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HOT DRY ROCK PROJECT URACH
- A General Overview –

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Abstract
Geothermal research activities in Urach started already during the mid seventies. It was the first Hot Dry Rock program performed at great depths and high temperatures within Europe. Since December 2001 the HDR Project Urach is supported within the framework of the Future Investment Program (FIP) of the Federal German Government. Throughout the FIP it's intended to create the subsurface system for a HDR pilot plant by drilling a second borehole and creating the heat exchanger. An extensive hydraulic program was run in the existing borehole Urach 3 during 2002. The geochemistry of the in-situ-fluid was determined by a production test and downhole fluid samples (salinity up to 90 g/l). The initial hydraulic parameters of the natural fracture system were derived from pre-stimulation injection tests. The following hydraulic stimulation was monitored with a seismic network. It consisted of five 3-component geophone sensors located within shallow boreholes. Based on an automatic locating software a real time monitoring was successfully carried out. Up to 50 l/s were injected during the nine-day hydraulic stimulation. Approximately 290 of 420 recorded events were located. The micro-seismic active zone lies in the center of the open hole section (3320 – 4445 m), and extents vertically from ~ 3400 m to ~ 4400 m. The lateral extension in NW-SE direction is up to 1000 x 500 m. The post-stimulation injection test demonstrated that the hydraulic permeability was increased by a factor of roughly 100. The hydraulic flowpaths within the reservoir have been determined by an innovative seismo-hydraulic modeling technique. Additionally, the flowpaths will be quantified by a newly conceived tracer test in the near future. The second well is planned as a directional drilling up to a depth of ~ 4500 m. Subsequently another massive stimulation experiment will be carried out to accomplish the second part of the heat exchanger. Finally a circulation test between the two wells will provide the technical and economic parameters for the power production by a binary cycle. The electric output of the power plant is projected to be around 1MW. Power production is intended to start within 2004.
<u>Keywords</u>: *Hot-Dry-Rock, micro-seismic monitoring, hydraulic stimulation, injection test*

Introduction

The Hot-Dry-Rock Project Urach is located in the center of a geothermal anomaly in southern Germany (~45 km SE of Stuttgart). Its favourable geothermal conditions combined with proper stress field parameters and a close located consumer potential makes it suitable for the creation of a HDR pilot pant. The first drilling operations started in the mid seventies. Borehole Urach 3 was drilled in three stages (see table 1). After its first extension (1982/1983) a single well circulation system was tested. Due to high flow impedances this concept was abandoned and substituted by a doublette system.

DRILLING PERIOD	FINAL DEPTH	BOTTOMHOLE TEMPERATURE
Phase 1 [3] 1977/1978	3334 m	143 °C
Phase 2 1982/1983	3488 m	147 °C
Phase 3 [12] 1992	4445 m	170 °C

Table 1: Urach 3 drilling history.

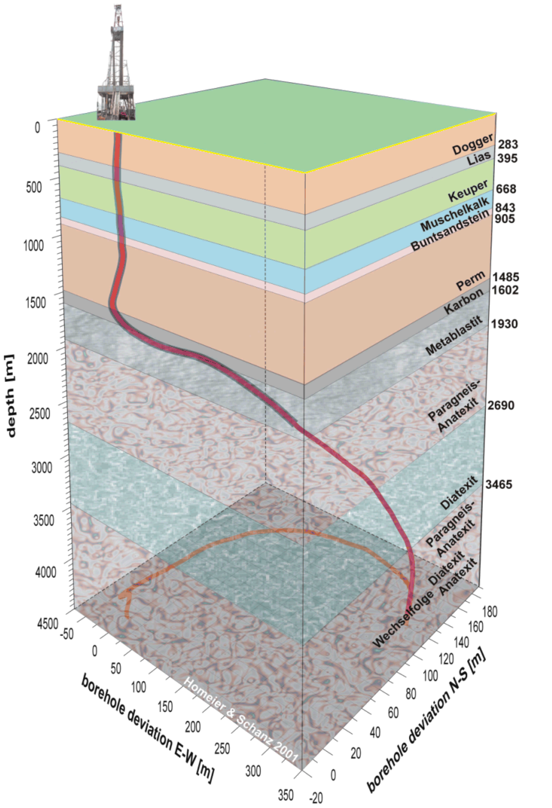

Fig. 1: Three-dimensional view of the drillhole Urach 3 trajectory and the geological formations (v:h ≈ 1:9).

