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Rock Mechanics with Emphasis on Stress

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Sustainable Development of Groundwater from Hard Rock Formations

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ABSTRACT

Water as drinking water, mineral water, thermal water, for the use in agriculture and industry is of vital importance with ever increasing demand. In India nearly 800.000 villages do not have sufficient water supply, similar is valid for large areas in Africa, South America, and Asia. Even countries with sufficient rainfall like Germany will face drinking water shortage problems in the near future because of shallow aquifer pollution due to disposal of untreated industrial waste and the use of fertilizers and pesticides in agriculture during the past. As a result we are forced to tap deeper aquifers mostly in jointed hard rock formations. In spite of intensive geological and geophysical exploration deep wells often show poor water yield. We were told that only 50 per cent of drillings for water on the Indian shield are successful, and wells drilled just a short distance from a dry well may be productive if the borehole intersects a water-bearing joint or fracture network. Here, it seems obvious to use stimulation techniques to artificially connect the well with the water-bearing network in its vicinity. We describe some case histories for water-well stimulation in Germany.

13.1 INTRODUCTION

Groundwater is of vital importance in meeting todays demand of water supply for domestic, agricultura and industrial use. Due to the extensive use of fertilizers and pesticides in agriculture and the disposal of untreated industrial waste, shallow aquifers in porous and permeable sedimentary rock formations often are polluted. In addition, increasing water demand due to rapid population growth and unresponsible over exploitation may lead to seasonal depletion of such aquifers. Both these qualitative and quantitative problems are recognized by scientists and politicians all over the world. The problems were particularly addressed for India by the International Groundwater Conference on Sustainable Development of Groundwater Resources held at Dindigul, Tamil Nadu, India in early 2002 (Thangarajan et al., 2002). This conference covered topics like groundwater assessment, recharge processes, pollution remediation measures, and resource management. It also touched upon issues like the necessity to drill deeper wells into non-porous, often crystalline rocks with the hope of drawing water from open joint and fracture networks. However, such drillholes often are without sufficient yield in spite of accompanying intensive and competent geological and geophysical prospection. On the other hand, there are many cases where a borehole drilled next to a dry hole may be highly productive if the drillhole intersects water bearing fractures and joints which often are steeply inclined.

13.2 STIMULATION TECHNIQUES

Before abandoning a well with insufficient water yield, efforts are made to increase the productivity of the well by blasting or acidizing operations. In most cases, such operations do not lead to a full success since their effect is limited to the close vicinity around the wellbore. In contrast, the hydraulic fracturing method as used in oil industry for borehole productivity enhancement offers a tool to either initiate and propagate a fracture far away into the massive rock to intersect existing water bearing joints, or to stimulate and open closed fractures such that water can migrate towards the wellbore (Fig. 13.1).

The hydraulic fracturing concept is simple and straightforward (Rummel, 2002). A borehole interval is isolated from the rest of the borehole by two inflatable packer elements which allow the interval to be pressurized until a fracture is induced in the borehole wall rock. The induced fracture can be easily propagated over large distances by further fluid injection. The critical pressure for fracture initiation, P_c, is depending on the rock tensile strength P_{co} and the acting stresses within the rock

