PROCEEDINGS, Twenty-First Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 22-24, 1996
SGP-TR-151

NON-LINEAR FLOW TRANSIENTS IN FRACTURED ROCK MASSES - THE 1995 INJECTION EXPERIMENT IN SOULTZ

T. Kohl[1], R. Jung[2], R.J. Hopkirk[3], L. Rybach[1]

[1] Institut für Geophysik, ETH-Hönggerberg, CH-8093 Zürich, Switzerland
[2] Bundesanstalt für Geowissenschaften und Rohstoffe, Stilleweg 2, D-30631 Hannover, Germany
[3] Polydynamics Ltd., Tuggenerstr. 8, CH-8008 Zürich, Switzerland

ABSTRACT

In July 1995 in the course of the Hot Dry Rock (HDR) site investigation studies in Soultz s.F. (France) multi rate hydraulic injection tests were conducted in the borehole GPK2. The downhole pressure records obtained from the lowermost depth domain between 3211 m and 3876 m demonstrate non-laminar hydraulic behavior. Such behavior was also observed earlier during a similar set of flow step tests in the GPK1 borehole Soultz. Like the analysis of these earlier data sets, it could be shown that the pressure records from July 1995 are corresponding to empirical flow laws established for non-laminar hydraulic regimes.

In this study a numerical model is described which is being developed for the analysis of non-laminar flow in fractures. Similar models have already been applied to production and injection tests at GPK1. The results show that the observed transient pressure record is well predicted by such a non-linear flow law. Conventional laminar flow models cannot reproduce these curves. An evaluation of the parameters resulting from both, steady state and transient analysis leads to assumptions on the geometry of the main fracture system. Our calculations show that surface areas above 0.05 km^2 and apertures in the order of 0.4 mm results in an excellent fit of the data.

INTRODUCTION

The development of Hot Dry Rock (HDR) technology has lead to progress in many experimental and theoretical fields. In particular, the evaluation of hydraulic data, originally developed for porous media is under re-examination.

The analysis of hydraulic data sets from the various HDR experimental sites has been mostly restricted to laminar flow assumptions. Since furthermore the hydraulic experiments are often set-up by a single pressure or flow step, there is little evidence of non-laminar flow behavior. An example of interpretations of hydraulic experiments at the Soultz site, based on laminar flow assumptions is the fit of the stimulation test of December 13th, 1988 (88DEC13) which was performed in a fracture zone intersecting the GPK1-borehole at a depth range of 1968-2000 m. Jung (1990) succeeded in fitting the beginning of the measured pressure increase by applying the analytical formulations of Cinco & Samaniego (1981). Also based on laminar flow assumptions Kohl (1992) subsequently succeeded in fitting the total of the stimulation test 88DEC13 by a Finite Element analysis.

Armstead & Tester (1987) show that laminar, Darcian flow conditions are commonly assumed in the interpretation of hydraulic data-sets from HDR tests. The most common non-linearity taken into account for the interpretation of large hydraulic injections are interactions due to mechanical aperture changes of a fracture combined with linear flow. The transmissivity is calculated by the cubic law. Such mechanical interaction was assumed by Bruel & Ezzedine (1994) who fitted the pre- and post-stimulation pressure response using coupled hydro-mechanical algorithms of a subsequent stimulation test in the same depth domain of GPK1. Also Swenson et al. (1995) using a coupled (hydraulic-thermal-elastic) simulation succeeded in fitting the transient pressure response of the injection and extraction well of the actual Fenton-Hill reservoir to a sudden closure of the well-head valves. Kohl et al. (1995a) demonstrated qualitatively the importance of such coupled considerations to the long term behavior of a HDR reservoir.

Unfortunately, there have been only very few studies which question the validity of Darcian approach for fracture flow. Such as are known are based on laboratory tests (for example Lomize 1951, Louis 1967) a drew heavily on the classical experimental work of Forchheimer (1930) and Nikuradse (1930). These studies show that non-laminar flow is likely to happen at even moderate flow rates through rough surfaces. This effect manifests itself by decreasing transmissivity with increasing flow.

To our knowledge, there have been even less field measurements from which non-laminar flow in fractured rock has been knowingly observed (Mackie 1982, Jung, 1989). In these cases it was concluded that non-linear flow behavior is most common in fractured rock even at quite a large distance from the borehole wall. However, the magnitude of this distance remains uncertain.

