



Report on the laboratory fracturing experiment, its boundary conditions, and its flow rates and fracture aperture versus time curves

D6.4

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Version 1

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Executive summary

This report is prepared by RWTH Aachen University, Germany as Deliverable 6.4 of Work Package 6 for GEMex (Grant Agreement No. 727550).

The report describes the hydraulic fracturing (HF) experiments done at a laboratory scale under controlled conditions at Chair of Geotechnical Engineering, RWTH Aachen in coordination with Institute for Applied Geophysics and Geothermal Energy, RWTH Aachen. Four HF tests are performed with similar boundary conditions in granite and marble rock samples obtained from Mexico. The report summarises the experimental procedure, the boundary conditions and the results (pressure vs volume curves) and fracture radii for every experiment.

The objective of the task is to generate benchmark data sets from hydraulic fracturing experiments which can be used for verifying different numerical codes used for stimulation designs. Therefore the results of these experiments are shared with the simulation groups within GEMex who are involved in designing stimulation scenarios for Acoculco and Los Humeros.

1 Introduction

Acoculco is one of the investigation sites of project GEMex and is characterised as a Hot Dry Rock (HDR) geothermal system. Two exploratory wells drilled in Acoculco, EAC-1 and EAC-2 encountered temperatures of more than 300 °C at a depth of 2000 metres without any considerable fluid loss [1]. The basement of Acoculco geothermal system constitutes limestone that was affected by contact metamorphism due to emplacement of hornblende granitic intrusion based on interpretation of drill cuttings from the wells.

In order to understand the response of the Acoculco basement forming rock types towards hydraulic stimulation, we collected outcrop analogues of granite and skarns/marbles with the help of local Mexican geologist and GEMex partners. These samples of granite and marbles are collected from the Las Minas site which is considered to be the exhumed system and best representative of Los Humeros and Acoculco subsurface geology. The quarry in Las Minas where we collected the samples from is considered as a site where the process of contact metamorphism changed the limestone to skarns and marbles. For our experiment, we collected the marble samples from this quarry whereas the granite boulders were collected from a river bed in Las Minas. According to information from local Mexican geologist, these rocks were tectonically emplaced in these area and represent the plutonic rocks of Los Humeros system.

Additionally, these experiments are conducted with an objective of generating a benchmark data set for verification of different numerical codes used for field scale hydraulic stimulation design. The experiments are conducted in the laboratory and at a scale where all the boundary conditions can be controlled to reduce any uncertainty during simulation of the experiment. The data generated from these experiments are distributed amongst the different simulation groups for testing their codes.

This report describes the experiment and reports the results which includes the pressure response of the granite and Marble samples towards high pressure injection and the process of initiation and growth of fracture within them. The fracture growth is monitored with acoustic emission events which are also reported in the results.

2 Experimental Setup

2.1 Sample

The samples have dimensions of 300 mm × 300 mm × 450 mm. A Cartesian coordinate system as shown in Figure 1 is introduced to enable a systematic description of the samples. The origin of the coordinate system is located in the centre of the surface A, the top of the sample. The z-direction (blue) corresponds to the borehole axis and points from the upper side A towards the lower side F. The y-axis (green) points to surface C and the x-axis points positively to surface D. A borehole with a radius of 10 mm is drilled through the center of the sample. While preparing the sample, a circumferential notch of radius 17 ± 1 mm is cut into the borehole wall at a height of $z = 225$ mm (Figure 2). The notch has a thickness of 0.6 mm and a depth of 7 ± 1 mm and is cut into the sample to make the crack initiation and its location reproducible.

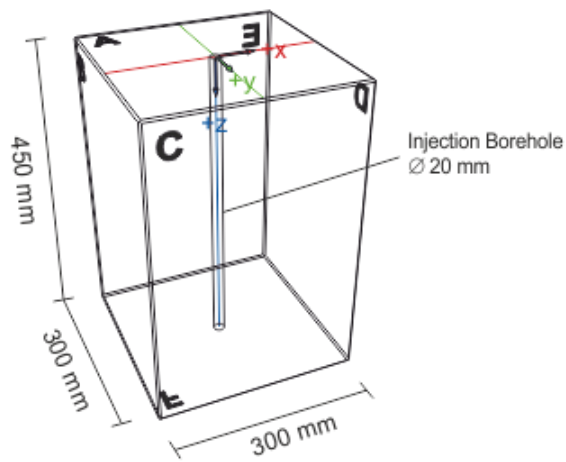


Figure 1: Sample: Dimensions, face designations and coordinate system [2, modified]

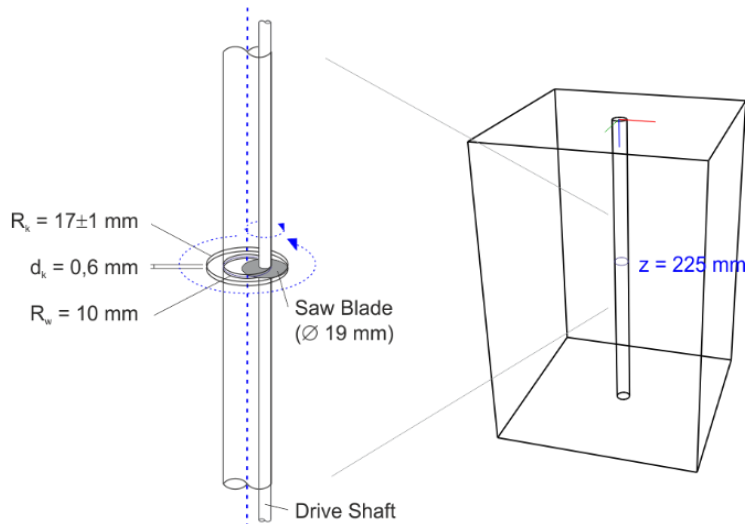


Figure 2: Dimensions and location of the notch [2, modified]

2.2 Injection System

For the injection of fluid for hydraulic fracturing the Syringe-Pump “Teledyne Isco 260 HP” is used. Figure 3 shows the pump and the injection system. The pipes of the injection system have an inner diameter of 1.76 mm. During the experiment Valve A and Valve C are closed and the volume of the pump cylinder is reduced to pressurize the injection system. The volume of the injection system is $V_{\text{sys}0} \approx 12 \text{ cm}^3$ plus the variable volume of the pump.

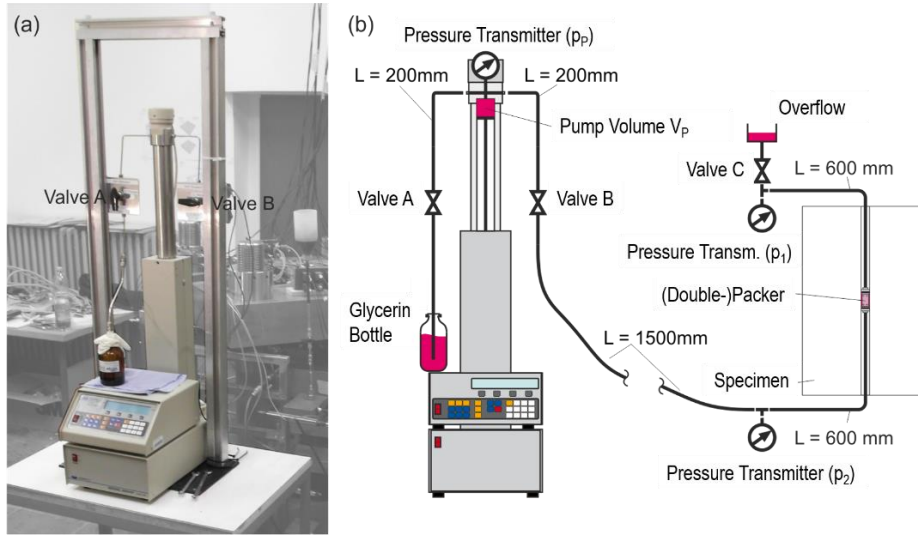


Figure 3: Injection Pump and Injection System [2, modified]

Figure 3 also shows the location of the pressure transmitter p_1 and p_2 . As it is not possible to measure the fluid pressure in the injection interval, the pressure transmitter p_2 (before) and p_1 (behind) are placed in same distance to the injection interval. Sensors of type Keller P33x/1000 bar/80794 with an accuracy of 0.1 MPa are used. The fluid pressure in the injection interval is assumed to be the mean value of p_1 and p_2 .

