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IMPROVING HYDRAULIC STIMULATION EFFICIENCY BY MEANS OF REAL-TIME MONITORING

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ABSTRACT

In contrast to geo-pressurized hydrothermal systems, where it is often possible to exploit the heat in a simple production mode, EGS (Enhanced Geothermal Systems) or HDR (Hot Dry Rock) systems in low permeability host rocks require the re-injection of fluid in order to sustain the pressure and a steady flow in the reservoir. In the ideal case, this is realized in a virtually closed loop system with a mass balanced circulation between the production and the injection wells. In turn, a balanced circulation places high demands on the connectivity of the man-made subsurface heat exchangers. To achieve the desired connections, a hydraulic stimulation has to be designed and performed in the context of the total reservoir geometry and not only for each well separately.

Numerical computations show that even small gaps between the stimulated zones result in a significant drop in productivity, even though each well has been individually stimulated to a high degree. For example, such a situation can arise when a stimulation job is aborted too early. On the other hand, field examples also show cases where the efficiency of a hydraulic stimulation decreased during pumping without being notified in the hydraulic data. This creates superfluous costs if the pumping strategy is not adjusted accordingly.

The risk of both, creating heat exchangers of poor connectivity and inefficient pumping can be significantly reduced when the spatio-temporal expansion of the stimulated zones is monitored and interpreted already during the operation. For this purpose, the analysis of microseismic events occurring during a massive hydraulic stimulation has established itself as the most promising method. However, the lack of computing power and reliable and fast algorithms, as well as the extraordinary size of the data sets, sometimes exceeding several ten-thousand events, has limited a real-time analysis of microseismic data in past experiments. In the field, the decision making with regard to the pumping strategy had to be done on the base of hydraulic data mainly, and information on the spatial impact of the operation was often not available when needed.

Recent developments have yielded a software package capable to process and interpret huge microseismic data sets automatically and in real-time speed. By an integrated seismo-hydraulic analysis this software provides a valuable tool for the decision making in the field.

THE IMPORTANCE OF HYDRAULIC CONNECTIVITY FOR EGS SYSTEMS

Aside from volcanic regions, most places in the world do not exhibit natural geological structures where temperature and rock-permeability meet the conditions required for a geothermal power production. The EGS concept implies the creation of an artificial subsurface heat exchanger by enhancing the rock permeability in a spatially confined region. Such a reservoir stimulation is achieved by injecting large volumes of fluid into the host rock under high pressures. Depending on rock properties and stress conditions, different types of mechanical processes may cause an increase of the permeability. Above the jacking pressure (~ the least principal stress), hydro-fracturing or hydraulic opening of pre-existent fractures can lead to a substantial permeability increase. However, to keep artificially jacked fractures open after the release of the stimulation pressure, the addition of proppants to the injected fluid is frequently required. In the EGS context, however, the addition of proppants is usually not recommended because of their limited penetration depth and their relatively high costs. Instead, the EGS concept relies mainly on the effect of natural or “self-propping” (Jung, 1987), which occurs below the jacking-pressure. The underlying principle is based on the excitation of shear displacement along fracture surfaces. After the pressure is released, the fractures do not collapse but retain a certain rest aperture due to the irregular, rough nature of the displaced fracture surfaces. Since this shearing process is accompanied by the emission of seismic waves, it directly provides access to the mapping of stimulated regions by locating induced seismicity. The importance of this kind of mapping is demonstrated by the following simple example.

One of the most challenging parts during the creation of a subsurface EGS system is the proper geometrical arrangement of the injection and production wells with respect to the stimulated zones, which determines both the friction losses and the thermal life-time of the system. This is illustrated in Figure 1 sketching two hypothetical scenarios for a doublet system consisting of an injector (left well) and a producer (right well). For both models the distance between the wells is identical (600 m) and both wells have been stimulated such that the permeability in regions surrounding the wells (denoted by ellipses) is increased by a factor of 100 compared to the host rock permeability. The only difference between the two models is the gap between the stimulated zones in model 1 being closed in model 2.

