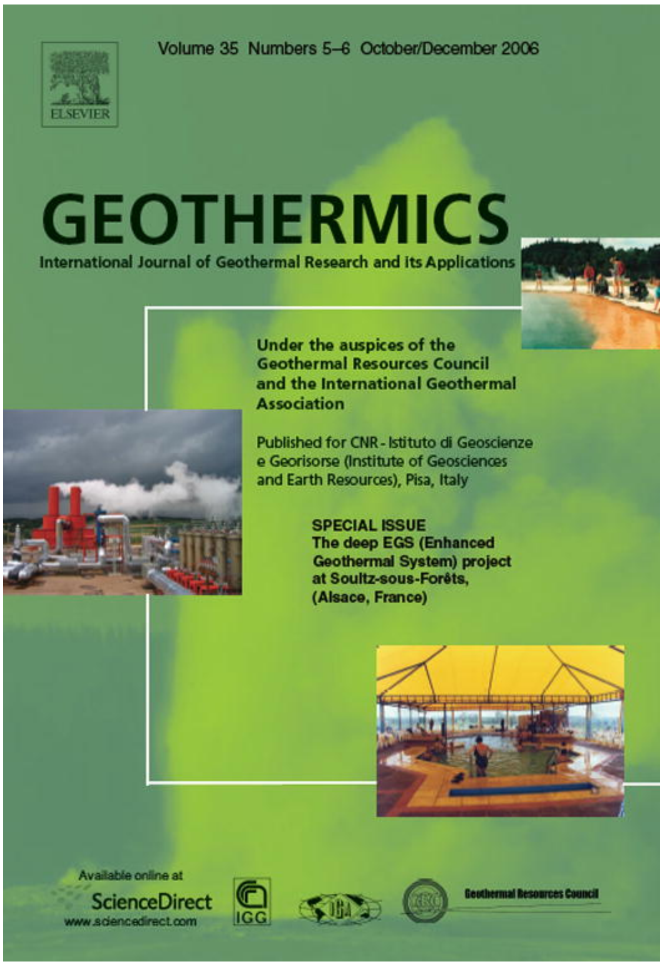
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The potential of the use of dense fluids for initiating hydraulic stimulation

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Abstract

To improve preferentially the permeability of fractures in the deepest parts of a geothermal reservoir, a dense fluid may be injected during the very first phase of a hydraulic stimulation test. To initiate such a permeability-enhancement process in the 5000 m deep reservoir of the European Enhanced Geothermal System (EGS) project at Soultz-sous-Forêts, France, a concentrated NaCl brine was injected. The effects of this injection were estimated using measured hydraulic and microseismic data. Two tasks associated with hydraulic stimulation have been shown to be important for this purpose: (1) determination of the failure pressures of the various fractures intersecting the open-hole section under stimulation, and (2) calculation of the transient hydraulic pressure profile in the borehole.

Using the numerical borehole code HEX-B, the transient pressure profiles during stimulation of wells GPK2 (June 2000) and GPK3 (May 2003) were calculated on the basis of measured wellhead data. A comparison of the temporal history of near-borehole microseismic events during the GPK2 test and down-hole pressure development in the open-hole sections of this borehole indicated that use of a dense brine helped stimulate the bottom part of this well. The corresponding analysis for the GPK3 test showed that the failure pressure of the fractures in the bottom part of the wellbore was never exceeded when injecting the dense brine. We can, therefore, assume that the brine had no effect on the fractures in GPK3.

Keywords: Hydraulic stimulation; Borehole numerical simulator; Fracture failure; Brine injection; Fluid pressure

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1. Introduction

Hydraulic stimulation is the method currently used to create an underground heat exchanger of lowest possible hydraulic resistance for an Enhanced Geothermal System (EGS) of the hot fractured rock type. The stimulation process has three main objectives:

1. Improvement of the injectivity/productivity of the EGS boreholes to achieve an economical and reliable circulation rate.
2. Preferential improvement of the deepest flow paths intersecting the wells, the production wells in particular, to achieve the highest possible fluid production temperature.
3. Enhancement of the bulk permeability of the host rock over a region of the reservoir as widely and uniformly as possible to avoid thermal short circuits between the injection and production boreholes.

The subsurface heat exchangers of an EGS system will typically be situated at depths at which the main contributions to throughflow are from paths within the fracture network. Therefore, improving the permeability of the host rock mass usually means increasing the apertures of natural fractures by causing them to fail and shear through hydraulic over-pressurisation. The failure of a fracture is accompanied by a release of stress, which can often be detected and localised as a microseismic event.

Technically, the overpressure in the subsurface can only be controlled at the surface via the pumping rate, the definition of specific injection steps and the density of the fluid. The density of the injected fluid can be influenced by its dissolved solids content (NaCl at Soultz) and also, but less feasibly, by its temperature.

During the initial phase of a stimulation, for example, a dense brine could be injected to open preferentially the fractures encountered in the deeper part of the target volume. This technique was applied to the Soultz project. Stimulation of the 5 km deep boreholes GPK2 and GPK3 started with the injection of a nearly saturated NaCl solution with density close to 1200 kg/m^3 at 10 °C (Fig. 1).

