAS COMMISION, 2012, adapted)

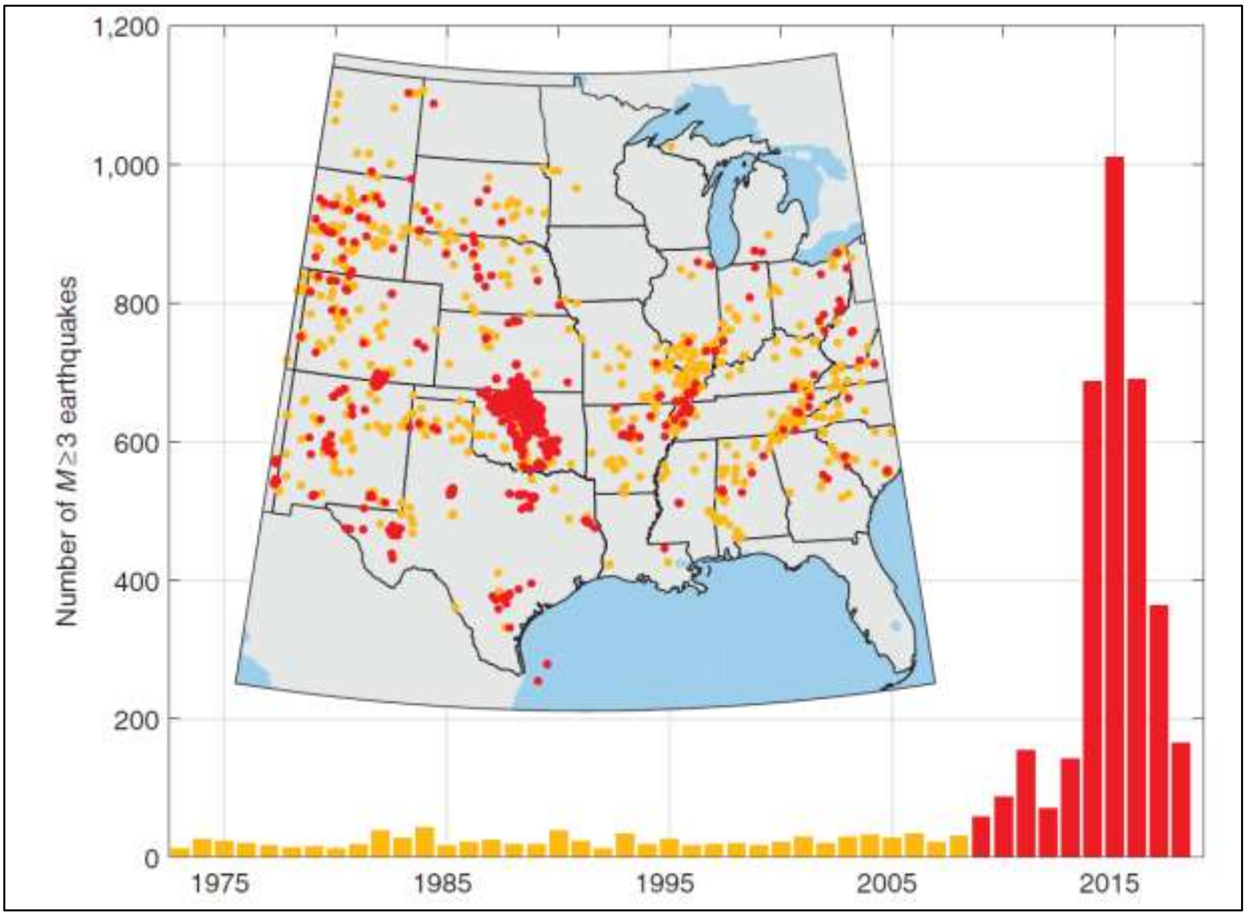


Figure 10: North American map, in cut, pointing out the number of earthquakes with M values greater than or equal to 3 (Y axis) on the Richter Scale. (Source: ZOBACK; KOHLI, 2019a)

The North American literature offers an analysis of these numbers and the exact origin of earthquakes. According to (RUBINSTEIN; MAHANI, 2015), the vast majority of earthquakes presented in Figure 9 are associated with the oil industry, but more related to the water disposal operation than to the hydraulic fracturing itself, being earthquakes associated with fracking more common in Canada.