The injection interval is isolated from the rest of the borehole through a packer. Figure 4 shows dimensions and function of the packer. Tightening the threaded washer presses the O-ring against the borehole wall which ensures, that the injection interval is sealed from the rest of the borehole and the packer is fixed in its position.

The injection fluid in the experiment is a mixture of 98 % Glycerol and 2 % ink. The ink is added to visualize the penetration depth of the fluid when the samples are opened after the experiment (see chapter 3). The density of the pure Glycerol is 1260 kg/m^3 at 20°C . The bulk modulus of pure Glycerol is 4.35 GPa. The highly temperature dependent dynamic viscosity of the injection fluid is measured for each experiment independently.

During the experiment the fluid, the pump, the injection system (pipes and packer) and the borehole within the injection interval are pressurized by reducing the volume within the pump cylinder. The measured pressure response is the sum of all these components. In additional experiments the bulk modulus of the pump was determined to 0.18 GPa. The bulk modulus of the injection system (pipes and packer) was determined to 2.7 GPa.

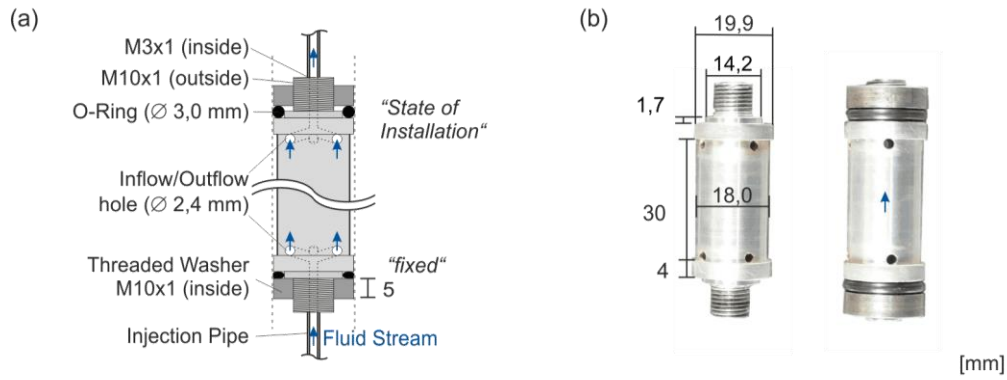


Figure 4: Dimensions and function of the packer [2, modified]

2.3 Loading system

To monitor hydraulic fracturing in the sample, 32 micro seismic sensors are attached to the surfaces of the sample. 6 sensors at each vertical surfaces (B, C, D and E) and 4 sensors at the upper and lower surfaces (A and F) are attached and enclosed in loading plates which have same dimensions as the sample surfaces where they are attached to. The edges of the load plates facing the sample are also chamfered to avoid contact between different load plates. At each side two Teflon films with thickness 0.5 mm are inserted to reduce friction between sample and load plate. Only at the positions of the sensors the films have circular openings to ensure that the sensors are attached directly to the sample surface. Figure 5 shows the load plates with their dimensions.

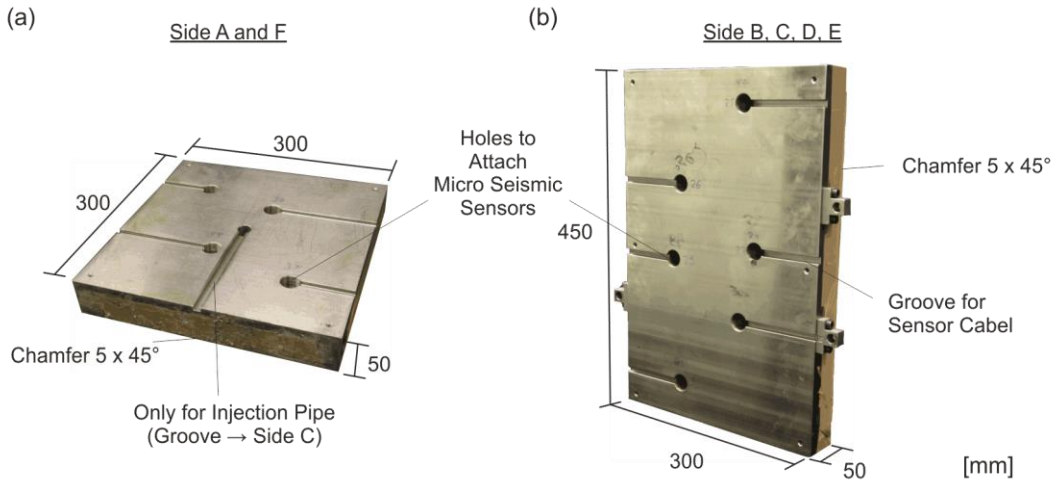


Figure 5: Load plates with space for sensors [2, modified]

To apply pressure to the sample, flat jacks are used. In each loading direction two flat jacks are positioned behind the load plates. The dimensions exceed the sample dimensions at each side by 10 mm (A, F: 320 x 320 mm; B-E: 320 x 470 mm) to ensure that the whole area of the sample is loaded equally. Valves at both fluid supplies help to fill, open and close the flat jack. Figure 6 presents both types of flat jacks and the detail of the joint structure.

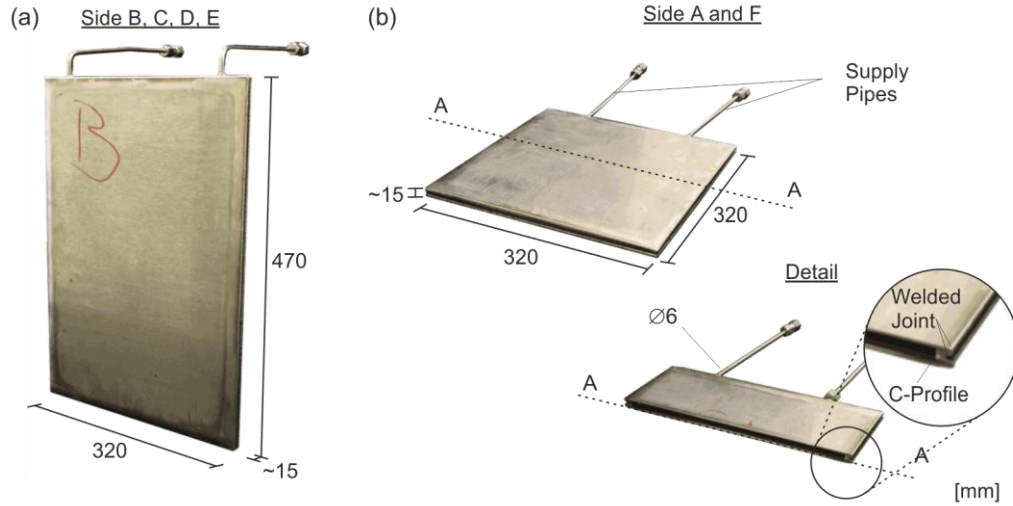


Figure 6: Flat jacks and detail of welded joints [2, modified]

The flat jacks apply a three-dimensional stress state to the sample which has to be supported by stiff abutments. Figure 7 shows the stress state in x-, y- and z-direction and its demands as well as the biaxial abutment for the x- and y-direction and the monoaxial abutment for the z-direction.

