Downhole Pressures Derived from Wellhead Measurements during Hydraulic Experiments

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ABSTRACT

The availability of reliable downhole pressure data during hydraulic tests is of crucial importance for interpreting the behaviour of the underground system. Especially in the case of EGS systems the high pressure and temperature conditions make downhole measurements rather a challenge. The downhole pressure data collected during recent stimulation experiments at the European EGS project site in Soultz-sous-Forêts, France, have shown several uncertain values and gaps – especially in the 5 km borehole GPK3.

With the new numerical borehole tool HEX-B the downhole pressure data taken during the stimulation test of GPK3 in May 2003 has been corrected and completed. The input parameters needed are: wellhead data for flow rate, pressure, density of the injected fluid and its temperature. HEX-B takes into account heat exchange processes with the rock mass, buoyancy forces and pipe friction. Deviations between the measured and the calculated downhole temperature in GPK2 have been identified as an upward flow in the annulus of warm water leaking at the casing shoe.

The location and time of occurrence of microseismic signals released by failure on individual fractures indicate where, when and how pressure has been exceeded. The near-borehole events detected during the stimulation of GPK3 have been related to calculated borehole pressures at the corresponding time and depth. The resulting failure pressure profile in the borehole specifies the minimum depth-dependent hydraulic pressure that a stimulation must generate in the host rock at this site to improve its permeability.

1. INTRODUCTION

In Spring 2004 drilling and completion of GPK4, the third of the three 5 km deep boreholes, at the European EGS project site in Soultz-sous-Forêts, France was terminated. A stimulation test of GPK4 was foreseen for Summer 2004. The first two deep boreholes, GPK2 and GPK3, had been stimulated already in June 2000 and May 2003. Data collected during these two stimulation tests provide a key to the understanding of stimulation processes.

In an EGS project hydraulic stimulation is used to improve the permeability of the subsurface heat exchanger with three principal aims:

1. Improvement of the injectivity/productivity of the boreholes to achieve an economical and reliable circulation rate

2. Preferential improvement of the deepest flow paths in the wells to achieve a production temperature as high as possible

3. Improvement of the permeability of the host rock distributed as widely and regularly as possible to avoid thermal short circuits between the injection and production boreholes.

Subsurface heat exchangers of EGS projects are typically situated at depths where the permeability is built up by fractured structures. Therefore improving permeability usually means increasing the apertures of natural fractures by bringing them to fail and shear through hydraulic over-pressurising. Technically the overpressure in the subsurface can only be controlled at surface via the rate and duration of each phase of injection, and via the density (NaCl-salinity) and temperature of the injected fluid. The practicable pumping rate depends on the developing injectivity of the reservoir, the engines and the surface installations.

In order to fulfil the three aims above, two tasks of paramount importance are:

- controlling the hydraulic pressure profile in the borehole during a stimulation – especially at the very beginning

- determining the failure pressures of the fractures in the depth range of the open-hole section.

In the following, an approach to these two tasks is discussed using the data of the stimulation test at GPK2 in June 2000 and GPK3 in May 2003.

2. DETERMINATION OF PRESSURE PROFILES IN BOREHOLES

2.1 Limitations of PT-Measurements

Downhole pressures can be measured with PT-tools either at a constant depth for the whole duration of an injection or as a log within a limited period. As experiences at Soultz have shown, data gaps or even incorrect measurements over extended periods occur (see Figures 5 and 8). During the stimulation test of GPK3 in May 2003 the downhole pressure values are inconsistent for about the first half of the injection period, which lasted in total more than 10 days. However, pressure measurements in boreholes give always only a very limited view in depth and time. It is therefore meaningful to use the measurements as input values for simulations of whole pressure profiles.

2.2 Simulations of PT-Profiles with HEX-B

The numerical borehole tool HEX-B has been developed for simulations of pressure and temperature profiles in boreholes during injections. In HEX-B, borehole diameter variations, defined fluid loss rates at exit points, the borehole trajectory and thermal properties of the rock mass along the borehole are all accounted for (Figure 1).

