Hydraulic Fracturing Stress Measurements
– Theory and Practice –

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HYDRAULIC FRACTURING STRESS MEASUREMENTS THEORY AND PRACTICE

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1. HISTORY

In rock mechanics the term hydraulic fracturing is used for fluid injection operations in sealed-off borehole intervals to induce and propagate tensile fractures. It was first applied in 1947 in the Klepper No. 1 borehole in the Hugoton gas field/W-Kansas for gas production enhancement (Clark, 1949). Since then, the technique is a standard procedure in oil and gas stimulation. In 1970 scientists of the Los Alamos Scientific Laboratory suggested to use the method also to induce large heat exchange surfaces in hot-dry-rock geothermal energy extraction systems (Smith, 1970).

On the basis of the Hubbert and Willis (1957) statement, that a fracture in the borehole wall will be initiated if the acting fluid pressure in the borehole exceeds the minimum tangential stress given by the far-field stresses, and the tensile rock strength, Scheidegger (1960, 1962), Kehle (1964) and Fairhurst (1964) suggested to use hydraulic fracturing as a stress measuring technique. After detailled laboratory studies (Haimson, 1968) first in-situ hydrofrac stress measurements were carried out by Schoenfeldt (1970) in northern Minnesota. In Germany the technique was first used in a 30 m deep borehole near the seismo-active Hohenzollern-Graben in 1973 (Rummel and Jung). These first measurements led to the development of a wireline hydrofrac-stress-measuring system at the Ruhr University Bochum (Rummel et al., 1981) which today is used by numerous researchers in the U.S., Japan, France, Sweden etc.. The state of the art of hydraulic fracturing for stress measuring was summarized in the 1981 Monterey international workshop (Zoback and Haimson, 1981).

New contributions towards the experimental procedure and the interpretation of hydrofrac pressure data came from Cornet (1981) suggesting to derive stresses from stimulating preexisting fractures or joints, and from fracture mechanics (e.g. Abou-Sayed - and Brechtel, 1978) considering the hydrofrac process as fracture propagation rather than fracture generation within an ideal material.

2. The Theory of Hydrofracturing

2.1. The Classical Approach

The classical treatment of hydraulic fracturing is based on Kirsch's (1898) solution for the stress distribution around a circular hole in a homogeneous, isotropic, elastic material subjected to external far-field compressive stresses. It is used in the Hubbert and Willis formula for the critical pressure at the moment of fracture generation,

$$P_c = 3S_h - S_H + P_{co} - P_o$$

assuming the borehole is vertical, the vertical stress is a principal stress, and is equal to the overburden stress, S_H and S_h are the horizontal principal far-field stresses, the rock is homogeneous, isotropic and initially impermeable to the fracturing fluid and has a tensile strength P_{co}, and that the induced fracture is oriented perpendicular to S_h . This last assumption yields the equilibrium equation

$$S_h = P_{si}$$

where P_{si} is the pressure to merely keep the fracture open after the pressurizing system is shut-in (shut-in pressure). P_o is the pore pressure in the rock mass and is usually assumed to be equal to the hydrostatic pressure at depth z where the fracture is induced. The azimuth of the fracture then is the orientation of S_H. The assumption that the stress concentration factors are $k_1 = 3$ and $k_2 = -1$ implies that the rock behaves quasi-elastic. Then, the principal stresses can easily be expressed as

$$\begin{aligned} S_v &= \rho g z \\ S_h &= P_{si} \\ S_H &= 3P_{si} - (P_c - P_{co}) \end{aligned}$$

which only requires to determine the rock mass density, the shut-in pressure P_{si} and the fracture reopening pressure $P_r = P_c - P_{co}$

2.2. Opening of Existing Fractures

Rock formations at depth are characterized by the presence of pre-existing fractures, generally joints with different orientations with respect to the orientation of the acting principal stresses. By fluid injection into a sealed-off borehole interval containing such a fracture, it will open as soon as the fluid pressure exceeds the normal stress S_n acting across the fracture plane. Like in the classical approach the equilibrium pressure to keep the fracture open can be determined by system shut-in ($P_{si} = S_n$).