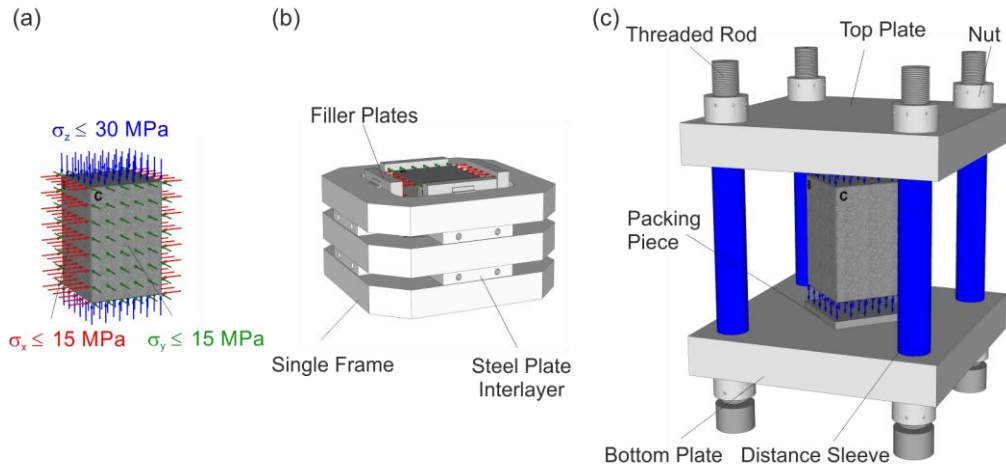


Figure 7: Stress State and concept of abutments [2, modified]

2.4 Acoustic Emission Data Acquisition

The acoustic emission (AE) data is acquired using GMuG data acquisition system which comprises of 32 piezo electric transducers which can act as both receivers and transmitters. The adopted sampling rate is 10 MHz. The sensitivity of the sensors range from 20 kHz to 1 MHz. The dimension of the transducer element is around 8mm – 10mm for the diameter and 2 mm thickness. In Figure 8 one of the piezo electric sensors is shown. These sensors are attached to the rock sample through the slots in the loading plates shown in Figure 5. Every sensor has a defined allotted slot as can be seen in Figure 8 (right). The DAQ comprises of pre-amplifiers, control unit and a PC with GMuG acquisition software, GMuG_Trans32. Details of the AE unit can be found in Reference [3].

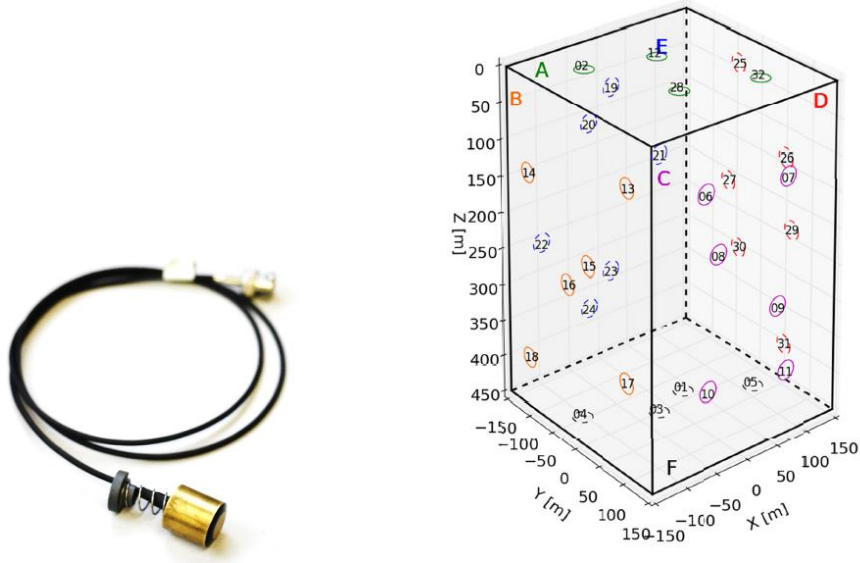


Figure 8: Acoustic emission sensor and sensor positions at different surfaces of the sample [2]

3 Experimental Procedure and Documentation

The experimental procedure is presented in Figure 9. The experiment begins by applying the initial stresses on the sample (σ_x , σ_y , σ_z). After that fluid is pumped through the injection system to de-air the system and fill the system with injection fluid (not shown). A leakage test is done to make sure the injection system is tight. During the leakage test at ~ -1800 s (Figure 9) the injection system is pressurized with 3 MPa for ~ 600 s. At the same time acoustic transmission is performed to determine the rocks seismic velocities. Every acoustic sensor is used as an emitter once while the other sensors act as receivers. After the leakage test the volume in the pump is reduced to $V_0 = 5 \text{ cm}^3$ and the acoustic emission recording is activated. Now the injection of fluid for hydraulic fracturing starts. The starting time of the pump is used as reference time ($t = 0$ s) for all recorded data. The duration of injection is controlled by injecting a defined volume ΔV_p after the peak pressure. After injecting ΔV_p the pump is stopped at ~ 1800 s (Figure 9). This phase of the experiment is referred to as “shut in”. When the pressure in the injection system drops below the minimum confining stress (σ_z), the pressure in the injection system is released followed by the unloading of the sample.

When the experiment is finished, the sample is removed from the experimental setup. The packer is removed from the borehole and a second hole is drilled to split the sample. The sample is split along the fracture plane and the fluid coloured fracture zone is outlined with a marker (Figure 10). Additionally photogrammetry is used to create a 3D model of the split sample.

In order to investigate the created fracture using a non-destructive method like Computed Tomography (CT) scan, it was decided to drill cores of diameter 20 cm through the fractured specimen. Two of the four samples (one granite and one marble, see chapter 5 & 6) were drilled for this purpose. However it was not possible to perform a CT-scan with the needed resolution to produce usable results. Therefore the drill cores were split along the fracture plane as shown in Figure 10.

