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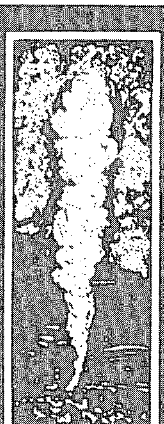

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PRESSURE TRANSIENT ANALYSIS FOR LARGE SCALE HYDRAULIC INJECTIONS IN THE CARNMENELLIS GRANITE, ENGLAND

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ABSTRACT

Large volume hydraulic injections into the Carnmenellis granite have been completed at the CSM Hot Dry Rock Project during the period October 1982 to July 1983, with small volume injections before and after this period. The effects of the injections on the hydraulic properties of the rock mass have been estimated by pressure transient analysis. The growth of the reservoir zone was tracked with microseismic locations, and the growth mechanism modelled with the computer program FRIP.

The limited duration of the transients amenable to analysis and the tendency for growth below the injection zone meant that the interpretations could only describe hydraulic conditions within about 100 m of the wellbores. The effect of the large volume injections was to increase permeability values from less than 100 μd to greater than 5 md, and to decrease skin values from about -3 to about -6.

The FRIP modelling explained the observed reservoir growth in plan with reference to measured in-situ stresses, jointing and rock properties and showed some of the limitations of continuum modelling.

INTRODUCTION

The background to the Hot Dry Rock (HDR) research project operated by the Camborne School of Mines (CSM) in Cornwall, UK, was summarised by Batchelor (1982) at a previous Stanford workshop on geothermal energy. Details were included of the hydraulic tests conducted to late November 1982.

The purposes of this paper are to give a brief update on the tests and the results, and to examine in more detail the uses and limitations of pressure transient analysis as applied during the project.

The interpretation of pressure transients arising during tests on wells in fractured rock is widely recognised as a challenging problem and a number of approaches have developed; eg, Gringarten, Ramey and Raghavan (1975), Earlougher (1977), Gringarten (1982), and Agarwal et al (1979).

The approach at CSM has been to use such analyses based on radial and planar diffusion, which assume no pressure dependence of key parameters such as formation permeability and compressibility. These tests are used to provide index values for the hydraulic parameters as conditions change within the rock mass during successive injection, shut-in and venting cycles.

At the same time, interpretations have been attempted using the geometry of the apparent shape and size of the created reservoir defined by microseismic location. In addition, injections have been modelled using the two dimensional joint-block computer model, FRIP. This modelling gives an insight into the relatively complex behaviour of elastic rock blocks separated by joints whose apertures are controlled by fluid pressure, in situ stress, strength and stiffness conditions.

BACKGROUND INFORMATION

The CSM HDR site is located towards the centre of the Carnmenellis granite outcrop which probably extends to a depth of at least 10 km. It is regularly jointed with two main sets of orthogonal subvertical joints and a set of subhorizontal joints. Vertical joints are spaced at typically 1 to 3 m at the ground surface increasing to about 10 m at 0.8 to 2 km depth. The strikes of the subvertical joint sets are shown in Figure 1. The joint profiles visible at surface and underground exposures are typically smooth, nearly planar to smooth, undulating according to the classification of Barton (1976).

In situ stresses in the Carnmenellis granite are markedly anisotropic. Pine et al (1983 a and b) measured the stresses to a maximum depth of 2 km using a combination of overcoring and hydrofracturing methods. At a depth of 2 km, the maximum and minimum horizontal and vertical total stresses are approximately 60-70, 30 and 52 MPa respectively. The bearing of the maximum horizontal stress is about 130°-310° relative to true North.

