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Analysis and Numerical Modelling of Pressure Drops Observed During Hydraulic Stimulation of GRT-1 Geothermal Well (Rittershoffen, France)

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ABSTRACT

Enhanced Geothermal Systems (EGS) are a promising source of geothermal energy. Nevertheless, induced seismicity associated with EGS projects is a major challenge for the large scale development of the technology, and thus many efforts are made to mitigate it. The accuracy with which the 2013 GRT1 Rittershoffen geothermal well stimulation was monitored offered new perspectives with the recording of a rarely observed phenomenon: injection pressure drops that seemed to be linked with the triggering of induced earthquakes. Here we propose to investigate this phenomenon and to characterize the relationship between pressure drops and seismicity. To do so, we analyzed the drop data recorded during the stimulation and made some early observations. We then used a numerical simulator called CFRAC to test the hypotheses developed from the initial analysis of the data. Firstly, we showed that it is difficult to link an earthquake to a specific pressure drop, thus contradicting a possible causality relationship between the seismicity and the drops. We also showed that the drops share a characteristic shape, which is an abrupt pressure loss followed by a more progressive increase of the pressure to a level lower than the triggering pressure. We noticed that most of the pressure drops are followed (after tens of seconds to a few minutes) by a small burst of seismic activity. These observations led us to a new hypothesis in which the drops are the origin of the seismicity, or at least part of it, and that they are the result of the opening of mode I wing cracks near the tips of the natural fractures in the reservoir. This hypothesis was tested using CFRAC. The simulations suggested that the drop signal is attenuated over very short distances and thus a highly transmissive fracture in the reservoir is necessary to convey the drop signal from the stimulated zone to the well. It also appeared that the drops are caused by the opening of the tensile fractures rather than by the equilibration of dry newly connected fractures, as we first thought. A high (10 MPa) matrix tensile strength is necessary to cause pressure drops during a stimulation. In the end, we cannot confirm that this is the origin for the drops, but our study shed light on phenomena that may be involved in the processes behind induced seismicity.

1. INTRODUCTION

Induced microseismicity can occur during reservoir development or operation of Enhanced Geothermal Systems (EGS). In fact, this type of reservoir is characterized by low matrix permeability, which implies that it is often necessary to stimulate the reservoir in order to reach good productivity indexes. In our case study located in the Upper Rhine Graben, we assumed that we reactivated natural fractures by hydroshearing, improving the connection between the well and the fractured reservoir. The stimulation techniques usually involve high pressure water injection into the wells, which can create induced seismicity. The induced earthquakes can sometimes reach magnitudes that can be felt by the local population. This kind of situation can even lead to the termination of a project due to social acceptance issues (e.g Basel). As a result, limiting induced seismicity is critical for large scale geothermal development. Understanding all the processes that generate induced seismicity is very important to be able to mitigate or even totally inhibit the phenomenon.

ECOGI is the first industrial deep geothermal project in France aiming to produce overheated water from the natural geothermal resource embedded at the interface between the Triassic sedimentary layers and the top crystalline fractured basement of the Upper Rhine Graben (Baujard et al., 2015) using an Enhanced Geothermal System.

During the stimulation of the GRT1 well of the Rittershoffen geothermal power plant, important data were gathered. In addition to seismic catalogues recorded by a very dense seismometer network, the injection data were accurately recorded (pressure, flow rate etc.). It allowed observation of a previously undocumented phenomenon, a series of pressure drops apparently linked to the seismicity. These drops could shed a new light upon induced seismicity, granting us access to a better understanding of its key processes. In this paper, we will try to clarify and understand what generates the observed drops and how they are linked to the seismicity.

The study will be based on both the hydraulic and the seismological data recorded during the well stimulation. Three seismological catalogues are available, each with their own advantages and disadvantages. By combining the three catalogues we will have a complete overview of the seismicity during the GRT1 stimulation which in turn will be compared to and coupled with the hydraulic data. Numerical modelling will also be conducted to fully investigate the drop phenomenon.

2. DATASET OVERVIEW

The work of this paper is based on the data acquired during the stimulation of GRT1, the first well of the geothermal doublet drilled in a deep-seated fractured granite reservoir in Rittershoffen. This stimulation was performed on June 27th 2013 around 11h20 GMT+2 and lasted 22h during which over 4000 m^3 of brine were injected. A detailed overview of the project, the well completion, geological profiles, as well as an extended description of the stimulation results can be found in Baujard et al., (2017).

2.1 Hydraulic data

The bottom hole pressure data were recorded using two different sensors. The first sensor was a wireline pressure gauge that records and sends the data in real time every two seconds. The second sensor was a memory gauge that records every five seconds. Both sensors were located at 1922-meter depth in GRT1. The sampling rate is the only difference between the data collected with these two sensors (Figure 1), therefore the work in this paper is based on the wireline data.

Two pumps were used during the hydraulic stimulation. The flow rates of the pumps were measured and recorded at one second intervals. The injection started on June 27th at 11h18 and 35s GMT +2. The flow rate was increased in steps. Each flow rate step lasted 2h except for the 40 l/s step, which lasted four hours. Seismicity began to occur during the 40 l/s step, and so further increase of injection rate was delayed to enable additional monitoring of the microseismicity before continuing. The pressure decrease was performed in steps in an attempt to mitigate the seismicity; it has been found that an abrupt shut in could increase the seismic activity in the reservoir. Previously, low-rate injections (up to 30 l/s) had been performed in April 2013, and micro-seismicity was induced during these injections (Maurer et al., 2015).

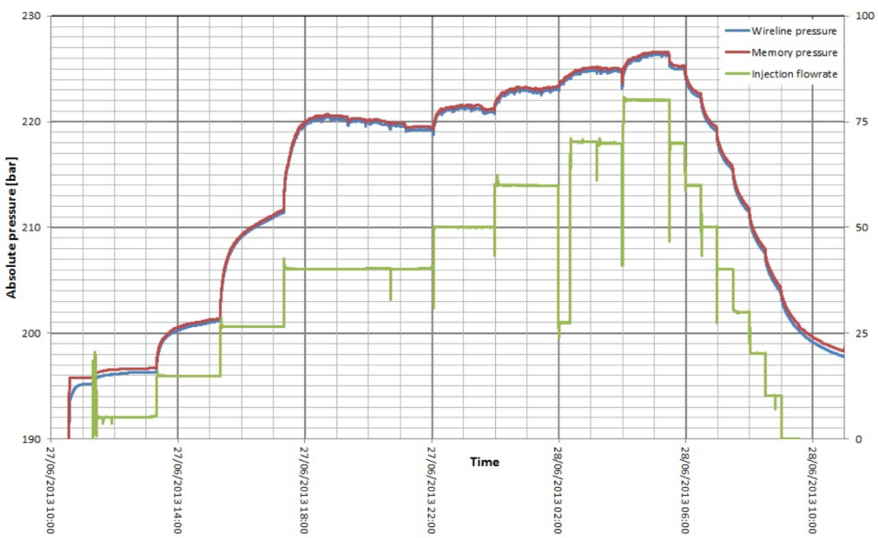

Figure 1: The pressure data recorded by the wireline sensor (blue) and memory (red). As they are very similar the catalogue with the smallest time step has been chosen (Baujard et al., 2017).