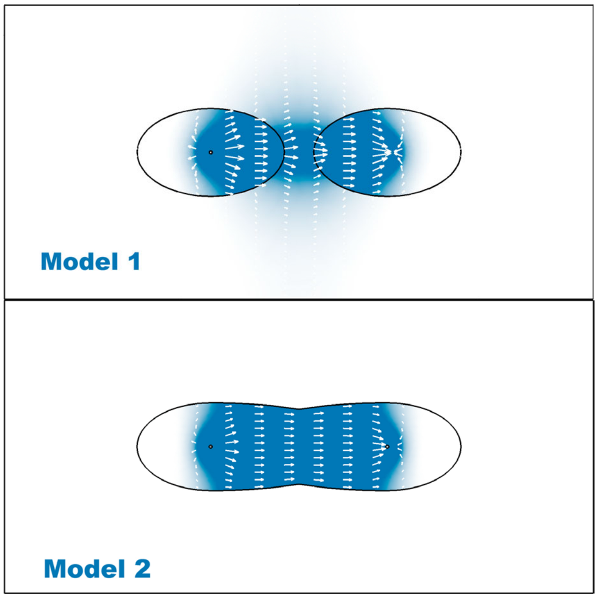


Figure 1: Numerical simulation of a doublet circulation. Non-overlapping (top) and overlapping (bottom) stimulated regions of enhanced permeability are denoted by ellipses. Arrow size and color intensity are proportional to flow velocity.

Although all wells have been stimulated to the same degree, the differential pressure required for circulating a flow of 25 l/s is 32 MPa for model 1, whereas it is only 3 MPa for model 2. Additionally, fluid losses occurring in model 1 (shaded area) may lead to a negative mass-balance in some cases, which in turn might considerably reduce the efficiency of the system. From an economic point of view, a system like model 1 would be probably shut down, whereas model 2 could represent a highly profitable EGS system.

What can be done to avoid a scenario like model 1 that could be a typical result from a stimulation abandoned too early? During a stimulation, there are various hydraulic parameters that control the reservoir formation. These include the injection strategy, determined by the injection rates, the injection pressures, and the injected volumes. But also fluid parameters like density, viscosity, temperature etc. or fluid additives can have major effects on the reservoir formation. Usually those stimulation parameters are pinned a priori in the test design, which is based on various considerations. Because of the complexity of the processes, however, the impact of hydraulic operations can be predicted to a limited extend only. Therefore, the theoretical design of a stimulation generally holds only for the rough planning of the operation, such as principal strategy, logistics etc. Experiences in more than a dozen massive stimulation jobs all over the world showed that monitoring and reacting is more important for a successful operation than designing and predicting. Generally, a stimulation strategy is modified a few times according to the actual reaction of the system. For controlling the impact of hydraulic operations and adjusting the parameters mentioned above, a combined seismo-hydraulic analysis carried out already in the field provides today's most promising approach for the generation of high connectivity systems similar to model 2.

SEISMO-HYDRAULIC REAL-TIME ANALYSIS

From a stimulation manager's point of view, there is a variety of desired "seismic" information that may critically contribute to the design and adjustment of a hydraulic operation. For technical reasons, however, not all of this information is available already in the field but requires a more time consuming data post-processing. Therefore automatic data processing plays a decisive role, especially if the data sets become so large that manual data processing is out of the question due to the sheer size of the data sets. In the following, we will focus on three field examples where we outline the importance of a real-time analysis in the field.

Injection experiment at the KTB (Germany)

The first data set exemplifies how critical information about the impact of an injection can already be obtained by very simple means. The data example stems from a scientific injection experiment conducted in 2000 at the 9.1 km deep KTB well in Germany (Baisch et al., 2002). The long-term injection was monitored by a 40-element seismic surface network in combination with a downhole seismometer located at 3.8 km depth in a nearby well.

Because of the comparably low sensitivity of the surface stations, the monitoring of induced seismicity during the injection experiment was primarily done on the basis of the downhole recordings. The single station analysis provided information on event rates, magnitudes, and hypocenter depths derived from time-differences between S and P phase onsets (Figure 2). Due to the limited number of events, this kind of data processing could be done by visual inspection in near-real time whereas data processing of the complete 40-element network could not be done with the means available at that time.

At the very beginning of the experiment, induced seismicity indicated that fluid was not injected into the open-hole section at 9 km depth (which would result in S-P times of about 0.6 s in Figure 2), but unexpectedly at much shallower depth (i.e. S-P times of about 0.2 s in Figure 2). On the basis of this observation, several leaks in the casing of the well were postulated already at an early stage of the injection, leading to a re-evaluation of the experiment design. The seismically detected leaks have been confirmed after the experiment by temperature and spinner logs.