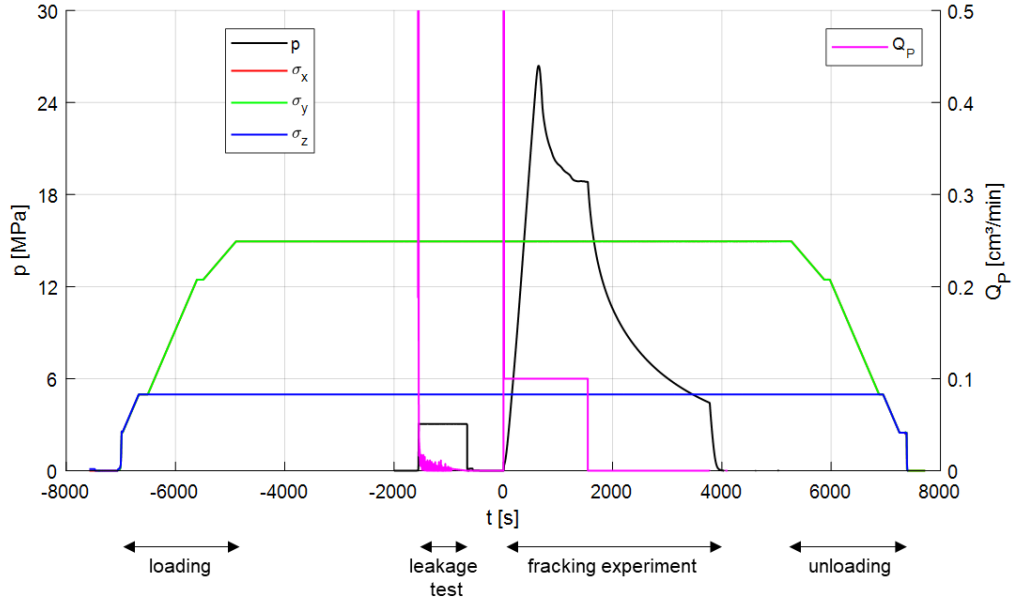


Figure 9: Experimental procedure

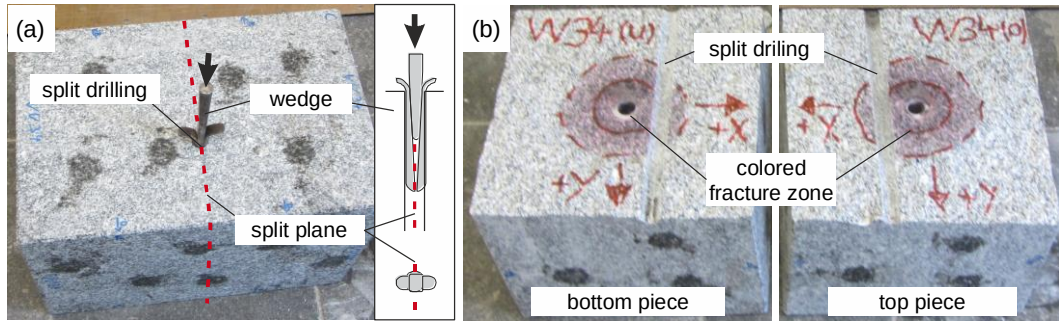


Figure 10: Splitting the sample documentation of coloured fracture zone [2, modified]

4 Evaluation of Acoustic Emission measurements:

Acoustic emission data is acquired in two different modes. Active transmission mode is used in order to compute the average P wave velocity of the rock sample and Passive monitoring mode is used for collecting acoustic emission data during fracturing. Both the modes and the data collected are explained below.

4.1 Active Transmission (AT) mode:

In this mode sensors attached to the sample are used as transmitter to create pressure pulses. One sensor acts as a transmitter at a time, while the rest act as receivers. This is done for all the 32 sensors. Each transmitter generates a sequence of n pulses composed of a 1000 kHz oscillation in a $\cos^4$ envelope. The highest signal-to-noise ratio is achieved with $n = 1$. Each pulse sequence is then repeated 8 times to provide comparable data for statistical analysis. The total number of transmissions per AT experiment is 256 (32×8) and total number of acquired traces is 8192 (256×32). After measuring the standard deviation of the noise for each channel, the trigger level is set to 3.3σ to exclude the 99.7 % of false positive events associated to the noise.

The active transmission (AT) is performed four times during each experiment. First measurement is performed immediately after setting up the experiment before the load is applied but after the borehole is filled with injection fluid. The next AT is performed with the rock under confining pressure. Once the hydraulic fracturing is done, the third AT is performed to check the difference in P wave velocity before and after fracturing. The last AT is done after unloading the rock. From the 4 set of AT measurements, average P wave velocity of the rock with and without loading is calculated.

The first arrivals of each trace is picked up by using AIC (Akaike Information Criteria) [4]. The AIC is an auto-recursive filter and is a measure of the order of the variance in a time series interval which can be used to demark the point of two adjacent time series with underlying statistics [5]. In this case, the time series of length 409.6 μs is divided into two parts. The first series is random low amplitude noise and the second series records the energy which is of interest. An AIC window length of 250 μs is chosen out of a total trace length of 409.6 μs . The pre-trigger is set to 122.9 μs as the first arrival in the 32 channels is expected approximately in the middle of the AIC window. The variance of a low amplitude time series is a small number. This number decreases as the number of samples with similar energy increases. However at the onset of an impulse, the variance in the samples increases sharply. This point is called the AIC minimum and is chosen as the time of first arrival. The AIC algorithm is robust and gives good results in the presence of high amplitude random noise. An event is localised with certainty when atleast 4 out of 32 sensors have the same signature.

The first arrival time is used to calculate the average P wave velocity as the transmitter and the receiver positions are known. Figure 11 shows the acoustic emission events (in blue dots) for active transmission experiments done for **GEMex 07** with load. The red dashed lines indicate upper and lower limit of velocities as measured in the laboratory using MSCL (Multi-Sensor Core Logger) in saturated and dry conditions respectively. It is to be noted that the measured velocities in saturated samples (almost overlay with the linear regression line (bold red) indicating a good match with the velocity calculated from active transmission data while the velocities in oven dried samples are lower as can be seen from the slope of the dashed red line.

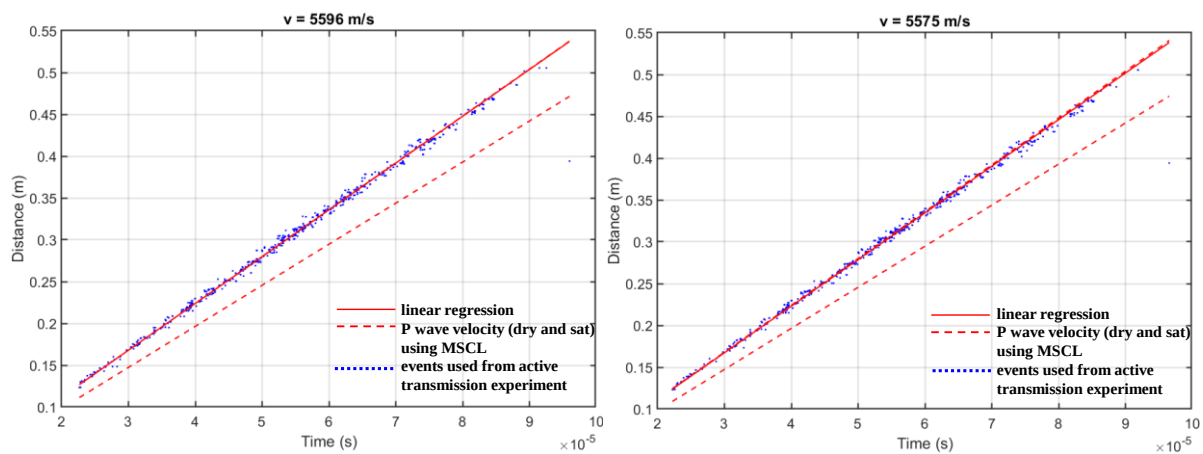


Figure 11: P wave velocity from active transmission before (left) and after (right) fracturing for GEMex 07

4.2 Passive monitoring – Acoustic emission analysis:

Passive monitoring involves recording the energy impulses which are generated during the cracking process. AE monitoring is one of the most useful indirect fracture monitoring technique. The first arrival times are picked up from the sensors using the AIC Criteria described in Section 4.1 and the events are

localised in space using the average P wave velocity calculated during the Active Transmission mode. The processing parameters were chosen such that

1. events which were not recognised by atleast 4 sensors were not used
2. events which were recorded by receiver on the same side as transmitter were not used.

