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SOME RECENT DEVELOPMENT IN THE SWEDISH HOT-DRY-ROCK PROJECT

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ABSTRACT

This paper reports from the ongoing hot-dry-rock project in Western Sweden. An intrusive, granitic rock mass is penetrated to 500 m depth by drillholes without steel casings. The zone between the drillholes at depth is stimulated by means of high-pressure injection of water and high-viscous gels in the first drillhole. The stimulation process is monitored by microseismic detection technique. The second hole is drilled on basis of this information to intersect the developed fracture zone, to assure hydraulic contact between the drillholes. This paper reports on geological, rock mechanical and geohydrological data from the experiments, as well as on stimulation results achieved.

OBJECTIVES OF THE SWEDISH GEOTHERMAL PROGRAMME

The Swedish geothermal programme involves research and development work within three areas of direct use of the heat. These areas include production of geothermal brines from relatively shallow sandstone aquifers in Southern Sweden, utilization of major crush-zones in the crystalline bedrock for warm water production as well as a project of hot dry rock (HDR) geothermal production.

Geothermal heat from sedimentary formations is used since 1984 as a base energy source for Lund, a town of about 50 000 people in Southern Sweden. Heat pumps of 48 MW thermal capacity utilize the 24°C water of a sandstone horizon at 800 m depth.

The crush-zone and HDR projects, on the other hand, are not yet commercial but are in a stage of research and development. Due to similarity between these concepts, plans exist to combine them into one project.

The Swedish HDR project is sponsored by the Energy Research Commission and operated by Chalmers University of Technology. In the ongoing research and development work a group of about 10 researchers are actively involved. The Swedish research group enjoys well established contacts with colleagues in England (Camborne School of Mines), Germany and France. The work is presently concentrated to a field experiment site in Western Sweden, as will be described in this paper.

The basic concept for the Swedish HDR development, as described in this paper, relies heavily on good control of such site characteristics as geological structure, geohydraulic interconnections and rock stress situations. Great emphasis is therefore put on the scientific control of these factors in the ongoing HDR development programme.

This paper summarizes the present state of development and some significant results; it furthermore gives some outlooks into the future of the Swedish HDR project.

THE SWEDISH HDR TEST SITE

Location and Equipment

A site layout is shown by Figure 1, including locations of the wells. The geothermal HDR site is located in the central part of a granite massif (Bohus Granite) on the West Coast of Sweden (see Figure 2). The landscape in the area is rolling, with granitic hills bounded by relatively steep valleys, typical for the coastal area within the Bohus granite. The HDR site is on the south-eastern flank of a granitic hill.

Earlier investigations have shown that the Bohus granite is highly heat-generating, and a potentially suitable rock mass for HDR geothermal energy extraction (Landström et al, 1980).

The ongoing research program started in April 1984. Wells Fjb0, Fjb1 and Fjb2 were drilled to 200, 500 and 70 m depth, respectively, by down-the-hole percussion drilling. The wells have a diameter of 165 mm.

