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HYDRAULIC AND MICRO-SEISMIC RESULTS OF A MASSIVE STIMULATION TEST AT 5 KM DEPTH AT THE EUROPEAN HOT-DRY-ROCK TEST SITE SOULTZ, FRANCE

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ABSTRACT

By 2004/2005 a geothermal pilot plant for electricity production shall be completed at the HDR site at Soultz. This plant will consist of two production wells, one injection well and a reservoir in an ambient temperature of roughly 200°C. As a first step towards this ambitious goal the existing well GPK-2 was deepened from 3.8 km, where a large reservoir was already developed, down to 5 km, where the temperature requirements for an industrial power plant have been met. In a second step, a massive hydraulic stimulation with injection rates of up to 50 l/s was performed in summer 2000.

During this operation a large rock volume was activated for seismic slip. The locations of the micro-seismic events show that the mechanically affected rock volume is rather heterogeneous in shape having extensions of roughly 2.5 km in length, 0.5 km in width and 1.5 km in height. This is the largest volume ever stimulated in a single operation at Soultz. 3-D analysis and visualization of the seismic data reveals crucial insights into the internal structures of the seismic cloud.

Hydraulic tests before and after the stimulation confirmed that the hydraulic properties of the granite were permanently enhanced. Although the concept of hydraulic stimulation developed in the shallower system of Soultz approved to be also applicable at 5 km, some significant differences came out. The stress conditions as well as the connectivity to large scale fractures/faults seem to differ from what was observed at shallower depth.

INTRODUCTION

During the past decade numerous experiments have been carried out at the European Hot-Dry-Rock research site at Soultz (France) in order to develop a technique for the heat extraction from hot but low permeable rocks. During that period vast amounts of water were injected under high pressure into the fractured crystalline rock around the two boreholes GPK-1 and GPK-2. These stimulation treatments improved the permeability of the reservoir by at least a factor of 20 creating a large sub-surface heat exchanger at a depth of roughly 3.5km.

The efficiency of this man-made geothermal reservoir was demonstrated by a 3-month circulation test between GPK-1 and GPK-2 in 1997. Nevertheless it was decided to create a second, deeper reservoir to increase the possible production temperature for a future geothermal power plant. After having extended the borehole GPK-2 to a depth of 5 km, several measurements have been made in order to test the undisturbed formation. Then, the new heat exchanger was initiated by a first massive stimulation carried out during summer 2000.

The main objective of this experiment was to check whether the same techniques successfully applied in the upper reservoir could be transferred to greater depths. In case of a success, the project was meant to be continued with the drilling of two more deep wells and finally the construction of the first industrial HDR power plant in the world.

TEST PERFORMANCE

The performance of the stimulation 2000 required enormous efforts in terms of personnel, logistics and coordination. More than a dozen organizations were directly involved in the operations on site and contributed to a comprehensive scientific and reservoir engineering program.

Hydraulics

During a 6-day pumping operation a total fluid volume of 23,400 m^3 was injected into the new uncased section of GPK-2 (length 650 m, casing shoe at 4400 m TVD = true vertical depth). For this job, five high-pressure ram pumps were installed on site, leaving some spare capacity to ensure a trouble-free operation without to interrupt the pressure build-up in the reservoir. The injection proceeded at three different steps, 30 l/s, 40 l/s and 50 l/s and the pressure response was recorded down-hole (see *Figure 1*) with a probe positioned close to the casing shoe. The probe was equipped with a pressure sensor, a temperature sensor and a spinner and was assigned for conducting several PTS-logs during the course of the program. Unfortunately, due to technical problems only one log could be completed during the entire experiment. Pressure was also monitored in GPK-1 and in some other shallower observation wells in order to see whether the new reservoir would be hydraulically linked to the previous one. The entire injection fluid was marked with chemical tracers for later tracer test analysis. The tracer program was conducted by BRGM, France and the Energy & Geoscience Institute at the University of Utah.

Geophysics

The micro-seismic activity induced by the injection was monitored with a comprehensive seismic network consisting of three down-hole accelerometers (4-axis), two down-hole hydrophones and 15 mobile surface stations. In addition, 48 electrodes were installed around the site to perform a large electromagnetic survey. While the seismic down-hole network is part of the permanent Soultz equipment, the seismic surface network and the electromagnetic system were supplied and operated by 'L'Ecole De Physique Du Globe' at the University Louis Pasteur, Strasbourg.