Moreover, despite the evident importance of non-laminar flow behavior, there exists only a limited number of detailed and systematic studies of the nature of the problem. If deviations from linear flow are admitted, they are mostly interpreted qualitatively as 'skin-effects' limited to a few centimeters close to the well bore. We know of two different approaches to quantitatively interpret the non-linear effects in a radial flow field measured at joints of laboratory scale. Rissler (1977) and Atkinson (1986) calculated numerically the two-regime (laminar-non-laminar) steady state pressure field that was monitored in a roughened fracture of 1.5 to 2 m diameter. Our approach tries to extend these studies for a transient analysis of a vertical fracture. For this purpose the finite element code *FRACTure* (Kohl & Hopkirk, 1995) has being extended. An application using a two-dimensional model will be presented to an injection test performed in July 1995 at the HDR test site Soultz.

SITE AND HYDRAULIC TEST DATA

The European HDR investigation site was installed at Soultz s.F. about 60 km north of Strasbourg. This location situated in a Graben structure is characterized by a high heat flow. Values above 150 mW m^{-2} were reached near the surface, within the crystalline basement (top at 1450 m depth) lower values around 90 mW m^{-2} were measured. A temperature of approx. 170°C was encountered in the borehole GPK2 at bottom hole depth of 3876 m.

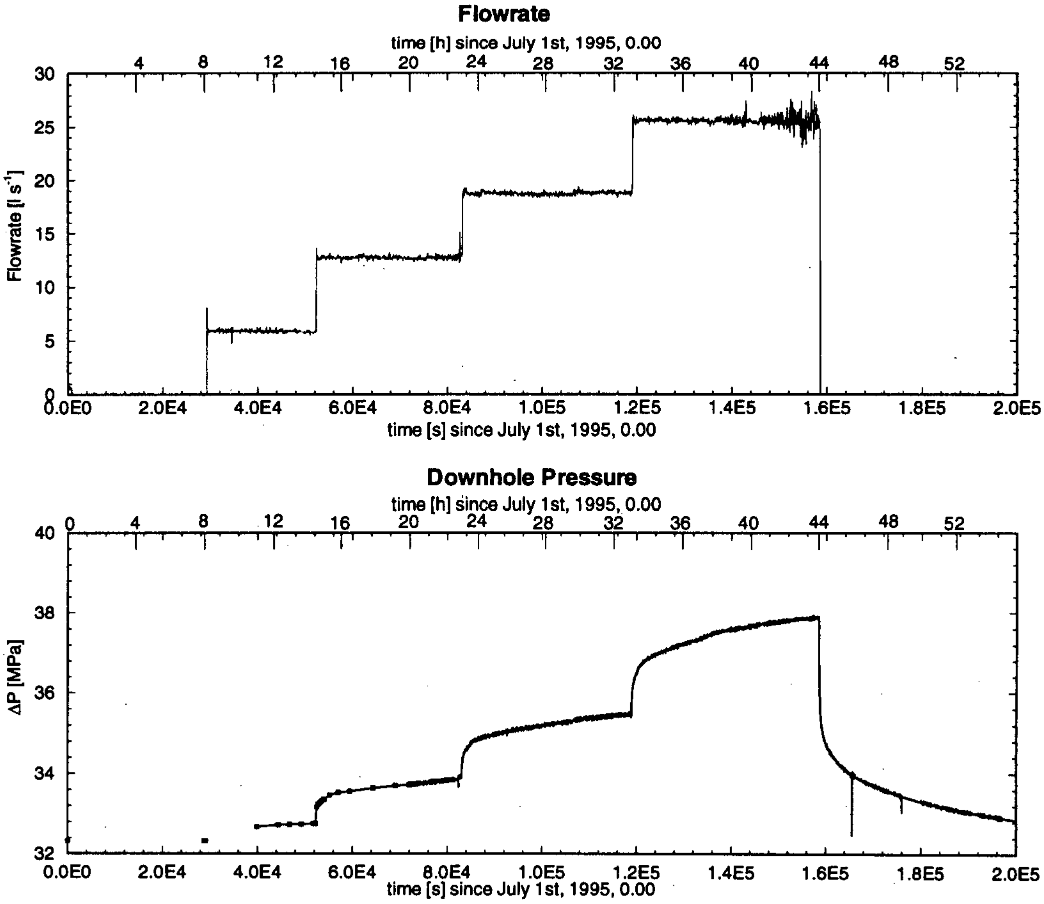

Fig. 1: The injection pressure records of 95JUL01. The lower x-axis indicates the seconds, the upper x-scale indicates the hours after July 1st, 1995.