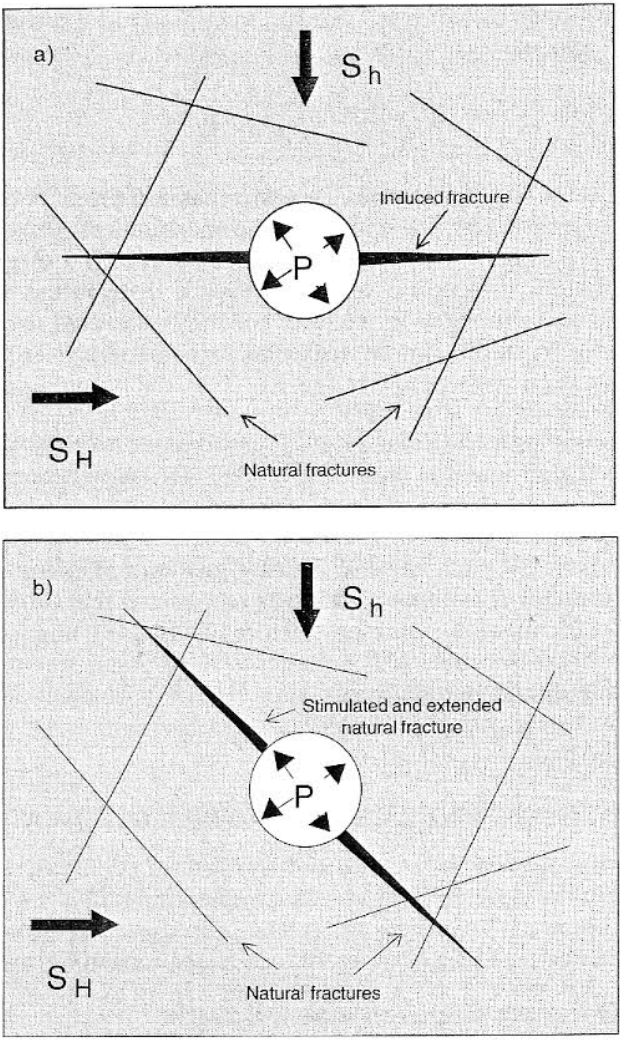

Fig. 13.1 The hydraulic fracturing borehole stimulation concept, showing (a) an induced fracture originating in a pressurized borehole and intersecting natural fractures. S_H, S_h principal horizontal stresses, P injection pressure, (b) a natural fracture being stimulated and extended.

mass. For a vertical borehole and the acting horizontal far-field stresses S_H and S_h ($S_H > S_h$, principal stresses) the condition for fracture initiation is given by the relation

$$P_c = 3S_h - S_H + P_{co} \tag{1}$$

Fracture propagation can be described by a simplified fracture mechanics relation of the form

$$P_c = \frac{K_{IC}}{k_3} + k_1 S_H + k_2 Sh \tag{2}$$

where K_{IC} is the rock fracture toughness, a material property (e.g. $K_{IC} = 2$ $MN/m^{3/2}$ for granite), k_1 and k_2 are dimensionless stress intensity functions ($k_1 \rightarrow 0$, $k_2 \rightarrow 1$ for large fractures), and k_3 is a stress intensity function mainly depending on the pressure distribution within the pressurized and propagating fracture. For moderate fluid injection rates the first term in eq. (2) can be neglected for sufficiently large fractures (fracture length a >> borehole radius R). Thus, the pumping pressure P_p for fracture extension is practically only controlled by S_h or the normal stress S_n acting perpendicular to the fracture plane. When the pumping pressure is higher than the normal stress S_n the fracture is open and large amounts of water can be pumped through the fracture. To keep the fracture open after pressure release oil industry uses various kinds of proppant materials such as sand. During geothermal energy extraction research from hot crystalline rock it was recognized that during fracture stimulation frictional shearing on fractures favourably aligned with the principal stresses occurs, which prevents subsequent fracture closure. Thus, simple stimulation of fracture may lead to permanent permeability increase of the rock mass and productivity enhancement of initially dry water wells (Baria et al., 1999).

13.3 CASE HISTORIES OF WATER WELL STIMULATION

In the following sections some case histories are presented which may demonstrate the development of water well stimulation from an initially empirical approach towards a systematic procedure. All of these studies were conducted by MeSy in different rock formations in Germany.