Stimulation strategy

In the past it was found that fractures were preferably stimulated close to the casing shoe rather than along the entire open-hole resulting in lower production temperatures. This effect was considered to be related to the difference between the stress gradient in the rock and the pressure gradient in the well. With the objective to overcome this effect, a two-point strategy was developed. First, the stimulation was initiated by injecting 400 m^3 of heavy brine (saturated with salt, density 1.2kg/l) instead of fresh water to reduce the difference between the stress gradients. After having injected the saturated brine, the density of the fluid decreased continuously during a transition phase before pure fresh water was used. As a second measure, the stimulation was immediately started at a flow rate causing an overpressure high enough to create stimulation conditions along the entire length of the open-hole. This instantaneous rather than a stepwise pressure increase reduces the risk that shallower fractures are massively opened before the fractures in the deeper part of the well are exposed to stimulation conditions. The scientific team at Soultz was convinced that these two measures enhance the chance of creating flow paths at the deeper and hence hotter section of the well.

Pre- and post-stimulation tests

After 6 days of continuous injection, the well was shut in and the pressure decline was observed for one week. Then, a step-injection test with rates between 15 l/s and 35 l/s was performed within a period of 2½ days in order to check the impact of the treatment. Prior to the stimulation a series of hydraulic tests such as slug, production and injection tests was performed with the objective to subsequently quantify the stimulation success in terms of permeability enhancement.

HYDRAULIC RESULTS

The injection scheme and the corresponding down-hole pressure response is shown in *Figure 1*. The initial pressure at 4412 m was 43.37 MPa just before the start of injection. Within a few minutes only, the overpressure in the well could be raised by 10 MPa, then it continued slower until it reached a peak value of roughly 12 MPa. It is striking that during the first two steps the pressure went through the same peak and then declined again. This 'breakdown'-pressure was much lower than what was anticipated from the extrapolation of previous stress measurements in the shallower reservoir (estimates between 2-7 MPa higher, e.g. *Hettkamp et al., 1998)*.

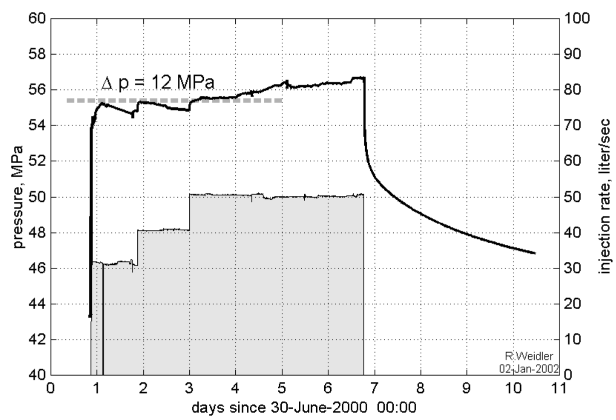

Figure 1: *Down-hole pressure (logging depth between 4412 m and 4436 m) and injection rate (gray) during the stimulation 2000. The dotted line marks an overpressure of 12 MPa.*

In contrast, during the last step the pressure first stabilized at an overpressure of ~12.2 MPa before to increase more or less continuously up to a final overpressure of 13 MPa. This anomalous behavior could be explained by a less permeable outer boundary of the reservoir allowing only small leakage to the far field. It is possible that during the last step the 'pressure front' reached this outer boundary and the ongoing injection continuously charged the reservoir. To overcome this barrier it might be necessary to inject at higher flow-rates and/or larger volumes.

The only successful PTS-log getting close to the bottom of the well could be run during the 30 l/s step. Due to the lack of caliper data below 4600 m, the conversion from spinner frequencies into flow rates contains some uncertainty. The main flow exits during the first injection step were localized at 4440 m (at the casing shoe), at 4760 m, at 4890 m and below 4950 m (all logging depths). It is remarkable that the exit at 4760 m (~20% of flow) coincides with a fracture zone predicted from the drill-cutting analysis and was also identified on temperature logs run during the pre-stimulation program. Following the converted flow rates, the deepest feature takes roughly 50% of the total flow. This feature was not detected by the cutting analysis but it also put a mark on the temperature logs. For future reference it has to be reminded that the given flow proportions are just estimates and that it is possible that the flow distribution changed during the following 5 days of injection.