Typical mechanical and hydraulic properties of the intact granite include a uniaxial compressive strength of 150 MPa, hydrofracture tensile strength of 15 MPa, deformation modulus

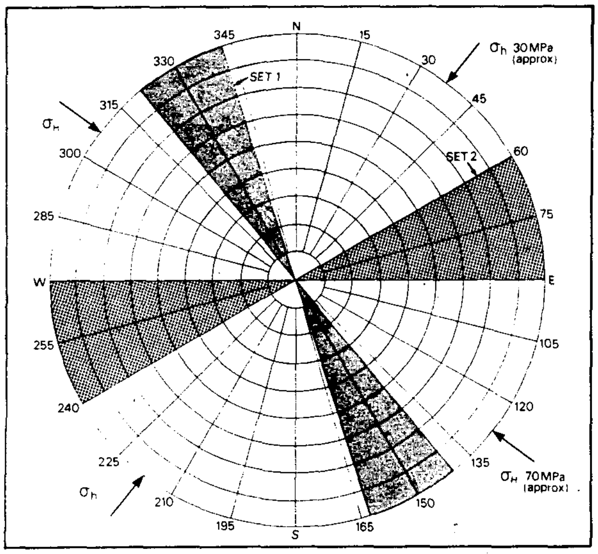

Figure 1: Directions of strikes of major joint sets and horizontal in situ stresses

of 60 GPa, Poisson's ratio of 0.2 and fluid permeability of 10 nanodarcy. The properties do not vary significantly from ground surface to a depth of 2 km.

Two deep wells have been drilled at the site to a vertical depth of about 2 km. The injection well, RH12, is cased to a vertical depth of about 1.75 km and the recovery well, RH11, to a depth of 1.45 km with open hole lengths of 357 m and 772 m respectively. The open hole diameters are approximately 0.22 m. Both wells are inclined at 30° from the vertical in the open hole sections, which lie in the same vertical plane on a bearing of about 125°-305°

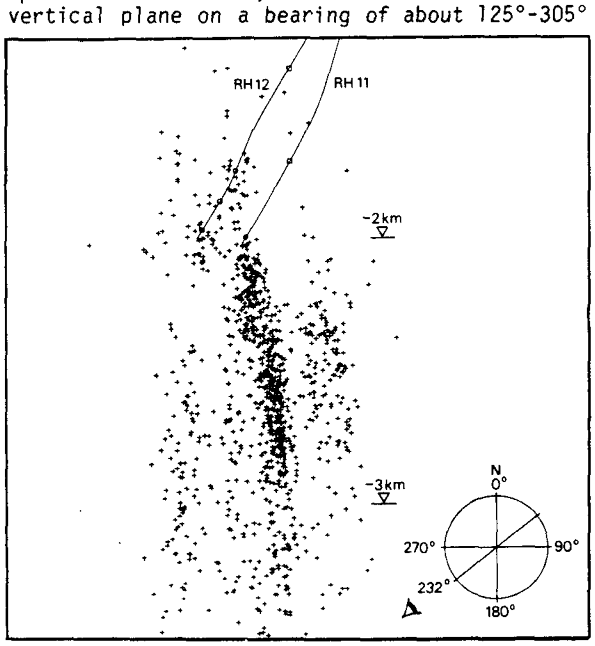

Figure 2: Vertical section showing microseismic locations viewed from the South West

with a vertical separation of 300 m. The relative positions of the wells in the injection zone are shown in Figures 2 and 3.

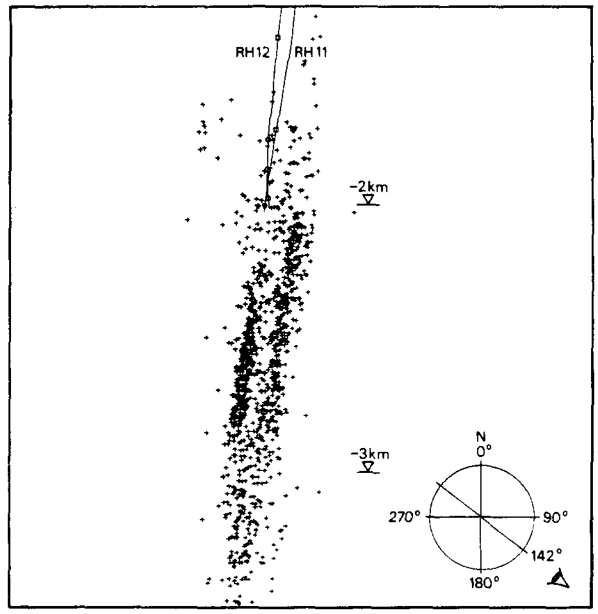

Figure 3: Vertical section showing microseismic locations viewed from the South East

SUMMARY OF HYDRAULIC TESTS UNDERTAKEN

The hydraulic tests which have been performed on the two deep wells can be divided into three groups:

i Low flowrate tests conducted before and after the major injections.
ii High flowrate major injections/stimulations.
iii Medium flowrate circulations.