13.3.1 Borehole Gunzenhausen, Bavaria

Borehole Gunzenhausen was planned for mineral and thermal water supply to stimulate recreation attraction in this area. The borehole was drilled to a depth of 460 m with a bottom hole temperature of 23°C. The borehole penetrates sedimentary rocks to a depth of 295 m, and then is in the crystalline basement consisting of a fine-grained granite. The hole was cased to a depth of 350 m. The diameter of the open-hole section below is 156 mm. The geophysical logs (caliper, salinity) indicated a major fault zone at 440 m which also caused borehole instability at this depth. The natural gamma log suggested clay fillings of some fractures. The water table was approximately 60 m below surface. Initial pumping tests yielded a productivity of 1.6×10^{-11} m^3/Pa s for the open-hole granitic section from 350 to 460m.

Stimulation tests in the open-hole section from 376 to 460 m were carried out with (i) a wireline double straddle packer system of 1 m test length and injection rates of some litres per minute, and (ii) with single packer and double straddle packer systems of 4 m test length which allowed injection rates of up to 3.2 litres per second. A typical test plot for test series (i) is given in Fig. 13.2 indicating the pressure decay after three pre-stimulation pressure pulse tests, and the pressure decay after system shut-in after the hydrofracturing stimulation. Evaluation of the test yields an initial rock permeability of (13 ± 3) μDarcy, and a permeability of (64 ± 13) μDarcy after stimulation. The normal stress acting across the induced fracture plane is app. 14 MPa. The permeability increase suggests that the fracture is not completely closed.

A total of 19 such stimulation test were carried out within the granitic open-hole section from 380 to 430 m. A final injection test with a single packer set at 376 m (Fig. 13.3) demonstrated a steady-state injection rate of

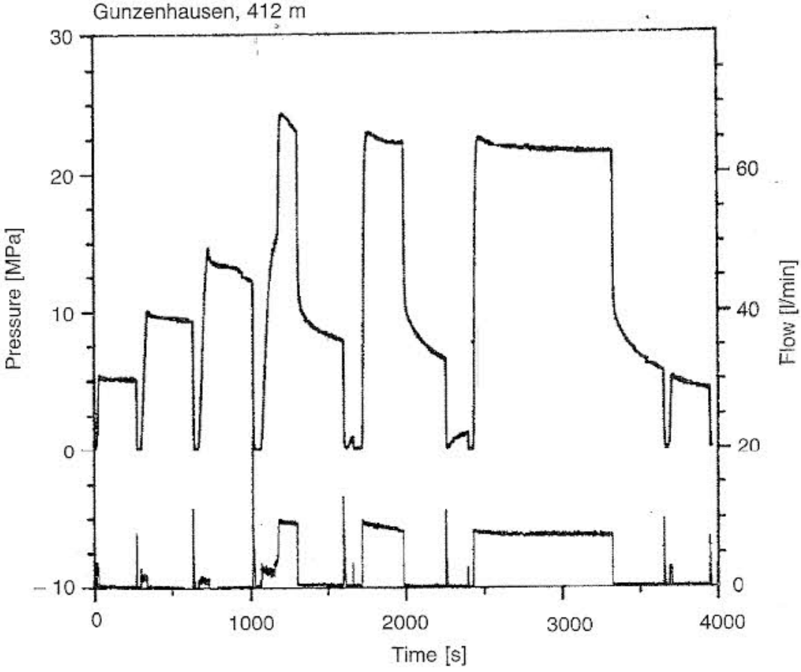

Fig. 13.2 Pressure and flow rate record of initial permeability tests. (i) hydrofrac test (ii) and Post-frac injection tests at a 4 m test section at 412 m depth in borehole Gunzenhausen.