When the well was shut in, the pressure dropped quickly by 4 MPa within 15 minutes before to turn into a very slow decline. Even after one week of shut-in, the pressure had still not reached its equilibrium value. Such a behavior was never observed before at the Soultz location. The upper reservoir, which is assumed to be in connection with a large-scale fracture network or fault system, respectively, always absorbed pressure disturbances within a short time compared to the duration of the disturbance (*Jung and Weidler, 2000*). *Figure 2* shows the shut-in curves of two comparable stimulation tests, one in the upper and one in the lower reservoir. The difference in the decline rate is obvious and supports the hypothesis that the deeper reservoir has tighter boundaries or is less well connected to a pressure absorbing system of fractures or faults.

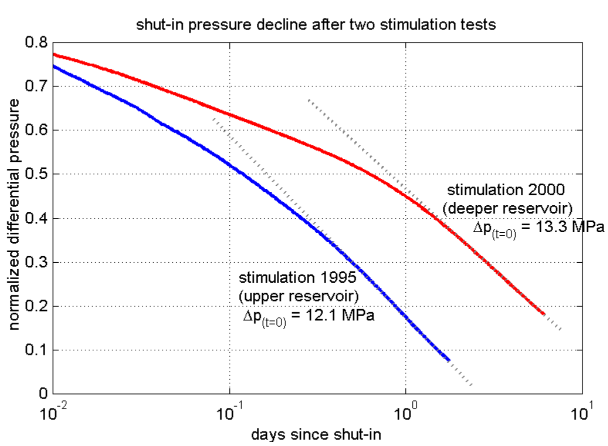

Figure 2: *Two shut-in decline curves after comparable stimulation tests in the upper (blue) and the lower (red) reservoir. The differential pressures are normalized and plotted in logarithmic time-scale. The dotted straight lines indicate the radial flow period and show the difference in the decline rate.*

On the other hand it appears that the internal permeability of the reservoir could be greatly enhanced. Prior to the stimulation a series of hydraulic tests such as slug, production and injection tests was performed with the objective to learn something about the natural conditions at 5 km depth and to be able later on to quantify the stimulation success. The results of the different tests were in good agreement suggesting a natural transmissivity of roughly 0.2 l/MPa/s or a transmissibility of 0.06 Dm. This is approximately 50% less than the value derived for the upper reservoir, which was precisely predicted from laboratory experiments and attributed to the increase in confining pressure (*Hettkamp et al., 1998*). It still exceeds the value of compact granite by 2-4 orders of magnitude thus proving the existence of naturally permeable fractures. From the post-stimulation tests it can be concluded that the transmissibility could be enhanced to a great extent. However, due to various technical reasons no data of sufficient quality could be obtained to date to make a precise quantification of the permeability improvement. The evaluation of the post-frac injection test became a difficult task because the down-hole probe failed during large proportions of the test and the overall test duration was too short. Nevertheless, a computation of the down-hole pressure was attempted and at least some data points could be retrieved from the test with sufficient confidence. These data points are plotted in *Figure 3* and compared with data from the upper reservoir before and after stimulation. The graph shows that – in spite of the uncertainty of the data – the effect of the two comparable stimulations in 1995 and in 2000 is at least in the same order of magnitude. A more precise investigation of the hydraulic properties of the new reservoir will follow in the near future.

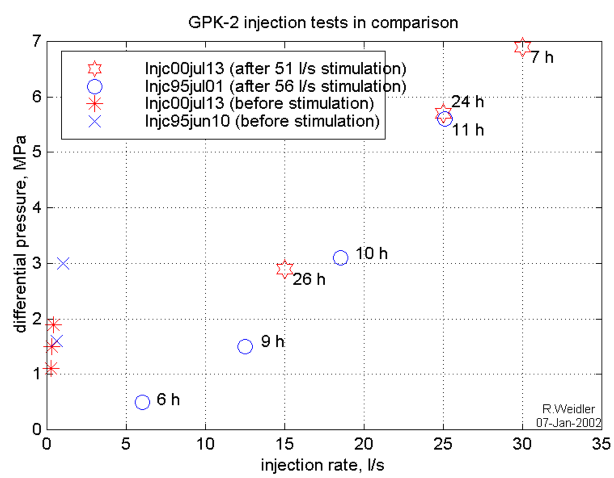

Figure 3: *Differential pressure values observed in the upper (blue) and the lower (red) reservoir before and after comparable stimulations for various injection rates.*

Another important conclusion can be drawn from the fact that no hydraulic response could be measured in any of the other wells. Hence, a direct pressure link between the upper and the lower reservoir can be excluded. This is also supported by the seismic data as will be shown in the next section.