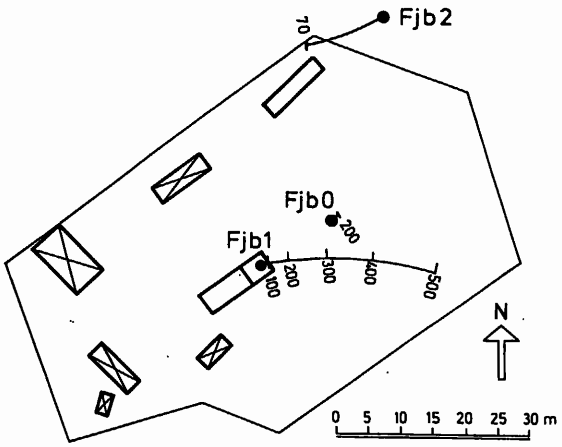

Figure 1 Site lay-out and plan view of the wells

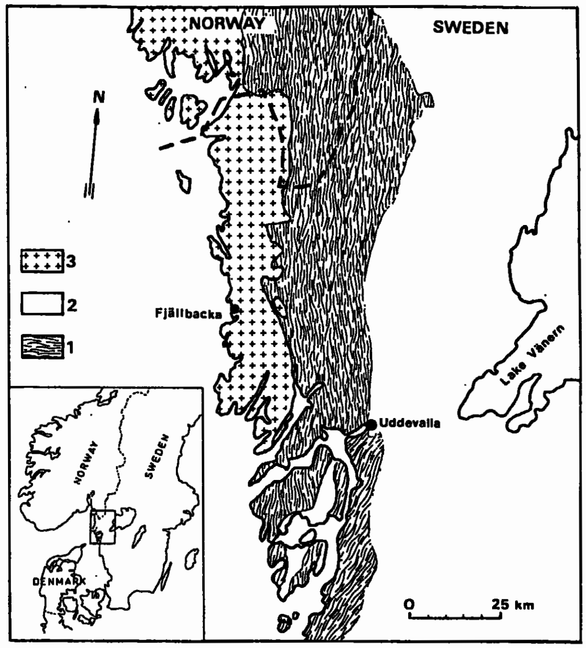

Figure 2 Generalized geological map showing the location of the Bohus granite and Fjällbacka. 1=Stora Le-Marstrand supracrustals, 2=SW Swedish gneiss region,' 3=Bohus granite

The drilling and the associated bedrock investigations are presented in detail in project reports (Geothermal Research Group, 1987), and is summarized briefly here.

Geological Conditions

The Bohus granite occupies a N-S trending area of about 20 by 90 km on the Swedish coast, Figure 2. It continues as the Idefjord granite another 40 km into south-eastern Norway. Structural and gravity data show that the granite is a flatlying, sheet-like intrusion dipping gently beneath the surrounding gneisses. According to Lind (1982) the thickness of the granite varies from about 7 km in the southern part to 0.5-4 km in the northern part.

The emplacement of the granite occurred after the main Sveconorwegian (Grenvillian) deformation, which to a variable extent affected most of SW Sweden and S Norway. The Rb-Sr age of the Bohus granite is 890 +-35 Ma (Skiöld, 1976) and since the granite does not show any signs of ductile deformation it has to be posttectonic in relation to the Sveconorwegian orogeny.

The topography of the Bohus granite area reflects a pattern of brittle tectonics which was imprinted on the crust after the intrusion of the granite. The orientation of the large morphological lineaments (valleys and fjords etc) is totally controlled by the major fracture zones in the granite.

The whole granite body, defined as monzogranite, has enhanced concentrations of U and Th, approx. 10 ppm and 50 ppm, respectively (Landström et al. 1980, Eliasson, 1987), with a mean heat flow of 58.3 mW m-2 and an average geothermal gradient of 16.2^{o}C km

The granite at the geothermal site includes fragments (xenoliths) of various types of older gneisses.

The local Th and U concentrations at the site, as determined by in situ gamma spectrometry, is 52 and 13 ppm, respectively. The corresponding heat production of 7.47 µW m^{-3} and temperature gradient 17.5^{o}C km^{-1}, are thus somewhat higher than average for Bohus granite.

Morphological lineaments (fracture zones and large fractures) of several km length and considerable depth have been mapped on aerial photographs and topographic maps. The prevailing orientation of lineaments is in NE-SW direction. Subordinately occur N-S and NW-SE to WNW-SSE striking lineaments. The fracture pattern at the site is composed of two dominant fracture sets striking approximately NE-SW and NW-SE, respectively. Subordinate occurs a N-S trending set of fractures (see Figure 4).

The mean fracture density with depth, based on televiewer log is 0.45 fractures/m, as illustrated in Figure 3.