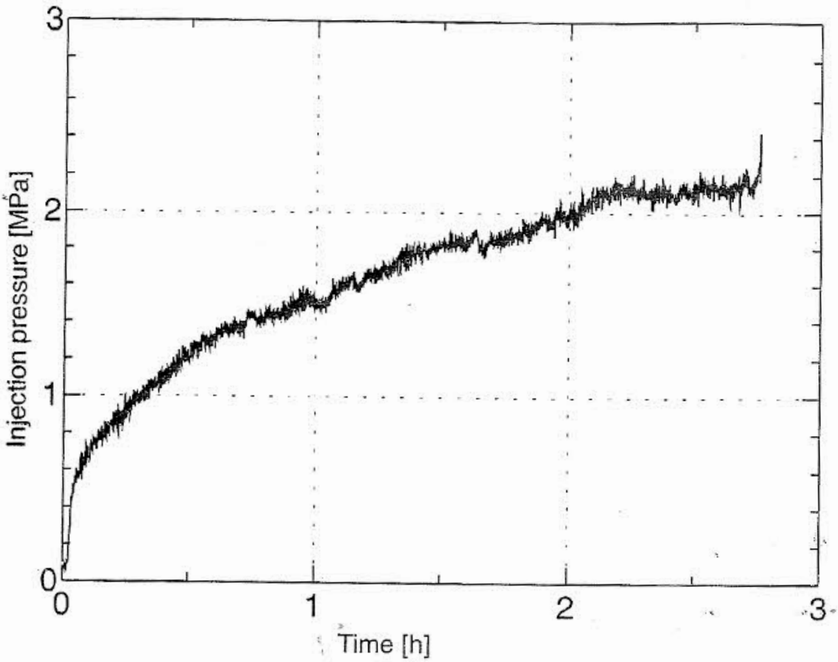

Fig. 13.3 Pressure response during the final injectivity test on the open-hole section 380 to 430 m in borehole Gunzenhausen (constant injection rate: 4.5 litres per minute).

4.5 litres per minute at a pressure of 2.2 MPa which yields an injectivity of 3.4×10^{-11} m^3/Pa for the total open-hole section, compared to the initial productivity of 1.6×10^{-11} m^3/Pa s an increase by a factor of two. This productivity increase, however, was not sufficient for an economical use of the crystalline aquifer at depth.

13.3.2 Borehole Waffenbrunn, NE Bavaria

The borehole with a depth of 150 m and a diameter of 250 mm was designed to contribute to the water supply of the community Waffenbrunn from the fractured gneissitic underground. The expected discharge was 3 litres per second, but only one fracture zone with a yield of 0.5 l/s at 55 m depth was penetrated. During an initial injection test with a single packer set at 41 m depth, the injectivity of this fracture could be increased by 30 per cent to 1.3×10^{-9} m^3/Pa s (Fig. 13.4).

Subsequently, 20 hydraulic fracturing tests with a double straddle-packer system with a test section length of 3 m were carried out below 55 m depth, to initiate and stimulate new fractures and propagate them to