An extensive research program followed including numerous borehole logs, the analysis of the local stress and temperature field as well as a detailed evaluation of the natural joint system. A summary of some essential results is listed in table 2.

Within the framework of the Future Investment Program (FIP) of the Federal German Government the research activities continued and a widespread hydraulic test program was carried out in 2002 (Fig. 2). It is intended to realize the subsurface system for a HDR demonstration plant during the FIP-program. The electrical output of this power plant is projected to be around 1 MW.

PHYSICAL PROPERTIES		DEPTH [m]
Mean Temperature gradient	$3{,}69\times10^{-2}$ K/m	0-4445
Temperature gradient in crystalline basement [6]	$2{,}9\times10^{-2}$ K/m	1600-4445
Specific heat conductivity [6]	2,9 W/m/K	1500-3250
Mean Heat flow density [6]	86 mW/m^2	500-3330
Transmissivity of rock matrix [10]	10^{-7}-10^{-6} m^2/s	3320-3488
Transmissivity of fractures [8]	10^{-4}-10^{-3} m^2/s	3320-3488
Maximum horizontal stress [9]	$S_H \approx$ 76-102 MPa	3352
Vertical stress [9]	$S_v \approx$ 89 MPa	3352
Minimum horizontal stress gradient [11], [14]	$S_h \approx 1{,}2$-$1{,}5\times10^{-2}$ MPa/m	0-4420
Orientation of maximum horiz. stress field [1], [7], [11]	N 170° E	2500-4445
Fracture aperture width [5]	0,1-10 mm	3400-4445
Orientation of joint system in reservoir depth [11]	North-South	3750-4445

Table 2: Summary of important physical properties measured in drillhole Urach 3.

Experimental

The timetable in Fig. 2 provides an overview of the work which has been done so far during the FIP-Program. It started with preparing a seismic network monitoring system and hydraulic experiments. This included a test of wireless seismic data transmission, a modeling of the seismic network resolution to optimize the geophone locations [4] and an equipment / pump test for the hydraulic experiments.

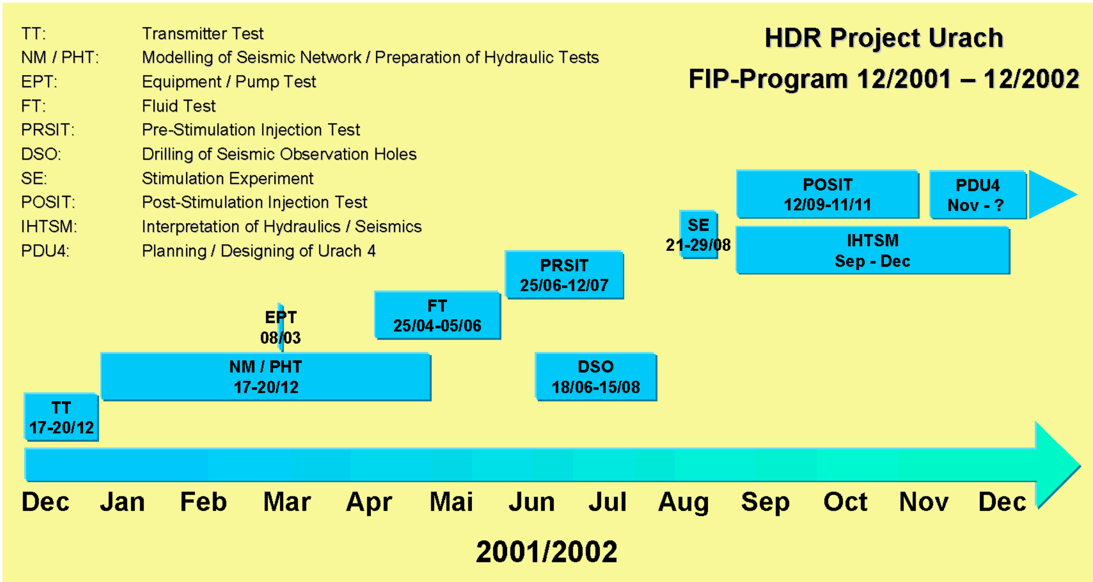

Fig. 2: Timetable of the accomplished work during the running FIP-Program.