The calculation starts with an initial wellhead pressure, with initial profiles for NaCl-molality in the borehole and for the temperature in the rock mass. Knowing the injection rates, the temperature of the injected fluid, its salinity and additionally the wellhead pressure, the pressure profile in the borehole is calculated, with the injectivity index II as a resulting parameter (Figure 2). This is one of two possible modes of HEX-B when the wellhead pressure is known after an injection. A second operational mode is provided to allow the wellhead pressure and the development of the pressure profile prior to an injection test to be calculated by predefining an assumed value for the injectivity index.
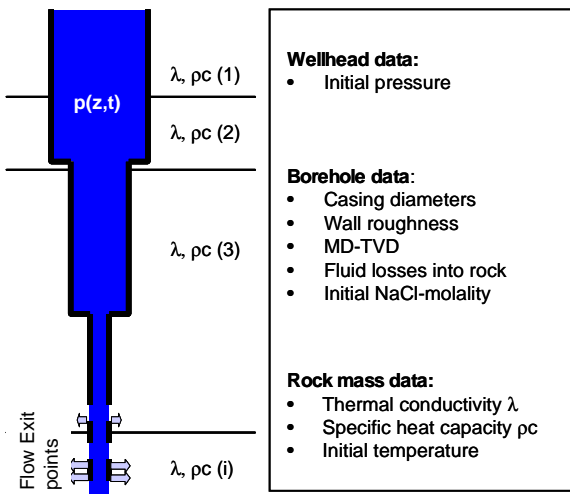

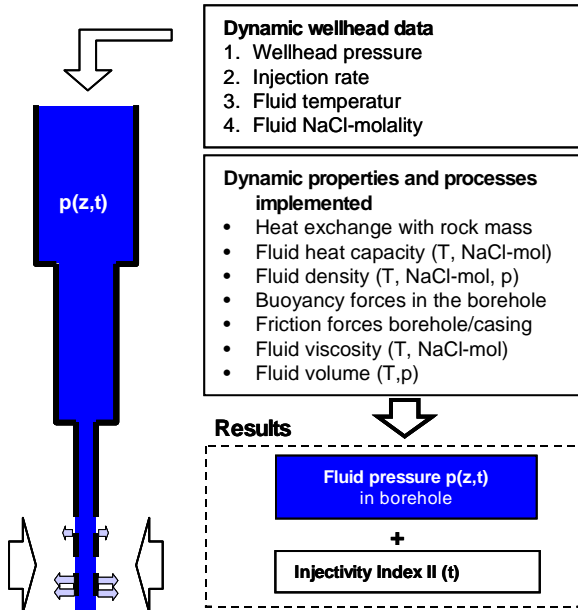**Figure 1: Model parameters and initial conditions implemented in the HEX-B code**

Figure 2: Input parameters, physical processes implemented and results of the HEX-B code.

2.3 Sensitivity of Pressure Profiles

A pressure at a given depth and time in the borehole depends on the current wellhead pressure, the variation of the density profile comparing to the initial state, and the pressure losses due to pipe friction. A corresponding sensitivity study has been carried out with the data from the stimulation test at GPK2 from June 2000 since reliable downhole pressure data are available for this test. The borehole model consist of five depth sections. Each section is defined by a distinct borehole radius, a percentage of flow defining exit points at the top of sections with flow rates below 100%, an average roughness for the wall of the casing or the open hole section, a thermal conductivity and specific heat capacity of the corresponding surrounding rock mass (Table 1).