The effects of these brine injections during the first phase of the injection tests are analysed in this paper, using pressure data and the occurrence of microseismic events in space and time from the stimulation test 00jun30 in GPK2 and from the stimulation test 03may27 in GPK3. Two kinds of results will be discussed:

1. The depth dependency in the 5 km deep domain at Soultz of the local pressure required to trigger shear failure of fractures and initiate near-borehole events.
2. The effect of using dense brine to induce selective failure of deeper fractures during the initial phase of a hydraulic stimulation test.

2. Methodology and data

During stimulation, the only location in the host rock where the absolute pressure can be determined with any accuracy is in the borehole and the immediate vicinity of its open-hole section. A near-borehole microseismic event during injection can be interpreted as the result of the local hydraulic pressure reducing the effective normal closing stress in a fracture that intersects the borehole, thereby causing its shear failure criterion to be exceeded. The failure

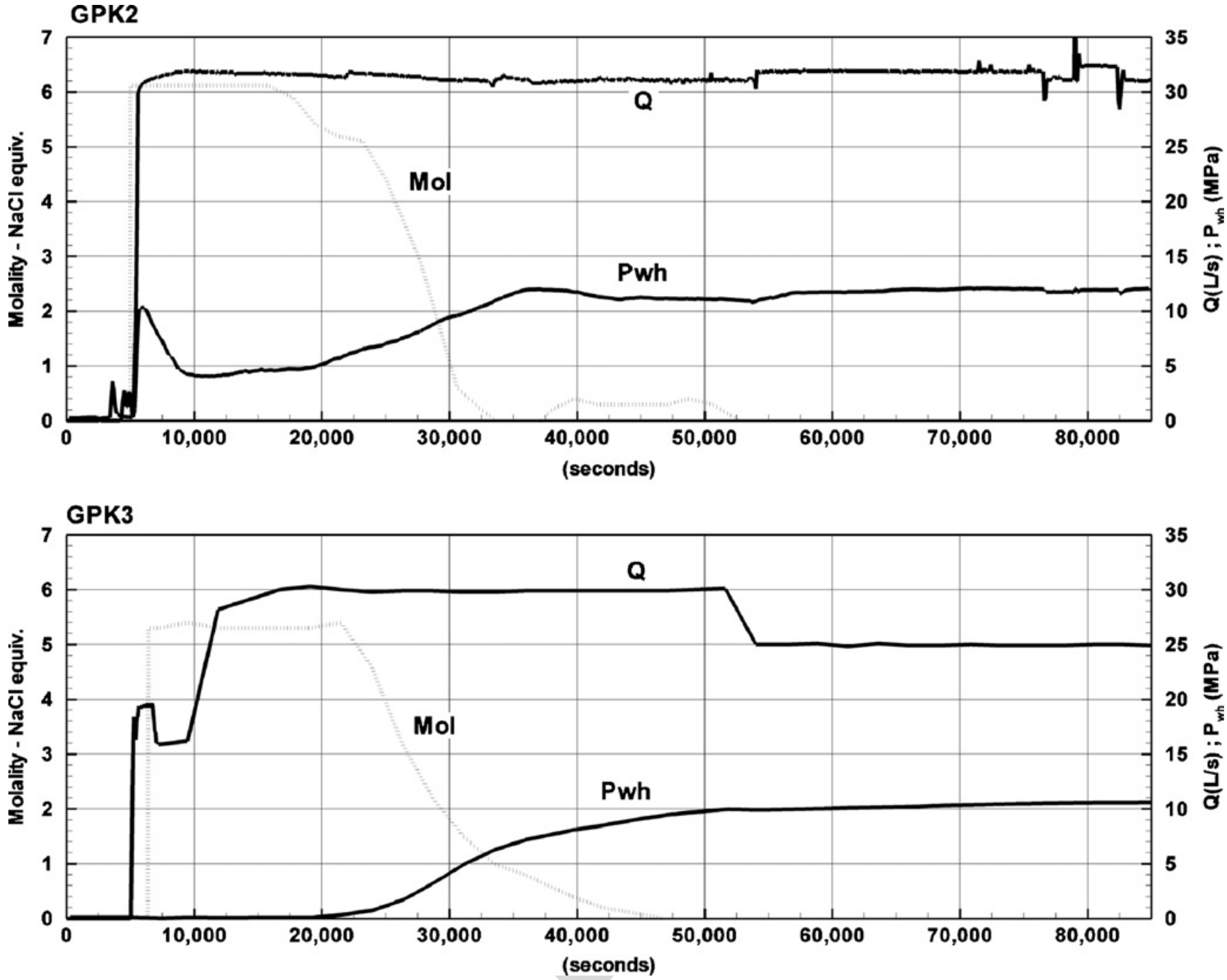

Fig. 1. Wellhead data during the first 24 h of stimulation test 00jun30 in GPK2 (top) and 03may27 in GPK3 (bottom): Q, flow rate; Mol, molality; P_{wh}, wellhead pressure.

pressure corresponds to the borehole pressure at the time and depth of the event. This interpretation defines two tasks:

1. Determination of depth and time of the near-borehole events from the stimulation tests 00jun30 in GPK2 and 03may27 in GPK3 at the depth of the open-hole sections (casing shoe is at 4410 m TVD in GPK2, and at 4499 m TVD in GPK3).
2. Calculation of the pressure profile in the borehole at the depth and time of each detected event, using the wellhead data measured during the tests.