2.2 Seismological data

The seismicity during GRT1 stimulation was methodically and accurately recorded. A network of 16 seismometers was deployed during the stimulation, in addition to the 12 already present around the wells in Rittershoffen and Soultz-Sous-Forêts. The data we used during this work come from three different catalogues:

Automatic Real Time catalogue (ART): These data were acquired with the automatic detection server SeisComp3 that was implemented during the operations. During the stimulation, the seismicity was monitored in real time and the data sent to the EOST (School and Observatory of Earth Sciences in Strasbourg, France) where they were localized with a 1D velocity model of Soultz-sous-Forêts (10km away from Rittershoffen). It contains 174 events distributed all along the stimulation and after shut in. More detail on the seismic monitoring of Rittershoffen is provided by Maurer et al. (2015).

Manually Picked catalogue (MP): Even though the automatic detection was accurate, a later study showed that only 1 induced earthquake out of ten was actually being detected by SeisComp3. Hence it has been decided to manually pick all the missing earthquakes from the raw data. This picking was done by seismologists working in deep geothermal energy experts in seismology (Maurer et al., 2016). The result is a very dense catalogue (more than 1000 earthquakes) but limited to the first 10 hours of stimulation. The newly picked events were localized with a new velocity model created for Rittershoffen.

Double Difference Relocation catalogue (DDR): The third available data catalogue contains 1393 events picked by correlation and relocalized. A relative moment was also available for every earthquake in it (Lengliné et al., 2016). The catalogues characteristics and differences are presented Table1 and Figure 2

Table 1: Characteristics of the seismological catalogues used.

Catalogue	Number of events	Time of first event GMT	time of last event GMT	Magnitude type	Remarks
ART	174	27/06/2013 14:45	04/07/2013 17:31	Mlv	
MP	1009	27/06/2013 15:25	04/07/2013 17:31	Md	only from 27/06/2013 14:45 to 27/06/2013 20:11
DDR	1393	27/06/2013 15:25	02/07/2013 21:15	Relative momentum	only from 27/06/2013 15:00 to 28/06/2013 02:00

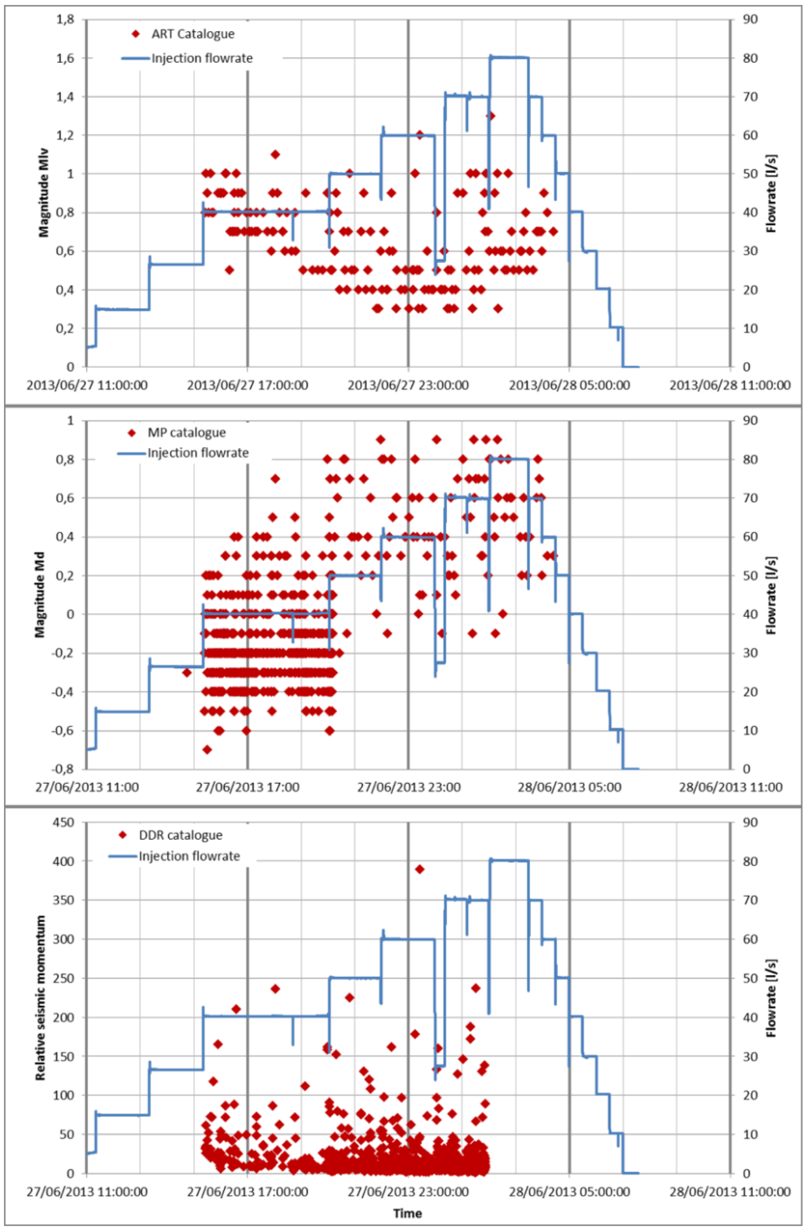

Figure 2: Comparison between the three seismological catalogues. On the top graph is the ART catalogue, in the middle is MP catalogue and in the bottom, the DDR catalogue. We can see that seismicity only starts during the 30 to 40 l/s flow rate step. This is an example of the Kaiser effect, in fact, GRT1 had been stimulated before the June hydraulic stimulation, and seismicity was triggered only when the pressure level previously experienced by the well was reached. The three catalogues are very different due to the difference in the way the data have been treated hence combining them is necessary to have the best apprehension of the seismicity in Rittershoffen possible.

3. DATA ANALYSIS

3.1 The pressure drops

Pressure drops are apparent in the GRT1 stimulation data, characterized by a very brief pressure draw-down (1-2 seconds) followed by a slow pressure increase to a level almost always lower than the initial pressure. Many drops also seem to be coupled with a short burst of seismicity that happens a few seconds to a minute after the initial drop. When it is possible to locate them, these events are all very close to the well and tend to align along linear structures. A typical drop is shown in Figure 3.