The theoretical arrival times are calculated according to Havskov et al. (2002), i.e. under the assumption that the source is a point source and the distance between sensor and receiver is large enough to avoid any significant influence from the near-field.

$$t_i^p = \frac{\sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}}{v} + t^E$$

where (x_i, y_i, z_i) are the coordinates of the sensor at the i^{th} channel, t_i^p is the time at which the p-wave arrives at the sensor, (x, y, z) are the required coordinates of the acoustic event, and t^E is the event time. From all the tuples, we find the one which minimizes the error between theoretical and experimental arrival times (t_i^{pexp}).

$$\min(x, y, z, t) \sum_i (t_i^p - t_i^{pexp})^2$$

To find the minimum of this function of several variables, the algorithm of Nelder & Mead (1965) is used. The sample body center point was chosen as the initial value for (x, y, z) and the initial experimental time is used as the starting value for the time.

The accuracy of event localization primarily depends on the correct identification of fracturing events w.r.t all the acquired events and secondarily on the precision of the time picked as first arrival. The uncertainty in the position of correctly identified events is estimated to be of the order of $\pm 4\text{-}8\text{mm}$. This is an acceptable range considering the diameter of the transducer component of the sensors to be 10mm .

5 Rock samples

5.1 Location and Rock type

As mentioned before, the lithology of the basement of Acoculco system constitutes mainly rocks like skarns and marbles which are formed as a result of contact metamorphism due to the granitic intrusion [1]. Therefore granite and marble samples seemed to be the best candidate for performing the stimulation experiment.

As shown in Figure 12a, the granite boulders collected from around Las Minas river bed are considered as the representative plutonic rocks of the Acoculco geothermal system. The plutonic rocks are exposed to the surface as a result of tectonic activity and are widely exposed in the entire Palma Sola Massif (the geological province where Acoculco is located). Figure 12b shows the skarn/marble quarry at Puebla Nuevo. The skarn/marble outcrops in this quarry are considered as analogues of Acoculco.

Table 1: Details of the sample locations

Type	Skarn / Marble	Granite
Location Type	Quarry	River Bed
Date	21.03.2017	21.03.2017
Location	Pueblo Nuevo	Las Minas
Country	Mexico	Mexico
State	Veracruz	Veracruz
Longitude	693048	694726
Latitude	2180273	2179109
Elevation (m a.s.l.)	2037	1260

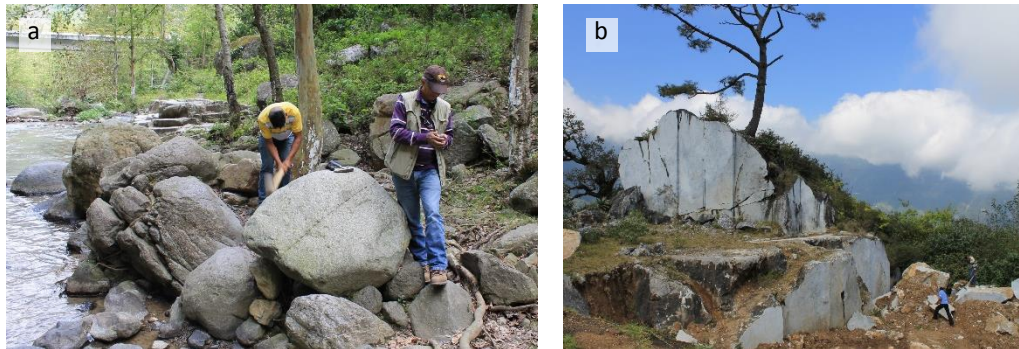


Figure 12: Sample acquisition in Mexico: a) Granite, b) Skarn / Marble

The big boulders of granite and marble samples were shipped to Germany with great difficulty due to transportation problems related to weight of the samples. Once the samples arrived, they were cut and polished according to the required dimensions for the experiments.



Figure 13: Samples after cutting and polishing

5.2 Petrophysical and elastic properties of material

The petrophysical properties of the rock samples – porosity, permeability and density are measured in the GGE laboratory. Porosity, bulk density and matrix density are measured by different techniques like Gas Pycnometer, Archimedes and MSCL (Multi Sensor Core Logger).

The compressional wave velocity of the sample is measured using MSCL in both dry and saturated conditions. These velocity measurements provide a good baseline for comparing the average velocity of samples obtained from Active Transmission experiment. The MSCL constitutes ultrasonic transducers to measure the P waves in a core and a gamma ray source and detector for measuring the attenuation of gamma rays through the core to provide density and porosity.

Intrinsic permeability of each sample is measured using Gas Permeameter. Permeability measurements are performed at 30 bar confining pressure. Measurements are made with Argon gas and converted to fluid-independent permeability according to Klinkenberg (e.g. Schön 1996).

Table 2: Properties of Marble

Property	Unit	Value	Method	Institute
Bulk density	kg/m ³	2721	MSCL	GGE
Matrix density	kg/m ³	2827	Gas pycnometer/ Archimedes	GGE
Young's modulus (static)	MPa	53600±9150	Chevron-Bend-Test	TU Delft/GiB
Poisson's ratio	-	0,28±0,02	Uniaxial compression test	GiB
Compressive strength	MPa	121±14	Uniaxial compression test	GiB
Tensile strength	MPa	10±2	Indirect tensile test	GiB
Permeability	m ²	10 ⁻¹⁷ *	Flow cell	GGE
Porosity	%	3-4	Archimedes	GGE
P wave velocity	m/s	4470 ±100 (dry) 5066 ± 34 (sat)	MSCL	GGE
Fracture toughness	MPa m ^{1/2}	1,15±0,52	Chevron-Bend-Test	TU Delft/GiB

Table 3: Properties of Granite

Property	Unit	Value	Method	Institute
Bulk density	kg/m ³	2707	MSCL	GGE
Matrix density	kg/m ³	2743	Gas pycnometer/ Archimedes	GGE
Young's modulus (static)	MPa	59500±1450	Chevron-Bend-Test	TU Delft/GiB
Poisson's ratio	-	0,28±0,07	Uniaxial compression test	GiB

Compressive strength	MPa	164±12	Uniaxial compression test	GiB
Tensile strength	MPa	15±1	Indirect tensile test	GiB
Permeability	m ²	9*10 ⁻¹⁸ *	Gaspermeameter	GGE
Porosity	%	1-2	MSCL	GGE
P wave velocity	m/s	4946 ± 57 (dry) 5542 ± 80 (sat)	MSCL	GGE
Fracture toughness	MPa m ^{1/2}	2,39±0,03	Chevron-Bend-Test	TU Delft/GiB

* reported permeability measurements are performed at 30 bar confining pressure.

6 Experiments and results

This chapter presents the results of the performed experiments on two granite and two marble samples. The table “Experimental setup” lists the boundary conditions for each experiment. The confining stresses σ_x σ_y σ_z are identical in each experiment as well as the pump volume at the start of injection V_{p0} and the injection rate during fracturing Q_p . In the first experiment “Granite 01” the fracture propagated to the outer edge of the sample. Therefore the Volume injected after peak pressure ΔV_p was reduced for the experiment “Granite 02”. In all other experiments ΔV_p is identical. The dynamic viscosity η of the injection fluid is temperature dependent and has been measured under experiment conditions for each experiment.

The figure “Pressure and injection rate” shows the injection pressure versus time as well as the injection rate. Further the number of accumulated acoustic events is plotted. The figure “Projection of localized AE and outline of coloured fracture zone” presents the results of the acoustic emission measurements. All localized acoustic events are plotted as dots in the z-x plane and the x-y plane and superimposed with the outline of the coloured fracture zone. The colour scale of the events represents the time scale and is identical to the one in the figure “Pressure and injection rate”.