Tab. 1: Borehole/rock model in HEX-B for GPK2, best fitting parameters

Bore hole parameters				Rock mass parameters	
Depth section MD [m] from: to:	Inner radius [m]	Flow rate [% of injection]	Average wall roughness [mm]	Thermal conductivity [W/m K]	Specific heat capacity [J/m^{3}K]
1	0	1500.	0.08	100.	0.15	3	2.2 10^6
2	1500	3800.	0.08	100.	0.15	4	2.2 10^6
3	3800	4430.	0.08	100.	0.15	3	2.2 10^6
4	4430	4800.	0.108	90.	2.0	3	2.2 10^6
5	4800	5010.	0.108	50.	2.0	3	2.2 10^6

The initial temperature profile used as a starting point of the calculations corresponds to an equilibrated temperature in GPK2 measured before the injection (Figure 3). The initial profile of the NaCl-molality in the borehole has been estimated as a linear function with depth fitting the steady-state pressure measured with a downhole probe.
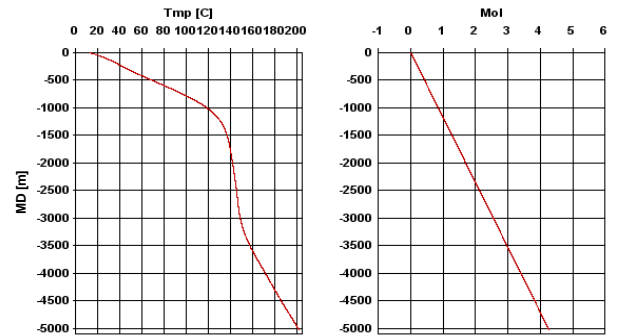

Figure 3: Initial values for temperature and NaCl-molality in GPK2 before the start of the stimulation test June 2000.

With the dynamic wellhead data measured during the stimulation of GPK2 in June 2000 (see Figure 4) the temperature and the pressure in the borehole has been calculated.

The NaCl-molality of the injected fluid has been determined from the measured fluid density and temperature. Since the function for the fluid density (Phillips et al., 1981) implemented in HEX-B has a limited accuracy against temperature, NaCl-molality and pressure, the derived NaCl-molality for fresh water under surface conditions has slightly negative values.

The density of the fluid is a function of the temperature, of the NaCl-molality and of the pressure itself. Therefore the profiles for density and pressure are calculated iteratively.
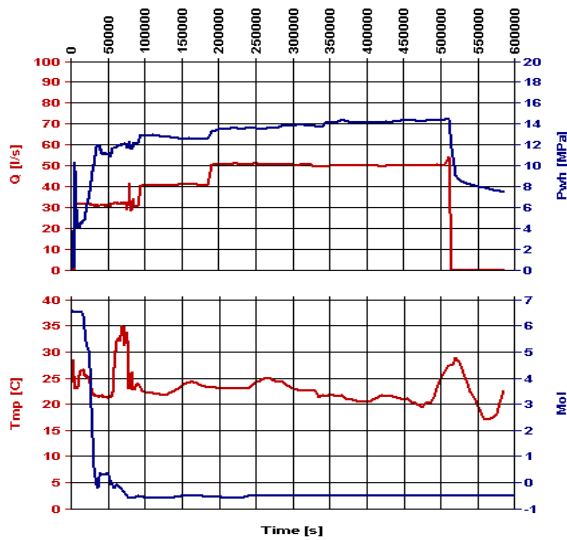