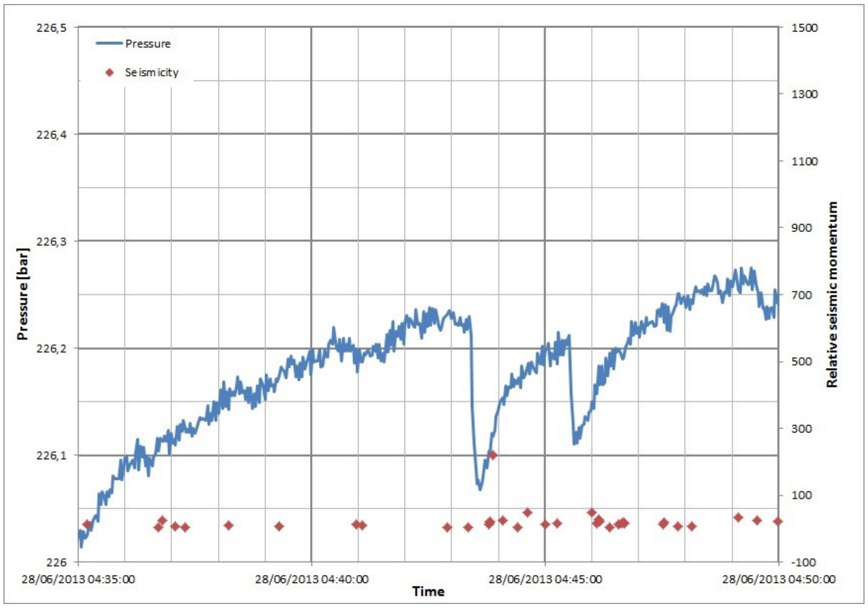

Figure 3 Two examples of pressure drops and their associated burst of seismicity at Rittershoffen.

3.2 Drop catalogue

In this section, we present the pressure drop data set. The drop catalogue contains 137 pressure drops with amplitudes ranging from 0.03 bar to more than 1.6 bar (**Figure 4** and **Figure 5**).

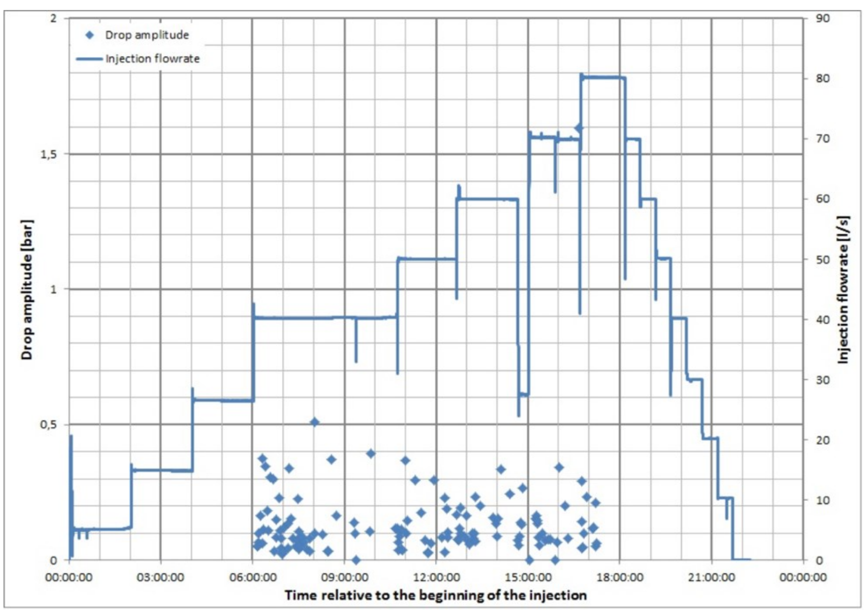

Figure 4: The drops' position during the GRT1 stimulation. We can also see that, like the seismicity, they start at the beginning of the 40l/s flow rate step and stop when the flow rate starts decreasing.

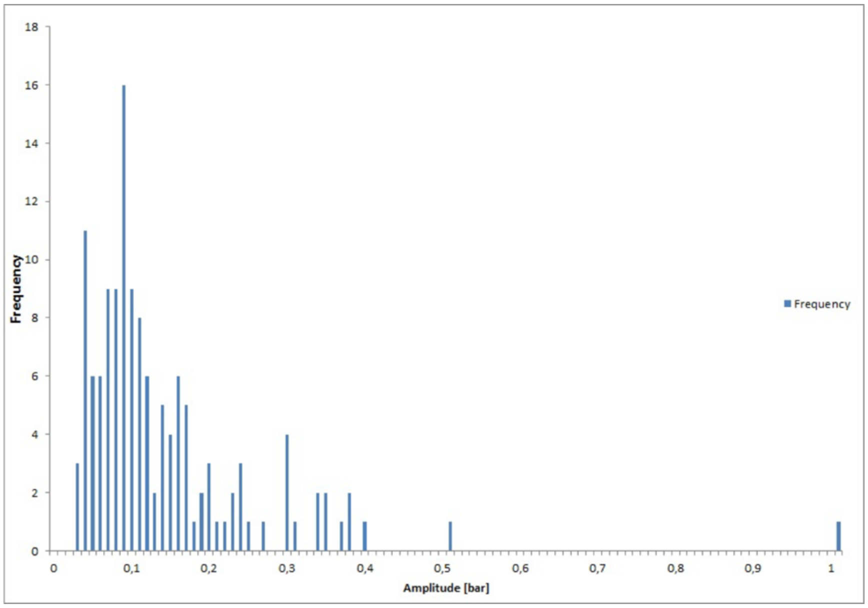

Figure 5: A histogram with the range of amplitude of the drops. The biggest drop isn't represented on this graph for clarity however there is no data in the interval 1.0 & 1.6.

3.3 Evolution over time

This dataset allows for numerous observations. Firstly, we can see that the drop rate (number of drops on a 10-minute time window) is tightly linked to the injection program. In fact, every flow rate step corresponds to a drop rate peak followed by a slow decrease in activity until the next step (Figure 6). Interestingly, when superposed over the seismic rate, the rates seem to be correlated. Therefore we conducted a correlation investigation between the drop rate and the MP catalogue to quantify the similarity of the two curves and the results are shown Figure 7. The correlation coefficient of 0.81 seems to indicate a rather good correlation between the two phenomena and the lag of a a few tens of second tends to indicate that seismicity arrives after the drops. This could be the proof of a link between the drop phenomenon and the induced seismicity. Finally, we can observe that the amplitude of the drop phenomenon is not time dependent. Moreover we do not observe any variation in drop amplitude over time (Figure 4).

