Hydrofracturing of Rocks as a Method of Evaluation of Water, Mud, and Gas Inrush Hazards in Underground Coal Mining

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ABSTRACT

The article treats the importance of the space determination of stress distribution and its change depending on the mining methods and local geological condition on the evaluation of the possible hazards of water, mud, and gas inrush in underground coal mining. Discussed are two test procedures, the combined measuring with hydrofracturing of rocks and the measuring with three axial hydraulic cells.

INTRODUCTION

A systematic study of water, mud, and gas inrushes onto the mine workings and roadways in the Slovenian mines made possible to determine to a large extent the mechanisms of their occurrence[(1)].

It was found out that an inrush is a consequence of different defavourable factors that ramdomly sum up at the site of the event. These factors are the result both of the occurrence of natural geological extreme conditions (tectonic faults, unindetified lenses of sand in the safety layer etc.) and of the mining process (uncontrolled excavation, irregular velocity of face, presence of safety pillars etc).

Ussualy such events is eliminated by introducing a safety coefficient into the mining criteria. These criteria are typically set with regard to normal mining conditions, and its value is prescribed and regulated on the experience basis for each mine separately. Such method of determination of criteria is the most widely used and most of the times is the only possible one, but its disatvantage is that it has a safety factor that is too high for normal mining conditions and too low for the rare cases of water inrush.

Thus in the determination of these criteria in the lignite mine of Velenje (extensive research was conducted there in view of the extreme importance of the mine for Slovenia - it supplies 40% of the total electric power energy needed by Slovenia) a very special attention was paid to the analysis of water, mud, and gas inrushes. As a result of this analysis we prescribed additional measures for the elimination of the discovered critical conditions. In the lignite mine of Velenje 5 million tons of lignite are mined yearly from the depth of 300 m in a 200 m thick seam in levels up to 17 m high, with a sublevel caving. A level is mined out in stages from the upper to the base level. The excavation height is defined by criteria that take into account the geomecanic properties of the coal and the hanging wall, the depth of the working face and the water pressure in the first aquifer above the coal.

Additional measures are therefore designed to impede the creation of most frequent critical conditions for the inrush of water and mud:

- the face height is determined for the most unfavorable condition

- the working areas are designed in such a way as to avoid sharp changes in the coal thickness

- if there is coal in the impermeable layer of the upper level the mining shall be designed and technologically solved in such a way as to prevent extreme extracting with sublevel caving onto the subsequent extraction levels

- it is necessary to assure, in design and in fact, an uninterrupted and simultaneous closing of the roof layers behind the excavation so as to prevent the formation of uncaved thick slabs of coal in the roof

- by prior drainage the pressure of water in the roof aquifers must be lowered

- the beginnings and the ends of levels shall not be vertical, and the changes in height of excavation shall be gradual, which will prevent the impermeable layer of clay from breaking, allowing it to coil continually onto the mined out area

- the leaving of unmined pillars of coal between excavations should be avoided.

The second significant measure taken was the improvement of measurement techniques for the definition of the safety layer thickness and the pinning out of the vicinity of critical points, such as faults.

We know from literature that identical or very similar factors provoke water inrushes onto working areas everywhere, yet each mine has its own specifics that has to be investigated thoroughly.

Dependent data can only be obtained by in-situ measurements showing the time and space change of qualified parameters in the vicinity of the working face and particularly in the safety layer. One of the crucial parameters is the space change of stress due to mining processes. Of outmost importance is the analysis of the stress distribution in critical conditions when an inrush is treatering. This article discusses the change of the stress state.

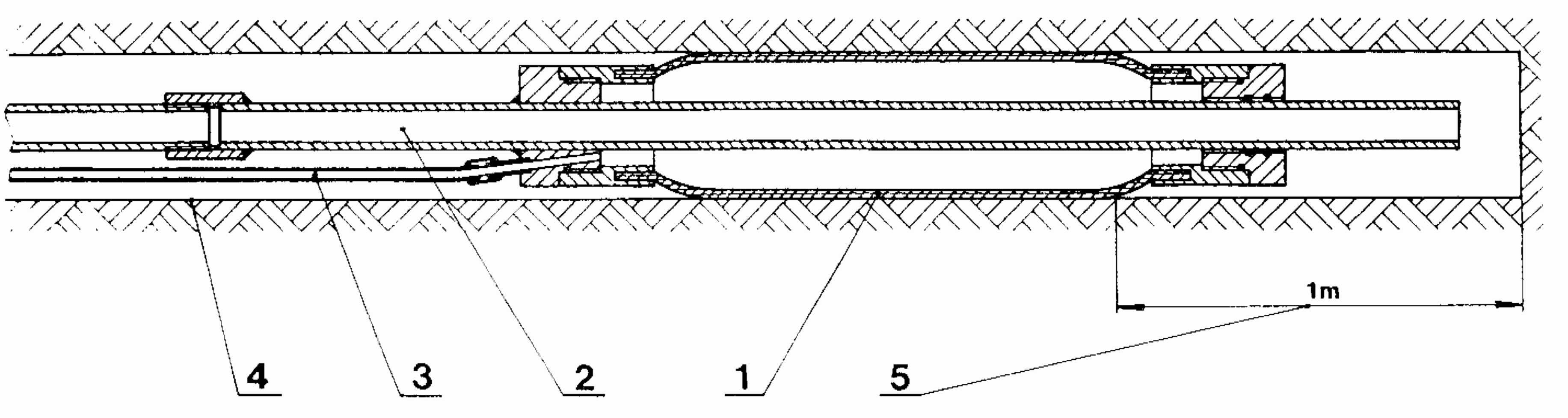
IN SITU MEASUREMENTS OF THE STRESS STATE