Figure 4: Measured injection values for flow rate, wellhead pressure and fluid temperature, as well as the NaCl-molality derived from the measured fluid density during the stimulation test on GPK2 in June 2000.
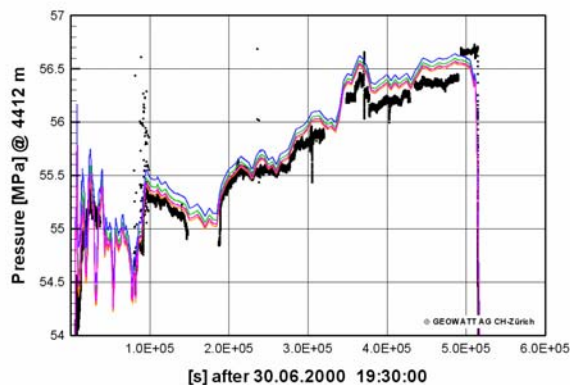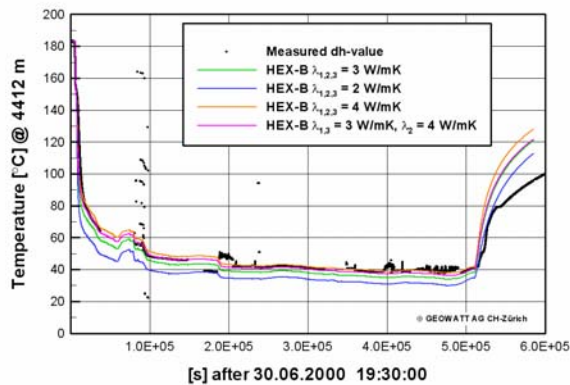

Figure 5: Measured and calculated values for temperature (top) and pressure (bottom) at 4412 m depth during the stimulation test on GPK2, June 2000, for different thermal conductivities of the rock mass.

The calculated values for the depth of the downhole PT-tool at 4412 m are generally in good agreement with the measured data for temperatures and pressures (Figure 5). Major deviations can be observed for the first 40'000 s of the injection test (see below).

2.3.1 Effect of Temperature on the Pressure

For the injection rates of 30 to 50 l/s a change of the thermal conductivity of the rock mass from 4 W/m/K to 2 W/m/K leads to a temperature drop of about 10 K at 4412 m depth (Figure 5 top). The maximum effect of this temperature variation on the downhole pressure is approximately 0.3 MPa (Figure 5 bottom).

During the whole injection test with the exception of the first 40'000 s (see also Figure 7), the calculated pressures are generally in good agreement with the measured values.

2.3.2 Effect of Pipe Friction on the Pressure

The difference in the downhole pressure between an average casing wall roughness of 0.01 mm and one of 0.2 mm has been determined as about 0.5 MPa. A best fit with the measured downhole pressure data has been reached with a value of 0.15 mm (Figure 6).
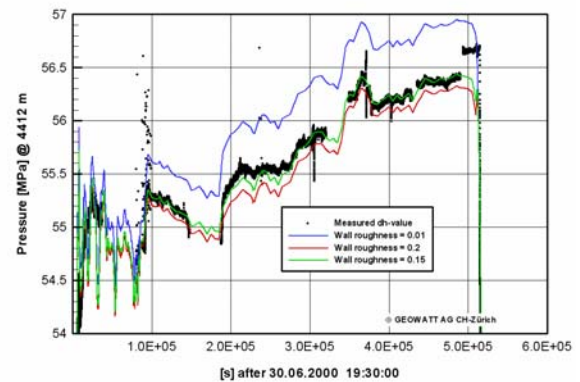

Figure 6: Measured and calculated values for pressure at 4412 m depth during the stimulation test on GPK2 in June 2000, for different average wall roughnesses of the casing.

2.3.3 Sensitivity of Pressure to the Initial Injection Phase

The calculated pressures at 4412 m depth for the first 40'000 s differ by between 0.5 and 1 MPa from the measured values. The first pressure deviation (left arrow in Figure 7) results from the faster decrease of the calculated temperature. The lower decrease in the measurements is probably the effect of warm water leaking into the annulus at the casing shoe and resulting in a strong upward flow. The slower temperature decrease above 4412 m results in a slower increase of density and pressure.