During the following year after the stimulation, three production cycles were run to retrieve fluid from the reservoir and to analyze the fluid chemistry and the tracer concentrations. From the analyzes of the chlorine content in combination with two different tracers it could be clearly proven that the tracers were conservative, i.e. stable under the given conditions and that the injected fluid mixes with formation fluid. The driving force of the mixing process is likely to be internal free convection in the reservoir.

MICRO-SEISMIC RESULTS

During the seismic monitoring period 31511 triggers were recorded on the down-hole network from which 13986 events were located. *Figure 4* shows the event locations together with the events form previous stimulation tests at Soultz. The extension of the '2000 cloud' is roughly 2.5 km in length, 0.5 km in width and 1.5 km in height, which is the largest volume ever stimulated in a single operation at Soultz. It is obvious that the seismic clouds of the two reservoirs show no overlap, which is in agreement with the fact that no pressure reaction could be observed in the upper reservoir.

The seismic activity was high throughout the entire experiment (see *Figure 5*). After shut-in it decayed rapidly but a significant event rate persisted for at least three more weeks being consistent with the observation of a very slow pressure decline. This again is a remarkable difference to the upper reservoir where seismicity faded much quicker after shut-in. The fact that shearing occurred even at very moderate reservoir pressures could be an indicator that the stress conditions in the reservoir are close to critical. It was also surprising to see that the cloud even continued growing after the injection stopped. Most of the events in the south (the less populated zone in *Figure 4*) occurred after the stimulation. Up to now there is no convincing explanation for this phenomenon.

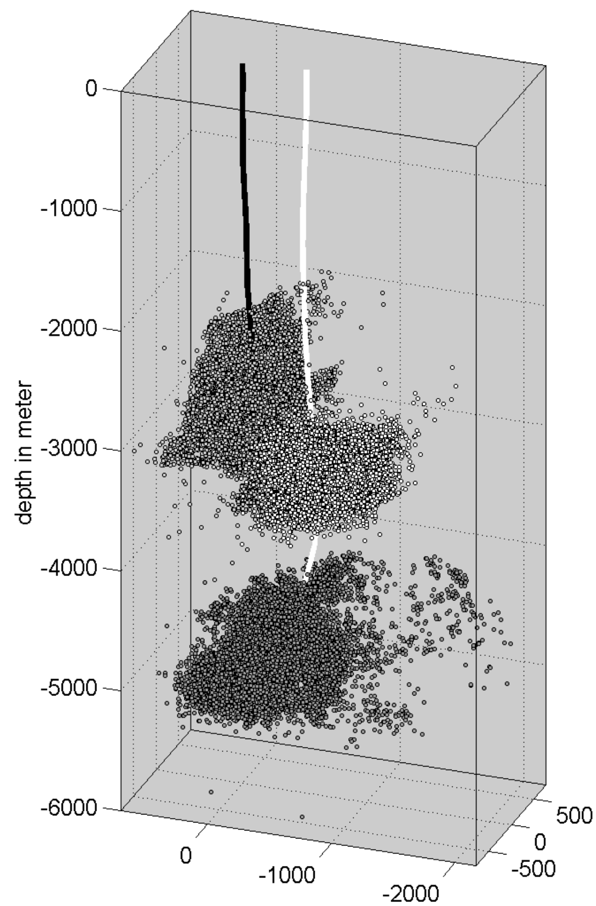

Figure 4: *Located seismic events in the shallower and the deeper Soultz reservoir. Black line: GPK-1; white line: GPK-2; dark dots: stimulation of deepened GPK-2; light dots: stimulation of shallow GPK-2; medium dots: stimulation of GPK-1. The long axis is positive to the North.*

