LA-UR-83-1677

CONF-830041--3

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

MASTER

LA-UR--83-1677

DE83 014190

TITLE: DOES HYDRAULIC-FRACTURING THEORY WORK IN JOINTED ROCK MASSES?

AUTHOR(S): H. D. Murphy, ESS-4
H. Keppler, Inst. for Geoscience & Natural Rexources (BGR)
Z. V. Dash, ESS-4

SUBMITTED TO: Geothermal Resources Council's 1983 Annual Mtg., Transactions
Portland, OR, October 13-27, 1983

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

DISCLAIMER

DOES HYDRAULIC FRACTURING THEORY WORK IN JOINTED ROCK MASSES?

Hugh Murphy, Hans Keppler* and Zora Dash

Los Alamos National Laboratory, Los Alamos, NM 87545
*Visiting Scientist, Federal Institute for Geosciences and Natural Resources (BGR) Hannover, Federal Republic of Germany

ABSTRACT

The hypocenter locations of micro-earthquakes (acoustic emissions) generated during fracturing typically are distributed three-dimensionally suggesting that fracturing stimulates a volumetric region, rather than the planar fracture theoretically expected. In this paper the hypocenter maps generated at six operating, or potential, HDR reservoirs in the U.S., Europe and Japan are examined in detail and the fracture dimensions are correlated with fracture injection volumes and formation permeability. Despite the volumetric appearance of the maps we infer that the induced fractures are mainly planar and may propagate aseismically. The induced seismicity stems from nearby joints which are not opened significantly by fracturing, but are caused to shear-slip because of local pore pressure.

INTRODUCTION

Hydraulic fracturing is used ever increasingly to stimulate conventional hydrothermal reservoirs and to create Hot Dry Rock reservoirs. The formations are often dense competent rocks which have pre-existing fractures, i.e., natural joints. Consequently questions arise about the applicability of conventional fracturing theory which is based upon homogenous elastic solids, to heterogenous and discontinuous geological media.

For several years investigators have been struck by the dual nature of the fracture systems created at hot dry rock reservoirs. The microearthquake hypocenters located during the fracturing experiments are distributed in three-dimensional space, often described as microseismic "clouds", and suggest that huge volumetric regions of rock are opened by fracturing. This model of the reservoir, an optimistic one regarding the amount of heat to be recovered, is called the volumetric fracturing model, and is sketched in Fig. 1a. However, pressurization and flow experiments conducted after the fracturing operations suggest that reservoirs consist of a discrete number of planar fractures. These discrete fractures are the main water conduits, but some interfracture communication is afforded by natural joints. The natural joints are more tightly closed than the main fractures and so are high flow resistance paths. This reservoir model, a more pessimistic one because the heat must primarily be transported to the few fractures by inefficient solid rock conduction, is referred to as the planar model and is sketched in Fig. 1b.

To examine which of these models is more appropriate correlations were sought between injection volume and the dimensions of the fractured rock volume determined by microearthquake mapping at several HDR reservoirs. If a truly volumetric reservoir were to be created, then the volume of the fractured region should scale linearly with injection volume, whereas, for a planar fracturing model, the area should scale with injection volume.

Data from six HDR reservoirs was reviewed, including fracturing experiments in both the Phase I and Phase II Fenton Hill reservoirs, the Phase II Rosemanowes reservoir in Cornwall, England,[1] Falkenberg in W. Germany,[2] Le Mayet de Montagne in France[3] and Yakedake, Japan.[4] The formations involved consist primarily of hard crystalline rocks like granite, but the Yakedake formation consists of slate and very competent sandstone, with 1 to 2% porosity. Reservoir depths range from 200 to 4250 m; fracturing pressures vary from 4 to 48 MPa as measured at the wellhead, and injection volumes range from 5 to 40,000 m^3. Ordinary water was used as the fracturing fluid with the exception of Le Mayet, where a sand and gelled water mixture was used.