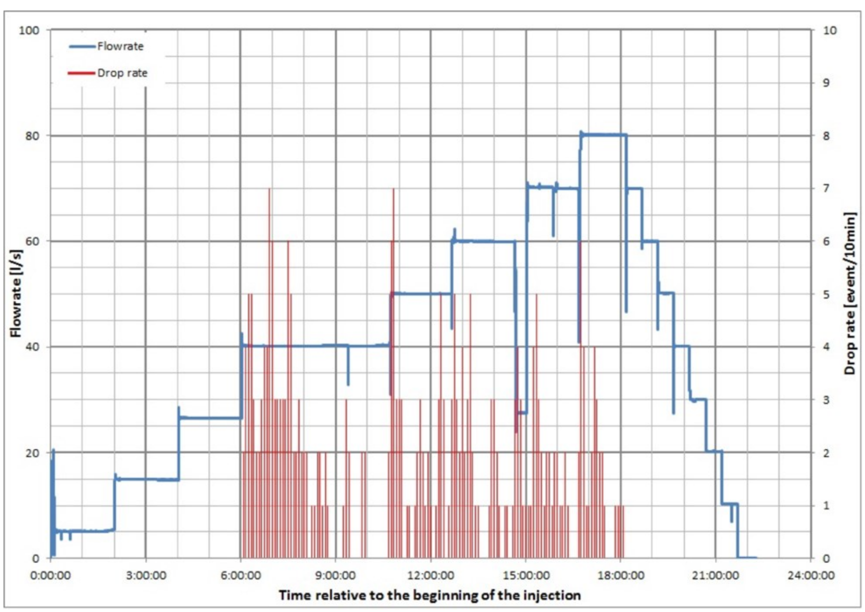

Figure 6: The drop rate with time in Rittershoffen. The flowrate steps appear to correspond to a drop rate peaks.

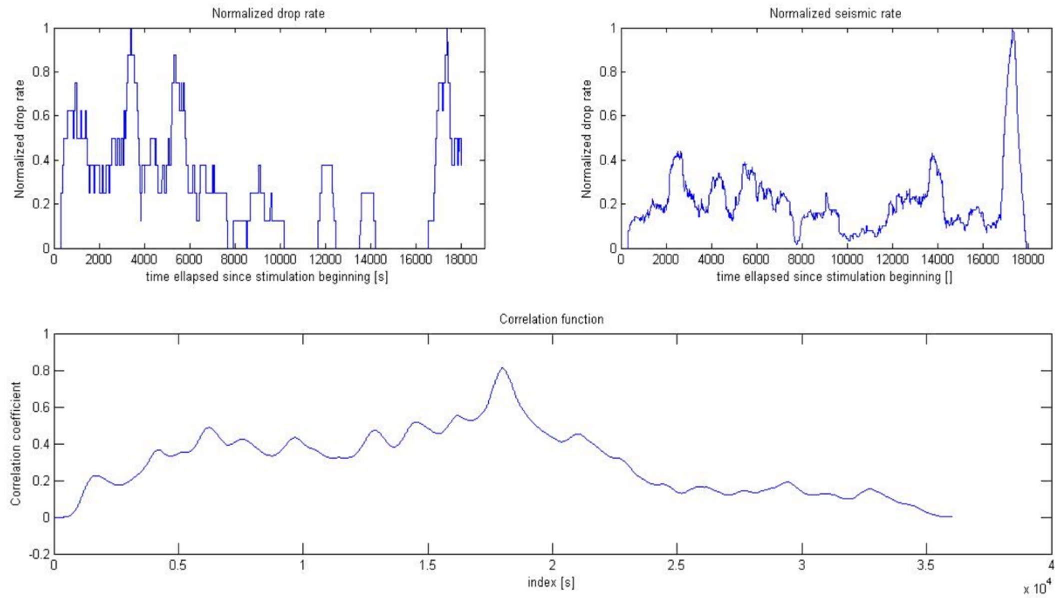

Figure 7: The correlation function of the drop rate (top left) and the seismic rate (top right). The maximum coefficient is equal to 0.81 which is a rather good correlation. The two rates are computed over 10 minute wide windows with a two second time step.

4. NUMERICAL MODELLING: CFRAC

4.1 Introduction

In this part, a theory for the origin of the drops will be tested. It is theorized that slipping on natural fractures is not the only mechanism of permeability enhancement during stimulation but rather that stimulation is a combination of tensile fracture openings and slippage on pre-existing faults. There is stress reduction around the fractures' tips when they slip, allowing the formation of wing cracks. The tensile fractures, while propagating away from the natural fractures, may reach other natural fractures that were previously equilibrated in pressure with the reservoir. When such a crack is connected to the stimulated part of the reservoir, the sudden equilibration might create a pressure drop that could be recorded in the well. During this balancing, the fractures could be destabilized and slip, which could create one or several induced earthquakes; this theory could explain the correlation between the drop rate and the seismic rate (Figure 8).

This mixed mechanism theory was first elaborated by McClure and Horne (2014). The lack of tensile fractures at the well, which is often considered as a proof of the non-creation of tensile fractures, can be explained by the fact that only the stress reduction around the natural fractures allows the nucleation of new hydraulic fractures; without this stress concentration, pressure never goes above the minimal horizontal stress and is not able to exceed the tensile strength of the rock. Under this hypothesis, each pressure drop could be the signal of the connection of a natural fracture to the reservoir and represents the permeability enhancement created by the stimulation.

In order to test this hypothesis, we will use the code CFRAC (McClure and Horne, 2014). This code was created to model complex stimulations in non-conventional reservoirs with very low matrix permeability. The main objective of this part is to establish wether we can recreate the drop phenomenon with conditions consistent with Rittershoffen.