The second pressure deviation (right arrow in Figure 7) and also the third one are probably the result of inaccurate density measurements of the injected fluid. Calculations with slightly modified injection densities show a strong effect on the downhole pressure (blue line in Figure 7). Calculating a pressure at 4500 m depth with an accuracy of ± 0.1 MPa means therefore that the density of the injected fluid must be measured with a resolution of ± 2.2 kg/m^3.
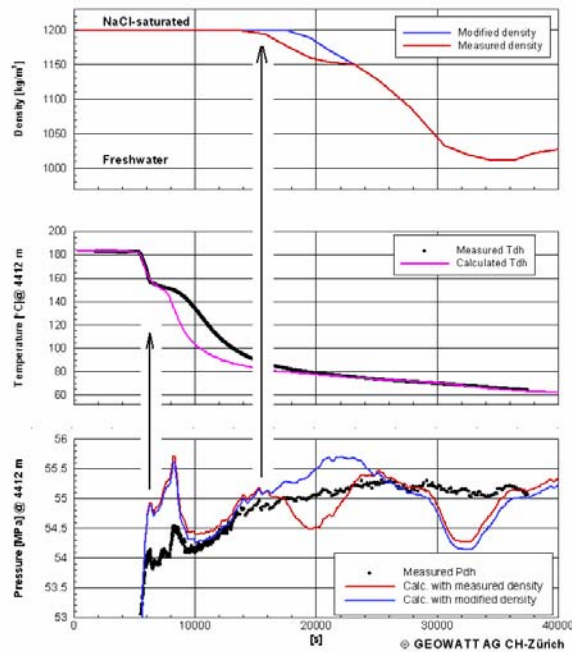
Figure 7: Density of the injected fluid (top), temperature and pressure at 4412 m depth in GPK2.

2.4 Correction of Pressure Data from GPK3

During the stimulation of GPK3 in May 2003 the downhole tool delivered very inconsistent data for long periods of the test. HEX-B has been used therefore to recalculate the downhole pressure data. The borehole model for GPK3 was derived from the best fitting parameter set from the sensitivity analysis on GPK2 (Table 2). The comparison between the measured and the calculated data shows that the downhole tool provided correct data after being moved to the new depth of 4244 m. Before this shift the error reached values up to 2 MPa (Figure 8).

Tab. 2: Borehole/rock model in HEX-B for GPK3, best fitting parameters derived from GPK2 calculations

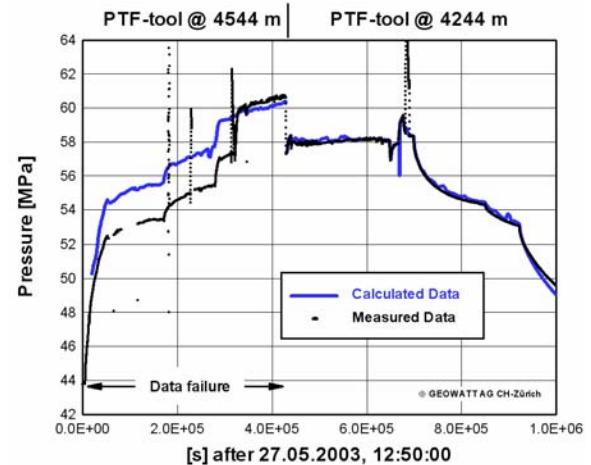|	Bore hole parameters				Rock mass parameters	
	Depth section MD [m] from: to:		Inner radius [m]	Flow rate [% of injection]	Average wall roughness [mm]	Thermal conductivity [W/m K]	Specific heat capacity [J/m³K]
1	0	1500.	0.11	100.	0.15	3	2.2 106
2	1500	3800.	0.11	100.	0.15	4	2.2 106
3	3800	4556.	0.11	100.	0.15	3	2.2 106
4	4556	4760.	0.108	100.	2.0	3	2.2 106
5	4760	5100.	0.108	30.	2.0	3	2.2 106

Figure 8: Measured and recalculated/corrected pressure for the stimulation test in May 2003 at GPK3.

3. DETERMINATION OF FAILURE PRESSURES

The failure pressures of the fractures intersecting the open-hole section and the development of the hydraulic pressure profile along this section of the borehole during an injection test define the depth at which failure starts. In the previous section it was demonstrated that the pressure profile in a borehole during injection can be determined with sufficient accuracy. It would be helpful for reaching aims 1 and 2 defined in the introduction - and also for pursuing the rather more complex aim No. 3 - if the failure pressures of the relevant fracture sets were indeed known.