All fracture dimensions were taken from microseismic maps of the hypocenters determined for each experiment. Some degree of judgment is required in defining dimensions from the microseismic "cloud" - occasionally several hypocenters fall outside the main clustering, and in these cases the outlying hypocenters were excluded. Because of the subjectiveness involved, it is estimated that each seismic dimension has an uncertainty of ±25%. Despite the volumetric nature of the "clouds", none is actually spherical. All can be characterized as ellipsoidal, with three axes - major, intermediate, and minor. With the exception of Fenton Hill fracturing experiments 2012 and 2016, the width is a horizontal dimension. The other two axes are referred to as the down-dip and along-strike dimensions. The microseismic maps of Expts. 2012 and 2016 suggest

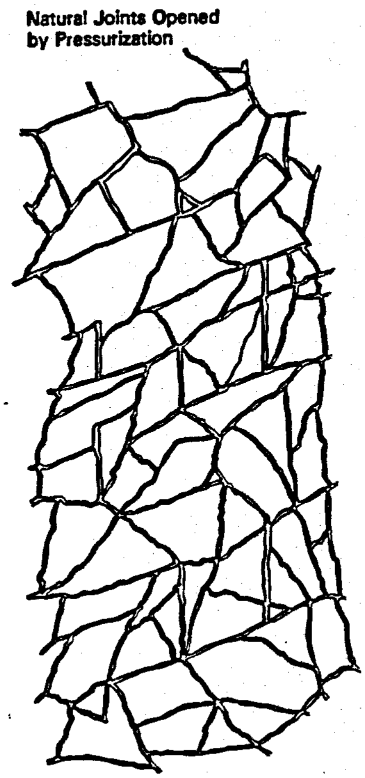

Figure 1a.
Volumetric Fracturing Model

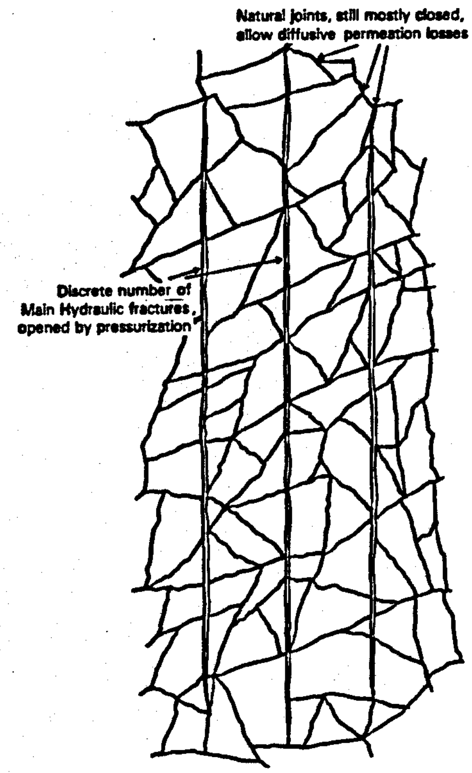

Figure 1b.
Planar Fracturing Model

fracture zones dipping at 45 ; however all other fracture experiments exhibited microseismic clouds with at least one axis, either the major or the intermediate one, which is approximately vertical. At Fenton Hill the strike bearing has been generally north.

In both Fenton Hill reservoirs the down-dip dimension ranges from 50% to 100% of the along-strike dimension, (averaging 60%), with the notable exceptions being the 45 zones of Expts. 2012 and 2016, where the dip dimension is roughly twice the strike dimension. The width at Fenton Hill has typically been one-half the strike dimension.

During the Rosemanowes fracturing experiments in Cornwall it was observed that the fractures grew preferentially downward, extending about 1 km below the injection well, and only 0.4 km above. Consequently the down-dip (vertical) dimension at Rosemanowes is typically twice the along-strike dimension. The width is about half the strike dimension and the strike bearing is N 50 W, which is nearly perpendicular to the measured direction of the minimum compressive earth stress and 15 to 30 west of the orientation of a major set of natural vertical joints.

At Falkenberg and Yakedake the dip and strike dimensions are roughly equal and the width is again roughly half the strike dimension.

CORRELATING THE DATA WITH THE PLANAR FRACTURING MODEL

Figure 2 is a log-log plot of injection volume versus seismic area. The area of the seismic zone was computed as that of an ellipse, $\pi/4$ times the product of the two largest axes, the down-dip and long-strike dimensions. A linear correlation, as required for the planar fracturing model, should result in a straight line with unit slope, and the intercept of this line is related to b, the water injected per unit fracture area. Apart from the Rosemanowes data, which will be taken up later, a linear correlation does exist, and the dashed lines which encompass the remaining data suggest that b ranges from 4 to 20 mm. To determine if this range of values is in reasonable accord with expected values we examine the separate components of b, that part due to the fracture aperture itself, then the part due to permeation.