The majority of the low flow rate tests were conducted from April to August 1982 and were described by Pine and Ledingham (1983). The purpose of these tests was to obtain datum values for the undisturbed hydraulic properties needed for quantifying the far field losses and the effect near the wells of the major injections. Constant pressure and flowrate injections and shut-in tests were conducted. Total water volumes of about 300 and 200 m^3 were injected into RH11 and RH12 respectively. The additional low flowrate check tests following the major injections were conducted in November 1983, when reservoir pressures had reduced to near hydrostatic.

The high flowrate tests were carried out mainly during the period October to November 1982, when a total net volume of about 100 000 m^3 of water was injected. The purpose of these tests was to stimulate the natural rock joints between the wells and create a relatively permeable flowing zone with sufficient surface area to keep thermal drawdown to an acceptable minimum during subsequent circulations. Both the injection well, RH12, and the recovery well, RH11, were injected and vented. There were also several shut-in tests.

An additional experiment involving a 400 m^3 viscous injection was undertaken in RH11 in May 1983.

The medium flowrate circulation periods were from November 1982 to April 1983 and from late May to July 1983. The wells were then shut-in until the recent low flowrate tests. The main purpose of the circulation tests was to determine the steady state hydraulic behaviour of the stimulated reservoir, which is not covered in this paper. However, during the course of these tests there were several pressure transients due to changes in pumping and venting flowrates. Several of these transients were suitable for analysis. Further test details are included in Table 1.

THEORY

Basic analysis

Pressure transients were analysed in the conventional manner; eg, Earlougher (1977), using log-log, semi-log and root time plots of pressure change against time. The analysis due to Gringarten et al (1982), which is based on infinite fracture conductivity for fractured sytems, was found to be the most convenient log-log analysis. Interpretation in terms of double porosity per Gringarten (1982) and finite conductivity fractures per Agarwal et al (1979) were also attempted. The modified time scale due to Agarwal (1980) was found useful for shut-in test analyses with log-log drawdown type curves.

The majority of the transients analysed were for injections and shut-ins, with a few drawdown and two-rate injections. All tests were analysed for the individual wells without consideration of any (minor) interference effects from the adjacent well. The radius of investigation for radial flow tests was estimated per van Poollen (1964).

Reservoir growth mechanisms and directions

The water injected into a jointed crystalline rock mass with a low matrix permeability such as granite moves predominantly within the existing network of natural fractures. Where injection pressures are high enough the apertures of the joints are increased by either jacking (opening against normal closure stress) or shearing (as a result of anisotropic in situ stresses). Evidence for the shearing mechanism is provided by the nature of seismic and microseismic signals detected by monitoring networks; eg, Healy et al (1968), Pearson (1981), and Batchelor et al (1983).

It can be shown theoretically that shearing will precede jacking in most circumstances; eg, Pine and Batchelor (1982, 1983). For relatively high injection flow rates, fluid pressures can become high enough to cause jacking near the wells with shearing further out. Beyond the zone of shearing, fluid movement can be of a diffusive nature through unstimulated joints. Shear growth will be mostly within joints subject to the least normal closure stress with some additional growth in other joints, depending on the joint and in situ stress orientations and stress magnitudes.

When a joint has sheared, part of the dilation will be irreversible because of non matching joint surfaces. The irreversible shear dilation will cause a residual increased permeability even when fluid pressures subsequently decline. Where shearing occurs as a result of sustained hydraulic injections, there will be a tendency for an upward or downward component to the zone of stimulation (Pine and Batchelor, 1983). Downward growth will be associated with significant anisotropies in the in situ principal stress gradients. This is likely to be common in hard jointed rock to depths of at least 4 km; eg, McGarr (1980).