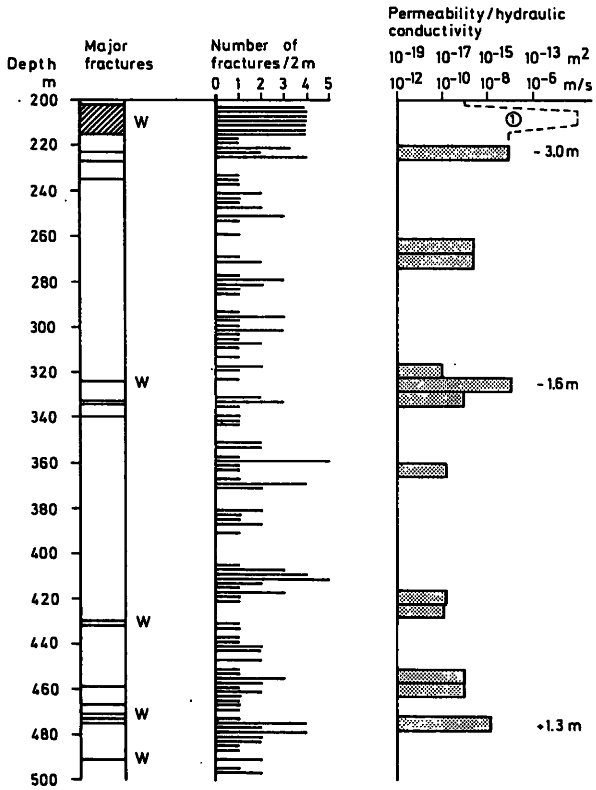

Figure 3 Plot showing major fractures, open fractures, fracture frequency, hydraulic conductivity and pressure heads in Fjb 1. W = naturally water conducting fractures ①Evaluated from pump tests.

Geohydrology and Hydrochemistry

The main objective of the geohydrological and hydrochemical investigations are to determine the nature of the ground water flow in the rock mass, to establish a permeability profile with depth and to document the ground water chemistry.

An extensive logging program was carried through in the first 500 m well (Fjb 1) and fracture orientations were investigated by Televiewer and TV-camera. Water conducting fractures were identified by different logging methods and packer tests. Water sampling from individual fractures were carried out with air blowing and pumping.

The major natural fractures and fracture zones are presented in Figure 3. Fractures conducting water, or fractures responding to hydraulic injection tests, were few and predominantly horizontal or subhorizontal. In Figure 4, the dominating orientations (strike) are shown.

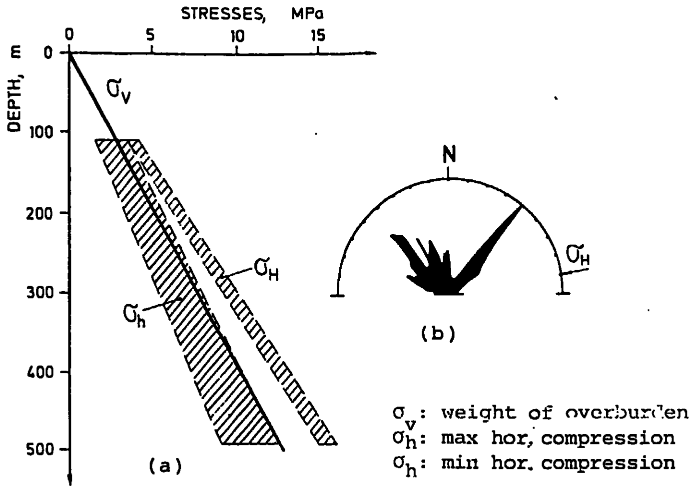

Figure 4 a) Magnitudes of the principal stresses as a function of depth.
b) Strikes of vertical/subvertical fractures on the surface and in the well Fjb1 and the direction of the largest horizontal principal stress.

Neglecting a very shallow fracture conducting fresh water, no water was found until the drill reached approximately 180 m depth. The water was salt, most likely sea water, with a pressure level corresponding to the sea water level.

Water stimulations were carried out at shallow depths when a system of open horizontal/subhorizontal fracture were created. As a result, the natural percolation of fresh water into the rock mass increased considerably and the water table rose by about ten metres. This induced a vertical downward flow of fresh water, affecting fractures at least down to 324 m.

A permeability profile below 220 m depth in Fjb1 was established from series of straddle packer tests. The results are presented in Figure 3 together with measured pressure heads in the major fractures.

A hydraulic conductivity of $3 \cdot 10^{-8}$ m/s was measured in Fjb1, mainly influenced by induced shallow fractures and the fracture zone at 210 m depth.

The results of the water chemistry analysis indicate that the deep water has a sea water origin. However water-rock reactions seem to have decreased the concentration of Mg, K and SO_4, and increased the amount of Ca. Water from 474 m depth is interpreted as "relict" sea water.

Rock Stresses

Rock stress measurements have been carried out at the HDR site with the hydrofracturing method. The measurements were conducted in the 500 m deep vertical borehole (Fjb 1), by Bochum University, FRG. The equipment used was a wire-line hydrofracturing system with an inflatable straddle packer. Eight successful stress determinations were performed on preexisting fractures with different dips and strikes. Fracture orientations were determined with an impression packer and a prefrac televiewer log.