Fracture Aperture. Geertsma and de Klerk[5] determined for a circular fracture of radius R, that the aperture δ was:

$$\delta = \left[\mu q R / G\right]^{0.25} \qquad (1)$$

where μ is fluid viscosity, q is injection flow rate and G is the rock shear modulus, which can be approximated as 30 GPa. At a typical injection temperature, 50 C, the viscosity of water is 5 x 10^{-4} Pa·s. A typical injection rate during

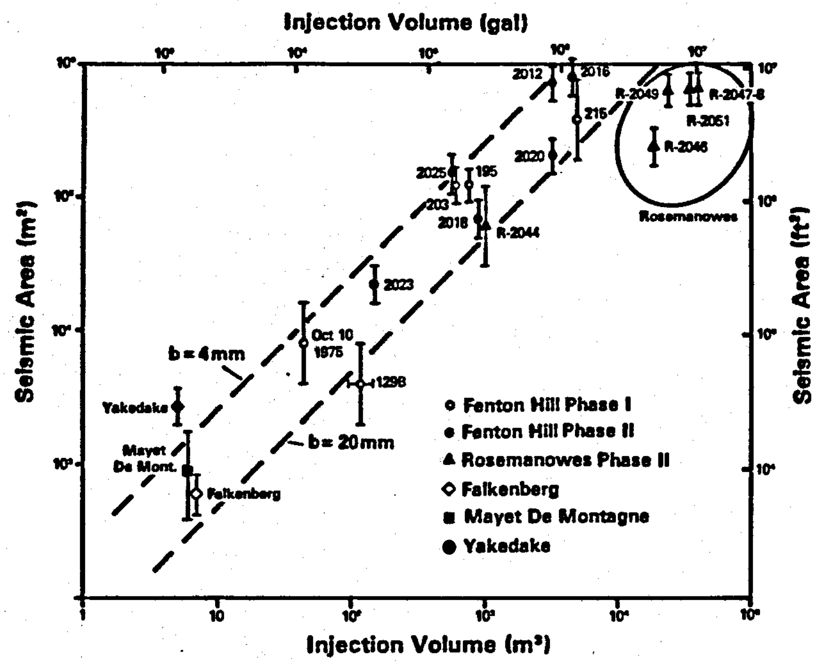

Figure 2.
Correlation of seismic area with injection volume.

fracturing is 50 ℓ/s (19 BPM), so that taking R = 400 m (a typical interwell spacing for HDR reservoirs), δ is 1.0 mm. Fracture apertures derived from measurements of modal volumes and heat transfer area in the Fenton Hill Phase I reservoir have ranged from 1.7 to 4 mm.[6] In view of the uncertainties in deriving the value $\delta = 4$ mm from the minimum value of b in Figure 2 the number of fractures must be regarded as rather speculative, but it appears that only one to, at most, four main fractures were propagated.

Equation (1) indicates that the average fracture aperture varies mildly with the fracture radius because δ scales with $R^{0.25}$, and approximating R as $\sqrt{area/\pi}$, then δ scales as $(area)^{1/8}$ and the injection volume should actually scale as $(area)^{9/8}$ rather than linearly. A detailed examination of Figure two indicates that there is enough scatter in the data to support this scaling law; therefore the planar fracturing model is not invalidated. Furthermore this slight correction is required only for that part of b directly responsible for the fracture aperture, δ. The remainder of b is due to permeation which, as will be discussed, does result in linear injection volume-area scaling.

Permeation. The remainder of b is attributable to fluid losses due to permeation of the rock surrounding the main fracture(s). Using Darcy's law it can be shown that:[7]

$$b - \delta = \Delta P\sqrt{\frac{\pi k \beta t}{\mu}} \qquad (2)$$

where k is permeability, ΔP is the downhole pressure change, t is fracturing duration, and β is the compressibility taken as 2.7×10^{-11} Pa^{-1}, which is a reasonable estimate for all the HDR reservoirs. Using the appropriate values, the permeability was computed for each experiment. The Fenton Hill reservoirs have formation permeabilities on the order of 1 μD; Rosemanowes is of order 0.3 to 0.5 mD, and the Falkenberg reservoir is about 3 mD. The values at Le Mayet, 6 mD, and Yakedake, 10 μD, must be considered as much more speculative because of the assumptions required regarding the viscosity of the fluid used (Le Mayet) and the formation compressibility (Yakedake). Much of the permeability variation is probably due to depth differences, i.e. the natural joints which account for almost all the permeability in dense rocks are more tightly closed at greater depths and pressures.