2.1. Microseismic data

The accuracy of the microseismic event locations is rather uncertain. We assumed a global value of ±25 m positional accuracy for the near-field events. The events at horizontal distances of less than 25 m and, separately, those occurring between 25 and 50 m from the open-hole sections have, therefore, been extracted from the dataset (Figs. 2 and 3), defining near-borehole fracture failures during the stimulations 00jun30 in GPK2 and 03may27 in GPK3. Only the first 24 h of both tests were analysed.

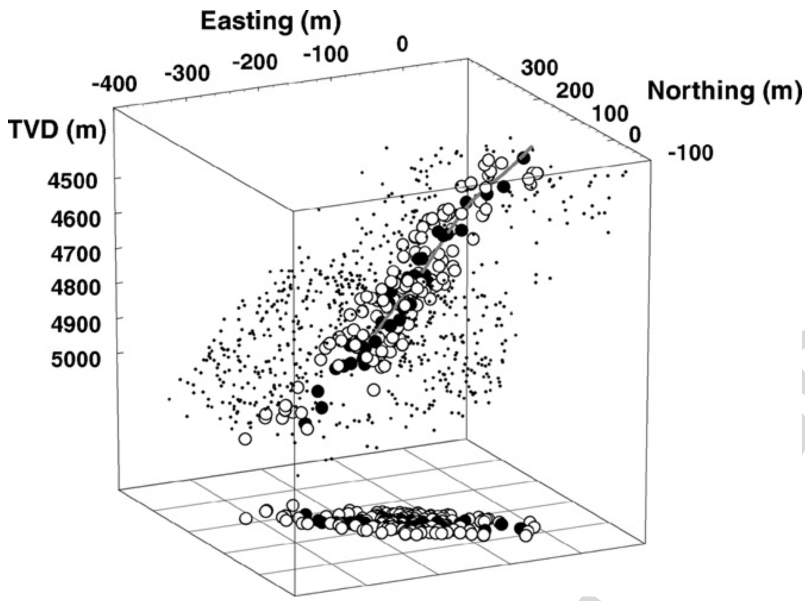

Fig. 2. Microseismic events for the first 24 h of stimulation test 00jun30 in GPK2 at horizontal distances from the borehole trajectory of less than, or equal to, 25 m (solid circles), between 25 and 50 m (open circles), and more than 50 m (small dots). Also shown are vertical projections of the event locations onto the horizontal plane and the trace of the open section of the well.

2.2. Fluid pressure data

The fluid pressure values at the depths and times of occurrence of the selected microseismic events have been determined using the numerical borehole simulator HEX-B (Mégel et al., 2005). This computer code calculates temperature and pressure profiles along a borehole by using measured wellhead data (i.e. flow rate, pressure, equivalent NaCl-molality and fluid temperature). The model parameters utilized, the processes implemented and different sensitivity considerations for

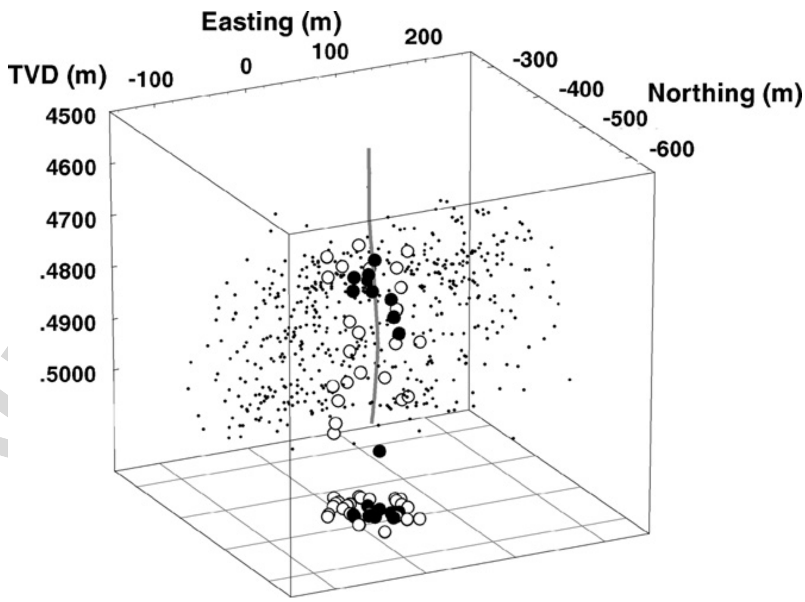

Fig. 3. Microseismic events for the first 24 h of stimulation test 03may27 in GPK3 at horizontal distances from the borehole trajectory of less than, or equal to, 25 m (solid circles), between 25 and 50 m (open circles), and more than 50 m (small dots). Also shown are vertical projections of the event locations onto the horizontal plane and the trace of the open section of the well.