Another commonly raised point is that much of the reinjected water comes from the hydraulic fracturing operation. According to (HORTON, 2012) and (KIM, 2013), a large volume of the reinjected water in Ohio and Arkansas is really from frac jobs, but bringing a counterpoint, (MURRAY, 2013) suggests that only 10% of the reinjected water in Oklahoma comes from fracturing operations and, from Figure 10 map, Oklahoma is the state that concentrates the majority of the recent earthquakes in the U.S. territory.

Finally, (RUBINSTEIN; MAHANI, 2015) question the statement that "if there was no hydraulic fracturing, there would be no earthquakes." According to them, this statement is not correct because, regardless of whether wells are fractured or not, water is always produced along with oil. One example that does this counterpoint well is the play of Hunton Dewatering, in central Oklahoma, which is one of the largest producers of water and recorded a large number of earthquakes, but does not use the hydraulic fracturing operation (WALSH; ZOBACK, 2015).

The following are three well-known case studies in the United States, as well as an emblematic case in Canada.

(SKOUMAL; BRUDZINSKI; CURRIE, 2015) carried out the analysis of earthquakes in Poland Township, Ohio through a numerical approach that adjusted and interpolated seismic data from the USGS (United States Geological Survey) and placed them in parallel with the geological conditions of the region to better elucidate the 3 ML earthquake that occurred. The study concluded that the fracturing operation that occurred near the city of Poland Township was probably responsible for the reactivation of an existing fault that connected to the crystalline basement, causing multiple seismic shocks, with intensity ranging from 1 to 3 ML, during the frac job period (eight days).

A second work carried out by (FRIBERG; BESANA-OSTMAN; DRICKER, 2014), analyzes shakings that occurred in Harrison County, Ohio, from September to December 2013. Through a parallel between seismic data from the USGS and wells (obtained through the Ohio Department of Natural Resources, ODNR), it can be seen 3 wells that went through the fracturing process and were directly related to earthquakes. This statement was made based on the convergence between information of the propagation directions of seismic waves with the information of the well and the frac job (depth, length of the horizontal section, exact time of the frac job, among others).

The fracturing operations occurred from September to October 2013, and seismic shocks were captured approximately 26 hours after one of the operations. The interesting point about these events is that, just like Skornal's study, Friberg's study pointed out a connectivity between induced fractures and the crystalline basement below the horizontal section of the well.

Finally, the work of (HOLLAND, 2013) analyzes a sequence of 116 small earthquakes within the period from January 16 to 22, 2011 in the Eola-Robberson field in the south-central part of Oklahoma, the most affected state by earthquakes according to Figure 10. According to the author's analysis, probably 14 fractured wells were responsible for the earthquakes, which ranged from 0.5 to 2.9 ML. The study points out that none of the previous earthquakes had directions or wave frequencies like those that occurred after fracturing operations, indicating that they were induced.

In a similar way to the study by (FRIBERG et al, 2014), the first earthquake occurred approximately 24 hours after the first frac stage began. Another interesting point is that due to poor weather conditions, some frac stages were delayed by more than two days, and this delay caused the earthquakes to have similar correlations of time between them. In this study there is no mention of fault mapping or reactivation. The author himself mentions that this type of occurrence is extremely rare, since in Oklahoma there were more than 100,000 wells in which hydraulic fracturing was performed and, until 2013, only three scientific studies were catalogued associating the occurrence of earthquakes with the fracturing operation, and even if there were more events, the total percentage would be very small.