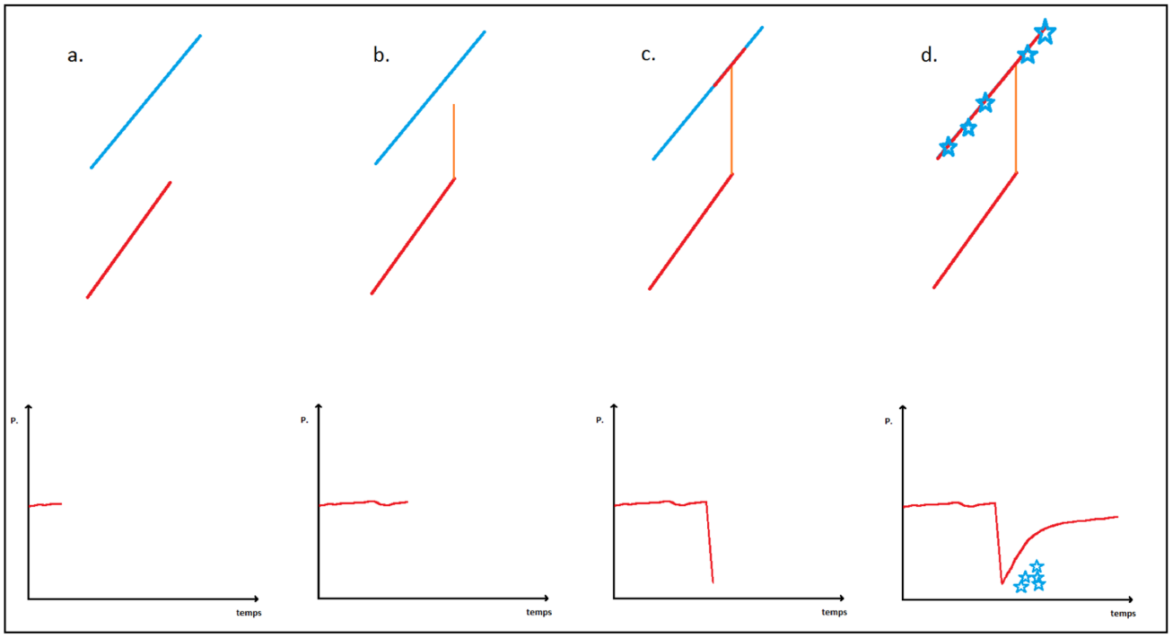

Figure 8: The diagram of the principle of the drop theory. In a, the initial situation, two natural fractures, one is stimulated (red) and the other is still at the hydrostatic pressure (blue). In b. a tensile fracture appears due to the stress reduction around the tips of the stimulated fracture. When the tensile fracture reaches the natural fracture, in c., the sudden balancing creates a pressure drop. Finally, with its pore pressure quickly increasing, the newly connected fracture is destabilized and slips creating the earthquake clusters (blues stars).

4.2 Code presentation

CFRAC is a numerical 2-D simulator that fully models rock-water interactions. It combines slipping, fracture aperture, transmissivity, strain, stress and flow. CFRAC is based on a discrete fracture network (DFN) in opposition to equivalent continuous medium based programs (ECM). Each fracture is discretized, which permits a better representation of the phenomenon taking place in the fracture network but can lead to a longer computing time. The code has already been used in many studies, proving its efficiency and accuracy (McClure & Horne, 2011, 2013, 2015). A more detailed description of the code can be found in the papers mentioned.

CFRAC considers the fluid to be single-phase and isothermal which is a limitation. Moreover, it can model the tensile fractures opening but the location where they may potentially form must be specified in advance. Finally, CFRAC has difficulty describing very low angle fracture intersections. This limitation had an impact on our study.

4.3 Simple model

Because CFRAC is a 2D simulator, a working depth had to be picked. 2370 meters appeared to be a relevant choice as it is the depth at which the main fracture in the GRT1 reservoir is intersecting the well.

GRT1 has been extensively studied in the past and this gives us access to very valuable information about the reservoir (Azzola 2016, Hehn et al., 2016; Genter et al., 2016; Sosio et al., 2016; Vidal et al., 2016a, 2016b). Using the literature and internal reports, it was possible for us to select accurate values for most of the input parameters. For values that were not known with good accuracy, we made reasonable estimates based on our knowledge of the reservoir.

<u>The fracture network</u>

CFRAC allows the user to place vertical fractures in a 2D space. The user specifies the locations where tensile fractures can form. The fracture network is one of the main input parameters of the simulation but also one of the hardest to establish properly. Because of its very nature, it is impossible to have a clear view of the repartition of the fractures in a reservoir but we can extrapolate from the fractures intersecting the well and the regional stress field (Azzola, 2016; Hehn et al. 2016; Vidal et al., 2016a).

A simple fracture geometry was assumed (Figure 9). Five parallel fractures were placed next to each other in order to see if we could recreate a drop sequence. The natural fractures are vertical 50m square planes. They are all separated by 2 meters and at every one of their tips can grow a tensile fracture. Those last can grow perpendicularly to the x direction, the direction of the minimum regional stress and stop when they reach the next fracture.

The orientation of the fracture network has been chosen to correspond to the 2370 m main fractured zone or local normal-fault (Vidal et al., 2016b). This fracture is the biggest of all fractures intersecting the well and plays a major role in the water flow in the reservoir. It has a N175˚W azimuth and a 65°W dip. In our study, we consider the x and y axis to be the direction of the stress field hence we have to orientate the fractures respectively to the stress field. In Rittershoffen it has been identified (Azzola, 2016, Hehn et al., 2016) to be N166°± 11°. Thus there is a 9° difference between the stress field and the fractures which will correspond to a 9° angle between the y axis and the fractures in CFRAC. Unfortunately, such a low angle can create numerical problems during the simulation, which is why it was increased to 15°. But this is still within the tolerance given by Azzola (2016).

The matrix permeability is assumed to be zero. Stresses are computed with the Boundary Element Method (BEM); therefore, it is only necessary to discretize the fractures. A discretization algorithm is used that refines the mesh near fracture intersections. We show an example of discretization in Figure 9.

CFRAC uses adaptive timestepping. Shorter timesteps are taken when simulation properties are changing rapidly. This method allows a good accuracy and limits convergence problems.

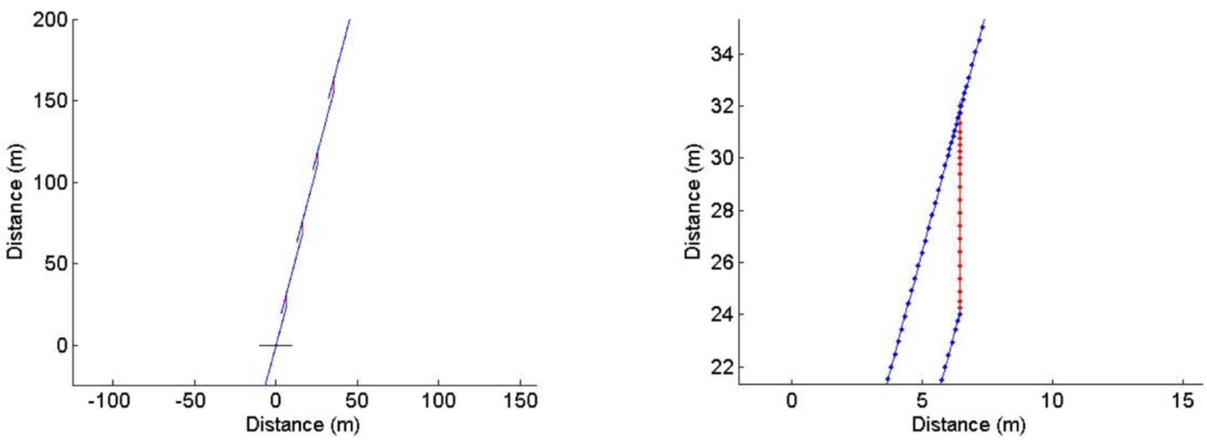

Figure 9: Fracture network chosen for the simulation (left) and fracture network discretization (right). In blue are the natural fractures and in red the potential tensile fractures. Each point represents the center of an element. We can see on the right zoom that the grid is finer around the fracture intersections.

Initial and boundary conditions

Initially in the model, the pore pressure P and the stresses σ_{xx}, σ_{yy} and σ_{xy} are considered homogeneous. In reality, we may have spatial heterogeneity due to differences in the rock properties between lithological layers (e.g an impermeable shale layer). Also, the occurrence of a large-fault which could introduce some local stress perturbations as it was shown at Soultz in the granite (Valley, 2007). Nevertheless, we neglect those effects here.