The normal stress S_n acting across a fracture plane of given orientation is related to the far field stresses by

$$S_n = \sum_{i,j} l_i l_j \sigma_{ij} \qquad \text{(i=1,2,3)}$$

or

$$S_n = \sum l_i^2 \sigma_i$$

where l_i, l_j are the direction cosinus and σ_i are principal stresses. Assuming that the stress field varies linearly with depth and that the vertical stress S_v is a principal stress leads to an equation of the form:

$$S_n = S_v \cos^2\alpha + \frac{1}{2}\sin^2\alpha\{[S_{Ho} + S_{ho} + (\rho_H + \rho_h)z] - [(S_{Ho} - S_{ho}) + (\rho_H - \rho_h)z]\cos 2(\theta - \theta^*)\}$$

where α and θ are the strike and dip angles of the particular fracture, S_{Ho} and S_{ho} are the principal horizontal stresses at $z = 0$, ρ_H and ρ_h are the horizontal stress gradients with respect to z, and θ^* is the divection of S_H. The equation includes 5 unknowns and the solution therefore requires a minimum of 5 measurements of S_n at various depth on fractures with different dip and strike. A more general solution also all allows that the vertical stress is not a principal stress and that the stress field orientation varies with depth (Cornet and Valette, 1984; Baumgärtner 1987).

Although the method is attractive since shut-in pressure values measured are generally rather reliable, the method can be improved if one also uses the pressure values at which the fractures start to open (P_r) :

$$P_r = S_v \cos^2 \alpha + \sin \alpha \{S_{Ho} + S_{ho} + (\delta_H + \delta_h)z - [S_{Ho} - S_{ho} + (\delta_H - \delta_h)z] 2 \cos 2(\Theta - \Theta^*)\} - P_o$$

This would also allow to determine the pore pressure P_o at depth z simultaneonsly.

2.3. Fracture Mechanics Approach

Rocks like other materials contain pores and microcracks of various dimensions. Therefore, when pressurizing a borehole during a hydraulic fracturing operation the problem is to define the critical conditions for the growth of existing cracks in the wall rock rather than predicting crack initiation. In fracture mechanics the stress situation for a crack is specified by the stress intensity for a crack tip. Crack instability occurs when the stress intensity reaches a critical value, the fracture toughness, which is a material property.

During the last two decades numerous fracture mechanics models have been proposed to describe the process of hydraulic fracturing. However, a closed three dimensional solution is not yet available. Here, I sketch a simple two-dimensional analytical model which has shown to be useful in the interpretation of hydrofrac work in crystalline rock with low permeability. The model is given in detail by Rummel (1987)and ist presently further developed (see KTB report Mesy, 1987).

In the model it is assumed that the borehole axis is oriented vertical, the vertical stress is a principal stress and $S_v = \rho g z$. In the wall rock microcracks of random lengths are distributed at random orientations. With respect to the horizontal far field stresses S_H and S_h the most critical is a symmetrical double crack extending radially from the borehole into the rock and oriented perpendicular to the direction of S_h (Fig. 1). When fluid pressure is applied to the borehole and fluid also penetrates into the crack, the mode I stress intensity (tensile fracturing mode) in the vicinity of the tip of this crack is given by superposition of stress