Test group	Test type	Peak pressure (MPa)	Flowrate (1/s)	Permeabilities (md)		Skin factors	
				Range	Mean	Range	Mean
LOW FLOW	Injection	5.5	0.1 to 3.0	0.001 to 0.06		-1 to -3	
HIGH FLOW	Injection Shut in	14.0	46 to 90	3.7 to 13.0 2.2 to 3.9	7.6 3.2	-2.4 to -4 -4.6 to -5.7	-3.4 -5.1
MEDIUM FLOW	Injection Shut in Drawdown	12.0 11.0 8.0	20 to 33 5 to 15	3.0 to 5.0 1.6 to 4.1 0.3 to 2.9	3.9 2.8 1.3	-3.7 to -5.3 -4.4 to -5.8 -4.2 to -6.6	-4.9 -5.4 -5.6
LOW FLOW CHECK TESTS	Injection Shut in		3.2	1.4 1.1		-4.9 -4.8	

TABLE 1 Summary of pressure transient test analyses for injection well, RH12

Joint-block modelling

In recognition of the probable physics of jacking and shearing processes in jointed rock, the Fluid Rock Interaction Program (FRIP) was developed for the CSM project. The model was originally specified by CSM and subsequently developed by an external consultant, Cundall (1982, 1983). The model has been used to interpret some of the low flow rate injections, summarised by Pine and Ledingham (1983).

The model permits dynamic simulation of fluid flow in joints of variable aperture between elastic blocks of a uniform size in a grid sufficiently large to eliminate important boundary effects. It is in a finite difference formulation and solves the equations of motion for the blocks and the flow conditions for the joints at each time step throughout the grid. Laminar flow is assumed.

RESULTS

Transient test analyses

The results of the pressure transient analyses for RH12 are summarised in Table 1. Results for RH11 were similar but less extensive. Permeability, k, skin, s, and fracture half length, x_f, values were determined on the assumption that conditions were uniform throughout the height of the open hole section, and that the formation compressibility, β, had a constant value of $10^{-10}\ Pa^{-1}$. These assumptions are discussed later.

There was generally reasonable agreement between parameter values determined by log-log and semi-log or root-time analyses for the same tests. During injections there was a tendency for the flow to appear as a limited period of planar followed by a more prolonged period of radial diffusion with straight lines on root time then semi-log plots. During shut-in tests usually planar diffusion only was evident. There was no convincing evidence for double porosity type behaviour.

The undisturbed rock mass had very low values of permeability, a minimum of 1 μd in RH12 and 10 μd in RH11. These values were associated with s of about -1, and x_f of about 1 m. By completion of the low flow rate tests, the k had increased to about 60 μd and s had decreased to about -3, with x_f about 5 m.

The effect of the high flowrate injections was to cause very significant increases in k and decreases in s, as expected. The peak k value seen during a high flowrate injection was about 13 md. This was associated with a moderate s value of about -3. However, during subsequent shut-ins and medium flow rate injections these values fell to typically 3 md and -5 respectively.

Figure 4 shows a typical semi-log plot from part of an injection of 21 l/s which lasted for

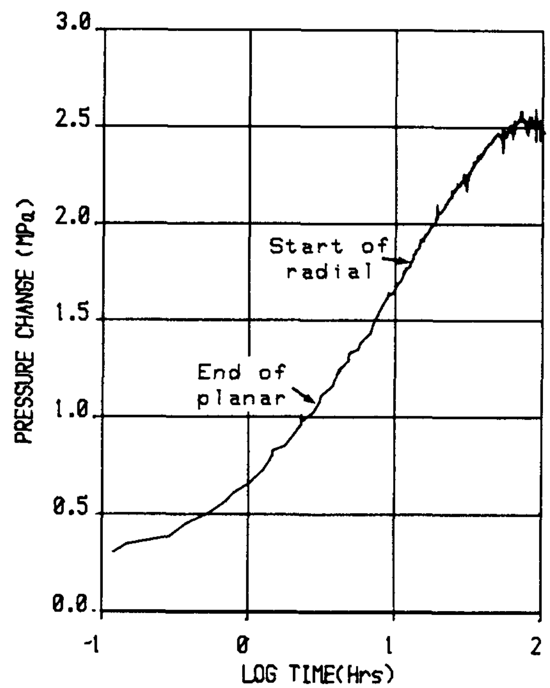

Figure 4: Pressure-log time trace for 21 l/sec injection into RH12, during main injection period

367 hrs. The end of the planar and beginning of the radial diffusion periods determined from log-log analysis were at about 3 and 12 hrs respectively. The values of k, s and x_f were about 4.5 md, -5.3 and 42 m respectively.