Because of the differently oriented (not vertical) fractures, the classical hydraulic fracturing interpretation is not applicable. Instead, a method was applied which is based on measurements of the normal stress acting on arbitrarily oriented planes (Cornet & Valette, 1984).

The necessary assumptions for this analysis are:

* The vertical stress component is a principal stress and equal to the weight of overburden.

* The stress field varies linearly with depth.

* The normal stress component is uniform all over the fracture surface and equal to the instantaneous shut-in pressure.

* The fracture keeps its orientation away from the borehole.

The analysis yields a non-linear inverse problem, which can be solved with a least squares criterion. Due to the quite small data base obtained, 8 tests and 5 unknowns, the results are rather unstable. Furthermore, particularly the second assumption above is a rather rough approximation and makes the results less applicable.

However, the computations gave a more or less East-West oriented maximum compresssion, shown in Figure 4.

From the pressure data, a maximum horizontal compression (principal stress) of about 15-17 MPa at a depth of 500 m, is obtained. The minimum horizontal compression (principal stress) scatters between 9-13 MPa at the same depth. This indicates that the vertical stress calculated as the weight of overburden (approximately 13 MPa) could be the intermediate principal stress at a depth of 500 m. The results are shown in Figure 4.

Mechanical rock properties

Mean values for the rock properties of the Bohus granite determined on small rock spcimens were presented by Wijk et al. (1978) as

Youngs modulus = 50 GPa
Poissons ratio = 0.15
Uniaxial compressive strength = 220 GPa
Uniaxial tensile strength = 8.3 MPa

The corresponding rock mass properties have not been evaluated.

THE SWEDISH HDR PRODUCTION CONCEPT

System Description

The basic concept for the Swedish HDR development includes the following steps, c.f. Figure 5:

* find a promising rock mass
* drill an uncased well to target depth
* design fracturing job on basis of well data
* stimulate or create fractures by fluid injection
* detect fracture system by passive microseismic monitoring
* drill a second, uncased well to intersect fracture system at suitable distance from first well
* pack off fracture zone in both wells and connect packed-off sections with pipes to surface
* circulate water through system to pick up geothermal heat in fracture system

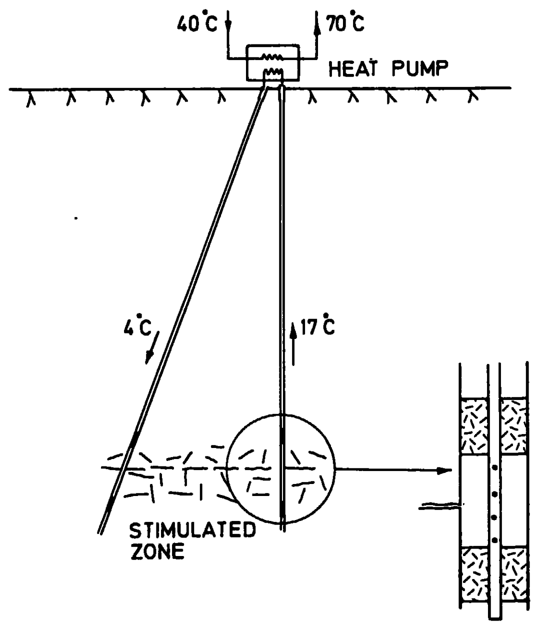

Figure 5. Principle of the Swedish HDR concept.

The selection of target depth must be based on economies: i.e. value of the heat versus the drilling costs. In Sweden, having low electric power costs, it tends to be economical to limit the drilling depth and use electric heat pumps to achieve desired temperature levels for space-heating purposes.

The selected depth for the Swedish HDR research project is at about 450-500 m, where rock temperatures are about 17°C. For a commercial operation in Sweden, the economical depth will most likely be greater.

The heat pumps will bring down the temperature of the produced water to about 4°C, before it is reinjected into the second well. The heat pumps will utilize this temperature drop of 13°C to produce warm water for space heating at a temperature of about 70°C, as shown in Figure 5.

Stimulation Design

Theoretical fracture models were used prior to the hydraulic stimulations as a tool to predict the width and areal extent of the created fracture.

By the use of the Geertsma and de Klerk (1969) radial (penny-shaped) fracture model, design values for the operational parameters, such as injection rate, pumping time and fluid viscosity were selected.