When the change of the stress-deformation field and the change of the principal geomechanical properties of the rock that is including in caving are known, the whole process of caving is thus defined. While measurements of deformations in coal and in the hanging wall by various anchors and extensometers are relatively simple to perform, the measurements of stress require, to be effective, much more hardship and skill. Stress measurements have been performed in the Slovenian coal mines since 1965(2)(3). Many different probes and jacks have been used.

An analysis of the results shows that the success rate of these measurements is quite uneven, ranging from total misses to measurements with highly divergent results to measurements that yielded huge changes in pressures. A characteristic of these measurements is that the obtained values of pressure changes in the probes are but relative estimates of stress changes, and not the absolute values. This deficiency was made good by introducing measurements by hydrofracturing.

The measurements were started in 1988 within the framework of in situ measurements for the verification of the new criteria of mining based on the evaluation of the range of the minimum horizontal component of stress in the area above the very caving area and the water bearing sands over the mining opening.

The method implies cracking the rock in a borehole by water pressure and the measuring of the shut-in pressure. The testing section was determined by analysis of the core in a compact or the least cracked part of the rock. During the test we sealed by packers the part of the borehole in which the water pressure was risen to reach the creept pressure. A rapid fall of pressure occurred to reach the minimum value of the shut-in pressure. The loading and the release was repeated several times.



Technical description

1.Inflatable packer
2.Fracturing water line
3.Packer water line
4.Borehole wall
5.Testing part of borehole

Fig. 1: Hydraulic cell

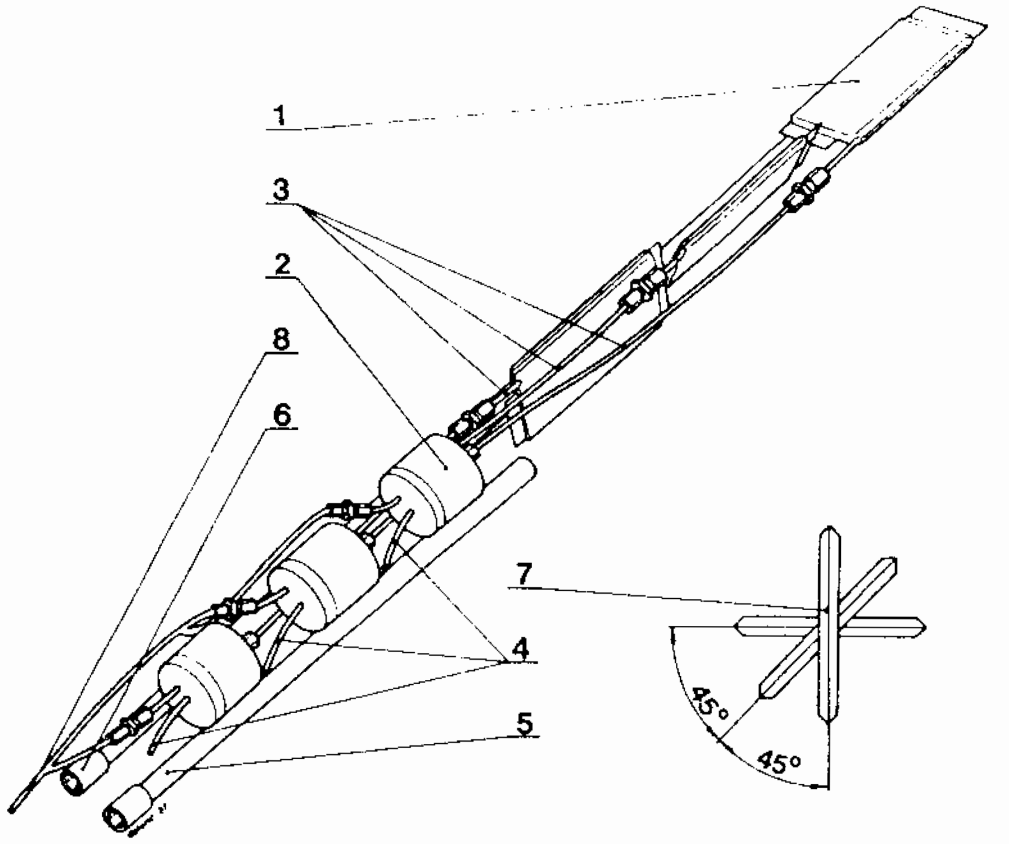
The results of the first measurements by hydrofracturing showed the adequacy of this method for the definition of the absolute stress values - and particularly the minimum principal stress σ_{min} .