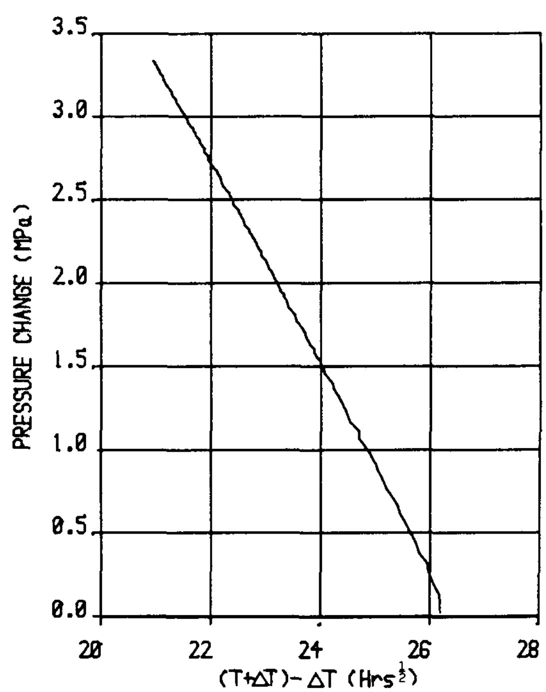

Figure 5: Pressure-root time function trace for shut-in of RH12, during main injection period

Figure 5 shows a plot of pressure vs the root time function $(t + \Delta t)^{\frac{1}{2}} - \Delta t^{\frac{1}{2}}$ for a shut-in period t of 35 hrs duration following an injection of 26 l/s for a period t of 700 hrs. There is a good straight line correlation, indicating planar diffusion. The theoretical end of the planar diffusion period from log-log analysis was at approximately 4 hrs although there is a similar slope for much longer. The product $A\sqrt{k\beta}$, where A is the total diffusive source area (one side), was about 3.3×10^{-8} $m^3 Pa^{-1}$. Using a k value of 4 md from a previous injection and assuming a β value of 10^{-10} Pa^{-1} gives an A value of 52 000 m^2, equivalent to an x_f value of 73 m for a full height symmetrical fracture.

The low flowrate tests of November 1983 showed only planar diffusion behaviour during both injections and shut-ins. (The pressure-root time response of RH12 to a 3.2 l/sec injection is shown in Figure 6.) This made the deduction of k and s values difficult because radial diffusion had not developed by the end of the test and an independent value for k could not be derived. Note that k had itself been affected by the stimulations since early measurements.

The values shown in Table 1 are for the infinite conductivity fracture model per Gringarten (1982). The equivalent x_f values are about 30 m. Using the finite conductivity fracture model per Agarwal et al (1979), k is only 110 μd and x_f is 130 m. The product $A\sqrt{k\beta}$ is about 10^{-8} $m^3 Pa^{-1}$ in both cases. This can be compared with a value of only 3 x 10^{-10} $m^3 Pa^{-1}$ from similar tests before the main injections.