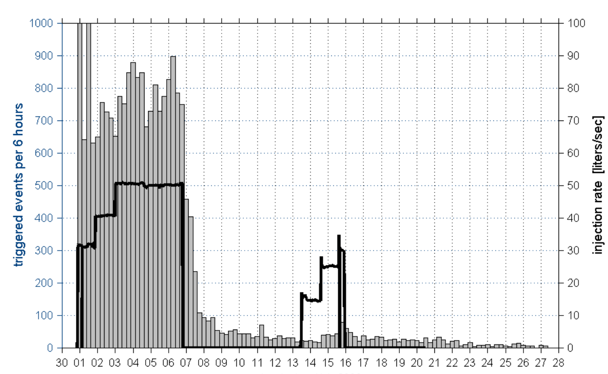

Figure 5: *The number of seismic events and the corresponding injection rates during the stimulation and the 'post-frac' injection test.*

The depth distribution of the events is plotted in *Figure 6*. The two main peaks correlate with the casing shoe and the permeable fracture zone that was identified in the drill cutting analysis (*Genter et al., 1999*), the PTS-log and the pre-stimulation temperature profile. Although the casing shoe still remained a preferred seismic zone – as expected from previous experiences – it is clear that the growth of seismicity was mainly downwards this time. A significant number of events as far as 400 m below the bottom of the well is again in total opposition to what was observed in the upper reservoir. It is possible that the applied stimulation strategy encouraged the stimulation of the deeper section but to extend this effect far beyond the well a stress field becoming more favorable with depth in combination with pre-existing permeable fractures seems to be essential.

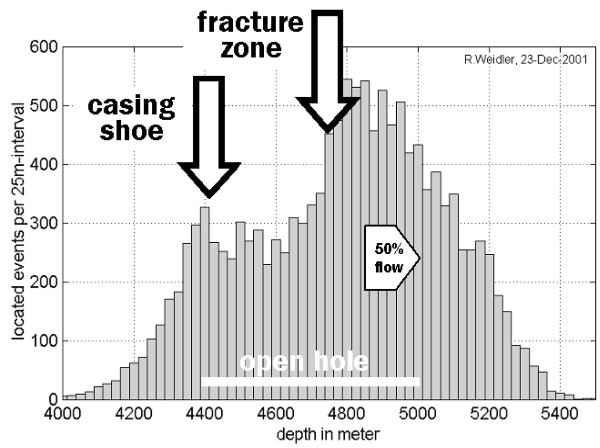

Figure 6: *The depth distribution of the located events. The open-hole and the section where about 50% of the flow left the well are marked. The main peaks correlate with the casing shoe and a natural fracture zone.*

In order to identify possible structures within the diffuse cloud, the spatial event distribution was analyzed using a 3D-visualization. Assuming that the reservoir contains dominant structures, like large fault zones, rather than to be formed by a more or less homogeneous network of small and medium scale fractures, it is conceivable that the large structures would become visible as zones of increased seismic activity. *Figure 7* shows the spatial event density on three orthogonal slices through the cloud demonstrating that the events are not evenly distributed within the activated volume. In this special representation the region of highest seismic activity can be described by a plane striking N157°, dipping 75° to SW. The plane intersects the well at about 4700 m TVD, which corresponds to a logging depth of 4760 m. It is striking that this depth again coincides with the repeatedly mentioned fracture zone and it seems that this feature has controlled the growth of the seismic cloud to a major part. The existence of such a seismically active fault is further supported by the fact that it would be favorably oriented for shear failure assuming the main horizontal stress roughly in North-South direction as it was observed in the upper reservoir.