HEX-B are described in detail in Mégel et al. (2005). Comparisons between calculated and measured pressures have shown that, between 4.5 and 5 km depth, the accuracy for the calculated downhole pressure is within 0.3 MPa of the measured value.

3. Results

3.1. Depth-dependency of failure pressure

The 03may27 stimulation in GPK3 started with a continuous, slow increase of the downhole pressure during the first 24 h. Thus, each of the near-borehole events can be correlated with a specific pressure in the borehole, which allows us to determine a depth-dependent fracture failure triggering pressure for GPK3 (Fig. 4).

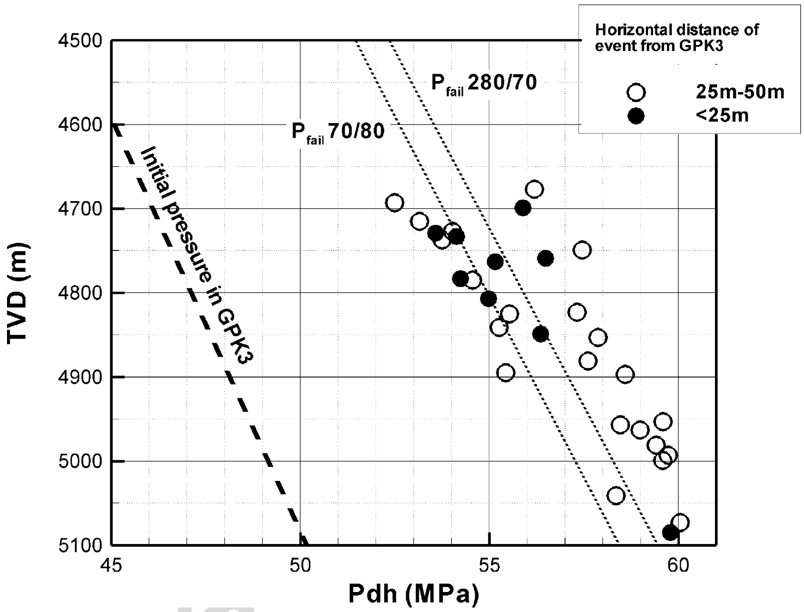

Fig. 4. Initial downhole pressures (P_{dh}) and depths of near-borehole microseismic events (at horizontal distance from the borehole <25 and 25–50 m) during the first 24 h of stimulation test 03may27 in well GPK3. Also indicated are the failure pressures calculated with the Coulomb friction law for the two most frequent fracture orientations in the open-hole section of the well (P_{fail}70/80 and P_{fail}280/70) and the stress field and friction coefficient given in Table 1.

Table 1
Parameters for estimating fracture failure pressure in the open-hole section of well GPK3 using the Mohr–Navier–Coulomb theories

Parameter	Value
Friction coefficient	1.0
Azimuth of S_H	169°
Stress field (MPa) (Cornet and Bérard, 2003)	$S_h = -1.11537 + 0.01377z$ (m); $S_H = -1.962225 + 0.024225z$ (m); $S_v = -2.0655 + 0.0255z$ (m)
Two frequent fracture orientations in the open-hole section of GPK3	P_{fail}70/80: azimuth of dip = 70°, dip = 80°; P_{fail}280/70: azimuth of dip = 280°, dip = 70°

Note: S_h, minimum horizontal stress; S_H, maximum horizontal stress; S_v, vertical stress.