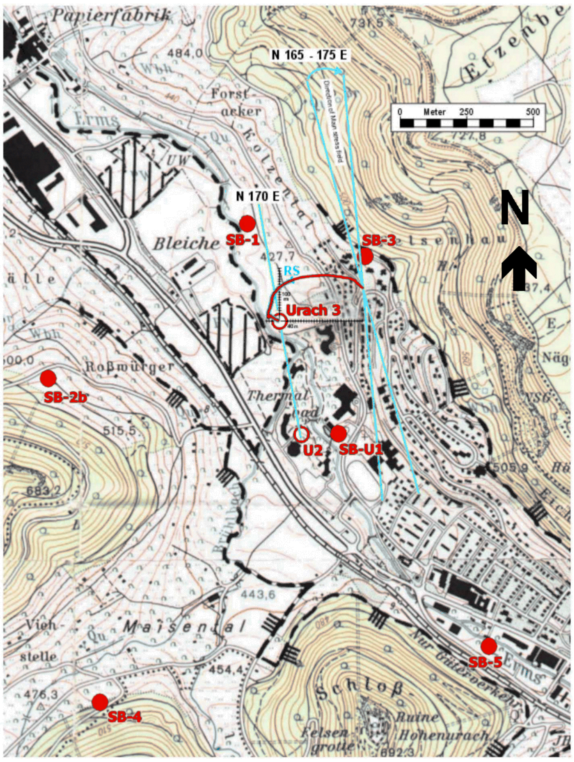

Fig. 3: Topopgraphic map of project site Urach displaying the trajectory of well Urach 3, the seismic observation holes (SB-X) and the direction of the main stress field (N 170 °E).

The seismic network consists of five 3-component geophones installed at the bottom of five shallow observation drillholes (~250 m deep, Fig. 3). To achieve an optimum geophone coupling the target depth of each borehole was to terminate within a formation where caliper logs of drillhole Urach 1 and 3 show smooth and consistent curves with no breakouts and the caliper equal to the bit size. The seismic data acquisition was carried out by two independent seismic data logging systems. One data logger was operated in a triggered mode, the second data logger recorded the seismic traces continuously to avoid data loss due to trigger difficulties [4]. To get information on the isotopes and geochemistry of the in-situ-fluid a production test was run with a total produced volume of ~ 75 m^3. Finally several fluid samples were taken within Urach 3 well at 2419 m depth (salinity up to 90 g/l). Subsequently pre-stimulation injection tests were performed to determine the initial hydraulic parameters of the natural fracture network (Fig. 4). First, a step injection test was run to prevent an initiation of fractures prior to the stimulation experiment. From this the appropriate parameters for the continuous injection test were determined. The massive stimulation experiment commenced with injecting saturated brine (ρ=1,19 g/cm^3, V = 300 m^3) during two refracturing cycles to improve the fracture initiation effect. Up to 50 l/s were injected during these cycles. For a safe operation of the wellhead and casing, the injection pressure was limited to a maximum of about 340 bar. An inspection and calculation of the casing strength was done before. To adapt for the steady pressure increase during injection, the flow rate was lowered continuously. Roughly twelve hours after starting the frac operation the injection rate had been reduced to a constant level at around 10 l/s for about 4 ½ days. After a second brine injection the flow rate varied from 7 to 4 l/s (see Fig. 5). A total volume of about 5600 m^3 fresh water was injected during the nine-day frac operation. To examine the effect of the frac operation a post-stimulation injection test finally was carried out (Fig. 8).

Results and Discussion

A. Pre-Stimulation Injection Test

During the step-injection test sharp pressure peaks at 170 bar followed by sudden drops of the wellhead pressure curve revealed that fractures could be opened against the least principal stress component (see top of Fig. 4). Therefore it was decided to keep the injection pressure significantly below 170 bar during the continuous injection test. Due to this an injection rate of around 11 l/min was selected. Two successive injection tests were run. The wellhead pressure curve of the first test was rather noisy and showed some spikes during the injection phase (see black curve at the bottom of Fig. 4). It was interpreted as remainings of cuttings of the previous extension drilling, which probably blocked infiltration zones within the openhole section of Urach 3. To clean the borehole several huff-puff tests as well as oscillation tests were successfully applied. The wellhead pressure of the second test was reduced by about 50 bar and its trend turned out to be much smoother and more consistent (see blue curve at the bottom of Fig. 4) indicating that the fractures could be cleaned. The transmissibility values derived from these injection tests were in the range of 0.001-0.01 Dm. Similar transmissibility values were determined by