For water inrush analysis the shut-in pressure that shows the σ_{min} component of the principal stress, obtained by hydrofracturing is an excellent criteria for forecasting of inrush probability[4]. Yet it is not accurate enough for the analysis of sand, mud and coal inrush on the mining opening and the roadways. A study of the past inrushes namely clearly showed that such inrushes are a result of a sudden collapse of a "pillar" between the area of water, gas or mud mass under high pressure and the working area. A "pillar" is that part of the coal or the hanging wall in which during the mining process accumulate pressures that exceed its bearing capacity. A pillar is also charged unevenly, on one side there is the pressure of the rock combined with the water or gas pressure, on the other side there is the open surface of the face, where pressure is 0. The charge of the pillar depends greatly on the progress of the mining and the local conditions.

During the advancing of the roadway or the working face changes occur both in the direction and in the value of the principal stresses that turn into the most unfavorable ones and then a sudden inrush can occurs. To be able to spot such moments in the lignite mine of Velenje we introduced in-situ measurements where consecutive hydrofracturing measurements are combined with measurements of space distribution of stress by three-axial hydraulic cells.

The three-axial hydraulic cells were used to measure the initial stress state and the stress change above and below the working face. From the measured components of the stress we calculated the space ellipsoid with all three components of the principal stress σ_1, σ_2 and σ_3 in relation to the direction of the placement.

The instrumentation, composed of thee flat cells (see Fig.2) was installed in specially drilled boreholes in a chosen direction. The mechanical properties of the sealant that allows for a perfect contact of the rock and the cell have been lab determined and are similar to the rock properties. Each cell is a measure system by its own. The pressures in the cells were measured indirectly, by means of membrane valves installed into the borehole together with the cells.



Tehnical description

1.Pressure pad
2.Pressure cell valve
3.Measuring line
4.Pressure line
5.Injection tube
6.Return grouting tube
7.Cell'sorientation
8.Return line

Fig.2: Threeaxial hydraulic cell

A combination of these two methods made possible a monitoring of relative and absolute stress changes and the determination of the direction of the principal stresses during the advancement of the roadway or the working face.

An example of combined measurements are the measurements that were conducted in the mine Pesje at the depth of 250 m below surface on a working area 80 m wide and 10 to 14.5 m high. The main daily progress was from 1.2 to 1.6 m. The measuring system was installed from the level under preparation into the hanging wall above the working face. It was installed into three inclined boreholes laid out in a fanlike layout (see figure 3). The system was installed approximately four months before the planned passage of the face over the testing area. In the meantime consecutive measurements of hydrofracturing were carried out and the space stresses in the hydraulic cells were monitored. Results are shown in Fig. 4 to 7.

