Hydraulic Fracturing Stress Measurements - Theory and Practice

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ABSTRACT

First hydraulic fracturing in situ stress measurement were conducted in 1968. Since then, theoretical analysis and experimental techniques of hydrofracturing have enormously been improved. Hydrofracturing has become a standard technique to measure in situ stresses for most large geotechnical projects. The paper sketches the historical developments, addresses theoretical aspects and describes the wireline technique as an economic practical solution to measure stresses along a borehole profile.

Key words: in-situ stress, hydraulic fracturing, wireline stress logging, fracture mechanics.

1. HISTORY

In rock mechanics the term hydraulic fracturing is used for fluid injection operations in sealed-off borehole sections to induce and propagate tensile fractures. It was first applied in 1947 in the Klepper No. 1 borehole in the Hugoton gas field /West Kansas for gas production enhancement [5]. Since then, hydrofracturing has become a standard oil and gas stimulation tool. In 1970, scientists from the US Los Alamos Scientific Laboratory suggested to also use the technique to create large heat exchange surfaces in the deep hot crystalline basement for geothermal energy extraction.

On the basis of the Hubbert and Willis concept [10] that a fracture is initiated in a borehole wall rock if the acting fluid pressure in the borehole exceeds the minimum tangential stress and the rock tensile strength, Scheidegger [16,17], Kehle [11] and Fairhurst [7] suggested to apply hydraulic fracturing as a method to measure stresses acting in the Earth's crust. After detailed laboratory studies [8] first in-situ hydrofrac stress measurements were carried out by von Schoenfeldt [18] in Northern Minnesota, USA. In the 70's, the wireline hydrofrac technology was developed at the Ruhr-University Bochum as a standard borehole stress logging tool to measure stress variations along vertical profiles [13].

Further contributions to the present hydrofrac technology came from Cornet [6] suggesting to measure stresses in jointed rock, and from fracture mechanics which deals with crack propagation in real materials rather than fracture generation in ideal materials [1]. Today, modern hydrofrac stress measurements are an integral part of geotechnical pre-site investigations for hydropower projects, tunnelling, underground waste or gas storage, for oil and gas stimulation design, etc., as well as for geoscience research projects to better understand lithosphere plate dynamics, to speculate on plate driving forces, and thus to contribute to earthquake mechanics research or to mining technology of the next century.

2. THE THEORY OF HYDROFRACTURING

2.1 The Classical Approach

The classical interpretation of hydraulic fracturing pressure and fracture orientation data is based on the Kirsch (1898) solution for the stress distribution around a circular hole in a homogeneous, isotropic elastic material subjected to external principal far-field stresses. The concept is used in the Hubbert and Willis formula for the critical fluid pressure in a borehole at the moment of hydraulic fracture generation,

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

assuming the borehole is vertical and parallel to one of the principal stresses (S_v not being the minimum principal stress), S_H and S_h being the horizontal principal far-field stresses, the rock has the tensile strength P_{co}, the rock mass pore pressure is P_o, and 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 shut-in the fluid pressure after pumping (shut-in pressure). The pore pressure P_o often is assumed to be equal to the hydrostatic pressure at depth. The stress concentration factors $k_1 = 3$ and $k_2 = -1$ imply that the rock is elastic. Then, the principal stresses can easily be expressed by

$$S_v = \sigma g z, \text{ z depth in meters}$$

$$S_h = P_{si}$$

$$S_H = 3\,P_{si} - (P_c - P_{co})$$

where $P_r = P_c - P_{co}$ is the pressure to re-open an induced fracture during subsequent pressurization cycles. The azimuth of the induced vertical fracture is the orientation of S_H.