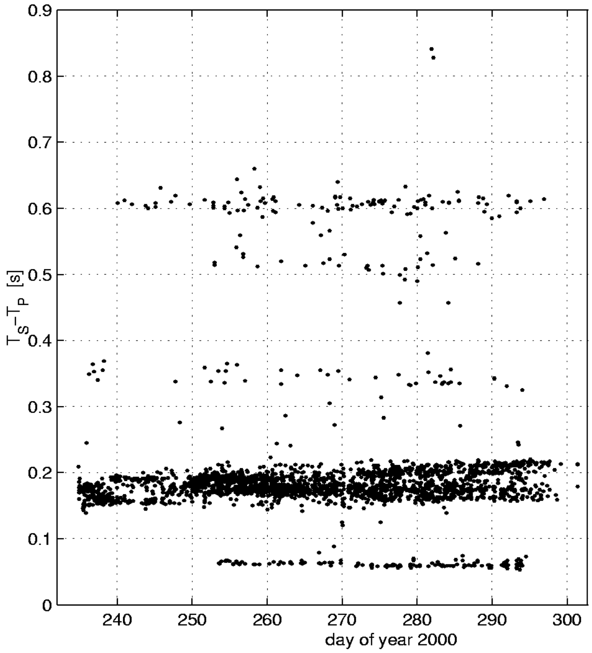


Figure 2: Time-differences between S and P onsets for injection induced events at the KTB (Germany) plotted against P-onset time (days in year 2000). The graph indicates fluid leakage at various depth levels. Events were recorded by a downhole instrument in ~3.8 km depth. Figure after Baisch et al. (2002).

Due to the specific motivation of this experiment, namely the analysis of earthquake source mechanism and the local stress field, it was possible to make a virtue of necessity and to continue the injection in order to study the parameters of interest as a function of depth. However, a similar scenario occurring in a commercial project had led to tremendous additional costs – if not a hazard – in case the pumping had been performed through unrecognized leaks.

Injection experiment at Bad Urach (Germany)

The second data example stems from an injection test conducted in the summer of 2003 at the EGS site in Bad Urach, Germany. This experiment was designed to (i) hydraulically test the reservoir that was created during the summer of 2002 (Tenzer et al. 2003) and (ii) to enlarge this reservoir by a long-term re-stimulation during a second phase. In order to avoid the disturbance of the well-testing data by any stimulation effect ahead of schedule, it was necessary to recognize the onset of re-stimulation and to adjust the injection plan accordingly. In the second phase, the efficiency and the geometrical impact of the re-stimulation had to be evaluated continuously to avoid reservoir growth in unwanted directions and unnecessary pumping costs, respectively. This placed a high demand on the continuous analysis of the experiment.

For cost reduction reasons, the seismic and hydraulic data were transferred constantly to Q-con’s offices and were processed in near-real time using an automatic processing software package (QUBE). From a combined seismo-hydraulic analysis it was then possible to recognize the onset of re-stimulation which occurred after ~ 10 days of pumping (Figure 3, top). Based on this observation, the well-testing phase was completed by a shut-in period. After the resumption of pumping (day 15), the observed hydraulic response of the system started to deviate from the curve computed with the reservoir model valid at that time (Figure 4), accompanied by a clear increase in the seismic energy release (Figure 4, green curve). This was indicating the change of hydraulic parameters obviously associated with the re-stimulation of the reservoir. Subsequently, the monitoring of the re-stimulation phase enabled us to continuously confirm the stimulation efficiency in terms of a continuous improvement of the hydraulic properties and of a reservoir growth into the desired direction (Figure 3, bottom). The seismo-hydraulic monitoring performed during a period of about 4 weeks allowed for an almost exact realization of the experimental design and a high degree of control.