Under which hydraulic pressure a fracture fails depends on its orientation in space, the mechanical properties of the host rock, the shear coefficient of the fracture and the local stress field at the corresponding depths. Even for fractures intersecting the borehole wall for which some information can be derived from different geophysical logs it is generally difficult to find appropriate values for all the parameters needed to characterise their response to hydraulic pressurising. Therefore the following approach has been envisaged:

- It was assumed that the fractures in the vicinity of the open-hole section of GPK3 have characteristics generally valid for this depth at the whole Soultz site.

- The time and location of the microseismic near-borehole events during the stimulation test of GPK3 in May 2003 reflect the moment of failure of a fracture (or slip patch) at this location.

- The hydraulic pressure in the borehole at the time and depth of a near-borehole event is assumed to be equal to the failure pressure of a fracture at this depth.

The stimulation test at GPK3 in May 2003 started with a continuous increase of the downhole pressure during the first 24 hours (Figure 9, blue line indicates the calculated/corrected pressure).
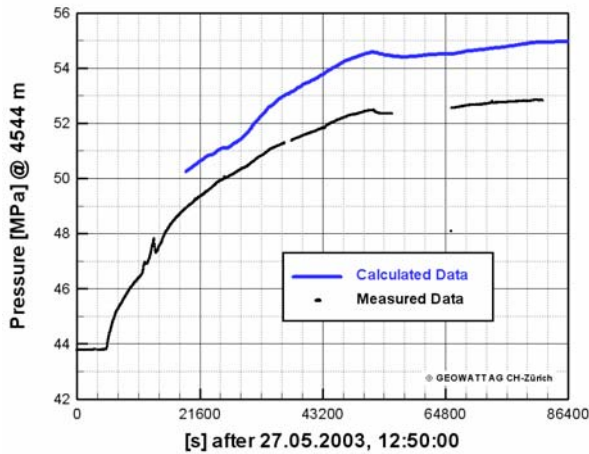
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Figure 9: Measured and recalculated/corrected pressure for the stimulation test in May 2003 at GPK3, first 24 hours of injection.

Within this period, events occurred continually in the vicinity of the open-hole section (Figure 10). The absolute accuracy of the locations is given as about 50 m, the relative locations can be assumed to be more precise. Since these locations seem to have a certain regular distribution around the open hole section of GPK3 most of the events can be regarded as the failure of fractures intersecting the open-hole section.

We assume that the time and depth of occurrence of a near-borehole event signifies the time and depth the pressure in the borehole exceeded the failure pressure of a fracture at this location. Therefore the failure pressures are related to the borehole pressures at depth and time of near-borehole events. The specific pressure values have been calculated with HEX-B.

The failure pressure for the near-borehole events in GPK3 increases between a depth of 4700 m and 5100 m from 52 MPa to 60 MPa (Figure 11). Since we can assume that the fracture orientations have a certain regular distribution along the open hole section and a general linear increase of the friction coefficient by a factor of over 1.5 within this depth range is rather unlikely, this increase of the failure pressure reflects the depth dependency of the stress field's principle components.

For several specific depths wide ranges of hydraulic failure pressures occurred. These pressure ranges give hints to the variability of fracture orientations at these depths. The strong variation of calculated failure pressures from 54 MPa to 57 MPa at 4750-4780 m could reflect the wide range of azimuths of failed fractures identified in the UBI log at this depth.