2.2 Opening Pre-Existing Fractures

The Hubbert and Willis approach neglects the reality that rock masses at depth are characterized by fractures and joint sets. Such pre-existing weakness planes will open by fluid injection. The pressure required to merely keep them open is equal to the normal stress S_n acting across its plane:

$$P_{si} = S_n$$

The normal stress on a fracture plane of given orientation is related to the far-field stresses by

$$S_n = \Sigma \quad l_j \, S_{ij}$$

where l_i, l_j are the direction cosini and S_{ij} is the stress field tensor. Assuming that the vertical stress S_v is a principal stress and the stress field varies linearly with depth, the normal stress S_n across a plane of weakness is

$$S_n = S_v \cos^2 \alpha + \tfrac{1}{2} \sin^2 \alpha \, \{[S_{Ho} + S_{ho} + (dS_H/dz + dS_h/dz) \bullet z]$$

$$- [S_{Ho} + S_{ho} + (dS_H/dz + dS_h/dz) \bullet z] \bullet \cos 2\,(\theta - \theta^*)\}$$

where α and θ are the strike and dip angles of a particular fracture plane at depth z_i, S_{Ho} and S_{ho} are the principal horizontal stresses at a depth z_o, the stress derivatives are horizontal principal stress gradients, and θ^* is the direction of S_H. The equation includes 6 unknowns, the solution therefore requires a minimum of 6 measurements of S_n at various depths on fractures with different strike and dip. A more general solution even allows a complete stress analysis for the case when S_v is not a principal stress [2,]. The method is attractive since shut-in pressures are easy to measure and are usually reliable. The stress analysis may be improved by also considering the pressure required to re-open the fractures, the refrac pressure P_r. The resulting equation for P_r is similar to the equation for S_n [3]. This data analysis also allows to estimate on the pore pressure P_o which is difficult to measure directly.

2.3 Fracture Mechanics Approach

Rocks like other materials contain cracks of various length. Therefore, pressurizing a borehole the critical condition is the pressure for crack growth rather than crack initiation. This situation is the subject of fracture mechanics where tensile crack growth instability is specified by the stress intensity K_I exceeding the fracture toughness K_{Ic}, a material property:

$$K_I \geq K_{Ic}$$

In the past several fracture mechanics models have been proposed for hydraulic fracturing. Here, a simple model is sketched [14]. The model assumes that the borehole is aligned to the vertical stress being a principal stress. The borehole wall rock contains micro cracks of random length and random orientations. The most critical crack is aligned parallel to S_H. When fluid pressure is applied the fluid may penetrate into the crack and contribute to the stress intensity. The stress intensity at the crack tip is the result of superposition of stress intensities from the far-field stresses S_H, S_h, the pressure within the borehole (P), and the pressure distribution within the crack of length a:

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

The critical situation is given by the pressure

$$P_c = (h_o / h_a)^{-1} \quad [K_{Ic}(R)^{-1/2} + f \bullet S_H + g \bullet S_h]$$

where K_{Ic} is the mode I fracture toughness. h_o, h_a, f and g are well-known normalized stress intensity functions [14].

Using this fracture mechanics approach, the tensile strength P_{co} and the stress concentration factors k_1 and k_2 of the classical hydrofrac relation can be defined on a physical basis:

$$P_{co} = K_{Ic} / [(h_o + h_a)\,(R)^{1/2}]$$

$$k_1 = g / (h_o + h_a)$$

$$k_2 = f / (h_o + h_a)$$

For the specific case of a lithostatic stress situation ($S = S_v = S_H = S_h$) crack growth will occur at

$$P_c = P_{co} + k \bullet S$$

with $k = (f + g) / (h_o + h_a)$. k can range between $k = 2$ for an un-cracked rock and $k = 1$ for a pre-fractured rock. The fact that the above mentioned frac relation contains the borehole radius R describes the size effect on hydro-fracturing.

More complicated models also describe the fracture growth dynamics by considering the energy balance between input energy and energy requirement for fracture growth, pressure losses at the intersection borehole and fracture, the pressure distribution along the propagating fracture as well as fluid compressibility, viscosity and fluid losses in the adjacent rock matrix.