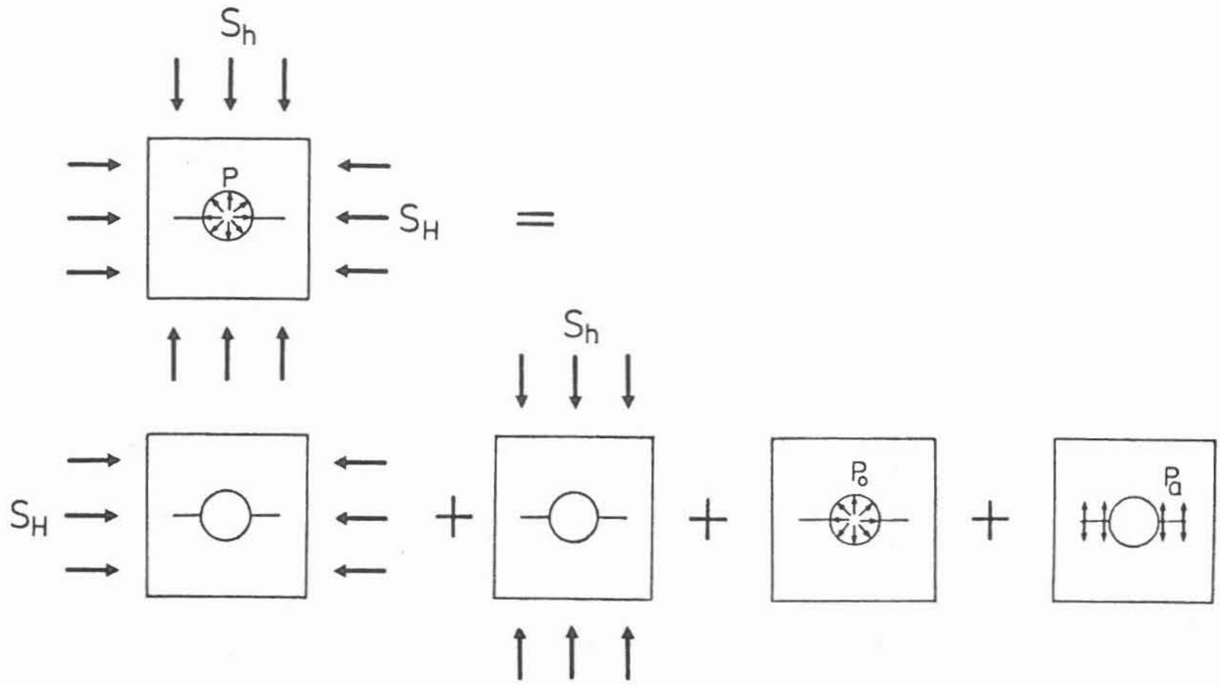

Fig. 1: A borehole with a symmetric double crack subjected to the far-field stresses S_H and S_h and to fluid pressure P. Superposition concept for the derivation of stress intensity during hydrofracturing

intensity factors from the 4 load sources S_h , S_h , the fluid pressure P in the borehole and the fluid pressure distribution P_a within the crack of length a:

$$K_I = K_I(S_H) + K_I(S_h) + K_I(P) + K_I(P_a)$$

Using the general formulation of the stress intensity factor for a tension crack of half-length a (Paris and Shi, 1965), the stress intensity factors for each load source may be derived and superposition then leads to the following relation for the critical borehole pressure at the moment of unstable crack extension:

$$P_c = (h_o + h_a)^{-1}[K_{IC}(R)^{-\frac{1}{2}} + fS_H + gS_h]$$

where K_{IC} is the mode I fracture toughness and h_o , h_a , f and g are well-known normalized stress intensity functions (e.g. Rummel, 1987).

Comparing this fracture mechanics hydrofrac relation with the classical frac-relation, the term tensile strength P_{co} and the stress concentration factors k_1 and k_2 in the classical relation can be defined in the sense of fracture mechanics:

$$P_{co} = \frac{K_{IC}}{(h_o + h_a)(R)^{\frac{1}{2}}}$$
$$k_1 = \frac{g}{(h_o + h_a)}$$
$$k_2 = \frac{f}{(h_o + h_a)}$$

The values of k_1 and k_2 reduce to the values $k_1 = 3$ and $k_2 = -1$ for zero crack length as assumed in the classical approach.