The stress boundary conditions depend on the status of each fracture element. Fracture status may be classified as closed, open or slipping. The fractures are assumed to be embedded in an elastic whole space, and so the far-field mechanical boundary condition is zero displacement. For flow, the edges of the system are assumed to be no-flow boundary conditions (which is implicit to the assumption of zero matrix permeability). The well can be set to either constant pressure limit or specified flow rate.

Input parameters

The reservoir parameters were chosen according to the values found in literature about GRT1 (Table 2). In our study, we varied a few key parameters. The others were set to default values.

Table 2: Input parameters for the model

Parameter	Description	Valeur	Source
Pinit	Initial pore pressure	23.7 MPa	Injection data
Sxx	X direction stress	29 Mpa	Azzola 2016
Syy	Y direction stress	36 Mpa	Azzola 2016
K1crithf	Stress intensity factor	1.5 Mpa.m$^{1/2}$	arbitrary (common value)
Tstr	Matrix tension strength	3 Mpa	arbitrary (common value)
matrixperm	Matrix permeability	0 m^2	arbitrary (no flow in the matrix)
height	Fractures heigth	50 m	GRT1 well data
maxtime	Stimulation duration	3100s	arbitrary
Cw	Water compressibility	0.0184 Mpa^{-1}	Injection data
hfinitonesize	Hydraulic fracture initial length	0.5 m	arbitrary (default value)
elltomatrixconnecti	Well casing	False	Injection data
E0	Fracture aperture	0.001 m	GRT1 well data
e0	Fracture hydraulic aperture	0.001 m	GRT1 well data
Ephidil	Dilatation angle	0°	arbitrary (to limit computation time)
ephidil	Hydraulic dilatation angle	6°	arbitrary (good coupling)
maxqinj	Injection flowrate	40 kg/s	Injection data
maxpinj	Maximum injection pressure	40 Mpa	Injection data
nu	Poisson ratio	0.25	arbitrary (common value)
G	Shear modulus	15000 Mpa	arbitrary (common value)

Sensitivity analysis

To assess the impact of a given parameter on the drop phenomenon, a sensitivity analysis was conducted. The results of the sensitivity analysis are summarized in the following paragraphs.

As stated before, the fracture network is a very important parameter for two reasons. Firstly, it directly influences the computing time, which affects the number of simulations that can be run practically. We observed that the simulation time is very long for fracture intersection angles less than 10° because of numerical difficulties. This is why the angle between GRT1's fracture and the maximum horizontal stress is set somewhat greater than 6°, the true value. Secondly, fracture friction stability is directly connected to its orientation in the stress field. If a fracture is optimally oriented, it will be much easier to bring it to failure. We observed that for low angles (10°) or for large angles (45°), drops do not appear. Hence to have drops during a stimulation operation, the natural fracture network must be optimally oriented because natural fractures are critically stressed. This is because when a fracture slips, its transmissivity is enhanced and the water can rush in it even faster. Eventually, it will become easier to propagate the drop signal from the failing fracture to the well making it easier to record.

Generally, we consider the natural fractures and the porosity to be under hydrostatic pressure when not stimulated. This means that the pressure in the fracture is equal to the weight of the water column above it. This hypothesis has been adopted here, so the initial pressure was calculated for the fracture at 2370m depth. Nevertheless, it is important to quantify the effect of the initial pressure on the drops. It has been observed that decreasing the initial pressure does not have a big impact on the drop phenomenon. When the initial pressure is decreased, the drops globally have the same shape as the drops in the reference case. In contrast if we increase the initial pressure, the drop's amplitude tends to decrease. This can be explained by the differential pressure between the stimulated reservoir and the newly connected fracture when tensile fractures appear. If the initial pressure is too close to the minimum horizontal stress, the differential pressure will not be high enough to create a sudden drop when tensile fractures will form and thus we will not observe any noticeable drop.

Minimum horizontal stress determines the pressure at which new tensile fractures form. It was observed that as expected, the minimum horizontal stress has a huge impact on the drops. Naturally, it increases or decreases the pressure at which the drops appear because we cannot have drops without having tensile fractures. We can also notice that Sxx has an effect on the general shape of the pressure curve. Stress anisotropy is also important when considering fracture slippage so when Sxx increases, the stress anisotropy (Mohr circle diameter) decreases and the slipping is harder to achieve, limiting the transmissivity enhancement.

The maximum horizontal stress is usually harder to measure on the field, but it has a significant impact on our simulations. Here its reference value was chosen arbitrarily trying to remain coherent with the reality of the field (Azzola, 2016). Decreasing Syy means decreasing the stress anisotropy which can explain the disappearing of the drops when decreased. Conversely, increasing Syy increases the stress anisotropy and again, favours the slipping which encourages the drop phenomenon.

The tensile strength is the tensile stress one must apply to a rock to break it. This parameter is important as it changes the pressures necessary to create tensile fractures. It appeared that tensile strength is the parameter which has the greatest impact of all so far both on the drop amplitude and on their shape. It was observed that, as we expected, a Tstr increase also increases the pressure at which drops start but it also greatly increases the drops amplitude. It even alters the drops' shape which becomes sharper, the drop is more sudden and the following pressure augmentation linearizes. This can be explained by the fact that Tstr creates a pressure build up around the fracture tips and when the tensile fracture finally initiates, the pressure relaxation is much bigger than before. Tensile strength is a critical parameter. Unfortunately, it is very hard to estimate in a heterogeneous reservoir.

The dilatation angle characterizes the coupling between the amount of slip on a fracture and the hydraulic aperture increase. We arbitrarily chose 6°, which corresponds to a fairly good coupling. As was expected, decreasing dilation angle leads to a decrease in the drop phenomenon (McClure et Horne, 2011). When the transmissivity of the fractures is poorly enhanced when they fail, the drop signal both has a small amplitude and is poorly transmitted to the well.

The fracture's reference hydraulic aperture, e_0, represents the effective opening of a fracture for flow prior to shear stimulation. It was observed that when e_0 is too low, fluid flows too slowly for drops to occur. On the other hand a good hydraulic aperture favours the drops propagation.

Model Results

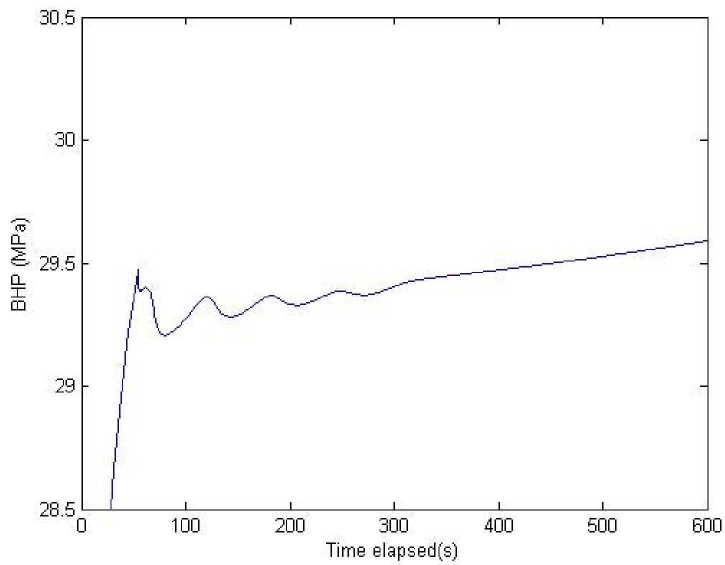

Figure 10: Model results for bottom hole pressure in the reference case. The drop phenomenon can be recreated with CFRAC.