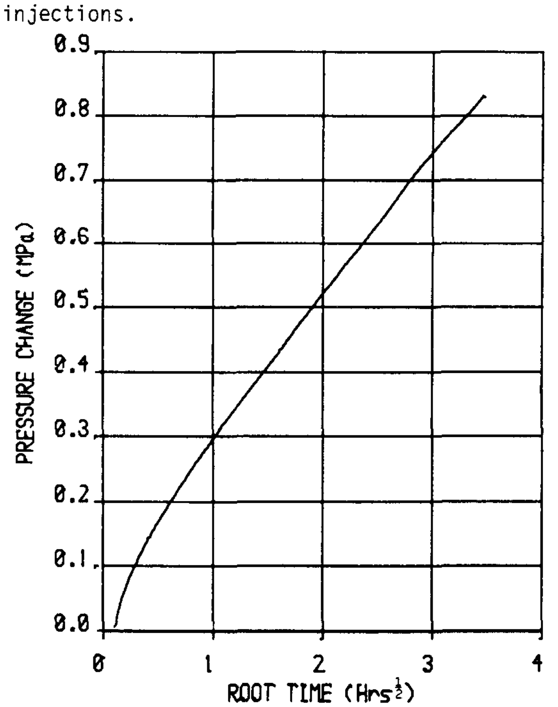

Figure 6: Pressure-root time trace for 3.2 l/sec injection into RH12, following main injection period

The viscous fracturing operation conducted on RH11 did not result in any significant increase in k or decrease in s. However, extensive new fracturing was observed in the wellbore with a TV survey, and subsequent circulation tests showed an improved connection between RH11 and the main reservoir.

Microseismic locations

The microseismic location system used at the CSM project and the progression of microseismic location with time during the high flow rate injections were described by Batcheor et al (1983). Figures 2 and 3 show the microseismic locations in vertical sections towards the end of these injections. Figure 7 shows a plan with the viewing direction approximately 10° off vertical to maximise the alignment of the locations. Preliminary versions of these plots were presented by Batchelor (1982).

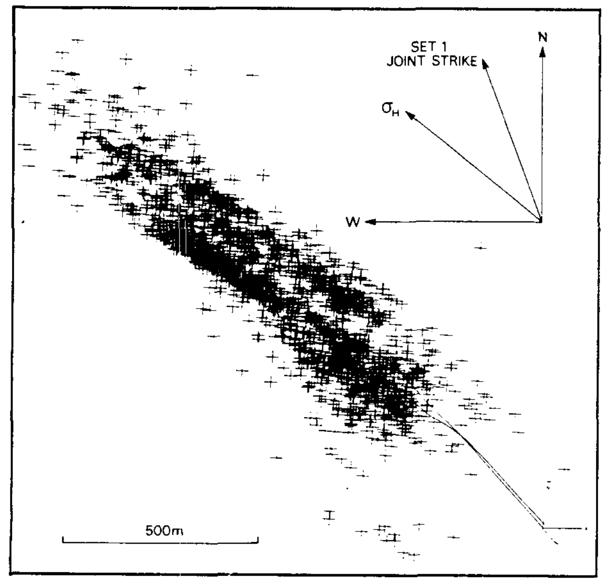

Figure 7: Plan view of microseimic locations viewed 10° from vertical

It is considered that the overall region defined by the microseismic locations contains zones of increased permeability, although it is not possible to conclude that individual locations are associated with the increased permeabilities.

Although the wells are enveloped by the microseismic locations, most of the reservoir growth has been downward. There is also a planarity to the stimulated zone aligned close to the maximum principal stress direction.

FRIP modelling

Some of the low flowrate injections have been successfully modelled using the FRIP program. Details are presented by Pine and Ledingham (1983). Modelling of the high flowrate injections using realistic rock and hydraulic parameters has been unsuccessful so far because of the high computer CPU usage. This problem has been avoided to a certain extent by modelling injections with artificially high viscosities, within relatively compressible rock blocks (Murphy and Pine 1984). These adjustments have the effect of accelerating joint stimulation and damping out short pressure transients, thus increasing time steps and reducing CPU usage.

Some results are shown in Figures 8 and 9. Both figures show plan views of an orthogonal vertically jointed rock mass subjected to a maximum horizontal principal stress aligned 30° anticlockwise from the strike of joint set 1 as applicable at the CSM site. Fluid was injected into a joint intersection at the centre of the models. The figures show the joint stimulation pattern. The dilation of the joints due to both shearing and jacking is shown by line thickness. The ratios of the effective in situ horizontal stresses σ_H'/σ_h' were 2 and 5 in Figures 8 and 9 respectively. (The effective horizontal stresses are the total stresses minus the hydrostatic pressure presumed to exist in the joints before injection).