For the specific case of a lithostatic stress field the frac equation is

$$P_c = P_{co} + kS$$

with $S = S_v = S_H = S_h$ and $k = \frac{(f+g)}{(h_o+h_a)}$, defining the hydrofrac gradient with respect to S , $\frac{dP_c}{dS}$. Using $S_v = \rho_r g z$ (ρ_r rock density), the critical hydrofrac pressure required to initiate unstabele crack growth is given by

$$P_c = k^* z + P_{co}$$

where $k^* = g(k\rho_r - \rho_o)$ is the frac gradient with respect to depth, $\frac{dP_c}{dz}$. The relation allows to estimate pressures required for hydrofracturing at depth, using only fracture mechanics data measured in laboratory experiments (K_{IC}, k, P_{co}) . Taking typical values for crystalline rocks ($k = 1.04$, $\rho_r = 2.65\frac{g}{cm^3}$) the frac gradient is $k^* = 0.172\frac{bar}{m}$, and the in-situ tensile strength to be expected in a 6 inch diameter borehole $(R = 8cm)$ is $P_{co} = 60$ bar assuming $K_{IC} = 1.7\frac{MN}{m^{\frac{3}{2}}}$ and an intrinsic crack length of some millimeters $(h \approx 1)$. From this we might estimate hydrofrac breakdown pressures of about 920 bars at 5 km and about 1780 bars at 10 km depth. These values are upper estimates. The existence of larger cracks and the anisotropy of the stress field will reduce the pressure substantially.

So far, the fracture mechanics approach considers only the instability of a crack. It does not describe the dynamics of the crack growth or the crack extension with time during the hydrofrac operation. This requires further to consider the energy balance between the energy required for crack growth (surface energy, energy losses in the form of heat and seismic radiation) and the energy available in the pressurizing system as well as the energy input by the pumping system. It also requires to speculate on the pressure loss at the crack inlet on the borehole wall, on the pressure distribution and the fluid flow within the fracture, fluid losses into the rock and on the fracture width as a function of crack lengthor operation time. Various complex solutions are available and are being used in the oil and gas stimulation industry dealing with massive hydraulic fracturing. These models are, however, inappropriate for controlled micro-hydraulic fracturing as required for stress measurement (numerous tests per borehole, borehole stability, small pumping rates, extremely small fracture width, generally extremely low rock permeability, water as frac fluid, etc.)

Presently, we are attacking the problem and include fluid dynamics into the fracture mechanics model described above. The model includes the following input parameters:

- compressibilty of the pressurizing fluid,
- stiffness of the pressurizing system,
- pressure loss at the fracture inlet,
- linear pressure distribution within the fracture, but variable with increasing crack length,
- constant height and width of the fracture
- fluid losses into the rock surrounding the borehole and the fracture plane.

A typical example for the fracture growth in granite as a result of hydrfracturing by a wireline system is given in Fig. 2. The input parameters are as follows:

depht:	$1000m$
borehole radius:	$8cm$
rock:	*granite*
rock fracture toughness:	$1.7\frac{MN}{m^{\frac{3}{2}}}$
rock density:	$2.7\frac{g}{cm^3}$
rock permeability:	$0\mu Darcy$
frac fluid:	*water*
fluid viscosity:	$1cPoise$
system stiffness:	$10^{-9}Pa^{-1}$
pumping rate:	$10\frac{l}{min}$
pressure loss at inlet:	25%
pressure distribution factor for fluid within crack, k_2 :	0.01

fracture height:	$1m$
fracture width:	$0.1mm$
vertical stress S_v	bar
horizontal stress $S_H = S_v$	bar
horizontal stress $S_h = 0.5S_v$	bar

The result compares rather well with hydrofrac field results in granite observed at various borehole locations. A more detailed description of the model is given in the KTB Mesy report 1987.