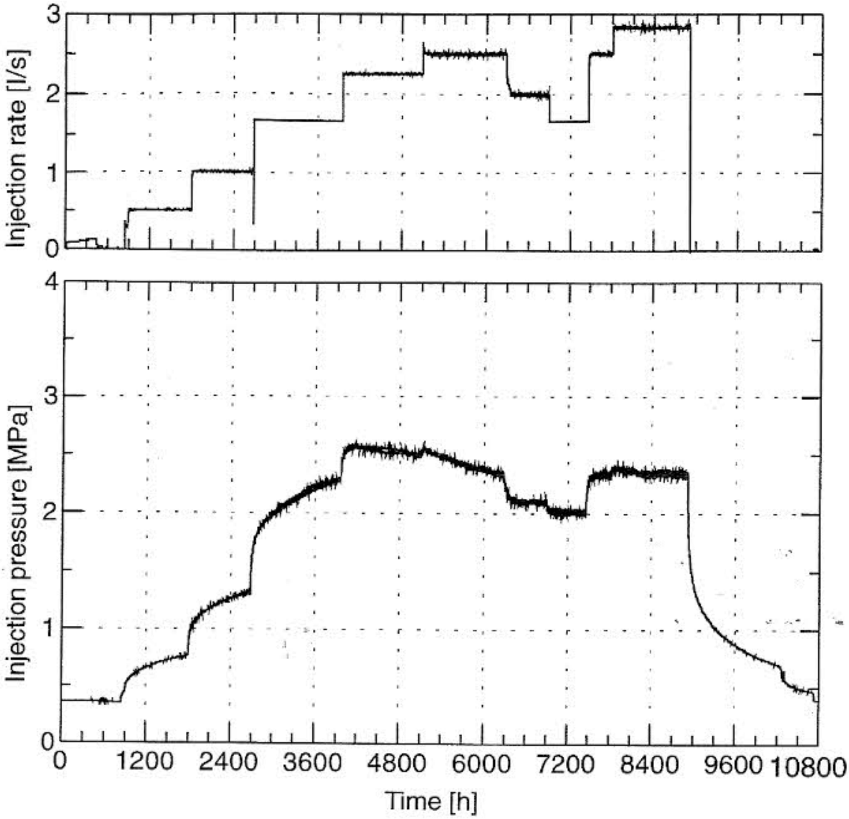

Fig. 13.4 Pre-stimulation injection test in borehole Waffenbrunn with an injection rate of up to 3 litres per second.

intersect water-bearing fractures in the gneiss rock mass. During each test a water volume of app. 1 m^3 was injected. To initiate fractures injection pressure values of more than 10 MPa were required. The conductivity of the rock within the test sections was increased from initially 10^{-10} m/s to almost 10^{-7} m/s (Fig. 13.5). Inspite of this, a single packer test at 80 m depth only showed an injectivity of 0.1×10^{-9} m^3/Pa s for the open-hole section below 80 m. As demonstrated by a final production test with a pump placed at 60 m depth, the production rate from the lower borehole section was at least 0.7 l/s (1.1×10^{-9} m^3/Pa s).

13.3.3 Borehole Lindau, N-Bavaia

The research borehole Lindau near Bayreuth was drilled to a depth of 530 m with a diameter of 146 mm. While the upper hundred metres were