An important addition to Holland's studies, (WALSH; ZOBACK, 2016) state that, in fact, fracturing operations in Oklahoma wells did not have a crucial participation in the total U.S. earthquakes. In their studies, six regions were mapped in the north-central part of Oklahoma, and it was identified that the number of wells where there was hydraulic fracturing or improved oil recovery (EOR) was minimal, and studies indicate that water injection is the most likely cause. Being more specific, the injection of large quantities between the reservoir and the crystalline basement (Arbuckle formation), according to Figure 11.

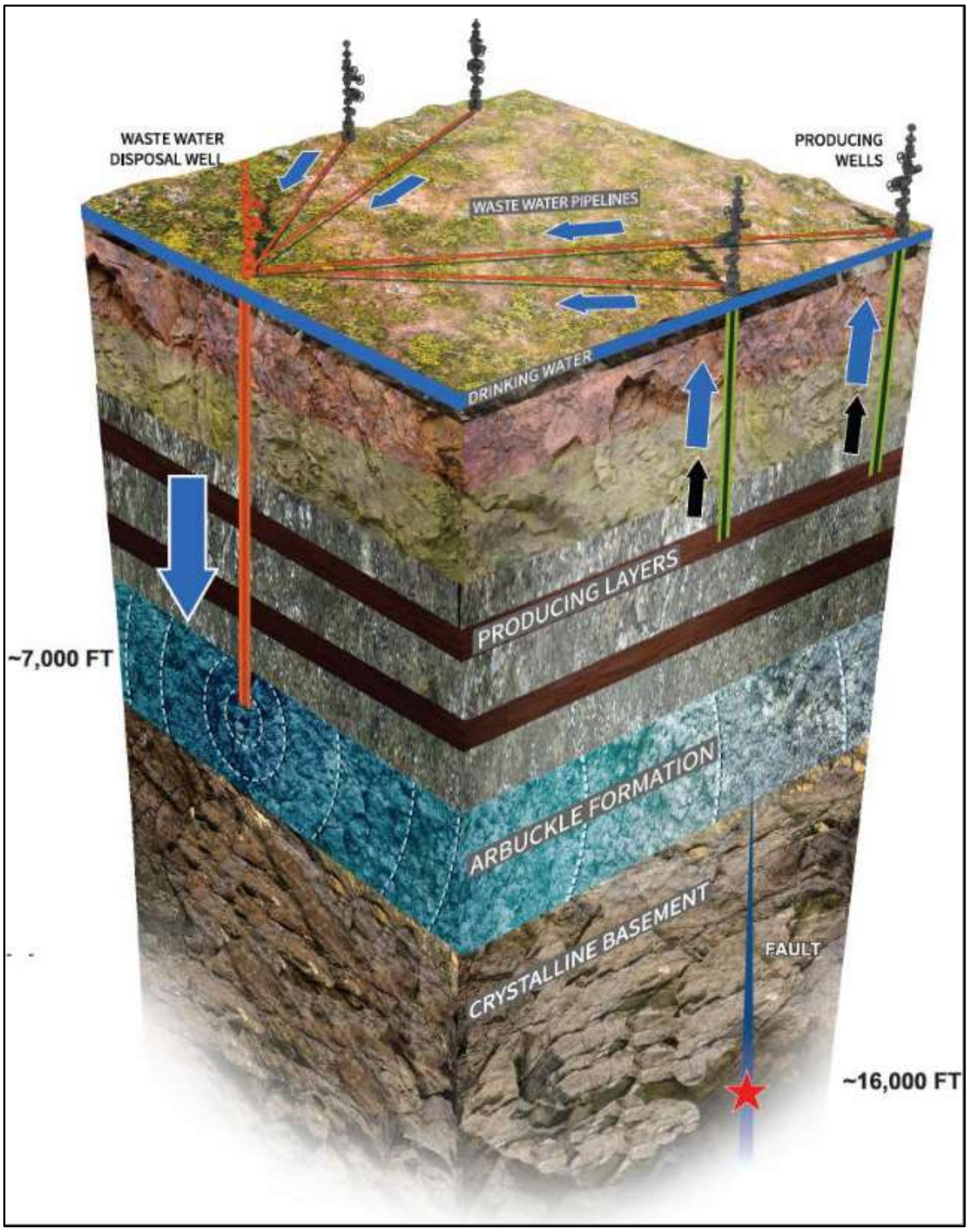


Figure 11: Illustration of the iteration between the injection of the frac fluid and the reactivation of a fault that is in contact with the crystalline basement. (Source: ZOBACK; DOUGLAS J. ARENT, 2016)