The growth of the reservoir shown in Figure 8 is similar to that shown by the microseismic locations in Figure 7. The shearing of joint set 1 induced by the injection reduced the normal stresses acting on set 2 sufficiently that fluid could penetrate and cause shearing in that set over a large area. This led to a step-like growth in an overall direction between those of joint set 1 and σ_H.

The growth shown in Figure 9 is quite different. Because of the still very high normal stresses acting on set 2 after shearing in set 1, shear growth in set 2 was inhibited. There was only a localised tendency for growth away from the direction of joint set 1, towards σ_H.

DISCUSSION

Pressure transient test results and analysis

The different responses to injections and shut-ins, as shown by the hydraulic parameters in Table 1, indicate the pressure dependent nature of the rock mass. The higher permeability and skin values seen during injections, with the apparent radial diffusion behaviour, suggests that the injections locally and temporarily overcome the influence of any planar structures, with joints opening up in all directions (sets 1 and 2). During the less energetic and prolonged shut-in and drawdown tests, joints not aligned near to the σ_H direction (set 2) close preferentially, resulting in a more planar type of diffusive behaviour.

The results of the November 1983 low flowrate tests show that the net effect of the main

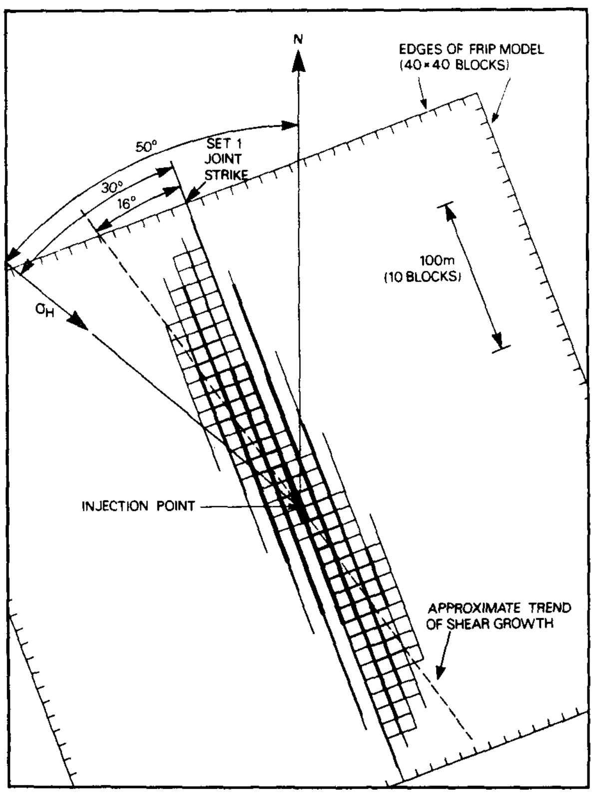

Figure 8: Plan view of hydraulically stimulated joint network from FRIP model; 2:1 horizontal stress ratio