The drop phenomenon has been recreated successfully using CFRAC. However specific conditions must be met. We managed to highlight which physical parameters have key roles in the occurrence of drops in the well. First, the overall fracture transmissivity in the reservoir is very important as it defines how fast the water will be able to flow from the stimulated reservoir to the newly connected fracture and thus the very initiation of the drop. This observation also applies to every physical property increasing the fracture transmissivity as for example the dilation angle. Secondly we saw that the fractures in the well must be well oriented with respect to the stress field in order to be able to slip, which eventually triggers the opening of tensile fractures thanks to the induced stress reduction around the tips of the slipping fracture. Finally, the tensile strength of the matrix appeared to be the most important parameter during the sensitivity analysis. Tensile strength has an impact on both the amplitude and the shape of the drop and determining the apparition of the phenomenon.

4.3 Stochastic models

Following this first approach, a stochastic model was run to assess the impact of the number of cracks in the reservoir over the drop phenomenon.

The fracture network

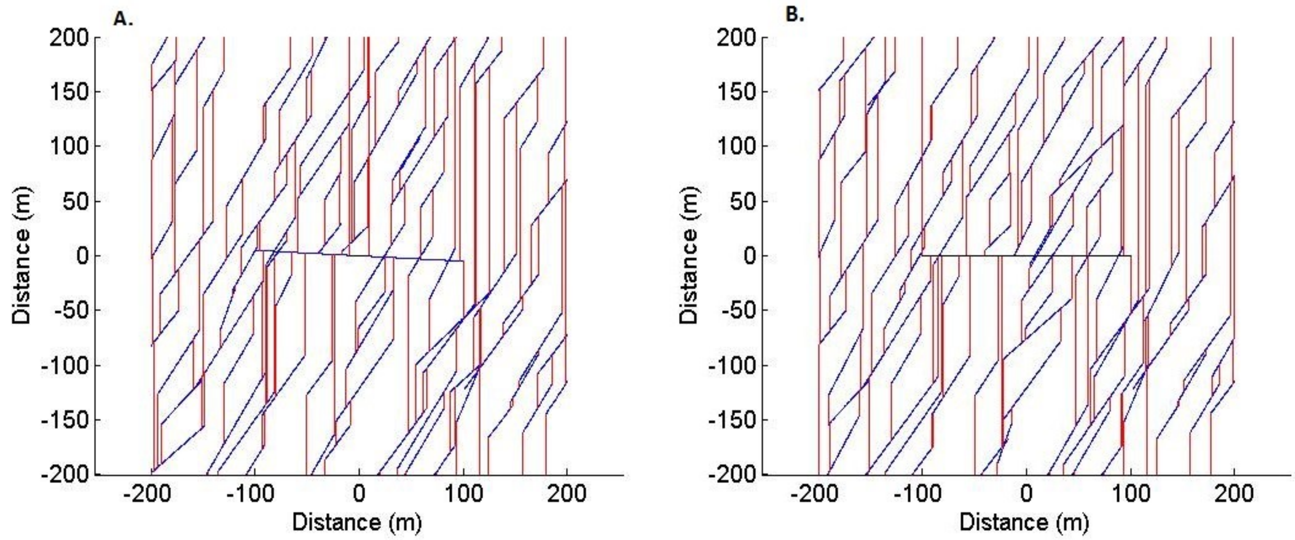

Figure 11 : The two fracture networks used during the second simulation. Diagram A has a natural fracture intersecting some of the natural tensile fractures in the reservoir (in blue) to connect the well to the reservoir. This connecting natural fracture is slightly angled as CFRAC can't deal with parallel fractures intersecting each other or the well. On diagram B, the connecting fracture is replaced by a longer, horizontal well section to model the presence of highly transmissive fracture connecting the well to the natural fractures.

In this model, we tried to recreate the drop phenomenon in a larger reservoir with randomly oriented fractures. The crack angles were randomly drawn as to have an angle of 30° +/- 10° with the y axis (Syy). This angle has been chosen to reduce the computing time which tends to increase with sharper angles. Two main situations were tested. In the first situation, the well is connected to the reservoir via a natural fracture with the same transmissivity as the other fractures in the reservoir. In the second case, the well is connected to the reservoir via a highly transmissive crack which is modeled using a longer horizontal section of the well as we cannot define specific characteristics for a given fracture in CFRAC. Except for these specificities, the parameters and the fracture network were kept the same in both simulations.

Initial state, boundary conditions and input parameters

The parameters used in this set of simulations are the same as the reference case in the sensitivity analysis except for the tensile strength which has been raised from 3 to 8 MPa.

Results

During the stimulation of the first case of the model, very few drops were recorded (Figure 12). In fact, we only observe one drop around 500 seconds. However, we can see some very slow negative drop-like pressure changes during the operation (Figure 12). These new phenomena seem to take place all along the simulation.

During the stimulation using the second case of the model, we can see many more drops that start around 100 seconds after the beginning of the injection (Figure 13). Their amplitudes ranges from a few 0.1 bar to several bar. Moreover, we can also observe the same slow drops in the last part of the stimulation.

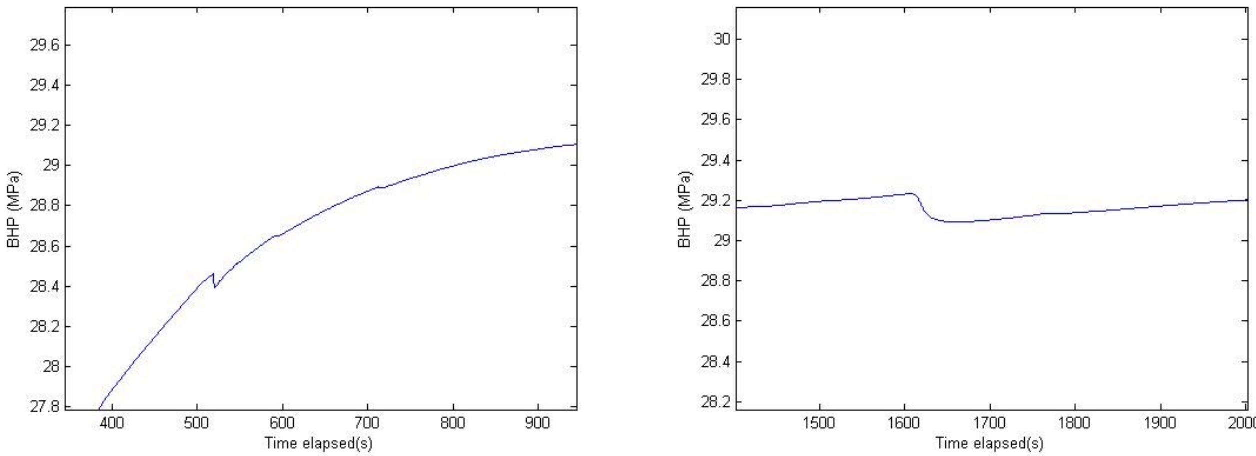

Figure 12: Left: the first and only drop in the first case of the simulation; right: drop like phenomenon during the simulation of the first case. It is important to note that similar phenomena were recorded during the second case.