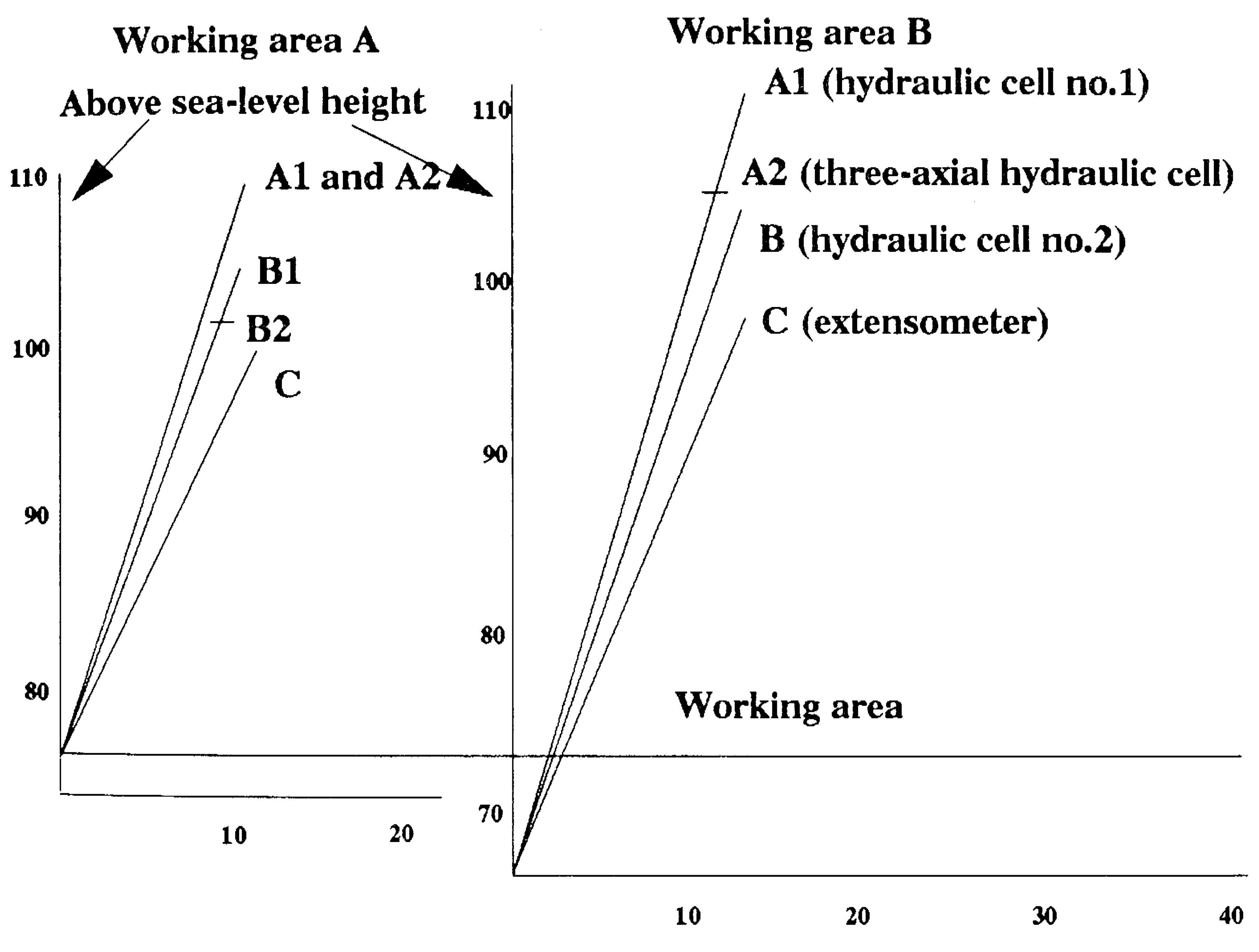


Fig.3: Installment of the measuring equipment

Fig. 4 and 5 are showen, besides the usual fracturing curves also the side pressures on the rubber packer, that accompany the fracturing pressures and are an additional feature for the interpretation of the results. Because of the fixed rubber packer and the repeated measurements it is impossible to take prints of the fractures on the walls of the borehole in the testing section. Thus to determine the exact space position of the stress ellipsoid we employ also the results of the measurements by a threeaxial hydraulic cell (Fig.7).

With consecutive measurements by hydrofracturing the area of hydraulic opening of cracks increases with each consecutive measurement. The direction of the fracturing in the rock changes with the spinning of the stress ellipsoid due to the approach of the working face. This is impossible to determine by a direct method.

A detailed analysis of the measured data was prepared. For lack of space we shall summarize it. Significant changes of stress occurred between the point when the mining face was less than 30 m from the micro locations of the probes and the moment of the destruction of the probes when the face passed the microlocation for 11 m. The fracturing measurements of refracturing pressures show a gradual fall of the pressures that went on until the cells were distructed. Cell A1 the experienced the greatest pressure fall at the distance of 28 m, cell B1 experienced the same at the distance of 18 m (Fig.6).

In contrast, the three-axial hydraulic cell shows in the last section, on all three diagrams, a gradual increase of the pressures (Fig.7).

A comparison of the two methods of stress measurement show that all the main changes in the measured parameters occurred simultaneously, yet it is typical that the three-axial hydraulic cells show, in the last stage of the measurement, an increase of pressure accompanied by a simultaneous decrease of the fracturing pressures. The foregoing is the result of the change of the value of both principal stresses and also the consequence of the rotation of the stress ellipsoid.

The evaluation of the principal stresses is carried out in a vertical plane that is perpendicular to the mining face (plane XY) and in the direction parallel to the excavation direction. Due to the large extent of the mining face we can assume the system to be in plane.

Before calculating the principal stresses it is necessary, because of boreholes inclined to the direction of the mining-out, to transform the data into the plane XY. This is done by the stress transformation equation[5] :

$$|\sigma^{*}| = |R| \cdot |\sigma| \cdot |R|^{T}$$

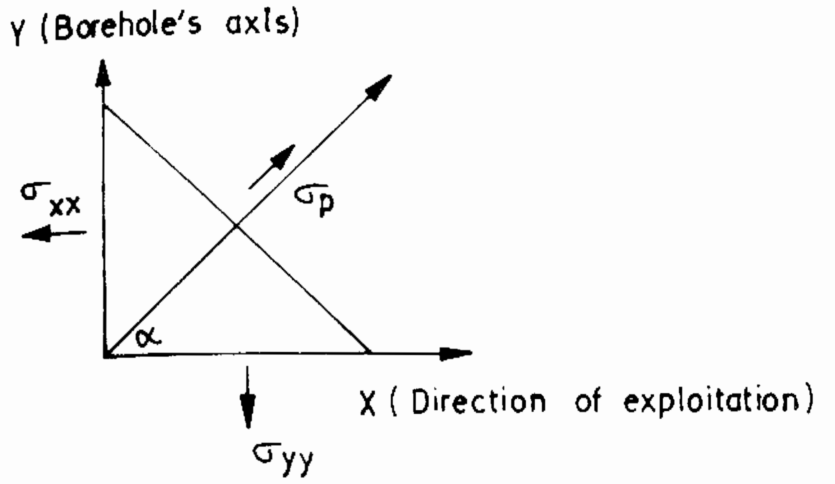
$|\sigma^{*}|$ stress matrix in a new coordinate system