In Canadian territory, (ATKINSON et al., 2016) examines whether there is a relationship between oil and gas activities in the western part of the Canadian basin (Western Canada Sedimentary Basin, WCSB) and seismic activities in nearby areas, from 1985 to 2015. Atkinson reaffirms the position of (RUBINSTEIN; MAHANI, 2015) that earthquakes can be caused by injection of waste water as well as by fracturing.

Another point where a parallel can be drawn is that, even though Canada has proportionally more earthquakes per number of wells than the United States, this number is still low, according to Table 4 (BAO; EATON, 2016; RUBINSTEIN; MAHANI, 2015). Thus, the same North American trend is repeated in Canada: injection wells continue to be the major causes of earthquakes in historical sequences, as can be analyzed through Figures 12 and 13.

(ATKINSON et al, 2016) states that, in fact, fracking has contributed to this increase in the total number of earthquakes with ML≥3, especially in the period 2010-2015, as can be seen on Figure 12 (big slope increases in the cumulative earthquake number curve) and Figure 13, which shows a more linear trend. The counterpoint offered by the author is that, even though the number of associated earthquakes is higher, there are more than 12,000 wells where there was a frac job, corresponding to a total of only 0.3% of wells with associated earthquakes, as shown in Table 4.

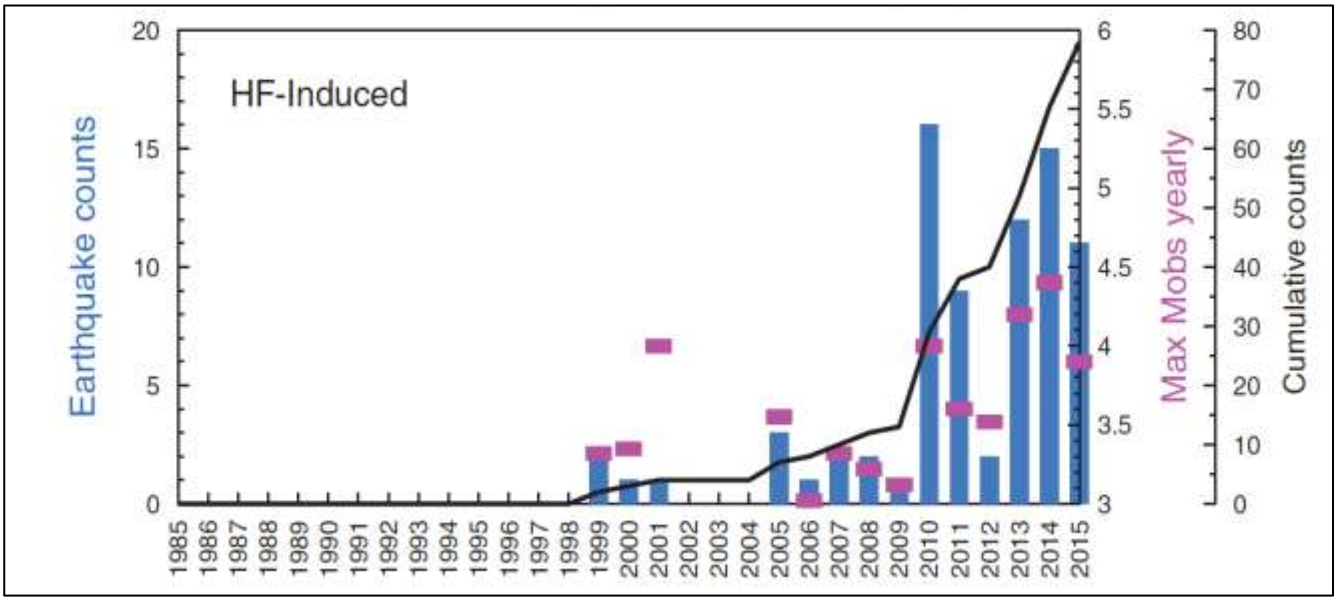


Figure 12: Graph of the amount of cumulative earthquakes (1985-2015) with ML≥3 values in WCSB to wells associated with hydraulic fracturing. (Source: ATKINSON et al., 2016)