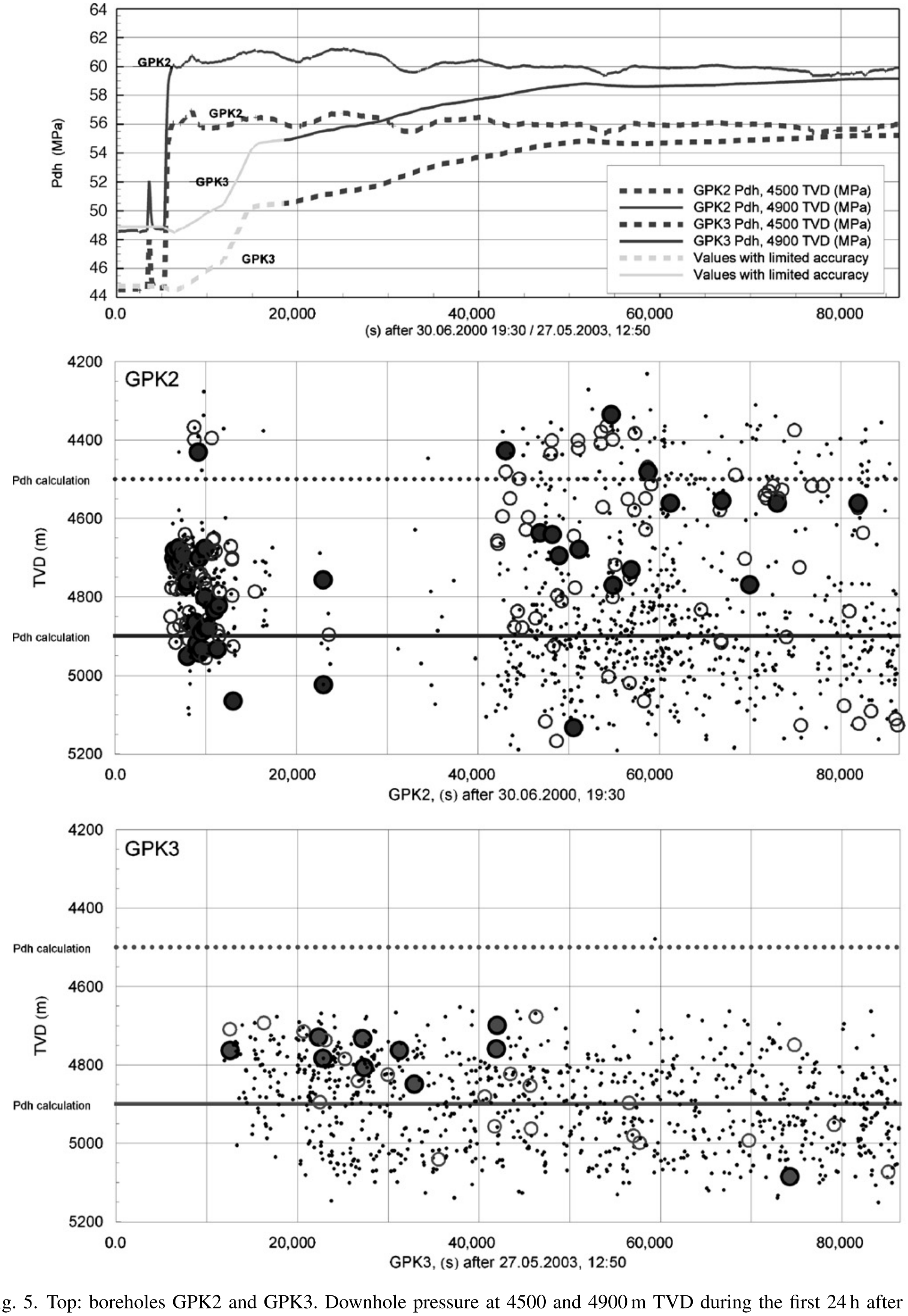

Fig. 5. Top: boreholes GPK2 and GPK3. Downhole pressure at 4500 and 4900 m TVD during the first 24 h after the start of the stimulation tests. Middle (GPK2) and bottom (GPK3): microseismic events at horizontal distances from the borehole trajectory of less than 25 m (solid circles), between 25 and 50 m (open circles) and more than 50 m (small dots).

Examination of the GPK3 data reveals two main features:

1. The triggering pressure for the near-borehole events in GPK3 increases from 52 to 60 MPa between 4700 and 5100 m depth. If we assume that the fracture orientations have a certain regular distribution along the open-hole section and, furthermore, that a general linear increase of the friction coefficient by a factor of over 1.5 is somewhat unlikely within this depth range, then this increment in the triggering pressure reflects the depth dependency of the stress field.
2. For any specific depth, the triggering pressure varies within a range of 2–5 MPa. The variation is probably due, at least in part, to the changes in the orientation of hydraulically activated fractures at that specific depth.

The shear failure pressure of a fracture with a given orientation and friction coefficient can also be estimated for a specific stress field by assuming that the rock behaves according to the Mohr–Navier–Coulomb theories for failure and slip. For this estimation, we used the calculated failure pressure of fractures with the most frequent orientations $P_{fail}70/80$ and $P_{fail}280/70$ in the open-hole section of GPK3. Utilizing the set of parameters in Table 1, we obtained a good agreement with the failure pressures derived from the near-borehole microseismicity (Fig. 4).

Comparing the values for the failure pressures with the initial pressure in GPK3, calculated using NaCl-molality and temperature profiles similar to those in GPK2 (Fig. 6), an overpressure of about 7 MPa seems to have been needed to bring the near-borehole fractures to failure. However, it must be emphasised that this is not the overpressure at which failing started. The first 2 identified near-borehole events in GPK3 (Fig. 5) are not indicated in Fig. 4 since the calculated downhole pressure during the first 20,000 s is only of limited accuracy due to a zero wellhead pressure during this period.

In contrast, the stimulation test 00jun30 in GPK2 started with a downhole pressure that was already between 55 and 62 MPa within the 4400–5100 m open-hole depth range (Fig. 5). Hence,