3. EXPERIMENTAL HYDRO-FRACTURING STRESS MEASUREMENTS

Hydraulic fracturing operations for oil and gas stimulation require fluid injection rates of the order of cubic meters per minute. For stress testing hydraulic fracturing is conducted with injection rates of the order of liters per minute. Also, the length of the sealed-off borehole section is small, generally the injection interval is about one meter long. This directly suggests to use double straddle packer tools on wireline similar to other geophysical borehole logging, instead of setting packers via drill pipes which requires a drill rig on-site.

The wireline hydrofrac technology was developed at the Institute of Geophysics, Ruhr-University since 1973 [4,13,15] and is presently used by others [9]. Originally a typical university development, presently available commercially designed wireline hydrofrac systems are used to a depth of several thousand meters [12]. A schematic view of such a system is shown in Fig. 1. The system consists of the straddle packer unit with downhole sensors for packer and interval pressure and hydraulic valves to guarantee packer setting and deflation as well as interval pressurization, a logging winch with a standard seven-conductor logging cable, a stainless steel coil tubing as the hydraulic line parallel to the logging cable, and the surface installations with a hydraulic pump and an appropriate digital data acquisition system. For fracture orientation the most reliable technique still is the impression packer together with a magnetic single shot tool, to produce an image of the induced or stimulated fracture. However, MeSy GmbH Bochum has just tested a prototype of an ultrasonic borehole televiewer scanning the borehole wall between packers of the hydrofrac tool during hydrofracturing. Such a development could replace time consuming impression packer testing.

In Fig. 2 a typical hydrofrac record is shown for a hydrofrac test in 3.5 km depth at the European Hot-Dry-Rock Geothermal Energy research site Soultz-sous-Forêts, France [12]. The hydrofrac pressure record demonstrates a so-called pressure pulse test to derive rock mass permeability, the frac-test for fracture "generation", and some subsequent injection tests for fracture propagation. This particular test at 3.5 km depth and a rock temperature of almost 170°C required to use packers where the conventional rubber was replaced by aluminum.

The deepest hydrofrac stress tests so far were conducted in the borehole of the German Continental Drilling project KTB to a depth of 6 km. These tests provided a first estimate on plate driving forces [19].

However, most stress measurements are conducted for geotechnical projects at rather shallow depth to a few hundred meters. As an example hydrofrac stress data are shown for Central Germany (Fig. 3,4). The figures show both the orientation of maximum horizontal compression as well as the variation of stress magnitudes with depth for various borehole locations (normalized horizontal stresses with respect to the overburden stress). The data demonstrate the regional trends but also demonstrate the existence of local stress regimes.

4. CONCLUSIONS

Hydraulic fracturing tests yield reliable stress data both, for shallow jointed and fractured rock as well as at great depth in hostile environment (high temperature, highly saline fluids). In most cases the interpretation of hydrofrac pressure data, however, requires the application of inversion methods rather than the use of the simple classical Hubbert and Willis concept. In addition, the fracture mechanics approach allows to simulate the field pressure records by selecting appropriate model parameters.

During the World Stress Map (WSM) project [20] of the International Lithosphere Program most of the available hydrofrac stress data were collected. Parallel, the Institute of Geophysics at the Ruhr-University Bochum and MeSy GmbH Bochum have established a Hydrofrac Stress data bank. Presently, this data bank includes entries from about 200 locations world-wide. The intention is to develop a crustal stress atlas for both orientation and stress magnitudes available for scientific needs as well as to geotechnical and civil engineering projects.

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Routine application of hydrofracturing stress testing as a part of the pre-site investigation of geotechnical project requires reliability of the data but also economic test conduction. The wireline method to move the packer sondes in the borehole was a valuable development. However, the impression packer technique to spatial orientation of the stimulated fracture is still time consuming and contains uncertainties if more than one fracture trace is recorded within the test interval. The integration of an acoustic televiewer into the hydrofrac straddle packer sonde will solve both, make the impression packer tests abundant and will allow to differentiate between hydraulically active and non-active fracture features on the borehole wall. Recent in-situ test results with a prototype sonde demonstrate promissing data.