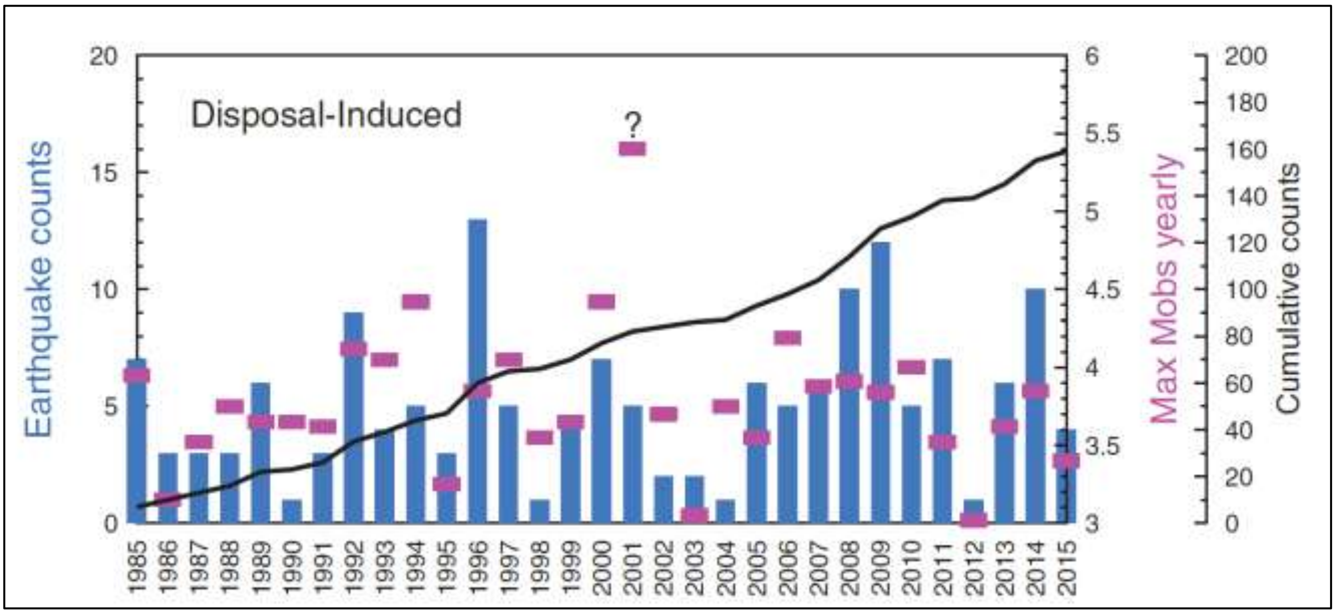


Figure 13: Graph of the amount of cumulative earthquakes (1985-2015) with ML≥3 values in WCSB to wells associated with water disposal. (Source: ATKINSON et al., 2016)

Once understood how earthquakes and induced fractures can occur, risk management will be explored, as well as response strategies in case of an uncontrolled event. The way to deal with a negative event associated with hydraulic fracturing will be through anticipation, risk assessment and monitoring before, during and after the fracturing operation.

| | Water Disposal induced | HF induced | Tectonic ($M_L \geq 3$) |
|---|---|---|---|
| **Number of candidate wells** | 1236 | 12.289 | - |
| **Number of wells associated with $M_L \geq 3$** | 17 | 39 | - |
| **Association % for wells ($M_L \geq 3$)** | ~1% | ~0,3% | - |
| **Number of $M_L \geq 3$ (1985 to 2009)** | 126* | 13* | 14 |
| **Number of $M_L \geq 3$ (2010 to 2015)** | 33* | 65* | 7 |
| **Association % for $M_L \geq 3$ (2010-2015)** | 31% | 62% | 7% |
| **These totals each include 18 events for which both disposal and HF wells could be associated, 8 of which occurred from 2010 to 2015; in assessing % association rates, each such event has been counted as ½.** | | | |