$|R|$ rotation matrix

$|\sigma|$ transposed rotation matrix

$|R|^{T}$ stress matrix in the old coordinate system

The acquired values of the pressure measurements σ_{xx} and σ_{yy}, that are really the relative values of the actual pressures, are to be corrected in relation to the expected stresses in depth H. By taking the fracturing pressures as an estimate of the minimum principal stress we calculate, with the following equation[5] the missing components of the plane stresses:



$$\sigma_{max} = \frac{1}{2}(\sigma_{xx}+\sigma_{yy}) + \sqrt{\frac{1}{4}(\sigma_{xx}-\sigma_{yy})^2+\sigma_{xy}^2}$$

$$\sigma_{min} = \frac{1}{2}(\sigma_{xx}+\sigma_{yy}) - \sqrt{\frac{1}{4}(\sigma_{xx}-\sigma_{yy})^2+\sigma_{xy}^2}$$

$$\alpha = \arctan\left(\frac{\sigma_p-\sigma_{xx}}{\sigma_{xy}}\right)$$

σ_{xx} stress in direction of advancing of the working face
σ_{yy} vertical component of stress
σ_p (σ_{min}, σ_{max}) principal stresses
α deviation of a component of the principal stress from the progression axis

Results of the stress calculus in the period of passage of the face area under the measurement probes are shown in the table below:

distance of working face (m)	σ_{xx} bar	σ_{yy} bar	σ_{xy} bar	σ_1 bar	σ_2 bar	α °
-5	47	48	35	81	14	44
0	57	51	46	100	9	43
5	67	54	54	115	6	41

The values in the above table must be considered a rough estimate of the actual stress state, due to suppositions and simplifications in the correlation of the values of σ_{xx} and σ_{yy} and possible errors of measurements. Nevertheless the results obtained are reliable enough to prove a definite influence of mining that is evident in the change of values of the principal stresses and in the spinning of the stress ellipsoid towards the excavation.

Such distribution of stress in the mining face neighborhood was confirmed also by a mathematical model with the method of finite elements and confirmed the well-founding of the modification of the criteria of mining in the lignite mine of Velenje.

DISCUSSION

As it was pointed out in the introduction, the water, mud or gas inrushes onto the working openings are linked to extreme conditions that cause such a distribution of the stress state in the vicinity of the face that leads, in connection with other factors, to a creation of an inrush.

Dependent upon the stress state the most common causes for the incurrence of an inrush are the following:

- orientation of the minimum component of the principal stress towards the face area

- decrease of the minimum stress or conversion into strain stresses when the position of the stress ellipsoid is in the most unfavorable position regarding the working opening

- the minimum principal stress is roughly perpendicular to the layers or the fractures of the rock , together with their unfavorable position regarding the working area

- increase of stresses to the point when a sudden caving occurs of a part of the roof or bottom seams or coal along or in the vicinity of the working area.

Any analysis of the stresses in the vicinity of the working opening shall also take into consideration the time factor and the influence exercised by the changes in the geomechanical properties of the materials.

The analysis of all past inrushes[1] in the lignite mine Velenje showed that such extreme conditions were largely a result of extreme states resulting from past mining or local geological conditions. They are listed in the description of additional safety measures for mine design and the mining-out of coal (see page 1).

The following conclusions can be drawn from the studies presented in this article:

- most suitable for the determination of stress state change in the vicinity of the working area is a combined method of measurements by fracturing and measurements with hydraulic cells, that allows to obtain a space distribution of stress

- it is necessary to analyse the reasons for the occurrence of inrushes into a mine and define the influence of the stress distribution on their occurrence

- confirm the results of the in situ measurements of stress by a parallel method (mathematical and physical model) and , if possible, make a simulation of possible situations of inrush occurrence.

- on the basis of the factors that are a possible cause of inrush, among which according to the authors the stress distribution is the most important, propose measures and investigations to avoid risk situations for possible water inrush and consequently propose a modification of the mining method.