5. ACKNOWLEDGEMENT

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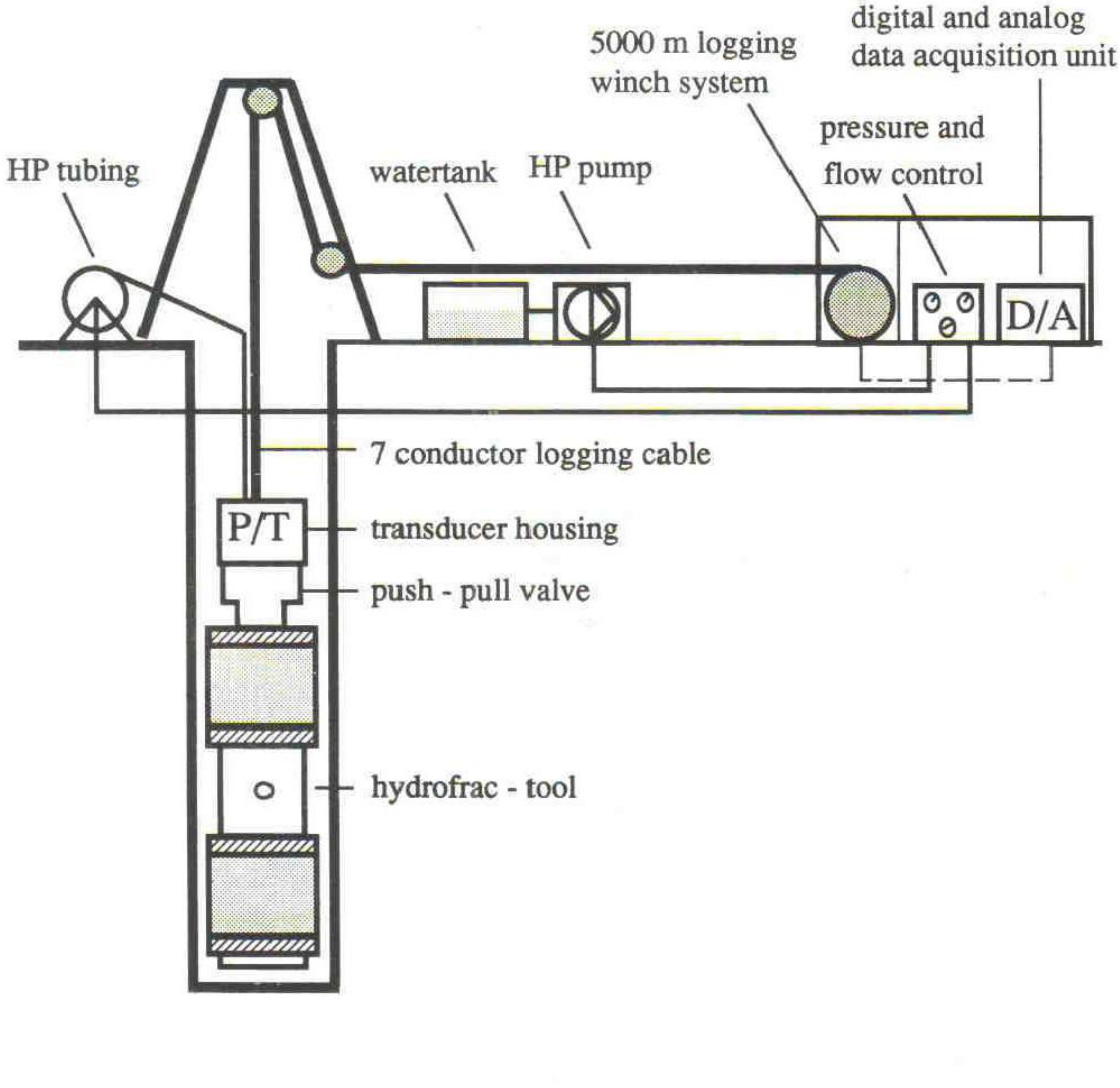


Fig. 1 : Schematic view of the wireline hydrofrac technology.