The stimulation program was performed in four injection sequences, as follows

Sequency	Est. quantities
1. Minifrac	20-50 m^3 gel
2. Hydrofrac	100 m^3 water
3. Main frac	200 m^3 gel
4. Propping	20-50 m^3 gel + sand

In addition, main parameters for the stimulation were set as:

* Target flowrate: 20-30 l/s
* Fluid viscosity: 70 cP (mPa s)
* Target radius: at least 150 m

The purpose of a minifrac test in advance of the main frac was to evaluate the leak-off rate. This was done, using the pressure decline versus time curves obtained during the shut-in period following the minifrac test. The fracture model applicable for penny-shaped fractures of Nolte (1979), extended by Lee (1985), was used. The leakage coefficient resulting from this analysis was inserted in the Geertsma-de Klerk (1969) and the Nolte-Lee models to simulate the main fracturing test and to recalculate the geometry of the fracture.

Stimulation Equipment and Procedure

Major contractors engaged were Norsk Brönnservice A/S (pumping) and Lasalle Pressure Data A/S (downhole monitoring), both Norwegian.

A straddle arrangement with a 30 m interval and a four feet long flow joint was constructed for the operation. Inflatable packers with long rubber sealings were chosen. Between the top packer and the wellhead a 2 7/8" tubing was installed.

Besides monitoring pressure, flowrate and accumulated volume at the wellhead a downhole pressure and temperature gauge was used.

Monitoring of Micro seismicity and Fracture Propagation

Sudden fracture movements in the bedrock may be seismically detected. At the HDR site the sensors were located at the surface rather far from the depth interval under fracturing. As a consequence, only shear slipping events can be expected to be recorded seismically. A significant sudden movement requires access to stored energy. This is only provided by the elastic rock stresses and they can not be expected to include tensions. Thus the fracture opening is not expected to generate seismic events with strengths comparable to the shear slip events.

Even if only the sudden parts of the fracture movements is seismic, information of the induced microseismicity is of considerable value, since it may be used for correlation with other observations on fracturing.

The places where the seismic events occur have probably good hydraulic contacts with the borehole of injection. In addition, the sudden shear slips will probably increase the conductivity of the moving fracture. In conclusion, the induced seismicity will point out places of increased hydraulic conductivity which are in hydraulic contact with the stimulated zone.

According to the discussion above, the most important result of the seismic analysis will be the event locations. The seismic analysis may however also give information about fracture orientations, stresses, fault surfaces and slip direction and slip sizes.

The microseismicity induced during the stimulations was recorded by 15 vertical geophones on granitic outcrops at the surface. The contractor for this job was National Defence Research Institute, Sweden. In addition a three component geophone was placed in a close borehole at a depth of 180 m. Totally 72 seismic events were detected and recorded digitally on tape with a sampling rate of 1000 Hz. The geophones had an eigenfrequency of 10 Hz. As a backup continuous analog recording was made on magnetic tape and the seismic activity was monitored on low speed paper recorder.

The analysis included the following methods:

Event locations:

* single event location by use of first P-arrival times

* joint hypocenter determination by use of both P-arrival and S-arrival times

Fault plane orientations:

* a combined use of P-wave first motions and of spectral amplitudes

* relative location of closely spaced similar events

Dynamic source parameters:

* spectral studies of the P- and S-waves to find the corner frequency and low frequency level

RESULT OF STIMULATION WORK

The main purpose of the deep hydraulic stimulations was to create a large permeable zone. The displacement of the pressurized fluid was followed by microseismic detection as to find a suitable position for the next well to be drilled.

The first minifrac was run with 70 cP gel with an average flow rate of 18.2 l/s. The wellhead pressure declined from 15 to 14 MPa during the half-hour test. A fracture efficiency (frac volume divided by injected volume) of 44% was calculated. Shortly after shut-in, two seismic events were recorded.

In the second minifrac test a fluid with higher viscosity (150 cP) was used. Flow rate averaged 18.7 l/s. The analysis of the injection indicates an only slightly higher fracture efficiency (52%) than minifrac 1. Three seismic events were recorded; one at shut-in and the others about one hour later.

The altogether five events recorded during both minifracs were located approximately 50 m WSW of the straddled section at about 450 m depth, see Figure 6.