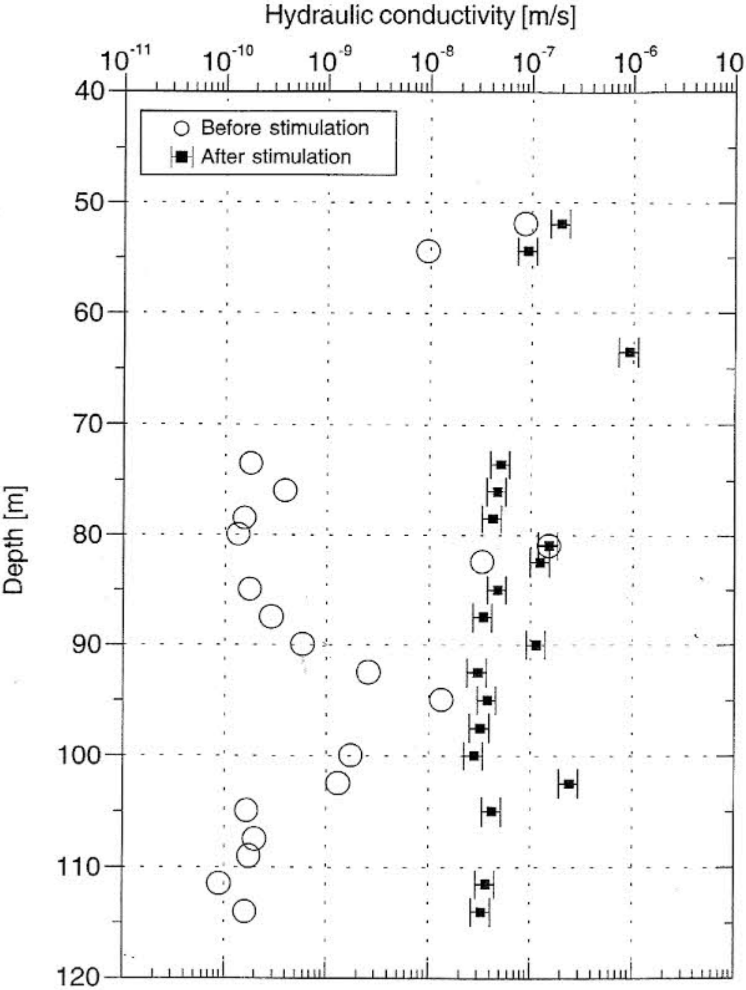

Fig. 13.5 Hydraulic conductivity of 3 m test sections in borehole Waffenbrunn before and after stimulation

cased, the borehole penetrates sandstones and conglomerates of the Lower Buntsandstone (to 178 m), then fine-grained sandstone of the Zechstone formation (to 281 m), and finally sandy claystones of the Upper Rotliegend formation. Early production tests showed a productivity of app. 4×10^{-9} m^3/Pa s with 97 per cent of the production originating from the Buntsandstone. After a massive hydraulic fracturing stimulation (300 m^3 of water) at app. 150 m, 165 m, and below 441 m depth the productivity could be increased to 6×10^{-9} m^3/Pa s.

To further investigate the possibility of productivity enhancement, 40 wireline hydrofracturing tests with a double straddle packer system of 3 m