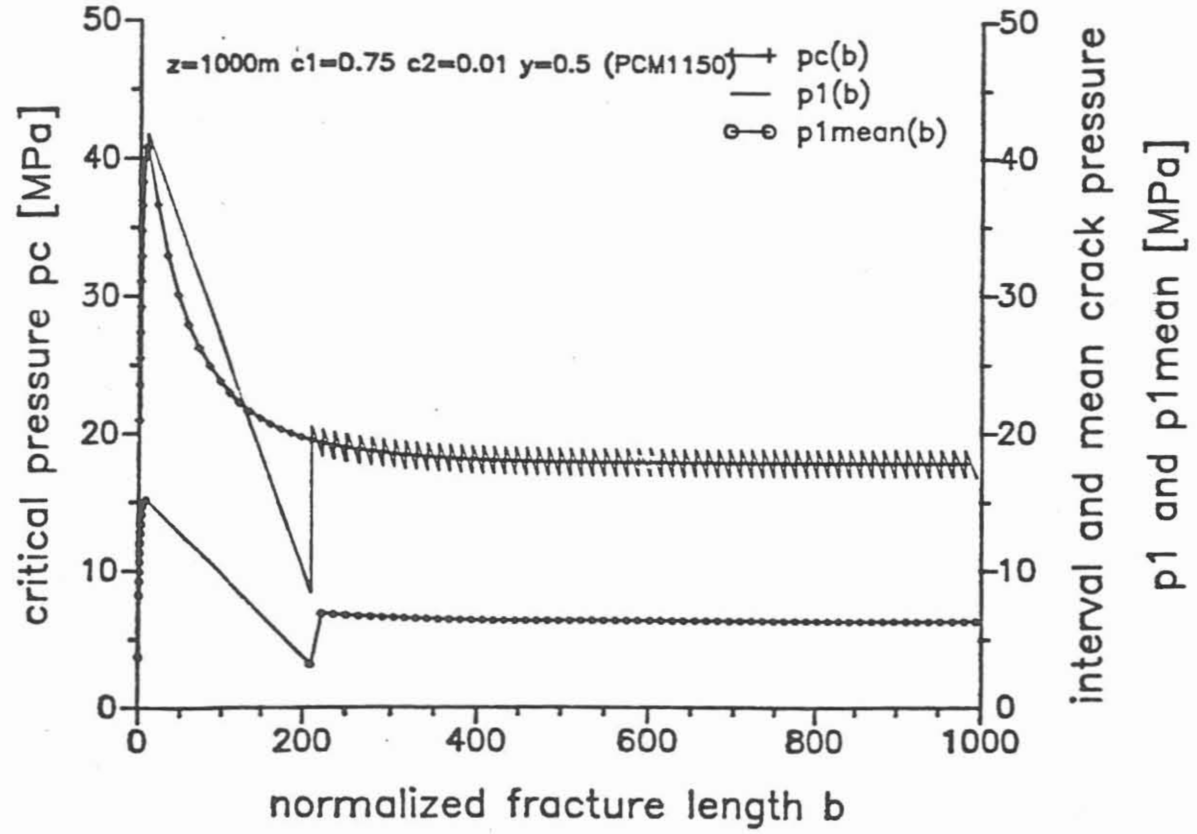

Fig. 2: Fracture mechanics determination of hydrofrac growth considering system stiffness. Calculation for fracturing granite at 1000 m depth assuming horizontal stresses $S_H = S_v, S_h = 0.5S_v$.

3. EXPERIMENTAL HYDRO-FRACTURING STRESS MEASUREMENTS

Massive hydraulic fracturing in oil and gas stimulation projects is conducted using injection rates of several m^3 per minute and high viscosity frac fluids. Hydrofracturing for stress determination is generally carried out using injection rates of several liters per minute, uses water as frac fluid and the total injection fluid volume is of the order of tens of liters. Also, the length of the sealed-off borehole interval is small (of the order of 1 m). Generally, a double straddle packer unit is used with inflatable rubber packers, and the unit is inserted to depth via high pressure drill-pipes whic h requires a drill rig onsite. The drill pipes also serve as a hydraulic pressure line to both set the packers and to inject the frac fluid into the fracturing interval. Still, most hydrofracturing stress measurements are conducted by such a system.