Additionally Photos of the split samples are shown in the figure “Split plane with coloured and marked fracture zone”. The sample “Marble 01” was hard to split due to existing natural cracks. All other samples split clean along the fracture plane. The samples “Granite 02” and “Marble 01” are the ones where a core drill was taken to document the fracture via CT-scanning (see chapter 3). These pictures show the split core of the sample.

6.1 Granite 01 (GEMex 05)

Table 4: Experimental setup of Granite 01

Stress state			Injection			
σ_x [MPa]	σ_y [MPa]	σ_z [MPa]	V_{p0} [cm ³]	Q_p [cm ³ /min]	ΔV_p [cm ³]	η [Pa s]
15	15	5	5	0.1	1.5	0.58 ± 0.02

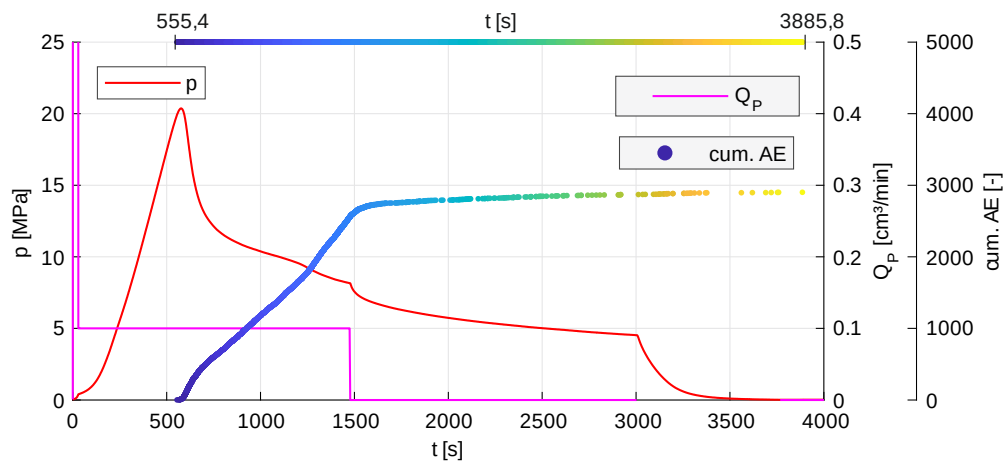


Figure 14: Pressure and injection rate of Granite 01

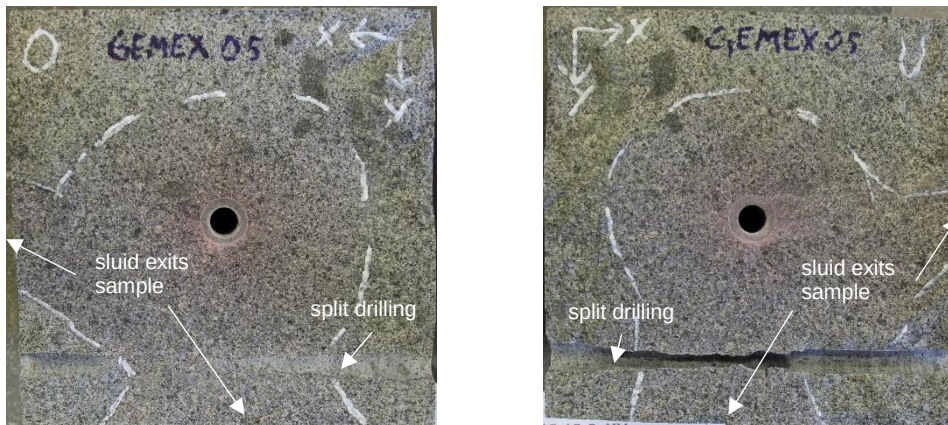


Figure 15: Split plane with coloured and marked fracture zone of Granite 01 (left: top piece, right: bottom piece)

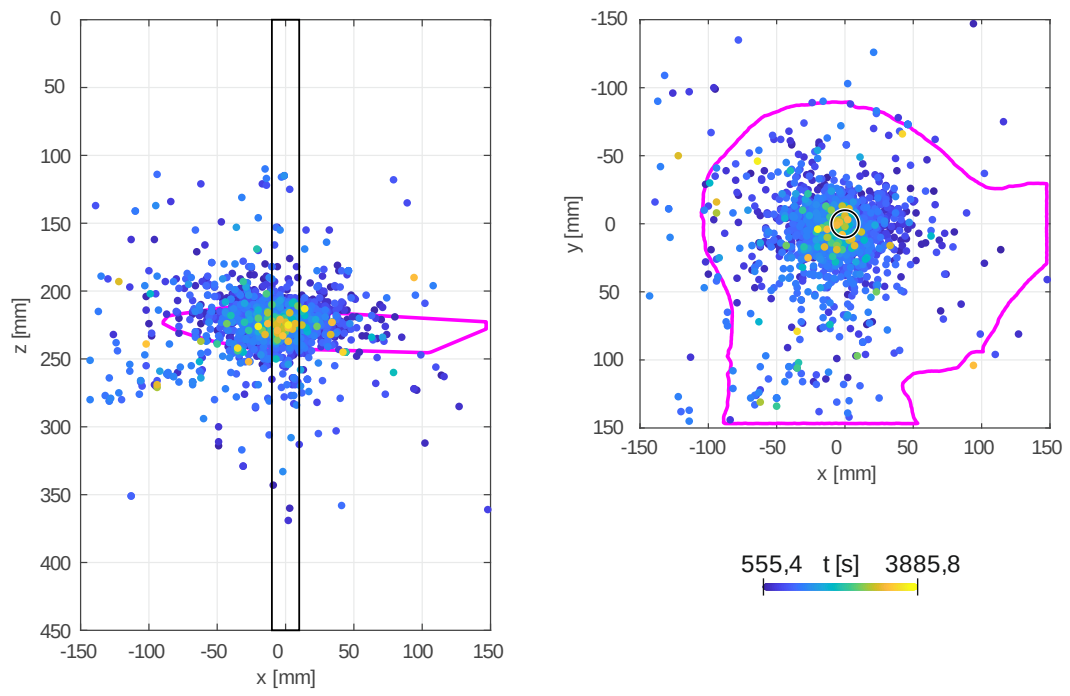


Figure 16: Projection of localized AE and outline of coloured fracture zone of Granite 01

6.2 Granite 02 (GEMex 07)

Table 5: Experimental setup of Granite 02

Stress state			Injection			
σ_x [MPa]	σ_y [MPa]	σ_z [MPa]	V_{p0} [cm ³]	Q_p [cm ³ /min]	ΔV_p [cm ³]	η [Pa s]
15	15	5	5	0.1	0.5	0.55 ± 0.02