During the main water injection, the flow rate was 30 l/s. The wellhead pressure rose to 16 MPa and declined slowly to 15 MPa until sharp discontinuities in the pressure curve after about half an hour. There was enhanced seismic activity during the pressure fluctuations with a total of 33 events recorded. The first pressure increase correlates to seismic activities about 80 m WSW of the straddled section and the second correlates to activities 100 m NE.

The flow rate in the main viscous injection with 70 cP gel was 21 l/s and 200 m^3 of gel plus 25 m^3 of gel and sand mixture were injected during three hours. Totally 35 microseismic events were recorded in connection with the main gel injection. The events were evenly distributed over injection time and localized to approximately 120 m W and NE of the injection zone.

The following shut-in showed a very slow pressure decline. Still after seven days an over-pressure of 3 MPa was recorded in the well. The venting gradient was linear and estimated to: $\Delta V/\Delta p = 0{,}35\ m^3/m$.

Temperature logging of the produced fluid was conducted during the venting procedure. The major inflow area was detected at a depth of 455 m which corresponds to the depth of the seismic events. A minor flow zone at 472 m may be related to an opened inclined fracture.

Table 1 summarizes the main stimulation results. All pressures at wellhead.

Phase	Volume m3	Visc. cP	Durat. min	Pmax MPa	Pmin MPa	ISIP 1)	PC 2)
MF1	30	90	30	15.0	13.0	6.8	5.3
MF2	30	150	28	13.0	11.5	7.2	5.8
MW	105	1	70	16.0	15.5	5.8	-
MV+P	225	70	180	13.2	10.7	6.0	5.3

Table 1. Parameters from injections

1) Instantaneous Shut-in pressure (MPa)
2) Fracture Closure Pressure (MPa)

The shut-in curves from the different test phases were evaluated with log-log plots of pressure change versus time, a method presented by Gringarten and Ramey (1974). The model is applicable for analysing a transient pressure behaviour of a well with horizontal fractures in crystalline rock. The model is used for identifying various flow regimes and for evaluating hydraulic conductivity.

Both minifracs show a storage-type flow, followed by a transition period and ending with a planar flow. The storage flow regime might correspond to a closure movement of the fracture. Estimated pressures of fracture closure are falling at the start of the planar flow regime.

The main water injection does not exhibit any storage flow type. No obvious planar flow is present. The shut-in curve of the main viscous injection starts with a transition period followed by a radial flow type.

The absence of planar flow in the shut-in curves of the main water and viscous injections might be explained by the presence of many stimulated vertical fractures. The radial flow is developed rather quick and the flow represents a stimulated zone rather than a single horizontal fracture.

From the analysis of the seimsic data, general conclusions may be drawn:

* most events occurred at a narrow depth interval, 440-475 m, up to 150 m from the borehole of injection. This indicates that a horizontal main fracture was opened

* mainly two parts of the rock mass were seismically active with quiet parts in between (the areacloser than 40 m from the borehole was seismically quiet)

* the seismicity spread successively outwards. Different parts were active during different times

* the induced seismic events were shear slip events with no significant fracture opening component

* strike-slip faulting dominated but mostly with a reverse faulting component

* most fault planes were close to vertical, intersecting the horizontal fracture

* much of the seismic activity was related to left-lateral strike-slip on steeply dipping ENE striking fractures

* the faulting areas had typically a width of 10-14 m (this may be the typical block size of the rock mass)

* the estimated static stress drops were 0.1-1 MPa (in places of repeated activity the accumulated shear stress drop could be a few MPa)

* the size of the seismic slips for single events were in the range 0.01-0.3 mm (in places of repeated activity the accumulated seismic slip was about 1 mm).

Figure 6 shows the locations of the induced seismicity as given by joint hypocenter determination. Based on these locations, the position of a second borehole was decided.

The more shallow seismic events are located rather far away from the injection. The closer events are all in the narrow depth interval. This fits the idea of a horizontal primary fracture which is seismically quiet. This fracture only opens to distribute the fluid pressure.

CONCLUSIONS AND PROGRESS OF WORK

By means of design models, based on rock mass investigations, reasonable predictions of stimulated zones seems to have been achieved in the Swedish HDR field experiment. By means of microseismic determination, a good forecast of the location of the induced fracture system has been developed.

Drilling of the second well to intersect this fracture zone is now underway. By the autumn of 1987, circulation and heat production should commence at the site.