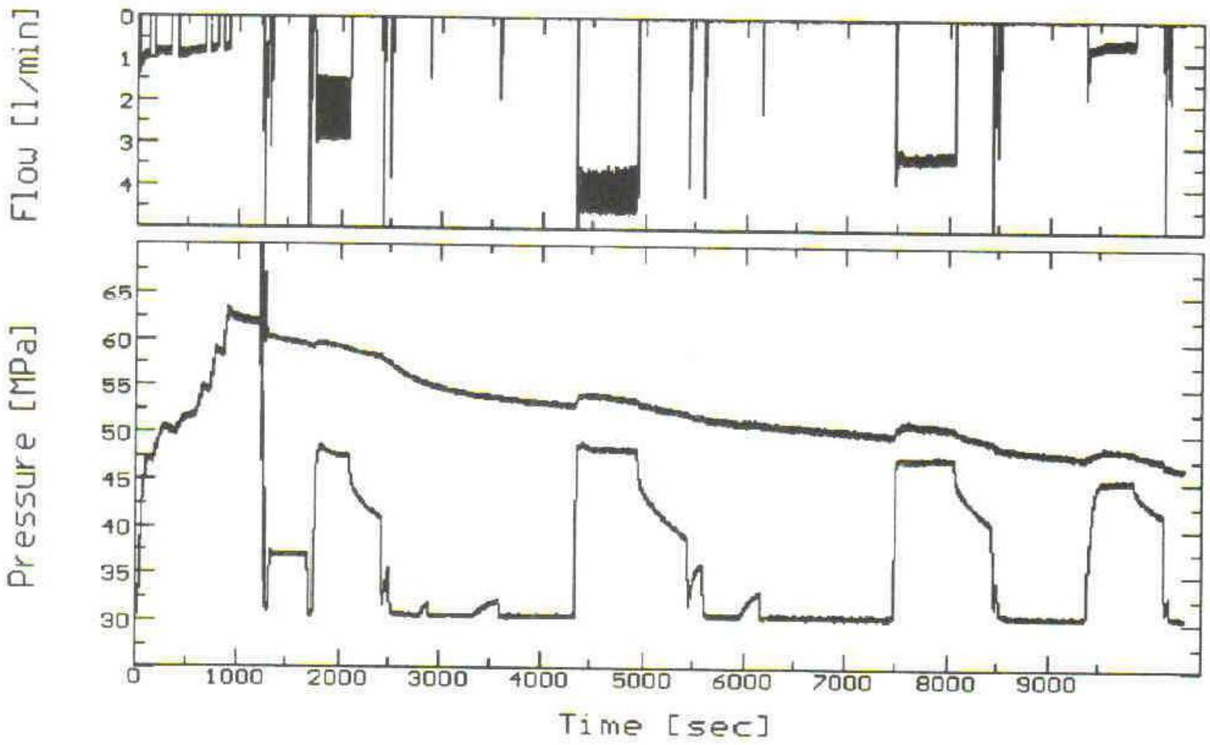