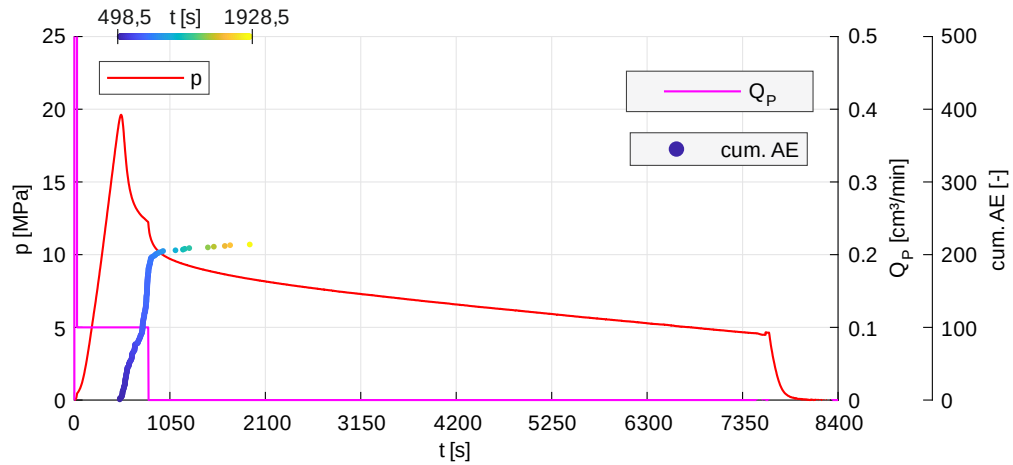


Figure 17: Pressure and injection rate of Granite 02



Figure 18: Split plane with coloured and marked fracture zone of Granite 02 (left: top piece, right: bottom piece)

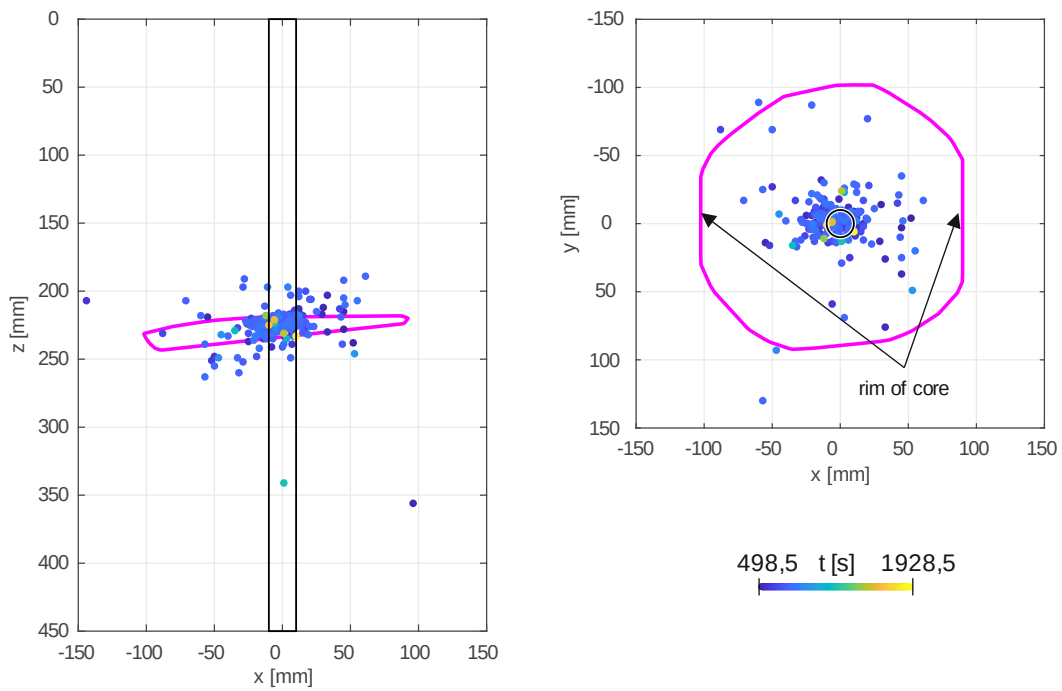


Figure 19: Projection of localized AE and outline of coloured fracture zone of Granite 02

6.3 Marble 01 (GEMex04)

Table 6: Experimental setup of Marble 01

Stress state			Injection			
σ_x [MPa]	σ_y [MPa]	σ_z [MPa]	V_{p0} [cm ³]	Q_p [cm ³ /min]	ΔV_p [cm ³]	η [Pa s]
15	15	5	5	0.1	1.5	0.56 ± 0.02

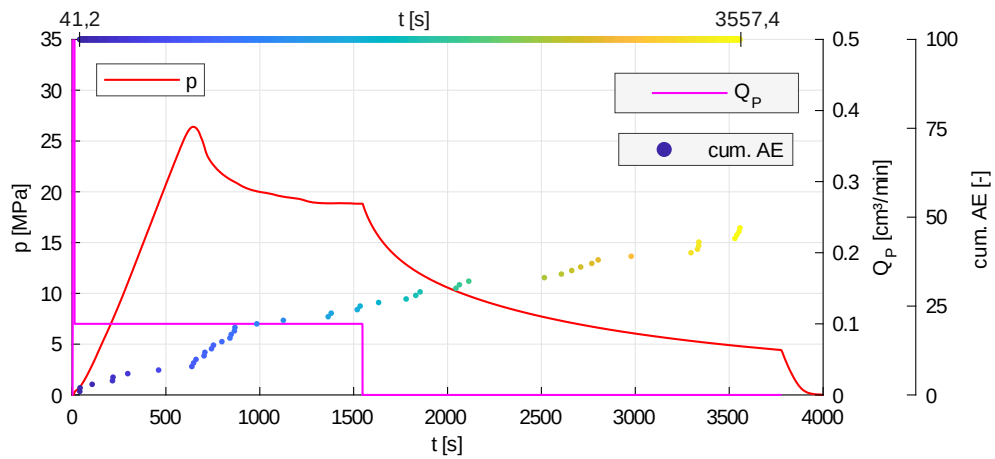


Figure 20: Pressure and injection rate of Marble 01



Figure 21: Split plane with coloured and marked fracture zone of Marble 01 (left: top piece, right: bottom piece)

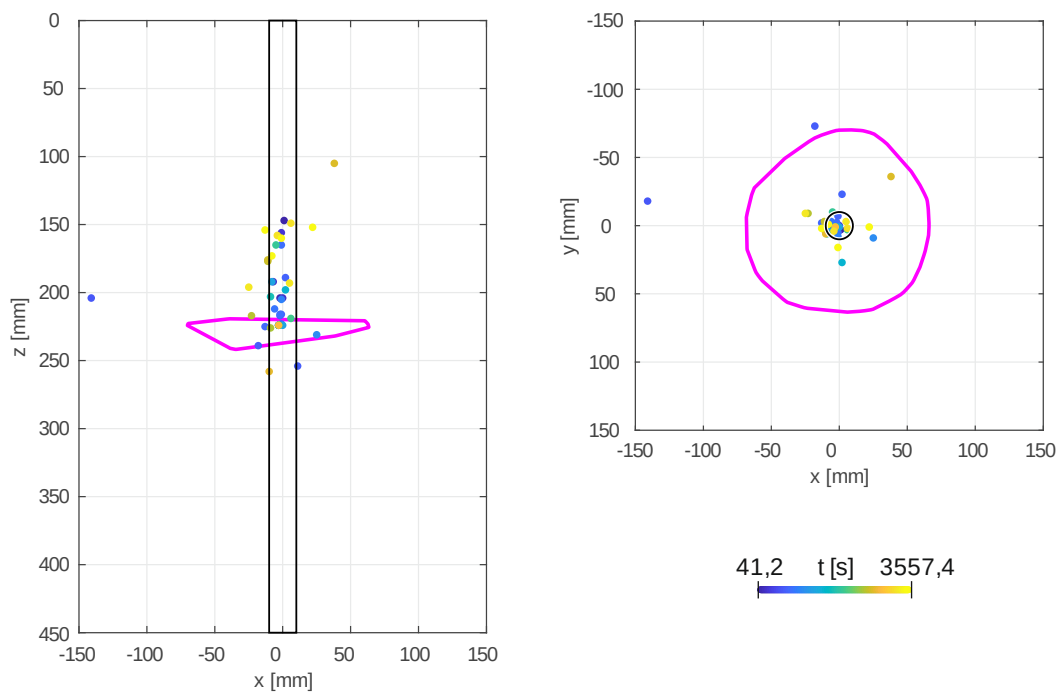


Figure 22: Projection of localized AE and outline of coloured fracture zone of Marble 01