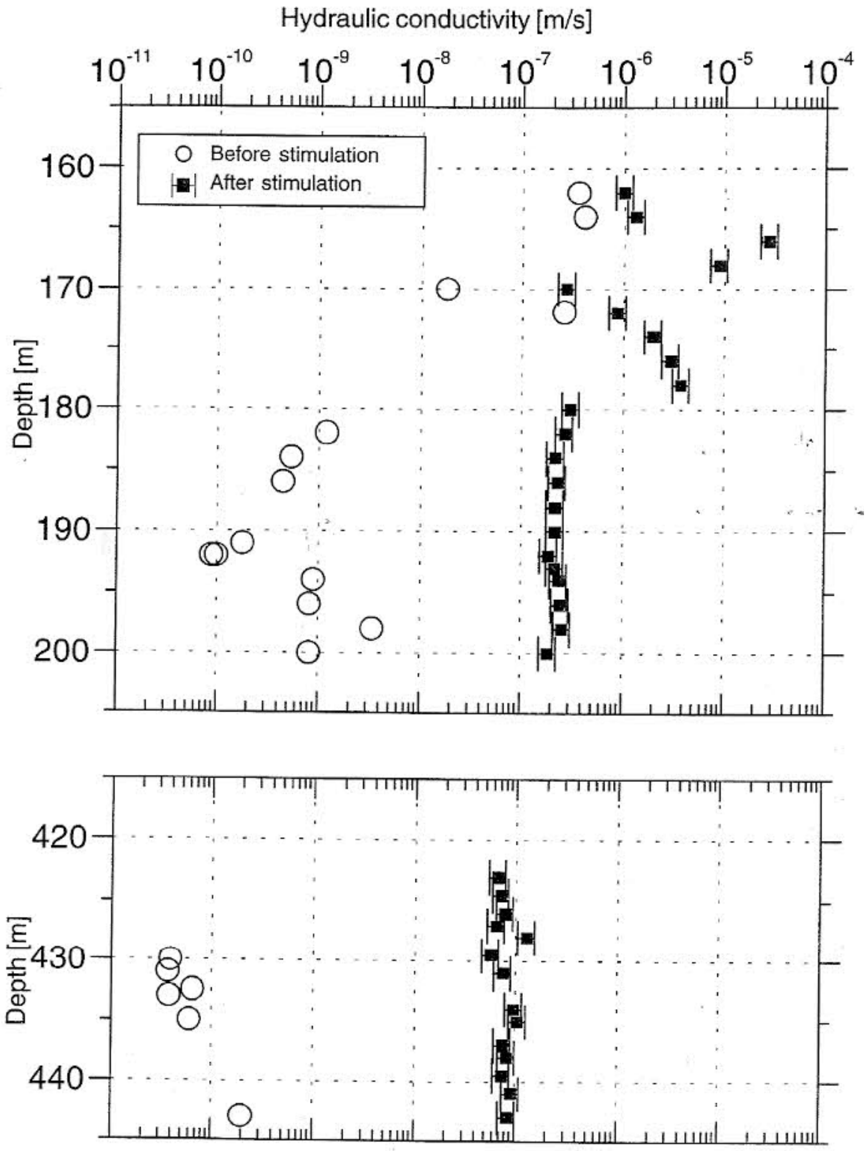

Fig. 13.6 Hydraulic conductivity of 3 m test sections in borehole Lindau before and after stimulation in Buntsandstone (162-178 m), Zechstone (178-200 m), and the Rotliegend formation (423-442 m).

test length were conducted, eight test in the rather permeable Buntsandstone, 14 tests in Zechstein sandstone, and 19 tests in the impermeable claystones of the Rotliegend formation below 418 m. The test series were carried out in such a way that a fracture was first induced at the bottom of the series and then extended zipper-like upwards with overlapping test intervals. At each test interval app. 100 litre water was injected into the induced fractures (or into the pore space of the permeable formation) at a rate of app. 0.5 l/s.

The results of this systematic investigation is shown in Fig. 13.6. The formation conductivity in the permeable Buntsandstone was increased by a factor of 16, the Zechstone conductivity by a factor of 220, and in the impermeable Rotliegend formation the conductivity increased by a factor of 860. However, the injectivity of the Zechstone/Rotliegendes still is 1 to 2 orders of magnitude smaller than the injectivity of the Buntsandstone. As shown by a final long-term production test the productivity of the borehole has only slightly increased from 4×10^{-9} or 6×10^{-9} to 8.6×10^{-9} $m^3/Pa\ s$.

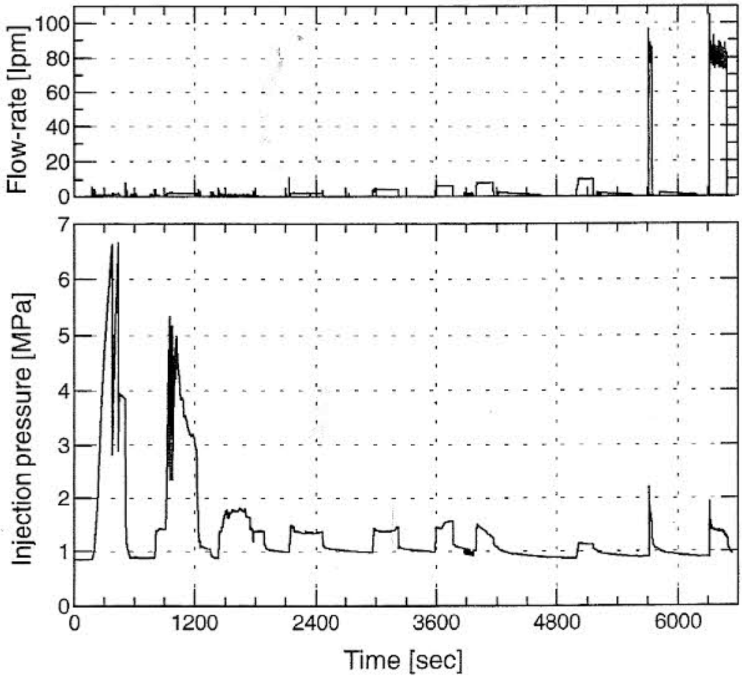

Fig. 13.7 Pressure and flow rate record during stimulation of the bottom hole section of borehole Herzog. Frac initiation at 7 MPa with an injection rate of 2 l/min, then fracture extension with high injection rates up to app. 100 l/min with negligible pressure response.