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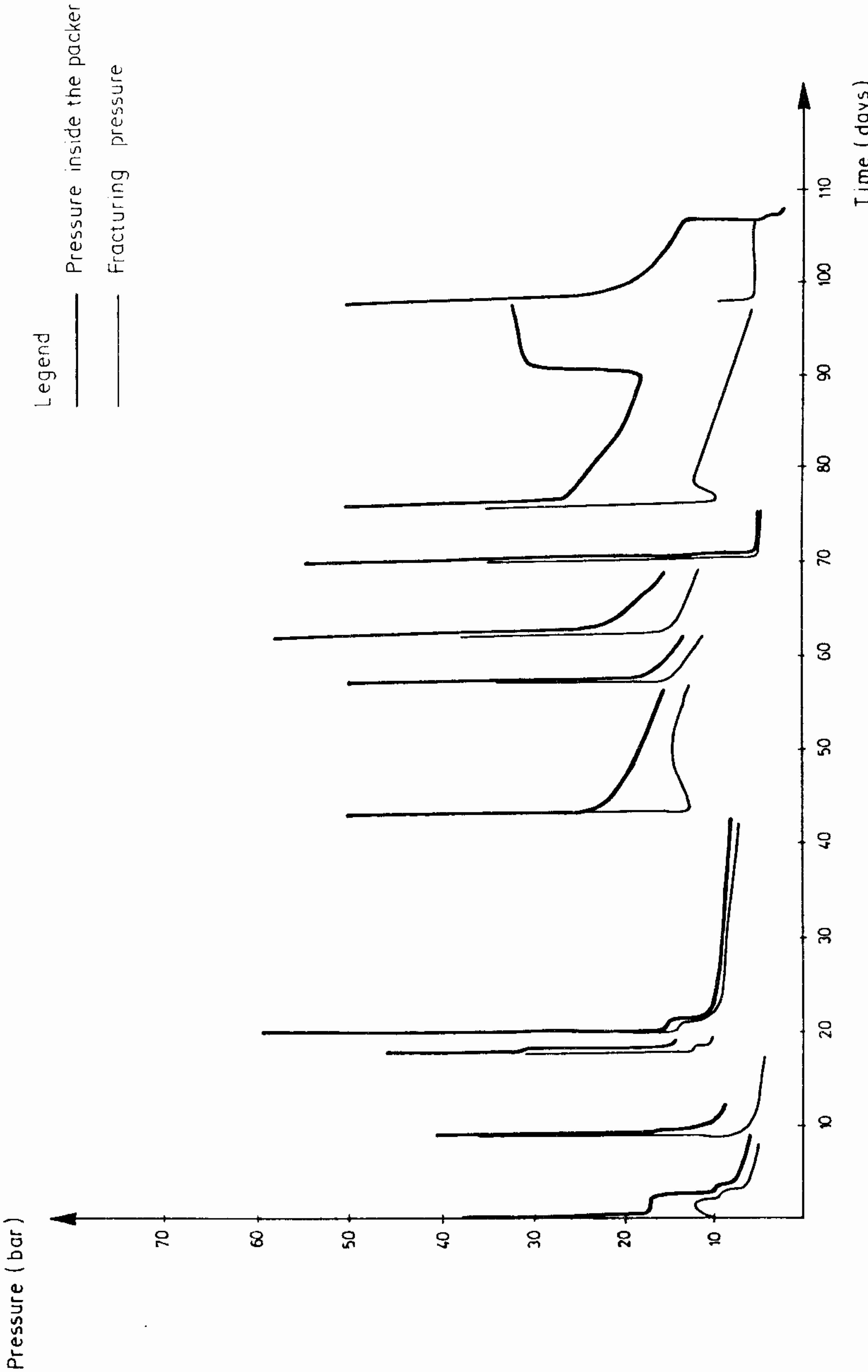