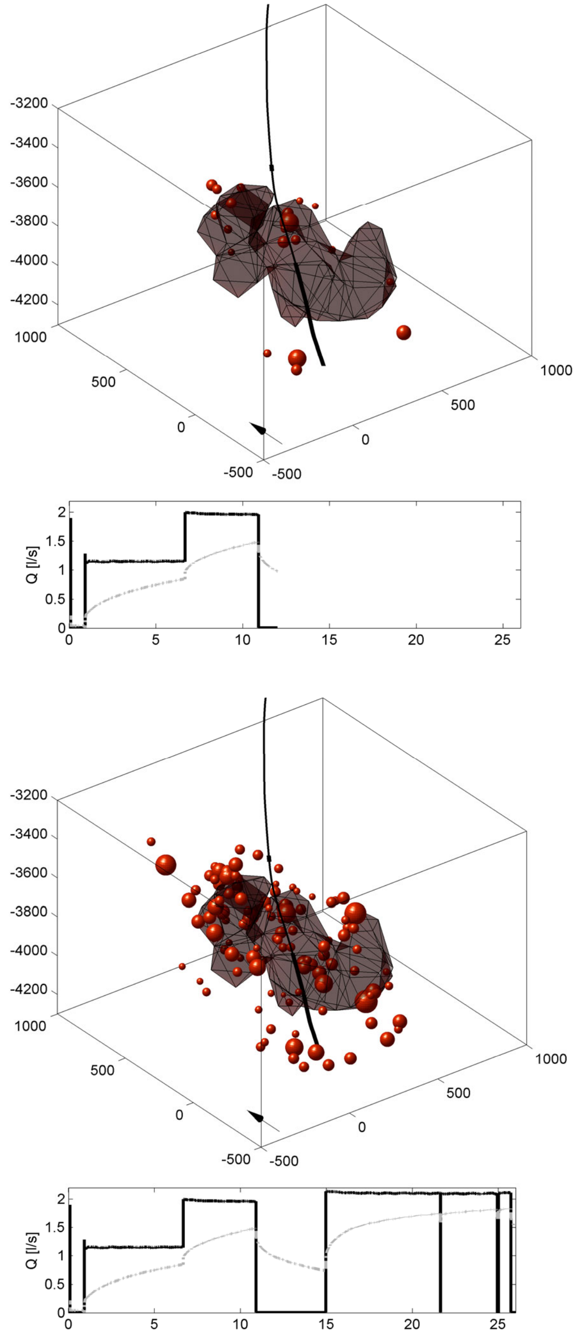


Figure 3: Induced seismicity (globes, scaled with respect to magnitudes), injection rates (black) and pressure (gray) after 12 (top) and 26 days (bottom) of an injection test at Bad Urach (Germany). The transparent iso-surfaces denote the seismically determined geometry of the region stimulated one year before.

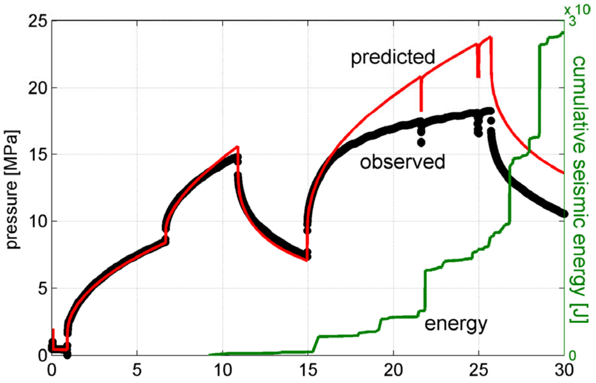


Figure 4: Predicted (red) and observed (black) hydraulic response (plotted against days) during an injection test at Bad Urach. Cumulative seismic energy according to the right axis label is shown by the green curve. Deviations from the predicted hydraulic response closely follows the onset of induced seismicity indicating non-stationary hydraulic parameters associated with the re-stimulation of the reservoir.

Stimulation experiment at Soultz (France) in 2003

The last data example demonstrates how very large data sets can be analysed in real-time using automatic processing software. The data example stems from an EGS stimulation of the well GPK-3 at Soultz-sous-Forets (France) in summer 2003. During approximately two weeks of stimulation activities nearly 80,000 seismic events were triggered at a 5-element downhole seismic network. Even with a trained team, a seismic data set of this size would normally require several months of manual processing, making comprehensive results available only long after the stimulation has been terminated. Therefore, fully automatic data processing algorithms provide a key to the real-time analysis of this kind of data set. We used the QUBE software package to process the seismic data set in an offline mode (after the stimulation) mimicking real-time conditions in the sense that the complete data set recorded over a period of roughly 2 weeks was automatically processed in less than 4 days. From the total number of roughly 80,000 triggered event files, about 13,300 hypocenters were determined automatically. These are shown in Figure 5. To evaluate the quality of the automatic processing we randomized about 6,000 samples out of the complete data set and visually re-inspected the automatically determined phase picks and associated hypocenters. This consistency check revealed that a considerably large number of rejected events (i.e. events for which hypocenters could not be determined automatically) is caused by very small events that were recorded only by a single instrument, and also by larger events that have been triggered more than once on the local acquisition system but were counted only once by QUBE. For all located events we estimate that more than 95% agree with the solution that could be expected from manual phase picking (within the confidence limits of typically several 10 m to 100 m).