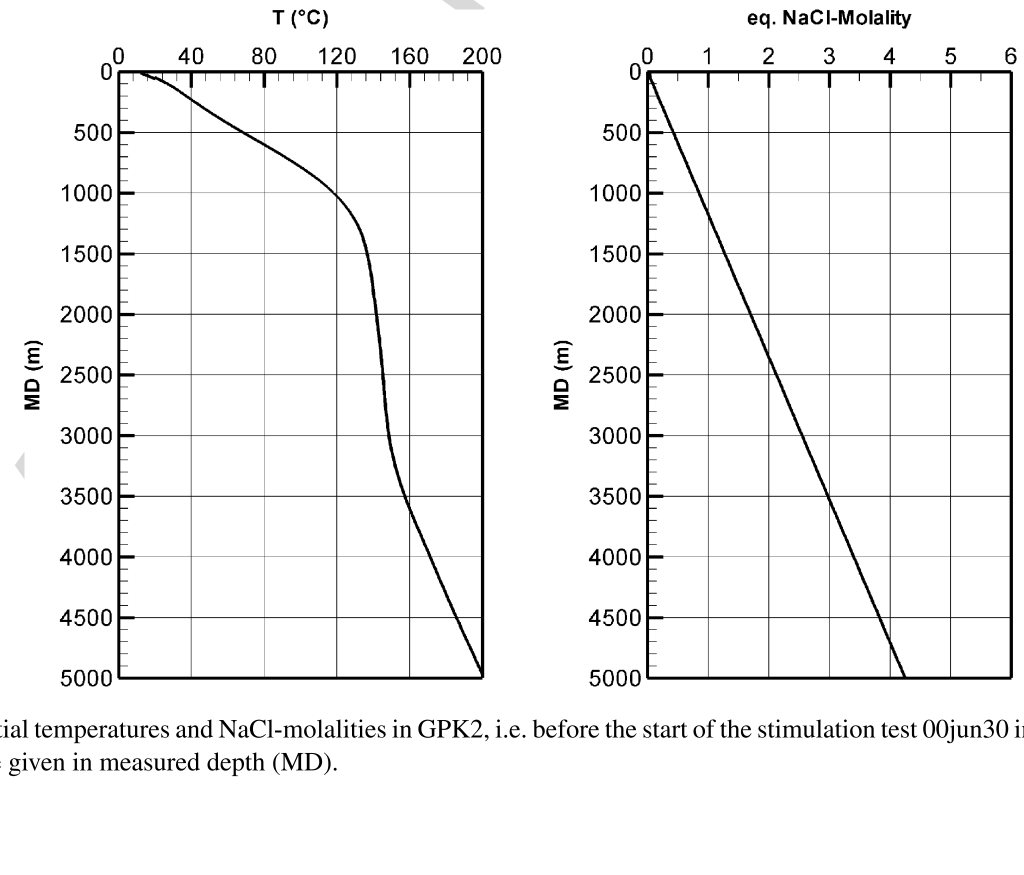

Fig. 6. Initial temperatures and NaCl-molalities in GPK2, i.e. before the start of the stimulation test 00jun30 in June 2000. Depths are given in measured depth (MD).