Table 4 – Summary of seismicity associated with wells in the WCSB. (Adapted from ATKINSON et al., 2016)

A possible way to anticipate an earthquake may be the application of mathematical models in order to simulate how the reservoir and adjacent areas would behave when subjected to stresses caused by fracturing.

Regarding the reactivation of existing failures, (ZOBACK; KOHLI, 2019b) state that the Mohr-Coulomb theory can be applied to fault modeling. This theory consists of a mathematical model that can describe how materials respond to shear and normal forces. Thus, if the geometry of the failure (strike and dip) is known, its orientation and depth, as well as the orientation and magnitude of the three main stresses at a given depth and finally, the variation of pore pressure in situ caused by fluid injection, it is possible to know whether a fault will potentially be activated or not (ZOBACK; KOHLI, 2019b). To better elucidate this issue, (LUND SNEE; ZOBACK, 2016) conducted an analysis of four sites where there were earthquakes in Texas, applied the Mohr-Coulomb theory and were able to prove that three of the four sites were actually under the imminence of earthquakes with minor changes in pore pressure. Thus, showing that some reactivations of failures can be anticipated if the parameters mentioned above are known.

However, all data for direct application of Mohr-Coulomb theory is not always available. In this unfavorable situation, it is necessary to apply different simulations to predict damage and, in this scenario, scientific research through probabilistic models in conjunction with geomechanical models should be widely used to better understand the problem.

In fact, there is an example of available software to calculate the probability of a failure exceeding the Mohr-Coulomb criterion by fluid injection. It is the Fault Slip Potential (FPS), developed by (WALSH et al., 2017) from Stanford University. Many other probabilistic methods and experiments with testimonies have already been carried out to try to replicate these situations at subsurface. It is only worth mentioning that the software ignores the poroelasticity property, as it is extremely difficult to know the distribution of pore pressure within a failed and fractured basement. For this and other reasons, it is not easy to apply the theory of poroelasticity in practice.

During the fracturing operation, mapping the spread of faults is important, and microseismic monitoring is one of the most successful used methods.

Microseismic monitoring consists in arranging receptors in strategic positions, which will be able to better obtain data regarding small shocks (microearthquakes) induced by some process associated with the well. In the case of hydraulic fracturing, the most common is that the receivers are placed in a well within the vicinity where the fracturing operation will be performed, as well as at a relatively close depth. The receptors detect the seismic energy generated by the microseism through geophones or three-component accelerometers, generating a three-dimensional image. Algorithms are then processed to locate the "event", using a variety of information obtained by the arrivals of compressional waves (P waves) and shear waves (S waves) (WARPINSKI, 2009).

Microseismic provides the means to monitor the spread of fractures during the frac job, enabling operators to react in real time to avoid risks such as reactivation of large failures. Another positive point of monitoring is the ability to perform design changes as a function of the results of each stage of fracturing. The distance between intervals to be fractured can be changed or even the number of intervals or sections that require fracturing (GILLELAND, 2015).

**Problems in Cementing and Relation with Fluid Migration**

Before addressing the problems associated with casing and cementing in hydraulic fracturing jobs, it is interesting to mention a study dealing with wells in conventional reservoirs that demonstrates a very small number of casualties when compared to the number of drilled wells.

For such analysis, (KING; KING, 2013) carried out a great work, which aimed to show the environmental risks associated with the construction of wells. The point of the work that matters most to us is the analysis of data regarding well failures in the North American states of Ohio and Texas. Among these failures, problems were listed in the following stages of the life of the well: drilling and completion (D&C), operations that include cementing and casing; operations related to production; orphan wells, related to poor maintenance; disposal of water; and finally, plug & abandonment (P&A).