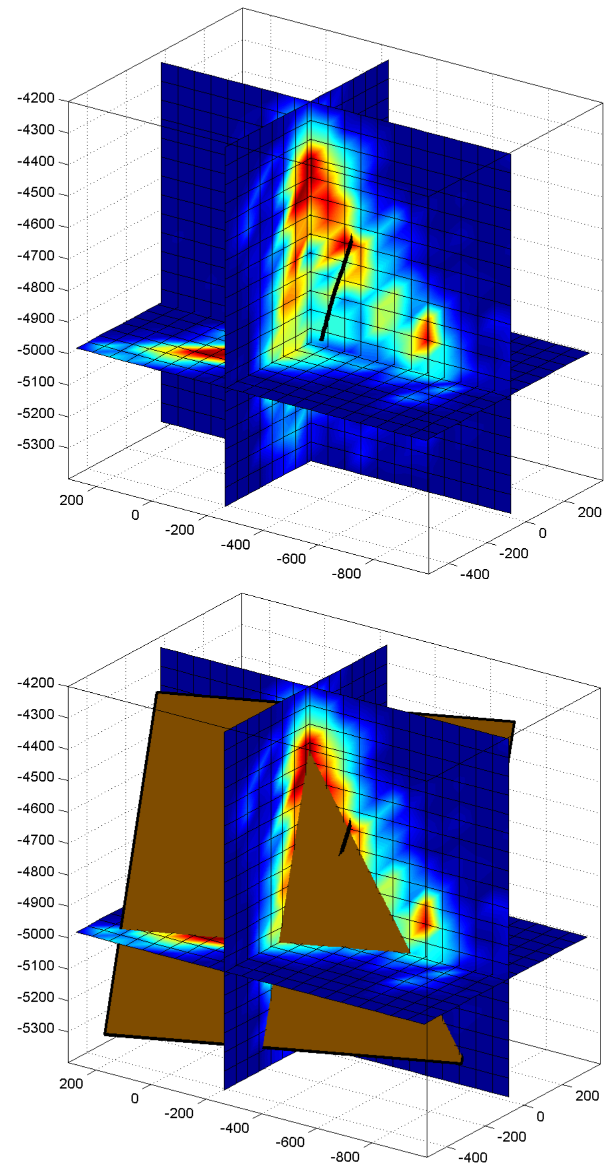

Figure 7: Upper: *Three orthogonal slices through the density distribution of the located seismic events during the stimulation 2000. Warm colors indicate high density. The black line shows the uncased section of GPK-2. The coordinate system is the same as in Figure 4.* Lower: *The region of highest seismic activity can be described by a plane striking N157°, dipping 75° to SW. The plane intersects the well at about 4700m TVD (~ 4760m logging depth).*

CONCLUSIONS

The stimulation 2000 proved that the concept of hydraulic stimulation developed at Soultz can be applied at a depth of 5 km with similar success. Prerequisite for this transferability is surely the fact that the granite encountered between 4 to 5 km depth also contains permeable fractures/faults. A large rock volume could be activated for shear failure causing a permanent enhancement of the reservoir's permeability. However, some significant differences to the shallower reservoir came out.

In contrast to the upper reservoir, the growth of the seismic cloud was mainly downward oriented. Due to the lack of stress data below 3800 m it is unclear to which part this was controlled by the stimulation strategy and to which part by the stress field or even by dominant pre-existing flow paths. However it be, the effect is very desirable since it promises higher production temperatures for the future power plant.

Another difference was observed concerning the seismic activity. Not only that the affected rock volume was larger than ever before but also that the seismicity persisted for a long time after shut-in when the pressure in the reservoir already approached its initial value. This phenomenon together with the fact that the stimulation pressure was much lower than anticipated from the extrapolation of previous stress measurements could be evidence that the reservoir is in a critical state of stress.

The shallower reservoir was often depicted as 'open system' because of its characteristic feature to absorb any kind of pressure disturbance within a short time. It is assumed to be connected to a constant pressure boundary that could be formed by large scale fracture or fault system. The deep reservoir behaves rather like a 'closed system' which is revealed by the continuous pressure increase ('charge') during the final injection step, the slow pressure decline after shut-in and the tight 'cap' on top of the reservoir (no pressure response in the upper reservoir). The reason for the tightness could be the missing link to the large-scale fracture/fault system.

The three-dimensional analysis of the spatial event density revealed a high concentration of events along a zone that can be very well described by a plane striking N157°, dipping 75° to SW. This hypothetical fault plane would intersect the well at about 4700 m TVD (~4760 m logging depth), which coincides perfectly with a fracture zone detected by various other measurements. The existence of such a fault having dimensions of several hundred meters would of course significantly influence the hydraulic and thermal behavior of the system and should also be taken into consideration for the targeting of the next borehole.

The principle mechanism of hydraulic stimulation in fractured hard rock is still not fully understood. It is therefore important to use all the information available and to make integrated interpretations. The information gathered in this paper will soon be used to define and constrain numerical reservoir models with the objective to foresee the long-term behavior of the system and to support the reservoir engineers in their design of the plant.

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