GPK2 is intended to be the injection leg of a duplet system. Drilling was completed in spring 1995. It was positioned south (i.e. in the direction of the maximum horizontal stress component σ_H) of the earlier tested and stimulated 3.6 km deep borehole GPK1 (designed as the production leg). GPK2 was targeted at the deeper part of the hydraulically activated rock masses from GPK1, aiming at the major grouping of microseismic events. During the stimulation of GPK2 - in total about 28'000 m^3 were injected into the open hole section (3211-3876 m) - a maximum overpressure above hydrostatic of 12 MPa could be measured (Baria et al., 1995).

After the end of the stimulation injections, a hydraulic test with different flow rates was performed during from July 1st to July 4th, 1995 in the open hole section of GPK2. This hydraulic test will be referred to as experiment 95JUL01. Although it was intended originally to hold flow-rate constant until steady-state conditions were approached, time constraints forced a maximum interval time of 11 hours. In the 95JUL01 experiment (Fig.1), injection flow rates of approx. 6, 13, 19 and 26 l s^{-1} were used. The strongly transient pressure records can be clearly recognized in Fig. 1. Unfortunately, automatic monitoring of the downhole pressure failed during the first and part of the second flow step. Registration by hand allowed to correctly reestablish the transient pressure increase from the first to the second flow step (see small symbols during the first 20 hrs in the pressure record of Fig. 1), however most of the data on the first pressure transient was lost. Hydrostatic pressure was found to be at 32.32 MPa at 3200 m depth.

The first circulation between GPK2 and GPK1 was achieved subsequently, but since details of this are not relevant to the present paper, they will not be described here.

Flow meter logs were regularly registered during the hydraulic experiments in GPK2. On Fig. 2, a typical flow meter log is shown (here the case of a 15 l s^{-1} injection). It is obvious, that there are several flow exits in the open hole section: between 3215-3240 m about 30%, between 3300-3350 m about 15% and below 3450 about 40% of the flow enters the formation.

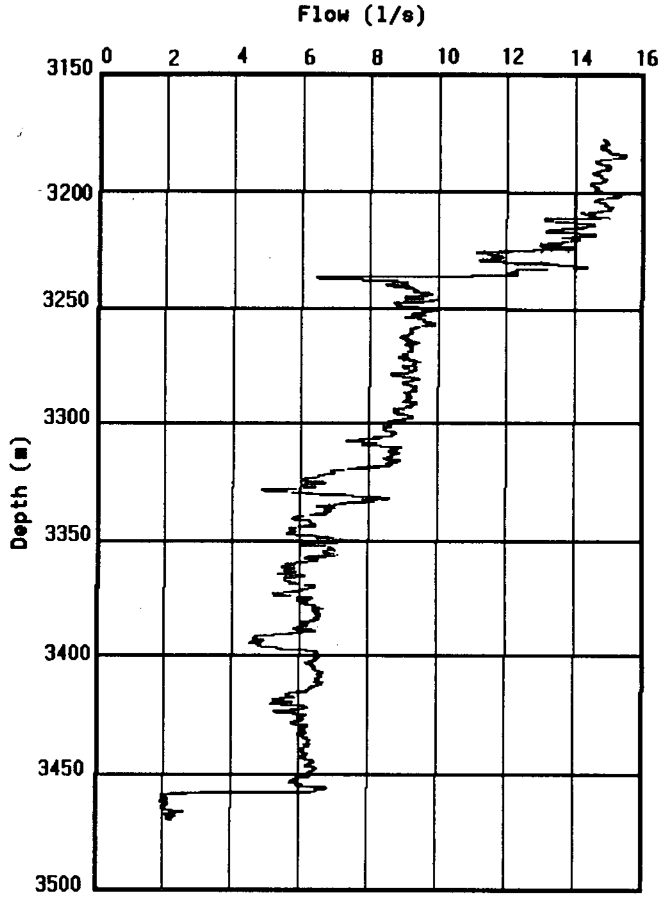

Fig. 2: Typical flow meter log in the open hole section of GPK2 (adapted from Baria et al., 1995)

NON-LINEAR SIMULATIONS

General Considerations

A model of simple geometry was set up to fit the pressure response in the data sets 95JUL01. Non-laminar flow is assumed to take place in a homogeneous, well conducting zone (*'conduit'*). In a homogeneous, poor conducting zone (*'bulk rock'*) laminar flow is assumed. The three different material sets chosen were: borehole, conduit and bulk rock. Thus, this model is similar to that of Cinco & Samaniego (1981), except that the flow in the conduit is non-laminar. In agreement with the stress field in the open hole section of GPK2, the rectangularly shaped conduit is assumed to be vertical which implies parallel flow in the conduit.