Recently, wireline systems for hydrofracturing stress measurements are being used (Rummel et al. 1983; Haimson and Lee, 1984; Baumgärtner, 1987). The wireline concept allows to take stress measurements similar like conventional geophysical data logging, i.e. fast and almost continuously without the presence of a drill-rig, and to obtain stress-log profiles. Originally a typical university development, the present commercially designed system is capable to carry out measurements to a depth of 1500 m at pumping rates of 10 liters per minute and pressures up to 500 bars. A new system for 5000 m depth is presently under design. A schematic view of such a system is shown in Fig. 3. At present, the strike and dip of the induced fractures are observed via an impression packer tool including a magnetic (or gyroscopic) orientation compass.

A typical pressure recording from a hydrofrac stress measuring operation in crystalline rock is shown in Fig. 4. It demonstates a pressure-pulse test into a so-called "intact rock section" to measure permeability, the formation breakdown and various phases of fracture propagation (refrac-phases). Typically for crystalline rock shut-in pressures are not clearly identified by sharp breaks in the record. This is due to the small pumping rate ($\leq 10l/min$) and the high "formation permeability" at high fluid pressures. However, the equilibrium pressure to compensate the normal stress is clearly determined from the pressure record of a slow pumping test (SP).

So far deep hydrofrac stress measurements have been conducted to a depth of 5 km, although only few measurements exist below a depth of 3 km. Existing deep hydrofrac-stress data ($\geq 500m$) are summarized in Fig. 5 and Fig. 6 (Rummel et al., 1986). The data suggest that the magnitude of the major horizontal stress S_H approaches the magnitude of the vertical stress (S_v), and the value of the minor horizontal stress approaches a value of $S_h/S_v = 0.5$.