6.4 Marble 02 (GEMex 06)

Table 7: Experimental setup of Marble 02

Stress state			Injection			
σ_x [MPa]	σ_y [MPa]	σ_z [MPa]	V_{p0} [cm ³]	Q_p [cm ³ /min]	ΔV_p [cm ³]	η [Pa s]
15	15	5	5	0.1	1.5	0.56 ± 0.02

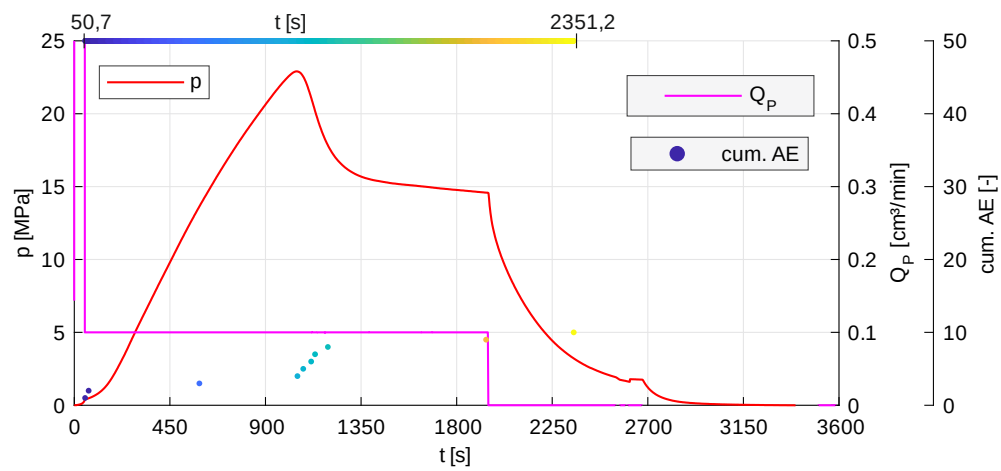


Figure 23: Pressure and injection rate of Marble 02



Figure 24: Split plane with coloured and marked fracture zone of Marble 02 (left: top piece, right: bottom piece)

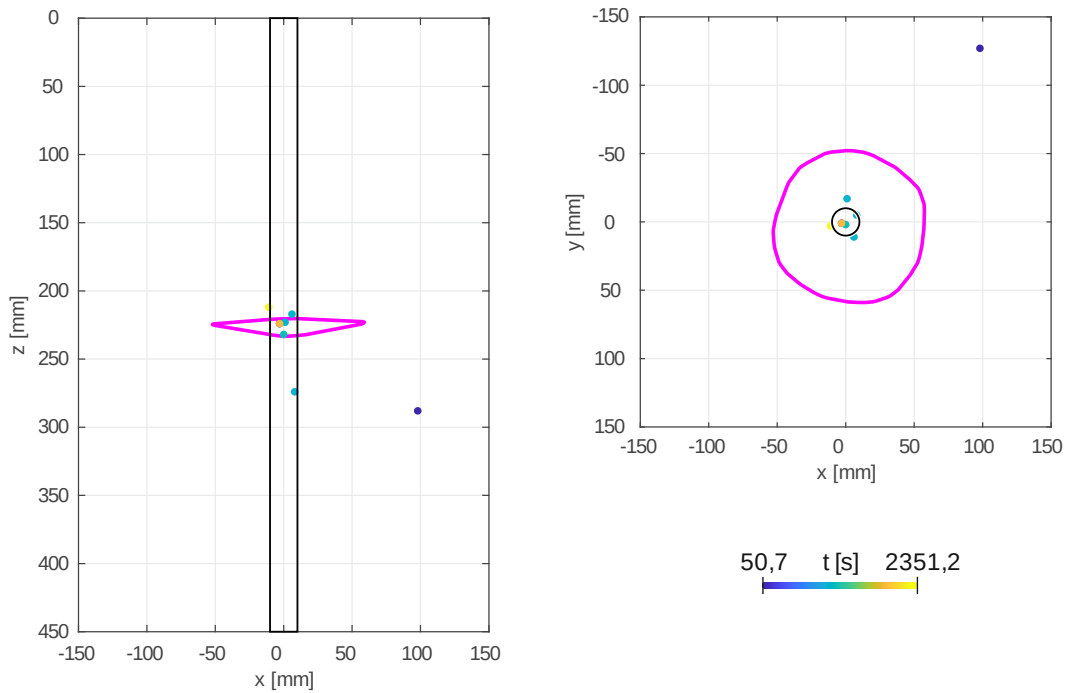


Figure 25: Projection of localized AE and outline of coloured fracture zone of Marble 02

7 Conclusion

With an objective of understanding the target formations of the EGS of Acoculco and generating a benchmark data set on hydraulic fracturing of rocks in laboratory conditions, experiments were performed on granite and marble samples under controlled conditions. Although only a small number of samples were available, reproducible results could be achieved. The peak pressure in the experiments with the granite samples was ≈ 20 MPa. The peak pressure of the marble samples had some deviation with 26 MPa for Marble 01 and 23 MPa for Marble 02. The fracture radii in the marble samples show good agreement (10-12 cm). For the granite samples the fracture radii cannot be compared due to the reduced injection volume in experiment Granite 02. Although the hydraulic fracture propagated to the outer edge of the sample in the experiment Granite 01, the pressure curve can be used for simulation. This report and the attachments include all information on the experimental setup and its boundary conditions necessary for simulation of the conducted experiments.

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9 References

- [1] Lopez-Hernandez et al., 2009, Hydrothermal activity in the Tulancingo–Acoculco Caldera Complex, Central Mexico, *Geothermics* 38 (2009) 279-293
- [2] Siebert, Philipp, 2017, Laborversuche zur hydraulischen Risserzeugung in dreiaxial belasteten Granitquadern, Doctoral Dissertation, RWTH Aachen University
- [3] Clauser, C., Willbrand, K., Ziegler, M., Feinendegen, M., Siebert, P., Fries, T.-P., Weber, N., 2015. Entwicklung eines Werkzeugs zur Auslegung von HDR-Risssystemen, (Unpublished) Endbericht zum BMWi-Projekt 0325167, Institute for Applied Geophysics and Geothermal Energy, RWTH Aachen University, Aachen
- [4] Akaike, 1973, Information theory and an extension of the maximum likelihood principle, *Proc. 2nd Inter. Symposium on Information Theory*, 267-281, Budapest.
- [5] Andy St-Onge, 2011, 058-Akaike_Information_Criterion_Applied_to_Microseismic_Data, 2011 CSPG CSEG CWLS Convention
- [6] Havskov, J., Bormann, P., Schweitzer, J., 2002. IS 11.1: Earthquake location. In: P. Bormann, (ed) *New Manual of Seismological Observatory Practice*, 2, p. 28, Deutsches GeoForschungsZentrum, Potsdam.
- [7] Nelder, J.A., Mead, R., 1965. A simplex method for function minimization, *The Computer Journal*, doi: 10.1093/comjnl/7.4.308.
- [8] Schon, J.H. (1996): *Physical properties of rocks*. Pergamon, Oxford.



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