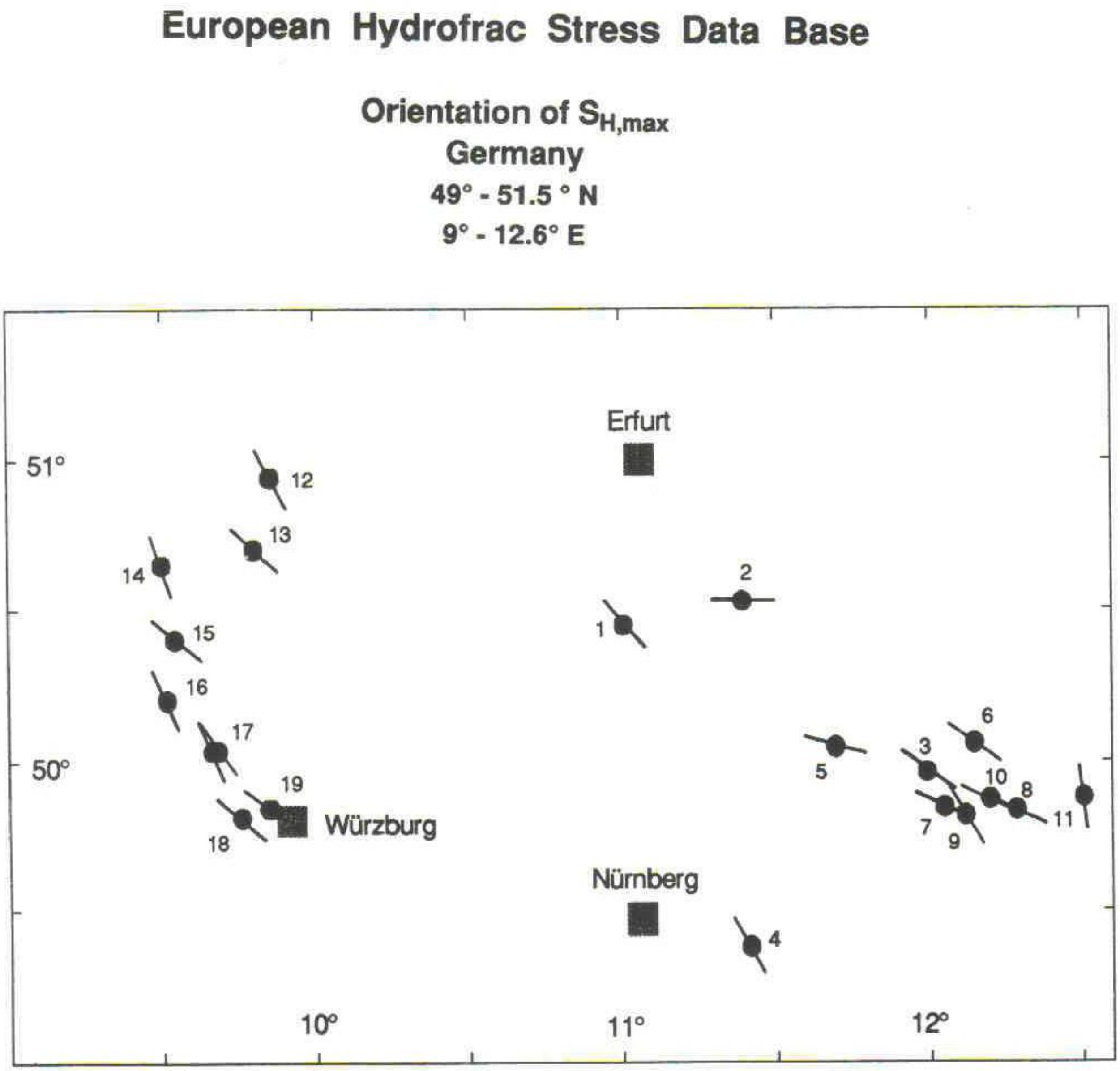