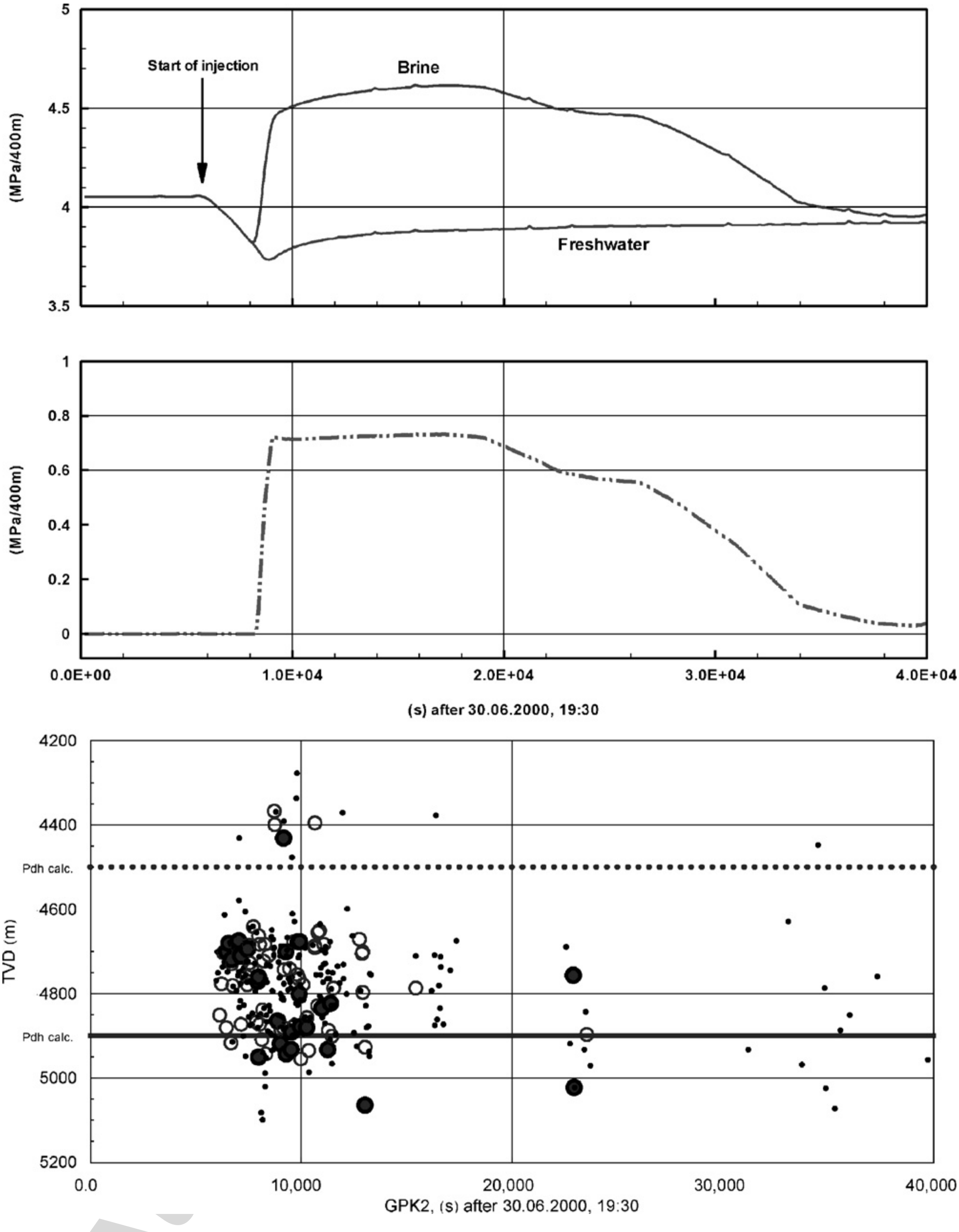

Fig. 7. Well GPK2. Top: pressure gradient between 4500 and 4900 m TVD for the first 10 h of the stimulation test 00jun30 when brine was used, and for an assumed injection of freshwater. Middle: difference between the pressure gradients in the open section of the borehole due to brine and freshwater injection. Bottom: microseismic events at horizontal distances from the borehole trajectory of less than 25 m (solid circles), between 25 and 50 m (open circles) and more than 50 m (small dots). The two lines labelled as "P_{dh} calc" indicate the two depths whose pressures were used to calculate the pressure gradient.