13.3.4 Borehole Herzog, Bochum, NW Germany

The local mineral water supplier has used an aquifer in the Upper Cretaceous Emscher claystone with boreholes drilled to app. 100 m since decades. To increase the supply one other borehole was drilled into the aquifer, but was essentially dry. The open-hole section from 72 m to 95 m had a diameter of 311 mm. An initial pulse test demonstrated a rock matrix permeability of 0.3 mDarcy. By application of the zipper-type hydraulic fracturing concept with overlapping test intervals, a fracture was induced in the bottom hole section at 92 m with a pressure of 7 MPa (Fig. 13.7) and then extended upwards to app. 80 m depth. The fracture extension pressure was only 2 MPa at injection rates up to 1.5 l/s. A total of 400 litres of water was injected during the stimulation operation. After pressure release no return flow was observed, an indication that the induced fracture had communication with a large aquifer. The final production test showed a constant production rate of 4.5 m^3 per day, the same yield as the neighbouring boreholes (Rummel, 1997).

13.4 CONCLUSIONS

For most areas in Central Europe a water well productivity of 10^{-9} m^3/Pa s (i.e. 2 l/s from a 300 m deep well) is not sufficient to significantly contribute to the drinking water consumption of a community. The situation could be different for rural areas in arid or semi-arid hard rock regions. The increase of the water yield from a well by a factor of 2 by hydraulic fracturing stimulation may not be economic but may be vital for the local population. As shown by the case histories, a productivity increase by factor of 2 is realistic.

By injection rates of some litres per minute, which are possible with a wireline straddle packer stimulation system, hydraulic fractures with an extension of deca-metres can be induced, however, the fracture width is much less than one millimetre. Shear offset on rough fracture planes is prevented by the shear resistance. Although large water quantities can flow through the fractures, they will almost close again after stimulation. Larger fracture widths can be obtained with high injection rates or using high viscosity fluids jacking the fracture open against the acting normal stress. Despite of the cost of such stimulation operations, the fracture jacking effect is mostly limited to the wellbore vicinity as shown by numerous laboratory studies (Klee, 1991; Teza, 2002). The use of proppants in water well stimulation has not been systematically studied simply because of high costs. Treatment of induced fractures with acidic fluids is not appropriate because of environmental risks. Thus, the problem of effective water well stimulation in hard rock remains and is directly related to the local stress regime which controls fracture opening and closure. The situation will be different in water-bearing highly fractured rocks where hydrofracturing stimulation will create permanent intersection between the wellbore and the fracture water reservoir. A major fault zone may be considered as such an aquifer to be tapped by stimulation.

REFERENCES

Baria, R., Baumgärtner, J., Rummel, F., Pine, R.J., and Sato, Y., 1999. HDR/HWR reservoirs: concepts, understanding and creation. Geothermics, *28*:533-552. Pergamon/Elsevier Science.

Klee, G. 1991. Experimental investigation of the pressure distribution in hydraulic induced fractures. Yellow Rep. No. 4, Ruhr University Bochum, Inst. of Geophysics.

Rummel, F. 1997. Stimulation einer Mineralwasserbohrung mit geringer Schüttung. Der Mineralbrunnen 10:458-466.

Rummel, F. 2002. Crustal stress derived from fluid injection tests in boreholes. *In: In-situ characterization of rocks (eds. Sharma and Saxena), chapt. 6*: 205-244, Balkema Publishers.

Teza, T. 2001. The role of fractures as hydraulic valves in rocks. *Yellow Rep. No. 29, Ruhr University Bochum, Inst. of Geophysics.*

Thangarajan, M., Rai, S.N., and Singh, V.S., 2002. Sustainable development and management of groundwater resources in semi-arid regions with special reference to hard rocks. *Proc Int. Groundwater Conference*. Oxford & IBH Publ. Co., New Delhi.