If we assume that the assembly of fracture depths and orientations identified in the UBI log of GPK3 is generally valid for the rock mass at 4000-5000 m at the Soultz site then the calculated failure pressures (Figure 11) correspond to the minimum depth-dependent hydraulic pressures a stimulation test must generate in a target rock volume to improve its permeability.
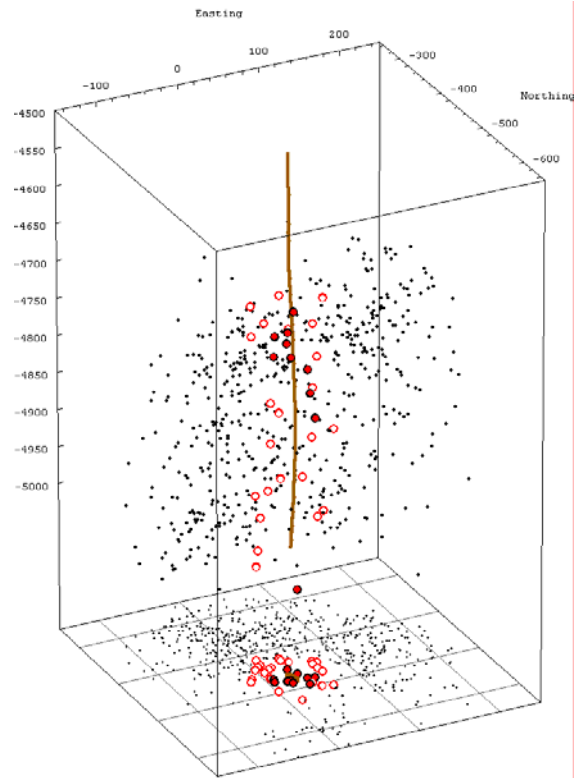

Figure 10: Microseismic events for the first 24 hours of the GPK3 stimulation in May 2003 with a horizontal distance from the borehole trajectory (brown line) < 25 m (filled red dots), between 25 m and 50 m (red circles) and > 50 m (black dots). Vertical projection at the bottom face.
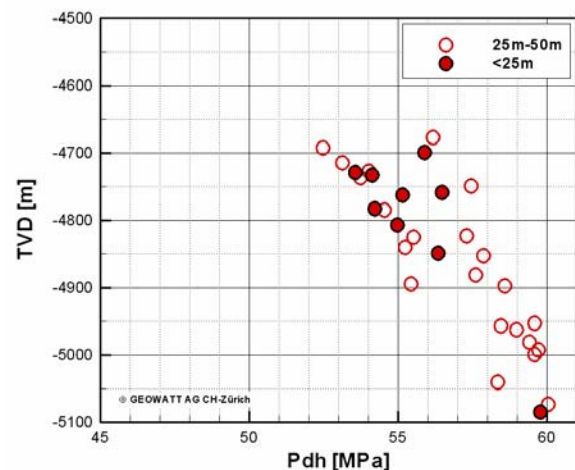

Figure 11: Borehole pressure at time and depth of near-borehole microseismic events (distance <25m and 25m-50m) during the first 24 hours of the GPK3 stimulation in May 2003.

4. CONCLUSIONS

Downhole pressure values during injection tests can be calculated from wellhead data for flow rate, pressure, density of the injected fluid and its temperature. When an injection sequence starts with a highly saturated brine, an accurate density measurement of the injected fluid is of paramount importance for the downhole pressure calculation.

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Deviations of a calculated downhole temperature from measured values provide indications of vertical near-borehole flow processes.

Detection and analysis of microseismic events can be used to indicate times and locations of failing fractures. The failure pressures of fractures identified from near-borehole events have been related to corresponding calculated borehole pressures. Supposing that the orientation and mechanical behaviour of fractures seen in the depth range of interest in a specific borehole are distributed regularly across the host rock at the site, then these failure pressures specify the minimum depth-dependent hydraulic pressure to be necessary for large-scale stimulation of a target rock volume to improve its permeability.

REFERENCES

Phillips, L., Igbene, A., Fair, J.A., Ozbek, H., Tavana, M.: A Technical Databook for Geothermal Energy Utilization, Lawrence Berkeley Laboratory, University of California (1981).