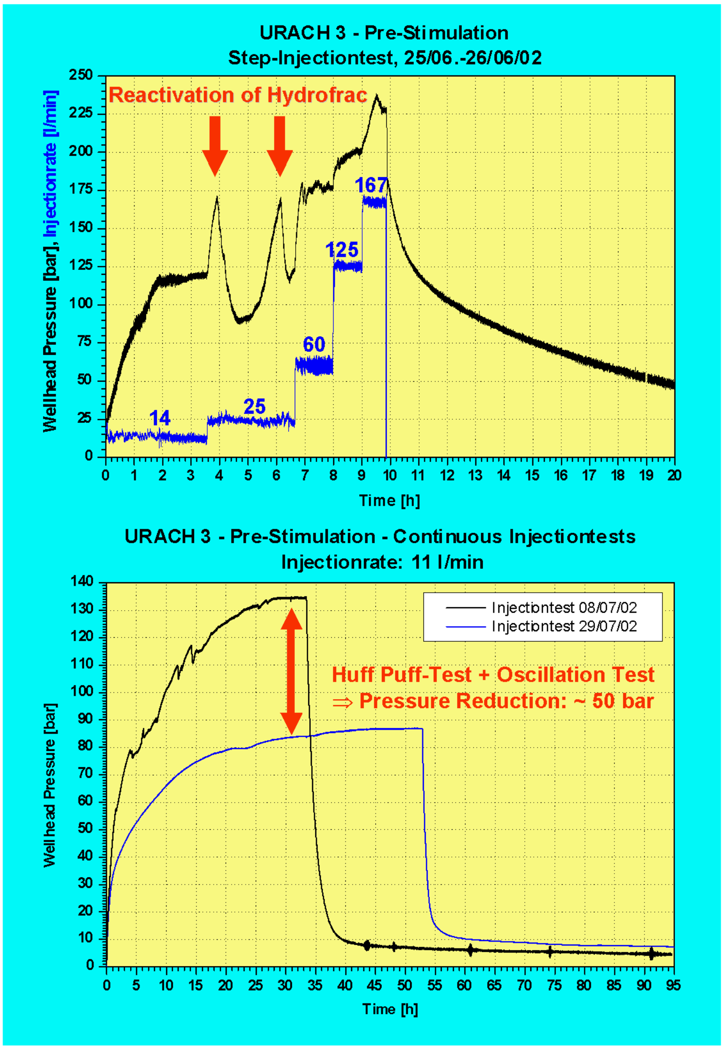

Fig. 4: Step-injection test (top) and continuous injection tests (bottom) prior to the massive stimulation experiment.

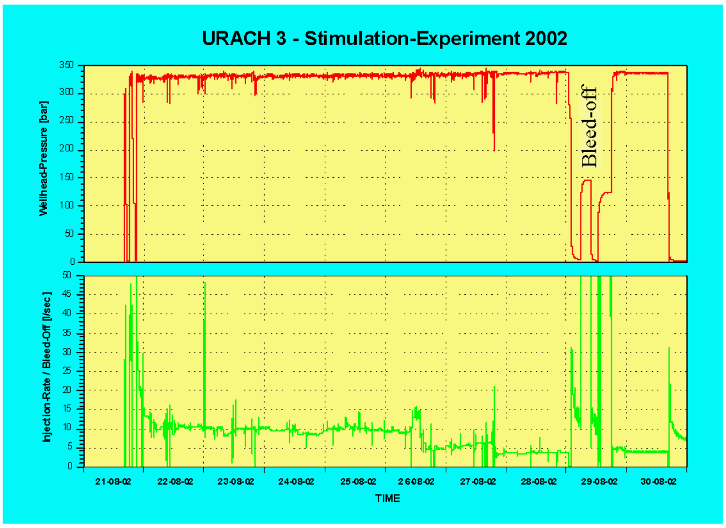

Fig. 5: Wellhead pressure curve and injection rate of the stimulation experiment.