(KING; KING, 2013) used data from the Ground Water Protection Council as their source. The period analyzed was from 1983-2007 (25 years) for Ohio and from 1993 to 2008 for Texas (16 years). Unfortunately, the upper limit of time has not considered the rapid growth of earthquakes that occurred after 2009 as it was studied by (ZOBACK; KOHLI, 2019a), not directly reflecting the frac boom in the United States. Nevertheless, the study is valuable in understanding how low the risks within the oil industry are if projects are well executed. In Table 5, it is possible to see that there is a proportion between the total producing wells with their respective investigated accidents. For both Ohio and Texas, this ratio is less than 1%.

| State | Ohio | Texas |
|---|---|---|
| **Studied Period (years)** | 26 | 16 |
| **Number of Producer Wells** | 65.000 | 250.000 |
| **Number of Investigated Cases** | 185 | 211 |
| **Related to Location** | 0 | 0 |
| **Related to D&C** | 74 | 10 |
| **Related to Fracturing** | 0 | 0 |
| **Related to Production Period** | 39 | 56 |
| **Related to Abandoned Wells** | 41 | 30 |
| **Related to Disposal Wells** | 26 | 75 |
| **Related to P&A** | 5 | 1 |
| **Non-identified causes** | 0 | 39 |

Table 5: Adaptation of the synthesis for the research data where (KING; KING, 2013) detail the statistics regarding cases of identified and investigated incidents.

Another interesting analysis refers to the number of failures associated with casing and cement in the state of Pennsylvania, in the United States, within the period from 2000 to 2012. (INGRAFFE et al., 2014) conducted research to better understand the relationship between the development of unconventional in Pennsylvania and failures in well integrity, especially regarding cement and casing. (INGRAFFE et al., 2014) do not rule out the possibility of aquifer contamination associated with integrity problems, however, point out that there is no consistent data relation on well integrity, since many structural integrity reports are confidential, which made difficult the data collection.

The latest case study that stands out is the one conducted by the China National Petroleum Corporation (CNPC) Research Institute. The research center sought to model and conduct experiments to better understand the problems faced in CNPC's unconventional well cementing operations in the Sichuan basin, China (YUAN et al., 2016).

The problems reported for cementing were fundamentally three: the horizontal sections were too long (1.5 to 2.0 km) and casing centralization became very difficult, increasing the number of sections with poor cement bonding; extensive use of oil base fluids for drilling deep wells, once this type of fluid has great capacity to adhere to the walls of the open hole, making it difficult to condition the well for the cementing operation; and finally, the difficulty of finding a cement formulation that were able to withstand the sudden changes in temperature and pressure resulting from fracturing.

To outline the described problems, some methodologies were adopted. The first one was to perform a numerical modeling to better understand the behavior of cement during the fracturing process. This method indicated that if there is a reduction of the Young’s modulus (modulus of elasticity), an increase in compressive force under cement or increased bonding strength, the greater the chances of the cement to maintain its integrity and prevent the development of preferential paths for the produced fluids (micro annulus).

The second methodology performed by the laboratory was the formulation of pre-flush fluids (injected after running casing in hole in order to condition the well for the cementing job). Several formulations of pre-flush fluids were analyzed, having as parameters of analysis the density, Young's modulus, wettability, fluid loss to the formation, additives, among others. These analyses are important in defining the situation where each of the formulations will have best efficiency. Finally, best operation practices in the field are mentioned, such as the use of centralizers; if possible, drill using water-based fluids to maintain the casing integrity of the previous section and therefore the cement, among other measures.