For the purpose of these tests, the geometrical extension of the conduit is slightly varied. It originally was taken from earlier analysis of the 1994 production and injection steps (Report in preparation).

It is assumed for the model that the vertical conduit connects the borehole to a major fault in the far field, which acts as a constant potential sink. The existence of such faults at Soultz was suggested originally by Jung (1992a). Also geological reasons support the existence of such features (Elsass, 1995). Furthermore, the total and immediate loss of drilling mud in a jointed zone near 2000 m during drilling GPK2 indicates that such a fault could exist.

The well described turbulent-like relationship of Louis (1967) was taken as constitutive flow law for the hydraulic regime in the conduit.:

$$\mathrm{v} = \tilde{K} \cdot \sqrt{\nabla P} \qquad (1)$$

where $$\tilde{K} = 4 \cdot \log\left(\frac{1.9}{k/_{D_h}}\right) \cdot \sqrt{\frac{a}{\rho}} \qquad (2)$$

v the fluid velocity, P the downhole pressure difference (to hydrostatic), k/D_h, the relative roughness of the conduit surfaces, a the aperture of the conduit and ρ the fluid density.

Thus, the transient behavior is described by:

$$S_c \cdot \frac{\partial P}{\partial t} = \nabla \cdot \left(\tilde{K} \cdot \sqrt{\nabla P}\right) \qquad (3)$$

with S_c the specific storage coefficient

Since pressures remained far below jacking pressure (at least 12 MPa above hydrostatic see Baria et al. 1995) during the injection test, changes in conduit aperture in response to the pressure changes are likely to be small. Therefore, fracture compliance effects on fracture transmissivity are neglected in this study.

Due to the presence of natural second order fractures in the bulk rock, the permeability value assigned to it needs to be greater than for intact rock. The laboratory measured matrix permeability near Soultz was found to be in a range of 10^{-16} to 10^{-18} m^2. In the model the equivalent porous medium permeability of the bulk rock is assumed to be 2.6×10^{-16} m^2, one order of magnitude higher than the in-situ bulk-rock permeabilities measured in the GPK1 before the stimulation (Jung 1992b). The fluid viscosity shows a strong temperature dependent behavior which requires individual correction for the actual fluid temperature. Taking the downhole fluid temperature of 130°C (approx. 40°C lower than undisturbed formation temperature) the dynamic fluid viscosity of 95JUL01 was approximated to 2.2×10^{-4} Pa s in the simulation.

During the curve fitting procedure, the crucial role is played by the coefficient of specific storage of the bulk rock (S_c), a parameter governing the long-term transient pressure response. The strong dependency on the geometrical size allowed a fitting procedure to be established. The purpose was to restrict the number of possible models by choosing reliable specific storage of bulk rock after being stimulated (about 5×10^{-11} Pa^{-1}).

A series of models were run with prescribed conduit geometry. First order conduit apertures were estimated by analyzing the extrapolated steady state pressure response. With these parameters in hand, different numerical transient forward calculations were performed with FRACTure to extract refined parameters on conduit aperture and the appropriate values for the storage coefficient of the bulk rock. In utilizing an option in the FRACTure code, that permits the definition of stepwise linear time-flow functions, the model's injection rate followed exactly the injection steps of the 95JUL01 experiment. Thus, it was ensured that the modeled pressure history is not submitted to a different flow rate history.

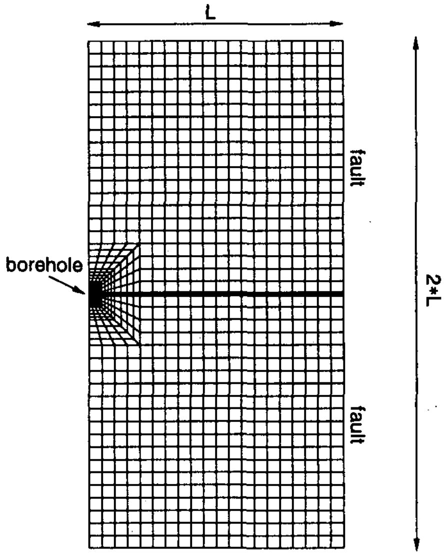

Fig. 3: Discretization of the model domain. The thick line in the center of the domain indicates the 1D conduit elements surrounded by 2D matrix elements.