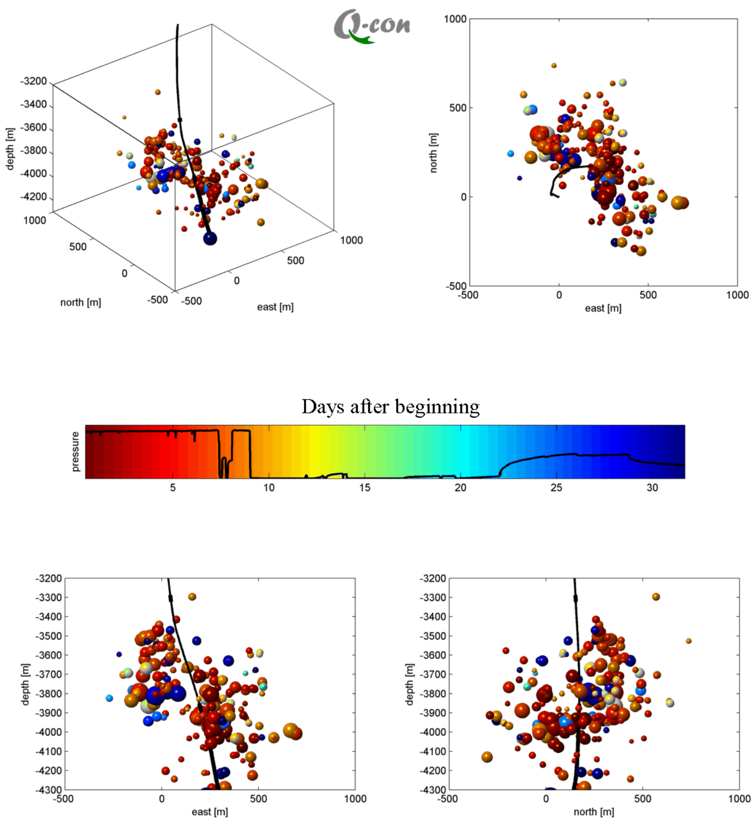

Fig. 6: Hypocenter distribution after application of a relative location method in different views. The size of the balls is scaled with respect to the seismic moment. The trajectory of Urach 3 well is shown as a black line. The time sequence of the events is indicated by their colour according to the colour bar. The black curve within the colour bar shows the wellhead pressure curve from the beginning of the stimulation until the shut-in phase of the post stimulation test [13].

Stober & Bucher [10] in previous hydraulic tests performed prior to the final borehole extension in 1992.

B. Massive Stimulation Experiment

Fig. 5 provides an overview of the wellhead pressure curve and injection rate during the stimulation experiment. The frac operations were successfully carried out and resulted in a significant improvement of the hydraulic transmissibility (see discussion in section C). The first seismic event was detected about 9 hours after starting the stimulation process. Based on an automatic locating software a real time monitoring of the triggered seismic events was successfully carried out providing the project management with a maximum control about the stimulation process [13]. Additionally, the seismic traces were checked by manual picking. Roughly 290 of about 420 seismic events were evaluated and located. A systematic growth of the reservoir with time was observed. The micro-seismic activity started close to the openhole section at a depth of around 3930 m. Two significant structures then evolved: 1. A flat structure which is dipping south at an angle of about 20 degree intersecting the well between 3900 and 4000 m. 2. A steeply dipping structure northwest to the well (see Fig. 7). It is possible that structure 2 connects the north-western part of structure 1 with the borehole at a depth of 3400 m. During the shut-in phases the seismic activity was focused on the boundaries of the stimulated volume, indicating a dense unstimulated surrounding rock matrix. The micro seismic cloud lies in the center of the open

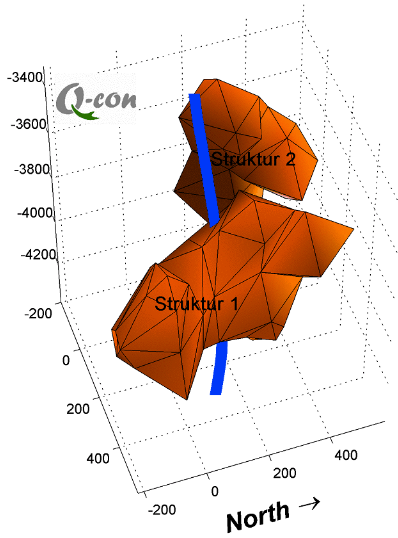

Fig. 7: The isosurface of the hypocenter density highlights the two significant structures which evolved during the stimulation process (see also Fig. 10).