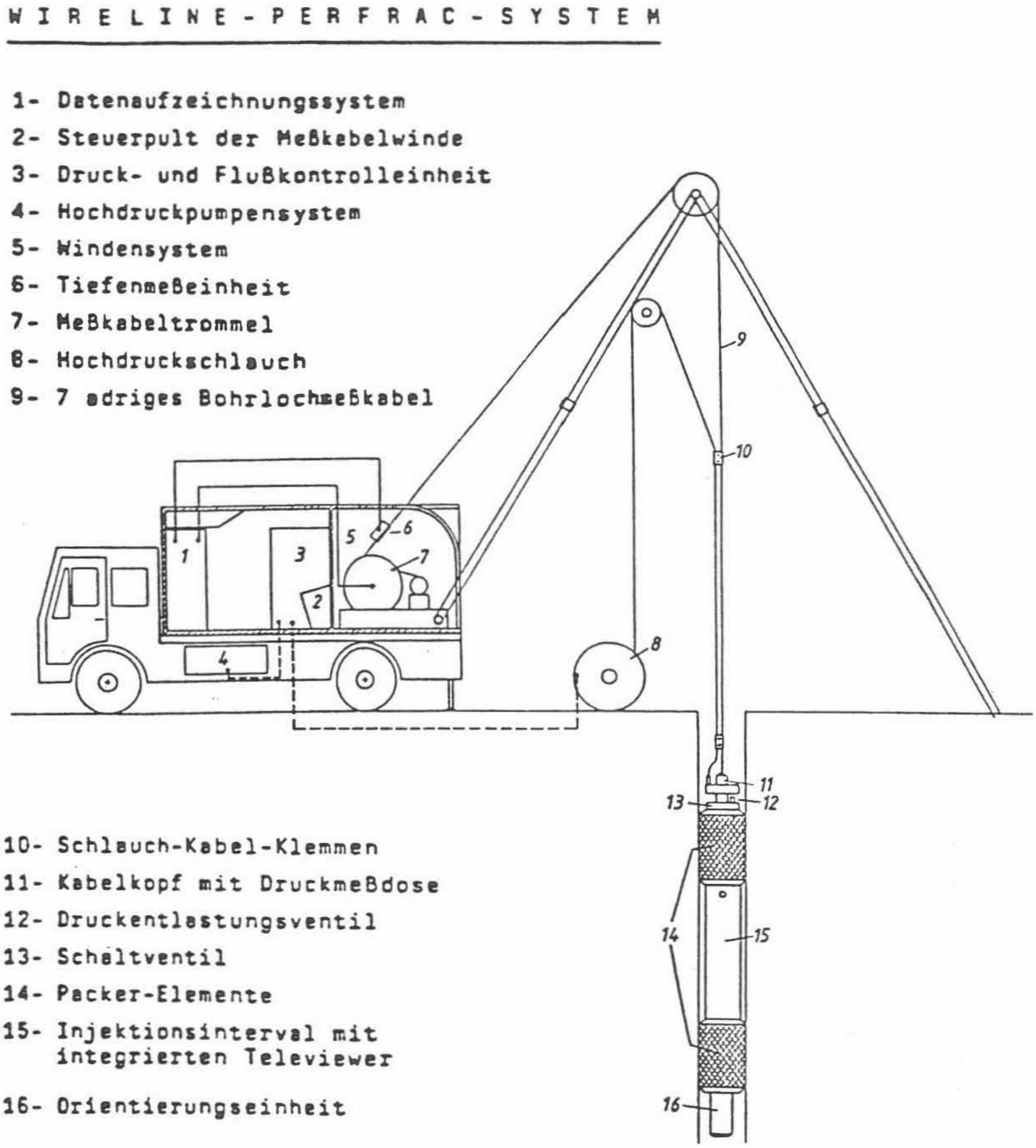

Fig. 3: Wireline hydrofrac concept for 6000 m deep boreholes to be developed by Mesy GmbH Bochum.

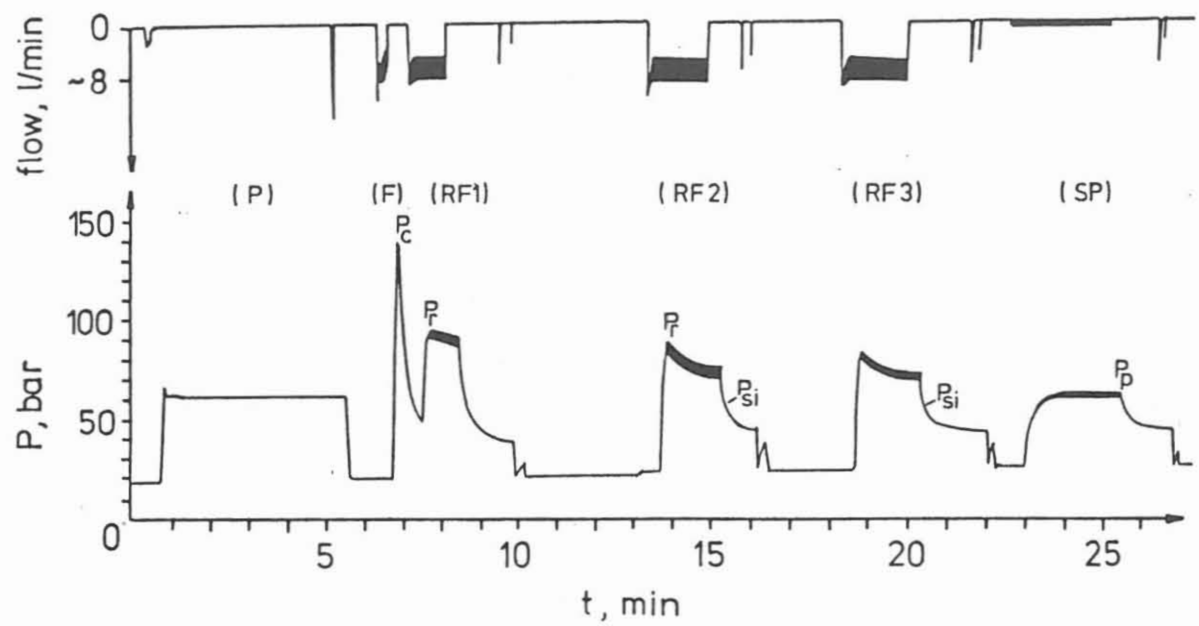

Fig. 4: Typical hydrofrac record obtained in a 100 mm diameter borehole at a depth of 210 m in granite.