We note that both the orientation and the overall shape of this seismic cloud is in good agreement with the existence of a wide extending fault zone postulated from the analysis of the stimulation of GPK2 in the year 2000 (Weidler et al., 2002). A combined analysis of both stimulations is part of current investigations.

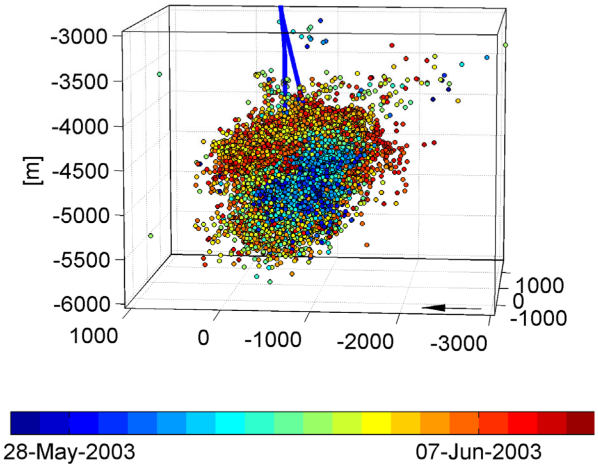
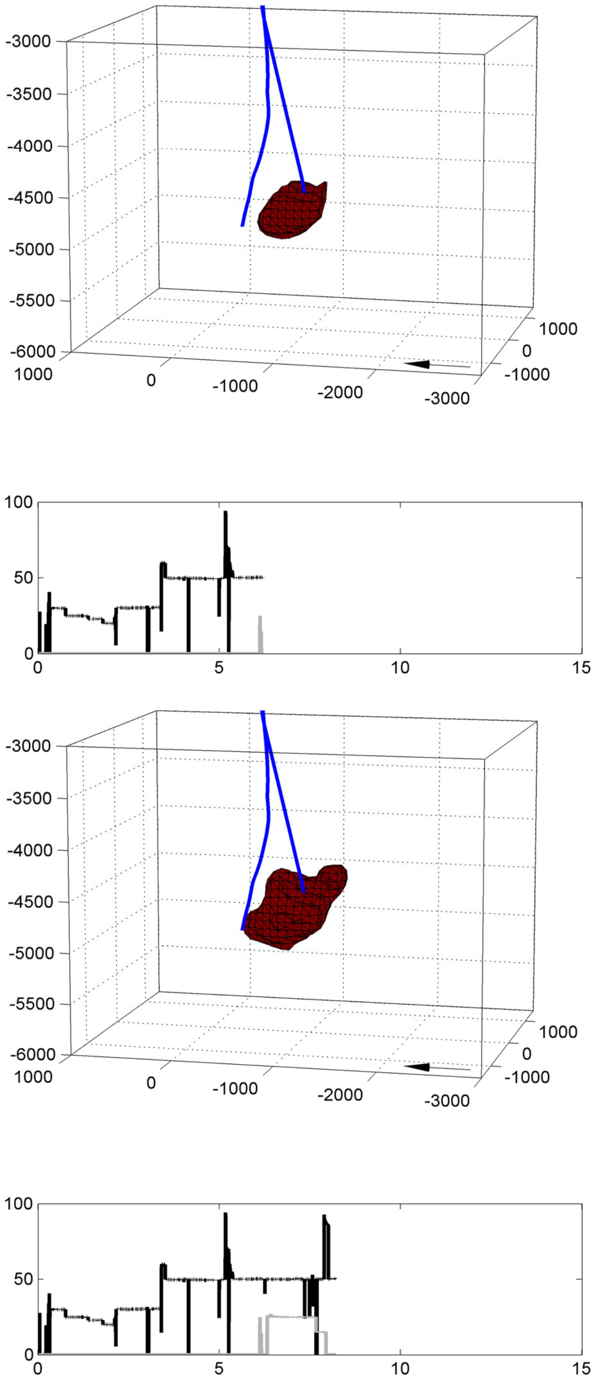


Figure 5: Hypocenter locations of ~13,300 events induced during the stimulation of the well GPK3 (right blue line) in 2003. Color encoding denotes event times according to the colour bar. Hypocenters have been determined automatically by the QUBE code.