Fig.4: Results of the measurements with hydrofracturing
Cell No.1; Borehole A-1

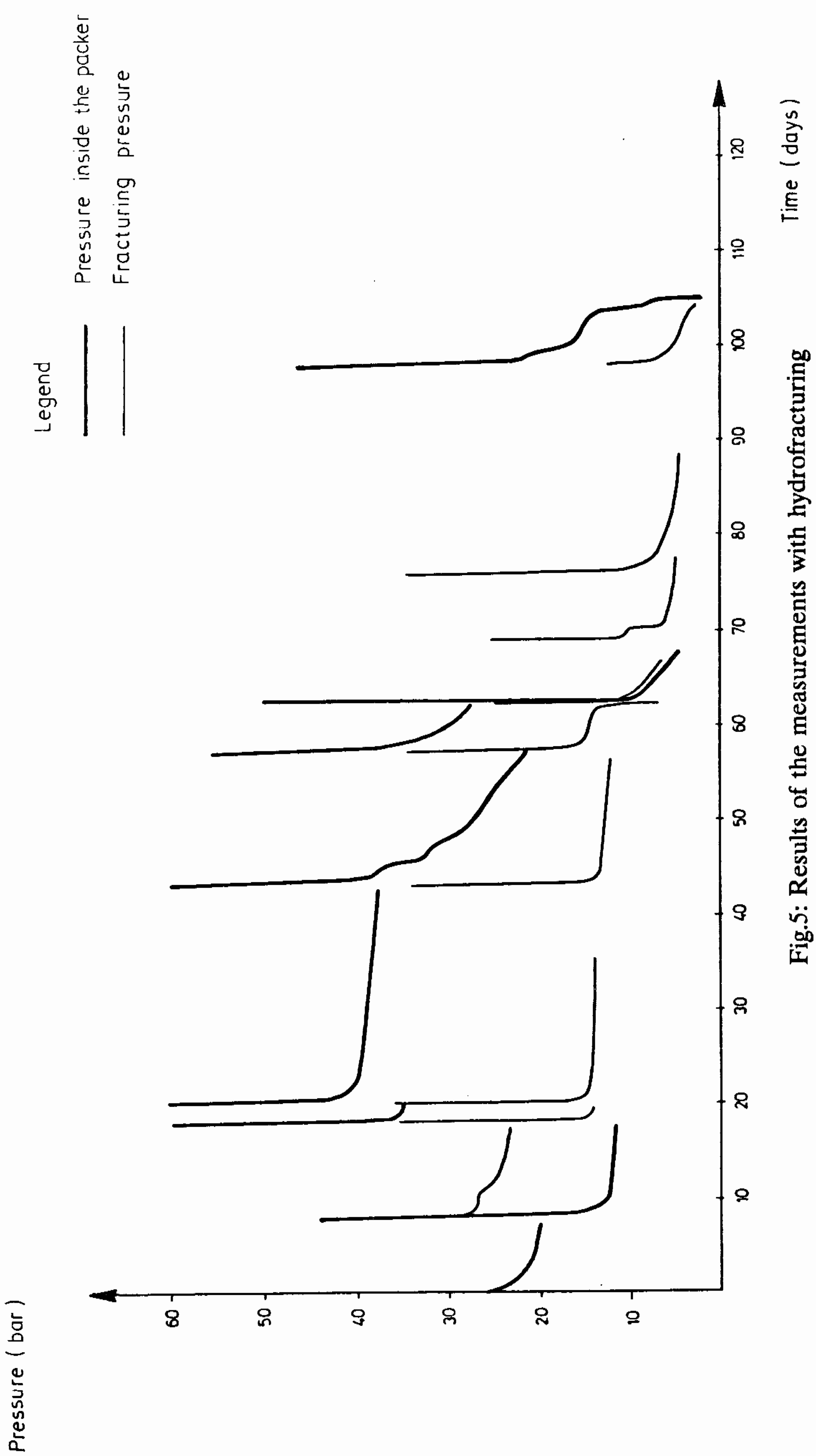

Fig.5: Results of the measurements with hydrofracturing