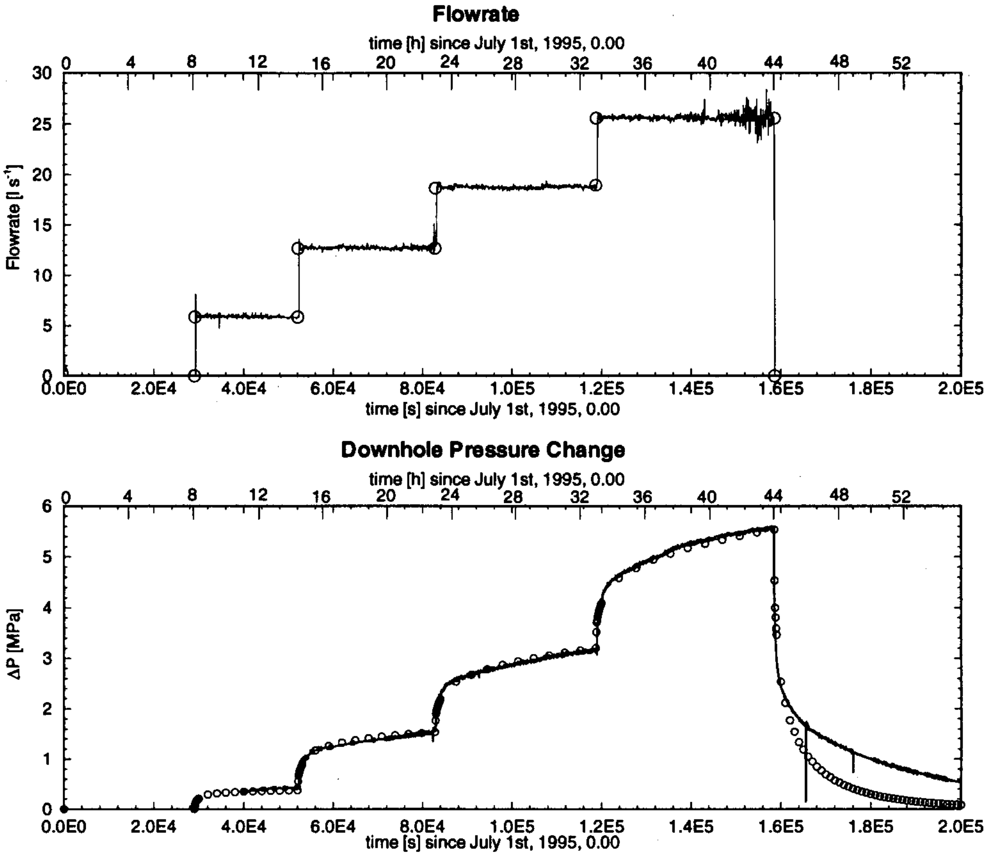

Fig. 4: Fit of the measured pressure record. The hollow symbols on the pressure record indicate the numerical results, on the flow data they indicate points of a stepwise linear interpolation function.

Numerical Results

The chosen numerical model consisted of 1300 nodes and 1200 matrix elements with linear shape function. The same rectangular grid-shape (length *L*, width *2*L*) was taken for all calculations (Fig.3). Different lengths simply were scaled up. The grid is most refined near the injection point, with a minimum element length of *0.0005 x model length*. The conduit itself is modeled by 44 one-dimensional elements. Thus a further feature of FRACTure is used, which allows for lower dimensional elements to be embedded between the surface of higher dimensional elements. Different time steps were taken. At the beginning of each step, an increment length down to 500 s was applied. When the steady state level was approached, the time increment was increased successively up to 10000 s.

Sensitivity analysis has shown that the specific storage coefficients of the conduit and of the borehole remain unaffected by parameter tuning in a range from 10^{-6} to $10^{-12}Pa^{-1}$. The results of the fitting procedure are illustrated in Fig. 4 for the case of a conduit with a length of 500 m, height of 100 m and an aperture of 0.41 mm. An excellent fit of the model prediction to the observations was obtained for all injection levels. In particular, the long term change in pressure towards an asymptotic level for all four flow steps is well predicted. Only in the shut-in period, the calculated data deviate significantly from the measured curve.