For comparison purposes Fisher and Tester[6] found from flow testing and thermal drawdown that the permeability of the Fenton Hill Phase I reservoir ranged from 0.1 to 1 μD, in very good agreement with the value derived here.

Pulse injection hydraulic tests at the very shallow Falkenberg reservoir[8] showed that when depth intervals were isolated which excluded natural joints, then k was as low as 0.1 to 1 μD, but when joints were present k was 3 mD. Fracturing creates a large surface area which is likely to intersect many joints, so as expected our value agrees well with the values for intervals with joints.

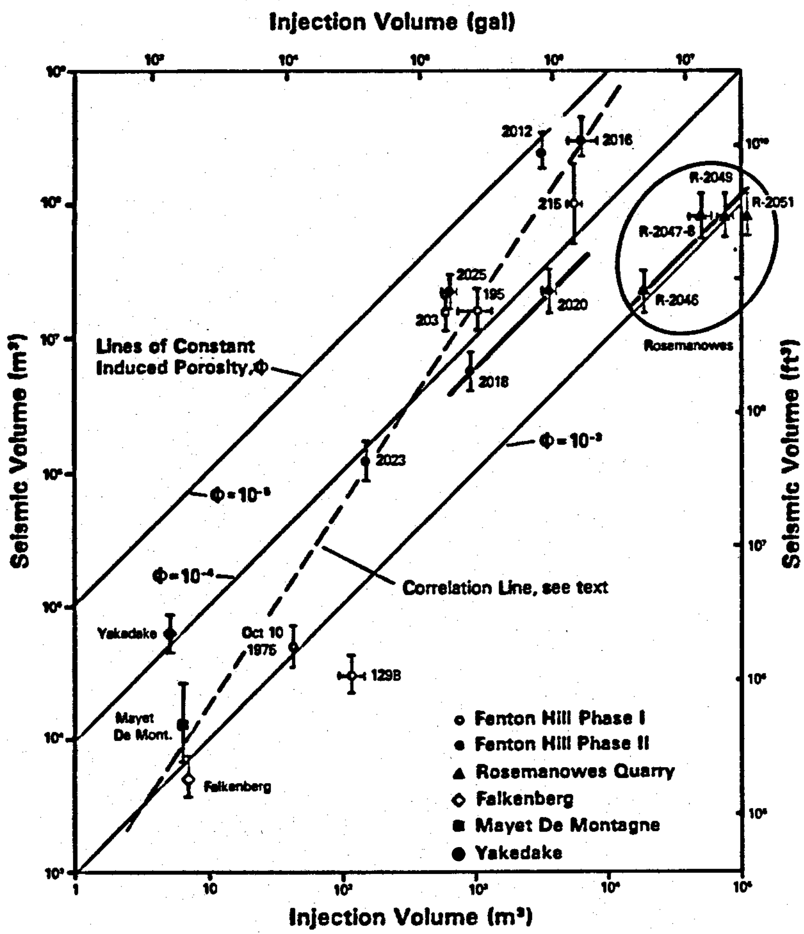

Figure 3.
Correlation of seismic and injection volumes.

CORRELATING THE DATA WITH THE VOLUMETRIC FRACTURING MODEL

Figure 3 is a log-log plot of injection volume, V_{inj}, versus seismic volume V_s. The seismic volume was computed as that of an ellipsoid, which is the area of the previous section times two-thirds the width. Assuming that the injected water is stored within the seismic volume, the volumetric fracturing model requires a linear correlation. Such a correlation results in a straight line with unit slope, and the intercept of the line is related to the total porosity, ϕ, as

$$V_{inj} = \phi V_s \qquad (3)$$

The data in Fig. 3 is too scattered, requiring a variation in ϕ of two orders of magnitude, to support a single linear correlation for all experiments. However the data for Rosemanowes and the Fenton Hill upper phase II reservoir experiments 2018 and 2020 could be forced on individual linear correlations as indicated by the bold lines in Figure 3. The inferred total porosity for Rosemanowes is 9×10^{-4}, in good agreement with the value expected from pressurization of the natural porosity. The value of ϕ for experiments 2018 and 2020 is 2×10^{-4}, a factor of five lower than $\beta \Delta P$, so the injected volume could have been absorbed by the natural porosity in these experiments also. Evaluating these experiments according to a volumetric fracturing model is still supported to a degree by the fact that the pertinent seismic clouds do not show any obvious planar features.