Cell No.2; Borehole B-2

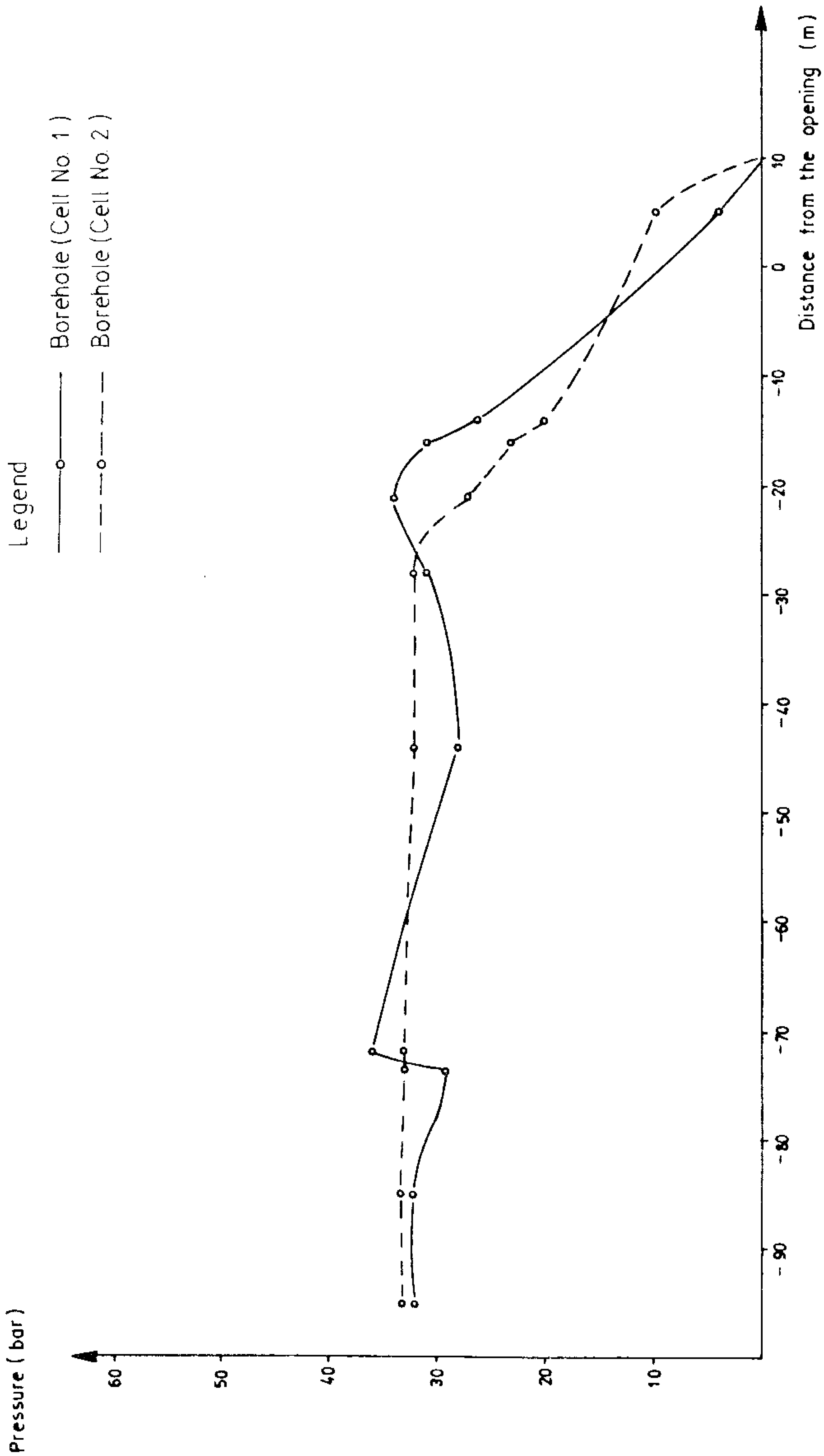

Fig.6: Fracturing pressure

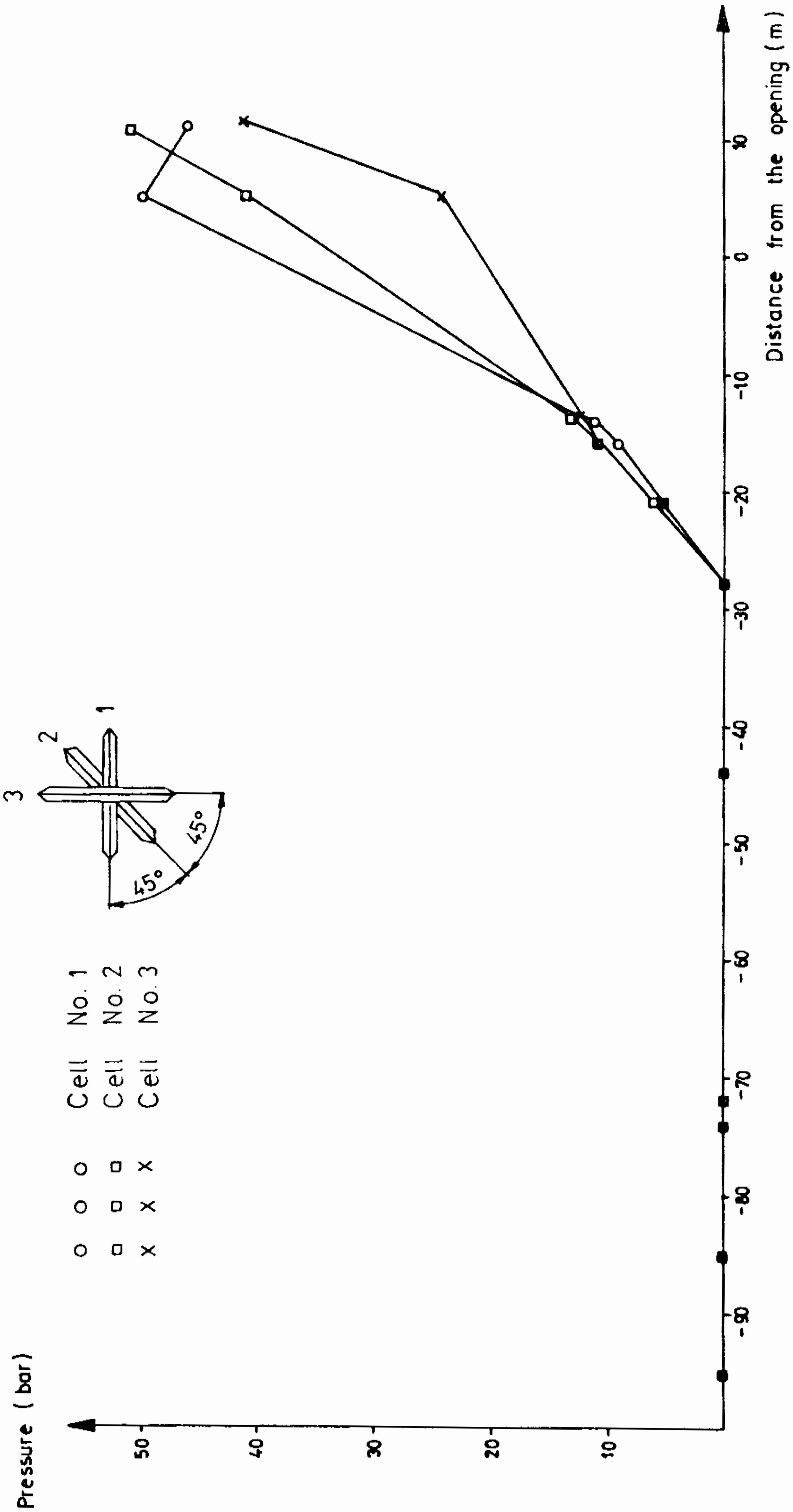

Fig.7: Measurements by a threeaxial hydraulic cell