To analyze the impact of the stimulation in more detail, Figure 6 shows injection rates and induced seismicity (displayed as isosurfaces of the seismic density) for different time intervals. At the very beginning of the stimulation, we note that the seismic cloud starts growing from the injection well GPK3 towards the second well GPK2. With the onset of a dual-injection (i.e. injecting into well GPK3 and GPK2 simultaneously) after approximately 6 days, a sudden and rapid growth of the seismic cloud towards SSE was observed (Figure 6; top, middle), followed by an upward migration of the seismicity in the centre region between the two wells (Figure 6; middle, bottom).



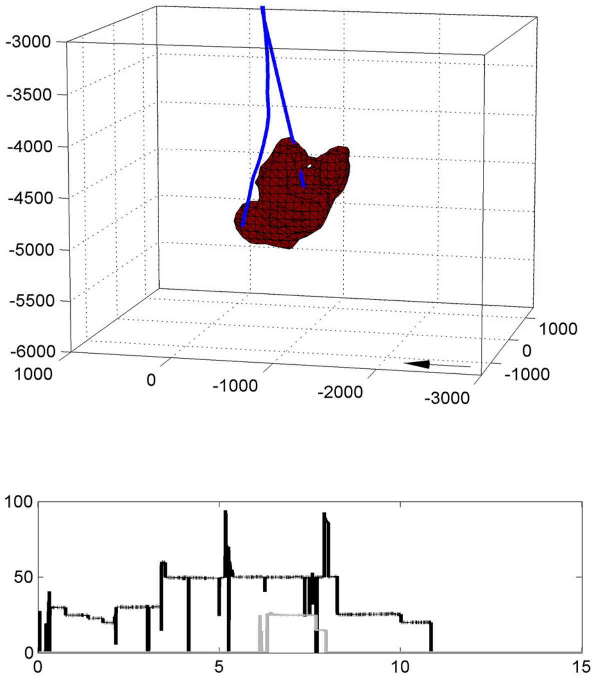


Figure 6: Seismic images of the stimulation of well GPK3 (right trajectory) and associated injection rates after 6 (top), 8 (middle), and 11 (bottom) days of injection. Seismicity is shown by iso-surfaces drawn at 12 events per cubic bin of 80 m side length. Injection rates are shown in the lower axes in liter/sec vs. days. After ~6 days a dual-injection was performed (gray line in rate-plots) using well GPK2 (left trajectory) as additional injector.

Simple hydraulic principles that had been considered during the design of the operation suggested that the implementation of a second injector has the same effect as a no-flow boundary in between the two wells causing a redistribution of hydraulic overpressures, especially an increase of pressure in between the two wells. To a certain extent, the seismic images shown in Figure 6 confirm that the technique worked as projected, even though a more quantitative analysis of the spatial distribution of overpressures based on hydraulic modelling is complicated due to the continuously changing reservoir geometry (i.e. the time-dependent distribution of permeability). Nevertheless, the evolution of the seismic cloud itself (as shown in Figure 6) can be regarded as an indicator for the spatial distribution of hydraulic overpressures. Following this line of argument we could interpret the observed increase of seismicity in between the two wells (Figure 6; middle, bottom) as an indication for comparable large overpressures in this specific region caused by the artificial no-flow boundary induced by GPK2. Since fluid flow from GPK3 towards GPK2 had been inhibited to a certain extend, this can also explain the observed growth of the seismic cloud towards SSE (Figure 6; top, middle), which is into the opposite direction of the no-flow boundary. As all these considerations can be made already in the field, the seismo-hydraulic real-time analysis provides a powerful decision making tool to steer even complicated operations such as a dual injection.

CONCLUSIONS

On the basis of several fluid-injection experiments it has been demonstrated how real-time data analysis can provide essential information for the stimulation management with respect to the efficiency, the cost reduction and last but not least the hazard prevention. It has been shown that automatic processing software is a crucial element, especially for massive hydraulic stimulation jobs where the data sets become too large for manual processing. Still, the seismic real-time software is only a component of an effective real-time monitoring. To provide a decision making tool it is necessary to combine seismic, hydraulic and other observations and to make an integrated field-interpretation, which cannot be provided by any 'black-box' software alone. However, today's technologies can significantly relieve the managers in charge of a stimulation job and offer a large potential for better controlling the development and operation of EGS/HDR systems.

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