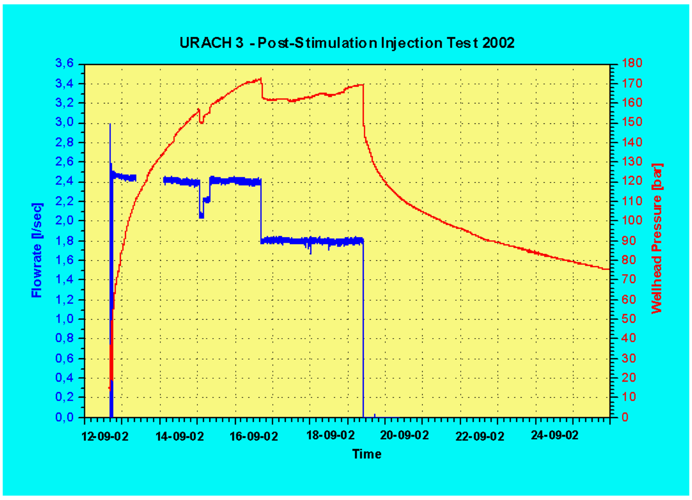

Fig. 8: Post-stimulation injection test.

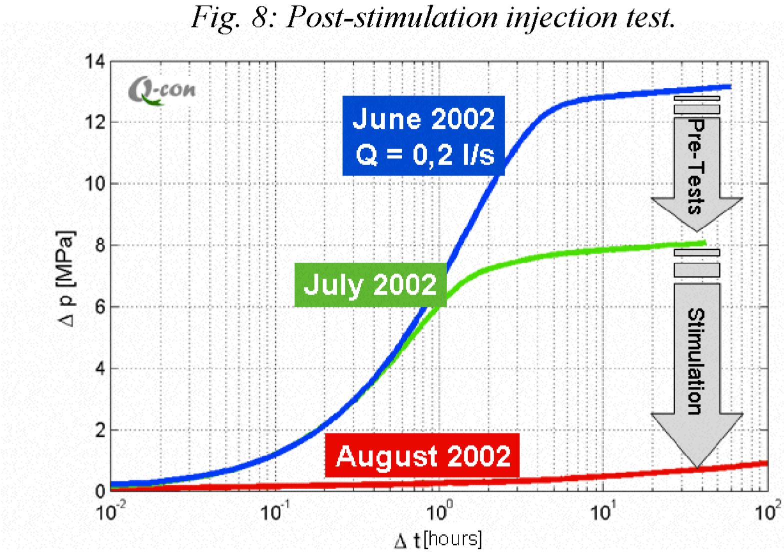

Fig. 9: Hydraulic improvement of the underground reservoir during the hydraulic program in 2002 demonstrated by the various pressure responses normalized to Q=0,2 l/s.

hole section and extends vertically from about 3400 m to approximately 4400 m. Its lateral extension reaches up to 1000 x 500 m [13].

C. Post-Stimulation Injection Test

Fig. 8 displays the trend of the wellhead pressure together with the injection rate. The evaluation of this test indicated a reservoir transmissibility of approximately 0,1 Dm. The various stimulation treatments could improve the transmissibility of the reservoir by about two orders of magnitude (see also Fig. 9). This is an important indication for the possibility to stimulate the crystalline underground at this project site. The productivity index for a doublette system was modeled as a function of the distance between the injection and production wells. At a distance of 200 m to 350 m between the two wells the productivity index ranges amid 0,2-1,0 l/MPa/sec. This is not sufficient for an economic use of the reservoir. But there are several thorough considerations how to increase the productivity up to 1,5-2,5 l/MPa/sec by further stimulation activities:

1. Increase of the injection pressure in excess of 340 bar
⇒ shearing of fractures with less favourable orientations.

2. Injection of larger fluid volumes
⇒ extension of the reservoir.

3. Synchronous injection into both wells
⇒ higher pressure values within the center of the heat exchanger.

4. Optimizing of the stimulation concept based on the experiences of the first stimulation test.

5. Utilization of viscosity reducer
⇒ higher injection rates.

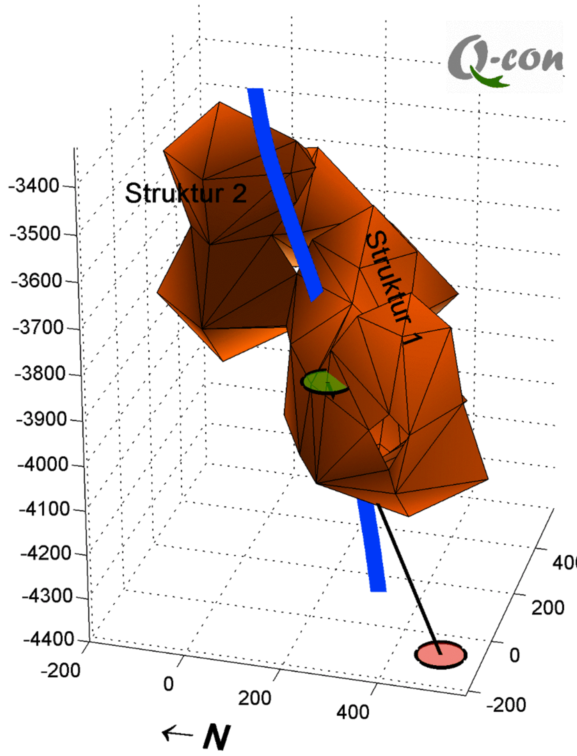

Fig. 10: The trajectory target of the new well Urach 4 together with the existing Urach 3 (blue line) and the seismic image of the stimulated reservoir (see also Fig. 7).

Based on the evaluations of the seismic and hydraulic results the positioning and trajectory of the new well Urach 4 is projected according to Fig. 10.

Conclusions and Outlook

The hydraulic program carried out in 2002 was a great success. It was demonstrated that the gneissic basement rock can be enhanced by the massive hydraulic stimulation technique and that a considerable improvement of the reservoir transmissibility could be achieved. Valuable informations of the created reservoir were derived from the micro-seismic data. For a better understanding of the reservoir's nature a new integrated seismo-hydraulic interpretation technique [2] has been carried out yielding an image of the flowpaths in the reservoir.

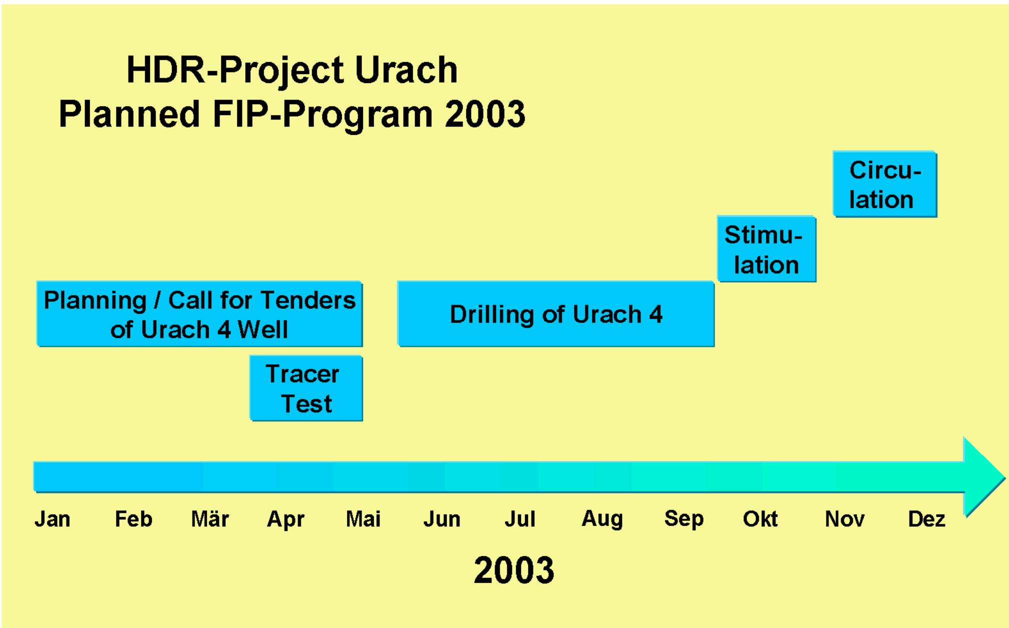

Fig. 11: Timetable of current and future activities during the running FIP-program.

To get additional information on the newly developed flow paths a tracer experiment is planned. Current project activities are focused on designing the new borehole parameters. It will be a directional drillhole with a projected target depth of around 4500 m. Drilling operations are planned to start around June this year. After the completion of the well another massive stimulation experiment will be carried out using an openhole packer system to start the fracture initiation at the bottom of the openhole section. Finally a circulation test between both wells will accomplish the work during the FIP-program. It will provide the technical and economic parameters to design the binary cycle for power production, which is intended to start in 2004.

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