To finish the study, the lab tested cement formulations were applied in twelve wells in the Weiyuan block, in the Sichuan basin. The cement quality along the horizontal sections averaged 92%, according to Table 6 below.

| S/N | Well No. | TD/m | Length of horizontal section/m | Density of drilling fluids/(g $cm^{-3}$) | Density of cement slurry/(g $cm^{-3}$) | | Rate of high-quality cementing in horizontal section |
|---|---|---|---|---|---|---|---|
| | | | | | Lead slurry | Tail slurry | |
| 1 | Wei 202H2-1 | 4370 | 1240 | 2.08 | 2.15 | 1.92 | 100.00% |
| 2 | Wei 202H2-2 | 4580 | 1480 | 2.10 | 2.15 | 1.92 | 98.66% |
| 3 | Wei 202H2-3 | 4693 | 1300 | 2.07 | 2.15 | 1.92 | 99.92% |
| 4 | Wei 202H2-4 | 4890 | 1600 | 2.12 | 2.20 | 1.92 | 91.26% |
| 5 | Wei 202H2-5 | 4835 | 1600 | 2.08 | 2.15 | 1.92 | 93.78% |
| 6 | Wei 202H2-6 | 4760 | 1500 | 2.08 | 2.15 | 1.92 | 91.73% |
| 7 | Wei 204H2-3 | 5585 | 1404 | 2.21 | 2.30 | 1.92 | 100.00% |
| 8 | Wei 204H2-6 | 5230 | 1460 | 2.20 | 2.29 | 1.92 | 74.40% |
| 9 | Wei 204H3-1 | 5355 | 1500 | 2.19 | 2.30 | 1.92 | 88.04% |
| 10 | Wei 204H3-3 | 5282 | 1500 | 2.20 | 2.30 | 1.92 | 69.70% |
| 11 | Wei 204H3-4 | 5315 | 1430 | 2.20 | 2.30 | 1.92 | 99.55% |
| 12 | Wei 204H3-6 | 5156 | 1149 | 2.25 | 2.30 | 1.92 | 97.70% |

Table 6: Summary of cementing data for the 12 wells analyzed in the Sichuan basin.

As mentioned above, the adoption of good practices that are already extensively known to the industry, along with the prediction of cement behavior after the fracturing operation, via numerical and experimental simulations, proved to be feasible in order to obtain better results.

Another good practice that must be adopted after any cementing job is to run an acoustic logging tool called CBL (Cement Bond Logging), which will show whether the cementing job was successful or not. This type of logging tool uses acoustic waves to attest bonding between cement vs casing and cement vs open hole.

Besides good practices regarding cementing, it is worth mentioning that a minimum vertical distance limit should be established between zones to be fractured and aquifers. This limit aims to prevent the fracture from growing in height up to the point of reaching the water zone, contaminating it. A reasonable distance would be around a thousand meters. As much as the fracture grows on the vertical axis, it is not reasonable to exceed 1,000 meters high.

## Conclusion

The hydraulic fracturing technique has been successfully applied in Brazil for more than six decades in conventional reservoirs. That doesn't mean there will be no challenges in the implementation of operations in unconventional reservoirs. Logistics is complex and, if not well managed, can make projects unfeasible.

Although Brazil has five basins with potential for shale gas exploration, Recôncavo Basin can be considered as the one that meets the most favorable conditions to be a candidate for the beginning of the development of unconventional reservoirs in the country. The existing infrastructure, the presence of operators, service providers and the skilled workforce position this region very well to host the construction of the transparent well and the probable subsequent projects.

Brazil has prepared companies, with very well-defined processes and already successfully implemented in countries such as the United States, Canada, Argentina, Saudi Arabia among others. Technically wise there should be no difficulties that could make the development of unconventional reservoirs unviable.

Dialogue with society is necessary and clarification regarding the advantages and disadvantages should be as clear as possible. The activity, if well planned and executed, can be an excellent motor for generating jobs and improving the life quality of local communities. However, there are risks that, if not well managed, may lead to serious consequences.

Seismic shocks and contamination of water resources are among the biggest concerns of the public in general. However, studies suggest that most cases where there were problems of both types, their causes are not directly associated with the hydraulic fracturing operation itself.

Finally, gas is the cleanest fossil fuel and energy transition process necessarily goes through it. Gas from unconventional reservoirs can bring the energy security needed for the country to focus its efforts on the development of renewable energy in the long term.

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