Fig. 2 : A hydrofrac pressure and pumping rate record measured in borehole GPK1 of the European Hot Dry Rock Project atSoultz-sous-Forêts at a depth of 3500 m at a temperature of about 150° C and in hostile saline environment.



European Hydrofrac Stress Data Base

Orientation of $S_{H,max}$
Germany
49° - 51.5 ° N
9° - 12.6° E

Fig. 3 : The orientation of the maximum horizontal stress S_H at about 20 borehole locations in central Germany.

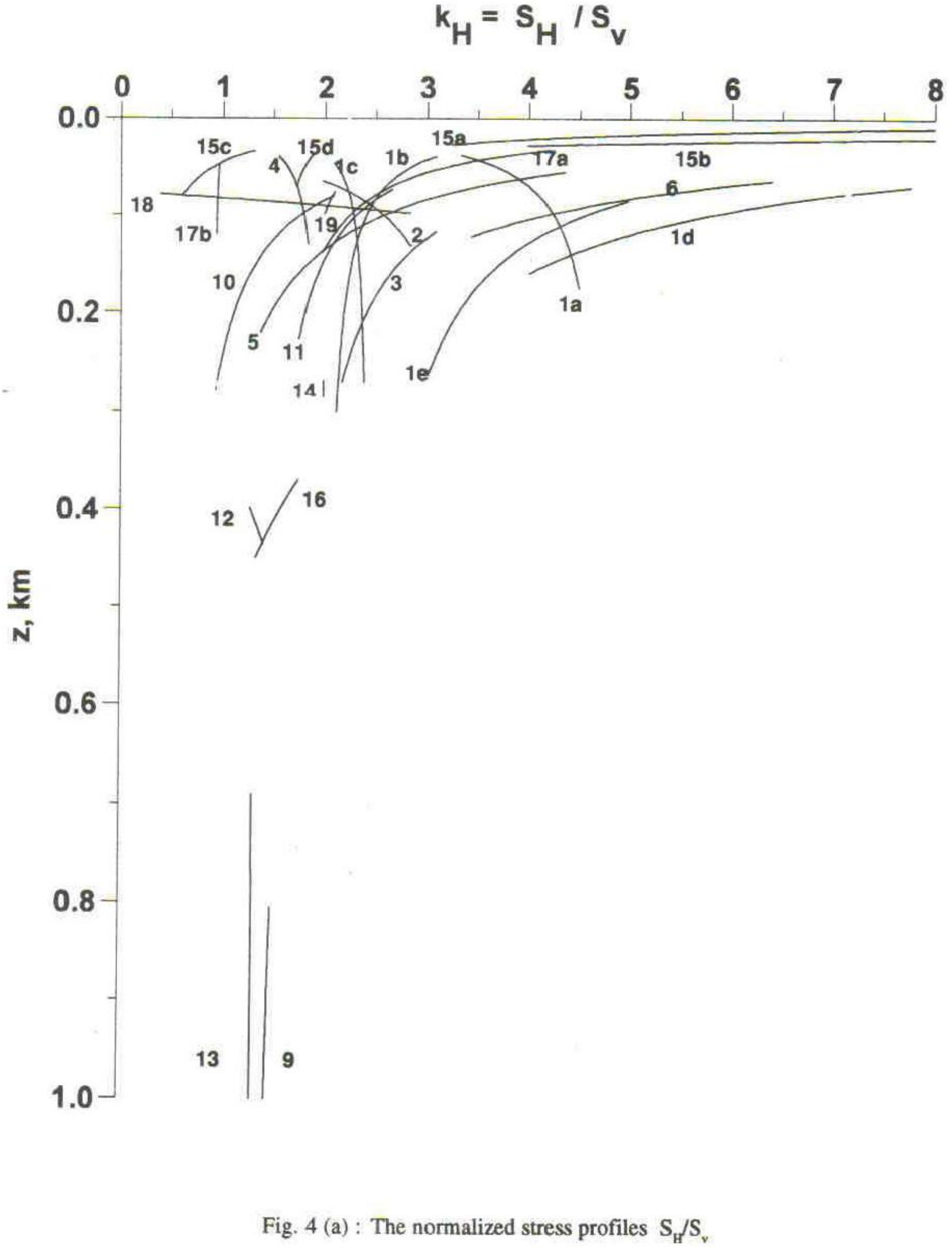


Fig. 4 (a) : The normalized stress profiles S_H/S_v

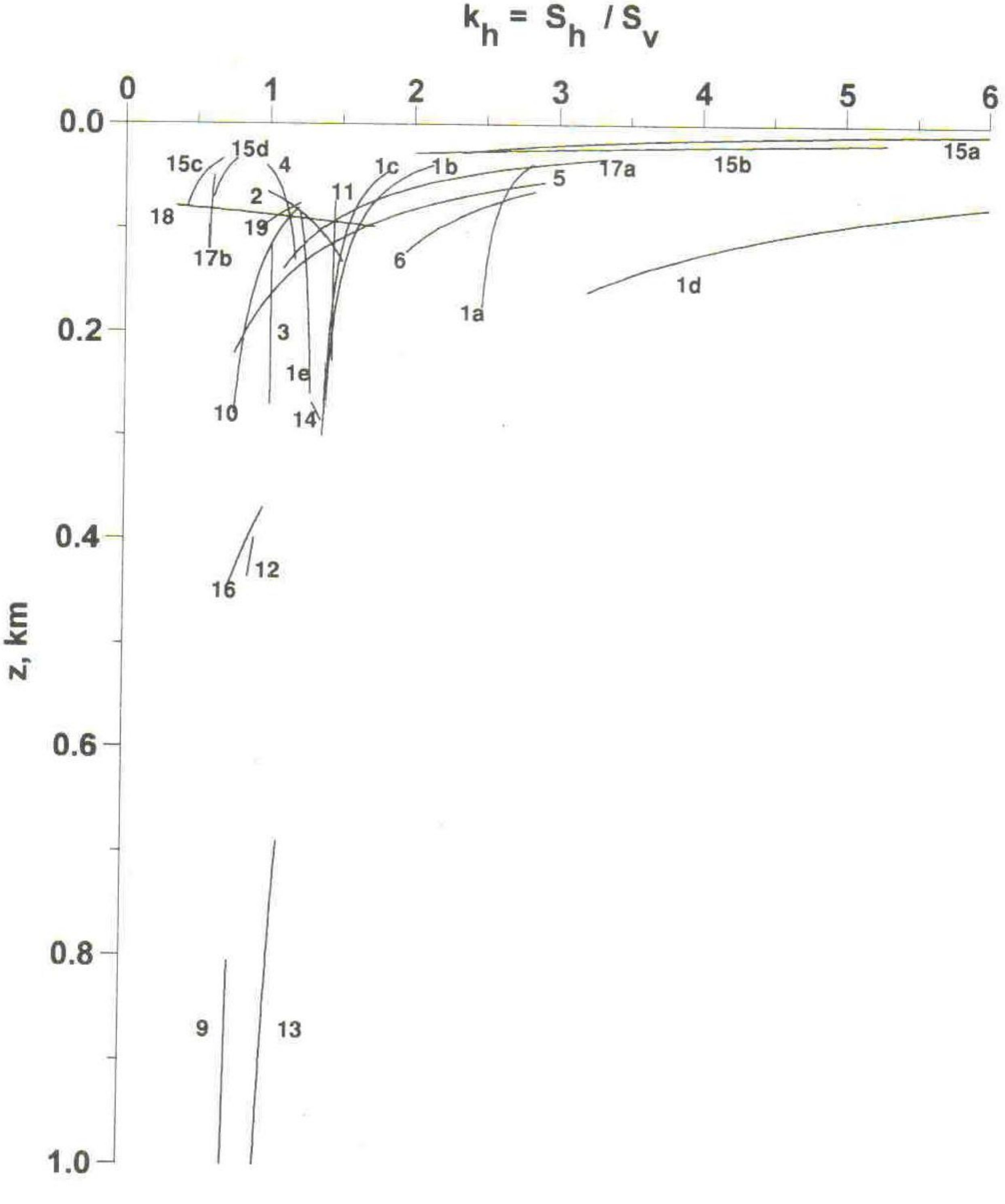


Fig. 4 (b) : S_h/S_v for about 20 borehole locations in central Germany.