As emphasized earlier (Kohl et al., 1995b) the non-linear transient is primarily governed by leak-off into the matrix. Flow within the fracture is established comparatively quickly, and thus influences only the initial steep rise in the transient. Since the leak-off flux is dependent on the pressure gradient in the rock adjacent to the fracture, it will decline with time as the pressure front penetrates the matrix. Thus, simple mass balance considerations require that fluid velocity within the fracture increase with time on the expense of fluid loss into the matrix. It is this that accounts for the slow rise in pressure.

During the modeling procedure the geometrical non-uniqueness of the problem became evident. Due to current studies on other data sets, they still have not been accurately evaluated. From that experience, we can state, that larger conduit sizes result in strong decrease of the S_c value (i.e. doubling the geometry leads to 10x lower S_c values).

Discussion

The hydraulic tests 95JUL01 can be explained by a model of simple geometry. It was not obvious that the non-linear analysis based on laboratory derived flow laws would lead to a hydraulic model with physically reasonable values.

However, the simulation results are based on a number of restrictions which due principally to the model geometry. One of the basic restrictions to the present model is the inability to respect in two dimensions the three-dimensional nature of hydraulic diffusion into the bulk rock. Assuming the same conduit's geometry, a fit with a 3-D model will be achieved with slightly lower S_c values. Thus, using the 2-D S_c values would result in a decrease of the flow surface.

Another concern is the reliability of the assumption of the homogeneity of each material. In reality, they will inhere different hydraulic structures consisting themselves of a series of heterogeneities. Thus, by the chosen geometry, the representative elementary volumes (REV's) are defined. With this approach, the data set can be explained only by two different REV's, defining a well conducting zone (*'the conduit'*) and a poor conducting zone (*'the bulk matrix'*). The 'conduit'-REV consists at least of the three major, independent outflow zones from the open hole section. The 'bulk rock'-REV probably consists of intact rock and second order fractures that are not oriented towards the local drainage sink (i.e. the far-field fault) or which simply have a minor hydraulic significance. Thus, the improbability, that the each material consists of one single real hydraulic structure needs to be emphasized.

Another point also needs to be stressed: this kind of analysis does not allow the real location of that far-field fault to be estimated. Since different flow paths (see Fig. 2) are hydraulically active over a 300 m depth range, they may be connected to different depth domains of this fault. The importance of such a far-field fault is highlighted by our simulations.

A series of model parameter variations was made to test the flow in the conduit necessarily has to be non-laminar over the whole conduit. A transition to laminar flow at some distance along the conduit gives no reasonable fit.

The poor fit for the pressure drawdown after shut-in is not yet sufficiently explained. It is probably inadequate to assume a non-laminar flow regime for this part of the pressure record.

CONCLUSION

The transient pressure response of the injection experiments can be explained by fluid transport along a conduit with a surface area above (0.05 km^2). All four flow steps were excellently fitted by using a model of simple geometry.

To our knowledge, our approaches represent the first fully transient interpretations of hydraulic measurements in fractured rock by a non-laminar flow analysis. Up to now, this and other studies (report in preparation) emphasize, that the fracture-flow relationships in a large part of the hydraulically active fractures can be described by non-laminar behavior. These obtained results furthermore clearly show, that an application of an empirical relationship based on laboratory test data (Lomize 1951, Louis 1967) leads to physically reasonable parameters. These and other studies clearly emphasize that non-laminar flow is likely to occur at equivalent parallel plate Reynolds Numbers much smaller than 2300 (see Kohl et al., 1995b). The present analysis suggests, that already at values of ~200 turbulent-like flow occurs. The authors wish especially to emphasize that such a flow characteristics does not necessarily correspond to fully-turbulence but that its pressure-flow behavior is similar.

It has not been possible so far to pinpoint the lower limit of flow rate, at which non-laminar flow becomes significantly at the Soultz site. The question whether the type of observations made here are unique to this site cannot yet be answered.

ACKNOWLEDGMENT

This study is part of the investigation of the Soultz HDR site. We thank the SOCOMINE core team responsible for supervising the field experiments. The HDR test was performed under the financial and logistic support of DGXII of the European Commission, ADEME, BRGM and CNRS (France) and the BMBF (Germany). The authors would like to thank especially the Swiss "Bundesamt für Bildung und Wissenschaft" (BBW) for generously supporting this project.

This is publication no. 893 of the Institute of Geophysics, ETH Zurich.

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