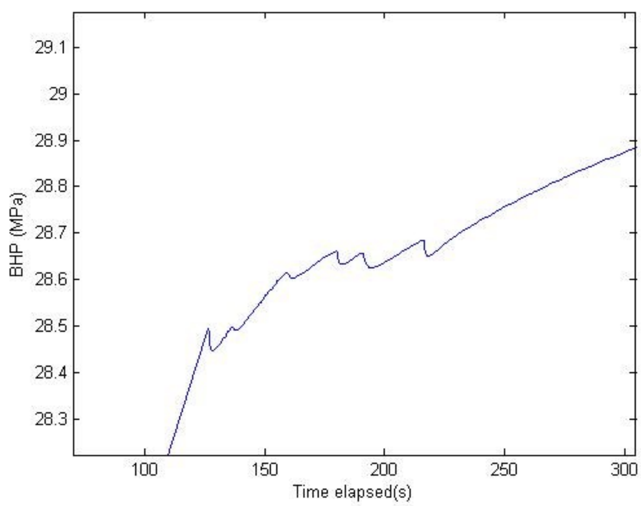

Figure 13: A series of pressure drops observed in the second case of the model.

The first conclusion we can draw is that the drops are attenuated over very short distances. In the first case of the model we can only see one drop which means that all the others are attenuated. The presence of a very transmissive local natural fault connected to the well can help propagating the drops but even in the second case, they are attenuated relatively quickly. In the end, we can only see the drops generated by the connections of faults close to the well.

CFRAC can create movies of the simulation results. If we compare these movies to plots of pressure versus time, we can notice that the drops do not happen when a fracture is connected to the stimulated part of the reservoir. Instead, they occur when a tensile fracture first forms. The sudden relaxation of the stress and pressure accumulated appears to be the origin of the drops. On the other hand, the flow from the stimulated zone to the newly connected fracture is responsible for the much slower pressure anomalies observed. This is why we noticed earlier that the tensile strength had such a great impact on the simulations. During the sensitivity analysis, we could see two parts on some of the drops (e.g. the reference case, Figure 10). The first one is the pressure drop due to the tensile fracture nucleation and the second one is the water rushing from the reservoir to the newly connected crack. The problem here is that the stimulated volume of the reservoir is much bigger than during the sensitivity analysis thus the part of the drop due to the flow is almost non-existent. Even in the reference case of the sensitivity analysis we could see that with each new connected fracture the amplitude of the drop was decreasing. This is because each fracture increases the total volume of water under the stimulation pressure.

We can conclude that in order to have drops during a stimulation, several conditions must be met. First, the reservoir matrix must have a high tensile strength, high enough to create drops when a tensile fracture appears. The second condition is that the fractures must have a sufficiently high diffusivity to propagate the pressure responses to the well. In Rittershoffen, these conditions could have been met by the 2370m depth major fault which is highly transmissive. In other places, these conditions are unlikely to be fulfilled. In formations without large, transmissive faults, these conditions may be unlikely to be met.

CONCLUSION

Our initial theory was that the pressure drops are caused by fracture slip (with associated microseismicity). However, observations suggest that the pressure drops occur before bursts of microseismicity, not after. This motivated the development of a second theory that the observed pressure drops occur when propagating tensile fractures connect to preexisting unpressurized natural fractures, leading to a sudden water flow into the newly connected fracture and a subsequent burst of microseismicity. To test this theory, we used CFRAC, a numerical simulator of fluid flow and fracture deformation (McClure and Horne, 2014). We attempted to reproduce the pressure drop phenomenon in realistic in-situ conditions based on Rittershoffen. We ran a sensitivity analysis which showed that the most critical parameters for the drop phenomenon are the tensile strength, the fracture network orientation and the transmissivity of the fractures.

The simulations suggested a third theory for the cause of the pressure drops. The third theory is that pressure drops occur when a tensile fracture initiates from a natural fracture as a wing crack. In contrast, the second theory was that the pressure drops occur when hydraulic fractures connect to previously unconnected natural fractures. Simulations suggest that rapid initiation of a tensile fracture could cause a sharp drop in pressure, similar to the drop in pressure observed in a 'breakdown' fracturing test. This theory requires that the tensile strength of the formation is relatively high, which enables a sufficient buildup of pressure to cause a sharp inflow of water when the new fracture forms. Tensile fractures can form even if the fluid pressure is below the minimum principal stress (which was the case at Rittershoffen) because of the concentration of stress near the ends of sliding pre-existing fractures.

When we tried this theory on more complex stochastic models, new results appeared. We observed that when the reservoir is much bigger, the drops are mainly created by the tensile fractures nucleation and not by the water rush in new fractures. The flow of fluid into a newly connected fracture only generates slow and low amplitude negative pressure anomaly. The pressure response is attenuated by distance from the well and the overall size of the reservoir connected to the well. We also observed that, in order to record drops at the well, a highly transmissive medium or fault must connect the well to the fracture.

While our proposed mechanisms appear plausible, the results are not strong enough to be conclusive. We showed that it was possible to have drops and that this phenomenon relies on the transmissivity of the fractures. The parameters that favour slipping are stress anisotropy, dilatation angle, and fracture orientation. We also showed that the drop can be divided in two components, the part of the drop due to the tensile fracture initiation and the part due to the water rushing from the stimulated natural fracture to the newly connected unpressurized one. This second mechanism becomes almost negligible when the reservoir becomes larger because the volume of the newly connected fracture is much lower than the volume of the stimulated reservoir. The simulations also show some potential problem with these hypothesized mechanisms. With CFRAC, we showed that the drop signal is attenuated over very short distances even with a highly transmissive fracture. Still, this could be consistent with the observation that all the events in the subsequent microseismic bursts are near the well. Pressure drops might happen everywhere in the reservoir but may only be recordable when near the well. The conditions necessary to have drop are very particular and are unlikely to be found in all formations. Also, it was challenging to exactly reproduce the characteristic shape of the drops with CFRAC. In conclusion, it is not possible to conclusively prove or refute the hypothesized mechanisms and further work needs to be done on the subject.

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