A nonlinear correlation. However, the seismic clouds for the Fenton Hill experiments 203, 195, 2012, 2016 and Falkenberg 79OCT17 do show one or more preferred planes upon which the hypocenters are arranged. Referring to Figure 3 there does appear to be a nonlinear correlation for these latter experiments as suggested by the dashed line:

$$V_{inj} \propto V_s^{2/3} \qquad (4)$$

where $\propto$ is the indication for proportionality. As V_s was defined earlier as the seismic area, A, times two-thirds of the width of the seismic zone, W, and because we showed earlier that $A \propto V_{inj}$, equation (3) implies that

$$W \propto V_{inj}^{0.5} \quad . \tag{5}$$

For much of the data in Fig. 3 the fracturing injection rate was very roughly constant, so equation (5) simply implies that the seismic width is proportional to $\sqrt{time}$. This is the diffusional relationship, so the correlation given by the dashed-line fit to the data confirms the planar fracturing model developed earlier.

SHAPE OF MICROSEISMIC ZONES

Despite the volumetric appearance of the microseismic zones, it was shown that fracturing usually results in the formation of a single, or at most, a few discrete, planar hydraulic fractures. Why then the appearance of microearthquakes in large extended volumetric zones? The best explanation appears to be due to Pearson,[9] who argues that the permeation of fracturing fluid away from the main fractures, along existing, but still tightly closed natural joints, results in a pore pressure increase in these joints. Using the usual Mohr circle analysis with a Coulomb-Mohr shear failure criterion, the pore pressure reduces the effective stress normal to the joints until a localized failure occurs. Numerical calculations[10] show that natural joints which are not aligned with the principal earth stress directions are most prone to failure, resulting in a local shear-slip microearthquake, with dimensions comparable to the joint spacing. This local failure is consistent with the microearthquake spectra, which indicate rupture radii of one to a few meters.

Failure cannot occur at distances from the main fractures which are greater than the distance to which the pore pressure diffuses, so the microseismic migration is limited to the diffusion distance,

$$\ell \approx 2\sqrt{\kappa t} \tag{6}$$

where κ is the hydraulic diffusivity, $k/(\mu\beta)$. Using the Fenton Hill values previously determined, $k = 1 \mu D$, $\mu = 1.2 \times 10^{-4}$ Pa·s, and $\beta = 2.7 \times 10^{-11}$ Pa^{-1}, a ten hour experiment results in $\ell \approx 10$ m, and a 100 hour experiment yields $\ell \approx 30$ m. However, these estimates are considerably less than the seismic widths. The explanation for this discrepancy lies in the statistical nature of the joints. When a spectrum of joints with various apertures is present, the water loss from a fracture is given by the sum of the permeabilities of all the joints. Thus the permeabilities derived earlier represent the average permeability:

$$k = \frac{\langle a^3 \rangle}{6s} \tag{7}$$

where $\langle a^3 \rangle$ is the average of the cubes of all joint apertures, and s is the joint spacing.

The diffusion of fracture fluid along an individual joint will be in accordance with the permeability of that particular joint, not the average joint. Consequently the outer limits of the microseismic zone are controlled in large degree by the joints with the larger apertures. The distribution of joint apertures, which is usually log-normal,[11] accounts for the unusual temporal distribution of microearthquakes. One often observes early in an experiment that some microearthquakes occur far from the injection point, presumably along joints with large apertures, and later some events occur much closer, along joints more tightly closed.

To illustrate the point more quantitatively assume that s is 10 m. Then if all joints had constant a, and $k = 1 \mu D$, as at Fenton Hill, then from equation (7), a must be only 5 μm, which is extremely small. Many joints must have apertures many times greater. Suppose several joints are ten times as large, then the individual permeability of such joints would be 1000 times greater, and from equation (6) the diffusion distance would be 30 times greater, so that a ten hour experiment would result in $\ell \approx 300$ m. Notice that these larger joints would have apertures of 50 μm, which would still be considered quite small, particularly in comparison to the main fracture apertures.