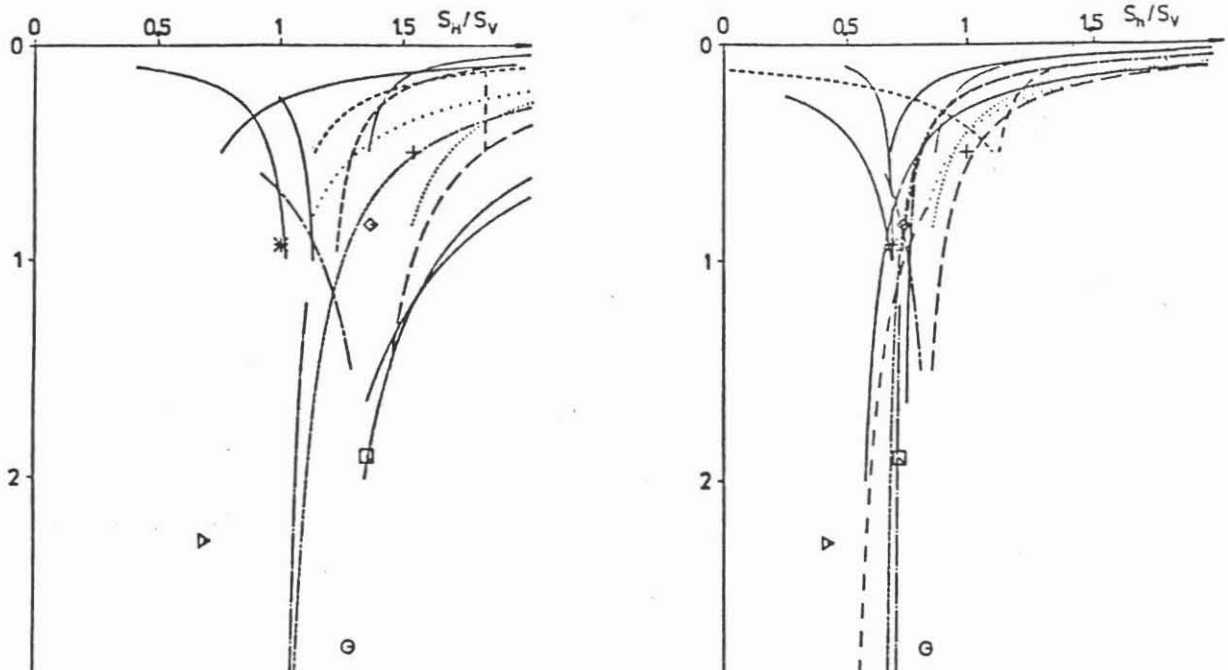

Fig. 5/6 Horizontal principal stresses versus depth measured by hydraulic fracturing. Stresses normalized with respect to the overburden stress S_v . Data are taken from Rummel (1986)

Although the present data base is very limited particularly with respect to depth, we may use it to speculate on mechanisms responsible for crustal tectonics. One important conclusion could be that crustal block sliding or crustal seismicity requires pore pressures higher than hydrostatic. Linerar extrapolation of the measured stresses to a depth of 10 km suggests shear stresses of the order of 1.5 kbar. This value is considerably smaller than expected from rock mechanics friction experiments. Shear stresses should rapidly decrease at geater depth where rock creep is the dominating deformation mechanism. Stress measurements in ultra-deep continental drill holes may provide an opportunity to observe such a crustal stress profile. However, this requires great efforts in the development of stress measuring methods suitable for high pressures and high temperatures. Due to its simplicity, hydrofracturing may be one of the techniques to be used in very deep boreholes.

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