ACKNOWLEDGEMENTS

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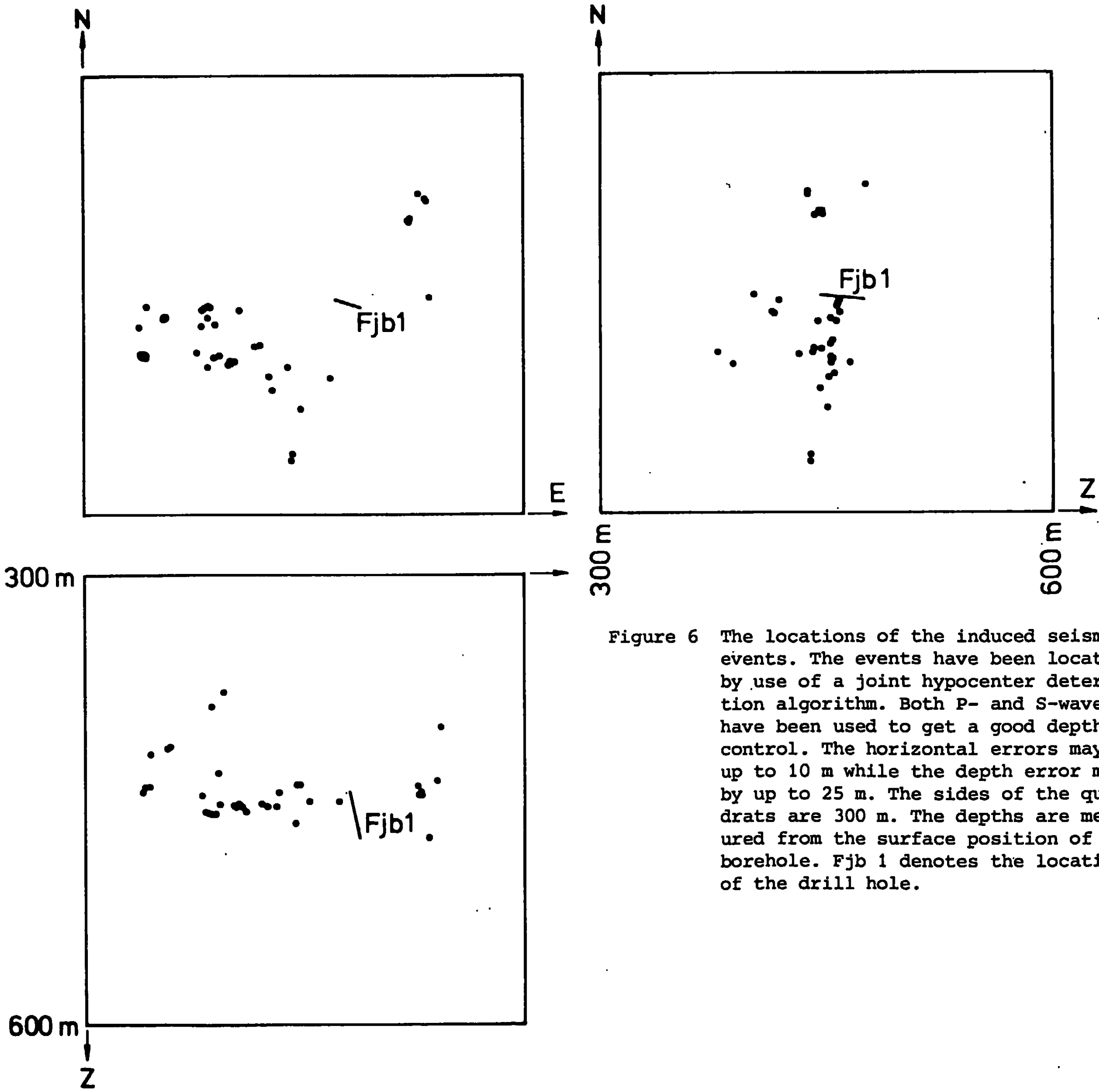

Figure 6 The locations of the induced seismic events. The events have been located by use of a joint hypocenter determination algorithm. Both P- and S-waves have been used to get a good depth control. The horizontal errors may be up to 10 m while the depth error may by up to 25 m. The sides of the quadrats are 300 m. The depths are measured from the surface position of the borehole. Fjb 1 denotes the location of the drill hole.