Where are the Main Fractures? Somewhere within the microseismic zones are hidden the main fracture(s). They are hidden because they are aseismic, or at least no more seismically active than the microearthquakes triggered by pore pressure diffusion. An obvious explanation for the aseismicity is that the main fractures are caused primarily by tensile, rather than shear failure. From typical seismic dimensions and durations it can be shown that the average fracture propagation velocity is of the order of 0.01 m/s, negligibly small compared to the Rayleigh or sound velocites, so the failure process is not an energetic one. It is quite likely that the process may be an episodic one, i.e, a sudden, short propagation with velocity comparable to the Rayleigh velocity, followed by a quiescent period while the fluid catches up and re-pressurizes the fracture, but the energy in each episode is evidently no more pronounced than the nearby shear failures. Furthermore, the propagation referred to here is probably not true tensile rupture of virgin rock but merely the opening of those natural joints with planes most nearly perpendicular to the minimum earth stress. In other words, hydraulic "fracturing" is the preferential stimulation, i.e., opening of those joints more or less continuous which are most perpendicular to S_3. The opening of these joints, along which there are no significant components of shear stress, would indeed be expected to be quiet compared to the joints inclined to the earth stresses, which, when partially stimulated by pore pressure increase, slip in shear, creating the microearthquakes.

CONCLUSIONS

Fracturing in jointed rock masses usually results in the opening of one, or at best, a discrete number of planar fractures, even in extensively jointed rock formations. Despite the volumetric, three-dimensional appearance of the microearthquake maps, truly volumetric fracture networks are not created. The three-dimensional appearance of the seismicity is caused by water diffusion along existing natural joints, which unlike the main fractures are not significantly opened by fracturing. The evidence cited for these claims is as follows:

(1) The area, not the volume, of the fractured zone scales linearly with the injection volume for most experiments.

(2) For short duration experiments the fluid injection volume per unit area, b, should be equivalent to the fracture aperture. The experimental values so determined are within a factor of two of theoretical estimates.

(3) For the longer duration experiments b is greater, but this is accounted for by fluid permeation along the natural joints. Increased b was used to infer formation permeabilities and these were in remarkable accord, with each of four reservoirs having consistent values of k for multiple experiments. The absolute values are in good agreement with other measurements.

REFERENCES

1. Anon. Geothermal Exploitation Research Bi-Monthly Information Circular 13, Oct-Nov 1982, Camborne School Of Mines, Cornwall, England.

2. G. Leydecker, Seismische Ortung hydraulisch erzeugter Brüche im Geothermik Frac Projekt Falkenberg, Archiv Nr. 86549, Bundesanstalt fur Geowissenschaften und Rohstoffe, Mar 1981, Hannover.

3. G. Leydecker, Seismische Ortung hydraulisch erzeugter Brüche im französischen Geothermik Projekt Le Mayet, Archiv Nr. 92297, Bundesanstalt für Geowissenschaften und Rohstoffe, Mar 1982, Hannover.

4. I. Matsunaga and M. Kuriyagawa, Personal Communication, Natl. Res. Inst. for Pollution and Resources, Ministry of Intl. Trade and Ind., Tskuba, Japan.

5. J. Geertsma and F. de Klerk, A Rapid Method of Predicting Width and Extent of Hydraulically Induced Fractures, J. Petr. Tech., December, 1969, pp. 1571-1581.

6. H. N. Fisher and J. W. Tester, The Pressure Transient Testing of a Manmade Fractured Geothermal Reservoir: An Examination of Fracture versus Matrix Dominated Flow Effects, Los Alamos National Laboratory report LA-8535-MS, September, 1980.

7. G. C. Howard and C. R. Fast, Hydraulic Fracturing Monograph, Soc. Petr. Engrs, Dallas, Vol. 2, p. 33, 1970

8. R. Jung, Hydraulische Experimente 1979 im Experimentierfeld bei Falkenberg/Oberfalz, Archiv Nr. 86151, Bundesanstalt für Geowissenschaften und Rohstoffe, Mai 1980, Hannover.

9. C. Pearson, The Relationship Between Microseismicity and High Pore Pressures During Hydraulic Stimulation Experiments in Low Permeability Granitic Rocks, J. Geophys. Res., 86, pp. 7855-7864, 1981.

10. H. D. Murphy, Modelling Hydraulic Fracturing in Jointed Rock, Camborne School of Mines Geothermal Project Memo 13/04/01, Dec 17, 1982.

11. D. T. Snow, The Frequency and Apertures of Fractures in Rock, Int. J. Rock Mechan. and Min. Sci., 7, p. 23, 1970.