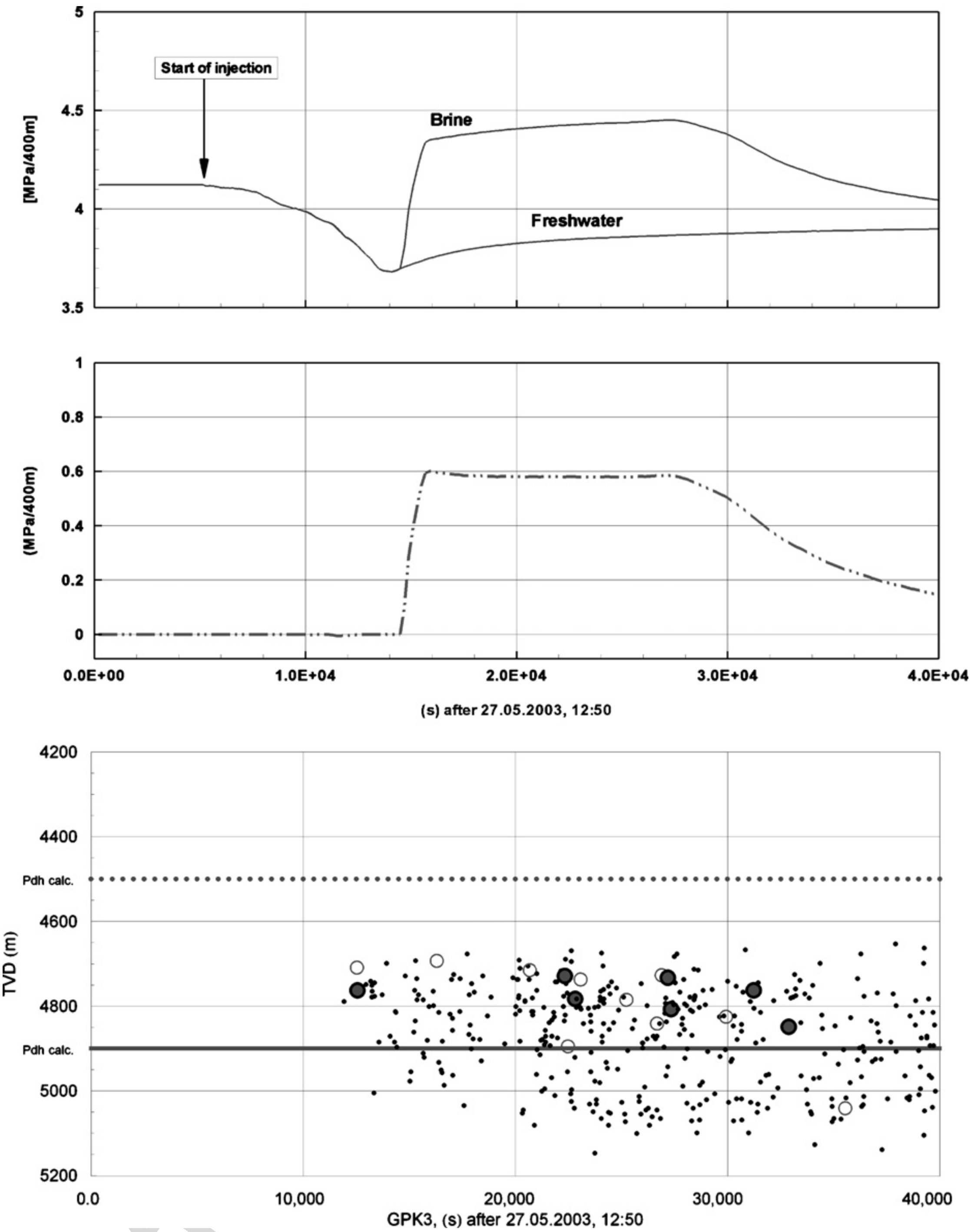

Fig. 8. Well GPK3. Top: pressure gradient between 4500 m and 4900 m TVD for the first 10 h of the stimulation test 03may27 when brine was used, and for an assumed injection of freshwater. Middle: difference between the pressure gradients in the open section of the borehole due to brine and freshwater injection. Bottom: microseismic events at horizontal distances from the borehole trajectory of less than 25 m (solid circles), between 25 and 50 m (open circles), and more than 50 m (small dots). The two lines labelled as "P_{dh} calc" indicate the two depths whose pressures were used to calculate the pressure gradient.

all the near-borehole fractures at each depth were subject to a hydraulic pressure above their failure pressure from the start and the microseismic events occurred along the entire open-hole section of GPK2 almost immediately. In this case, we were unable to carry out the depth-dependent failure pressure analysis we ran for the stimulation test 03may27 in GPK3.

3.2. Effect of the use of brine on fracture failure

The purpose of injecting NaCl brine is to increase the pressure gradient in the open-hole section of the borehole so that the deepest fractures will tend to be the first to shear. The absolute fracture failure pressure determined for stimulation test 03may27 in GPK3 has a gradient between about 5 MPa/400 m and 10 MPa/400 m (Fig. 4). The injection of an NaCl-saturated brine in the first phase of the injection tests in GPK2 and GPK3 produced a maximum pressure gradient of 4.6 MPa/400 m in GPK2 and 4.4 MPa/400 m in GPK3 (see top of Figs. 7 and 8, respectively). Both of these values are close to the failure pressure gradient derived from the GPK3 stimulation and shown in Fig. 4.

In both boreholes, a linearly increasing concentration with depth at the equilibrium state was assumed (Fig. 6 for GPK2). This assumption was confirmed at GPK4 using the values in the September 2004 pressure log. In the two wells, the pressure gradient in the open-hole section decreases after the start of injection (Figs. 7 and 8). This is due to the density reduction in the liquid column resulting from the downward movement of the initially linear gradient of NaCl-concentration. This effect exceeds the density increase caused by the decrease in fluid temperature. As soon as the highly NaCl-concentrated injection fluid reaches the casing shoe the pressure difference between the top and the bottom of the open-hole section increases due to the higher fluid density.

If fresh water had been injected instead of brine, the hydraulic pressure gradient would have been 0.7 MPa/400 m lower in GPK2 (Fig. 7) and 0.6 MPa/400 m lower in GPK3 (Fig. 8), assuming the same flow impedances into the reservoir as determined for the corresponding brine injections. Although the effect of the NaCl-brine injection is only minor, it does shift the hydraulic gradient closer to the most favourable pressure gradient for fracture failure found from the GPK3 stimulation data (Fig. 4).

4. Conclusions

The accuracy we can achieve in locating microseismic events associated with the hydraulic stimulation of wells is limited. The selection of near-borehole events is, therefore, rather vague, and the distinction between distances of 25 and 50 m, in particular, is somewhat arbitrary. Comparing the two different stimulation strategies utilized in GPK2 and GPK3, we can nevertheless make some statements about the role played by NaCl injection during the stimulation tests:

1. Considering only the location of events associated with the stimulation test 00jun30 in GPK2 that occurred within a horizontal distance of less than 25 m from the borehole, a predominantly downward trend of the events can be observed. This trend starts just as the steeper pressure gradient caused by injection of the brine becomes evident in the open section of the borehole (Fig. 7). Assuming the depth-dependent triggering pressures derived from the GPK3 data (Fig. 4) are also valid for GPK2, the downhole pressure in GPK2 was above the failure pressure for all fractures along the entire open-hole section from the start of the stimulation test. Therefore, the downward trend of the events could be due to the injection of the denser brine.
2. During the stimulation test 03may27 in GPK3, when the increased pressure gradient due to brine injection was in force, the absolute downhole pressure at 4900 m TVD was below 56 MPa at all times. The failure pressure for the fractures located below 4850 m TVD was, therefore, never exceeded during this period (Fig. 4). Hence, a significant downward trend of events as an effect of brine injection cannot be observed in GPK3 (Fig. 8).

Increasing fluid pressures will improve the injectivity/productivity of a deep well by inducing failure in any fractures that intersect the borehole wall. Apart from fluid pressure, the behaviour of these fractures will also depend on a number of other factors such as orientation, stress field and shear friction coefficient. Usually, the mechanical behaviour of fractures at a given site will be unknown before a first stimulation test has been carried out. It is, therefore, important that we increase the probability of early failure of deeper fractures by injecting a denser fluid, such as in the tests with a saturated NaCl solution attempted at Soultz. The technique offers the combined advantage of being relatively cheap and environmentally friendly. A further refinement for later stimulations at the same site could be achieved by adjusting the density of the injected fluid so that the overpressure in the borehole exceeds the failure pressure of all intersecting fractures simultaneously.

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