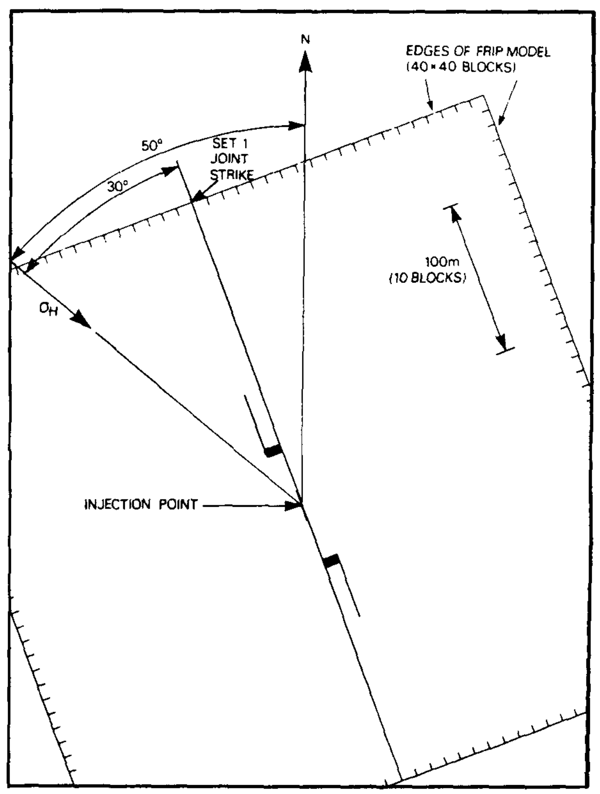

Figure 9: Plan view of hydraulically stimulated joint network from FRIP model; 5:1 horizontal stress ratio

injections was to create essentially planar permeable zones but with some uncertainty regarding dimensions and permeabilities. The higher permeability shorter fracture and lower permeability longer fracture options may be seen as compatible with the 2:1 and 5:1 stress FRIP models respectively. Further analysis of these recent results is in hand.

One difficulty with the pressure transient analysis was the selection of values for the formation compressibility β, needed for calculating s and x_f. When the joint system connected to the wellbore is actively dilating or compressing due to fluid pressure changes, the local formation compressibility, is lower than the overall value. The local compressibility depends on the joint porosity and the rate of joint dilation with fluid pressure changes.

Using dilation parameters for granite joints derived from Walsh (1981) and a local joint porosity of 0.1% to 1% results in compressibilities of about 5×10^{-11} to 2.5×10^{-10} Pa^{-1}. The overall compressibility for the Carnmenellis granite with a low joint porosity is about 2.5×10^{-11} Pa^{-1}. A constant value of 10^{-11} Pa^{-1} was selected for the pressure transient analyses.

Errors in the values of s due to errors in β will be small because of the logarithmic relationship. Errors in x_f are much greater, being approximately proportional to errors in β. The error magnitudes are probably less than 1 for s and less than 20 m for x_f for typical test results.

The shape and dimensions of the stimulated zone as defined by the microseismic locations show that only approximate values of near wellbore hydraulic conditions can be expected from pressure transient analysis. This is probably true for all HDR injection and recovery wells. It is evidently true for the CSM system where the major portion of the reservoir is below the open hole lengths of the boreholes.

Fracture half lengths of typically 50 to 100 m are inferred from the analyses conducted during the high and medium flowrate tests. Radius of investigation concepts for uniform radial flow conditions lead to similar dimensions for typical permeabilities and transient periods of up to about 100 hrs. These dimensions are much smaller than the overall reservoir dimensions.

The implicit assumption of uniform fracture conditions throughout the open hole length is also a simplification. Temperature and flowmeter logging have indicated discrete flowing zones, which have tended to polarise with increasing injection flowrates and pressures. Some of the fracture half lengths may be, therefore, significantly greater than calculated.

The results are, however, a useful measure of induced changes. They will be particularly relevant during the next phase of the project, when it is hoped to link a third, deeper well with RH12 via the existing stimulated zone. The planned separation of the wells is about 300-400 m.

Numerical modelling

The 5:1 effective stress ratio used in Figure 9 is closest to the measured stress conditions but the model with the 2:1 ratio shown in Figure 8 appears more compatible with the microseismic growth shown in Figure 7. Inspection of the joint directions shown in Figure 1 shows that set 2 is unlikely to be everywhere perpendicular to set 1. In this case joints in set 2 are likely to be oriented at considerably less than 60° to the σ_H direction (as in the model) and the types of shearing seen with the 2:1 stresses may well be possible with the 5:1 stresses.

The observed vertical growth of the reservoir by shearing during hydraulic injections cannot be demonstrated by the two dimensional FRIP formulation. A full three dimensional model would be necessary. However, this would raise further problems with computer CPU usage under current circumstances. Some efforts are being made to minimise the usage for the two dimensional model and there may then be some application to a three dimensional model.

The FRIP modelling has demonstrated some of the limitations of continuum modelling of pressure transients, whether of the conventional type with hydraulic parameters independent of fluid pressure or the more sophisticated finite element or finite difference formulations with pressure dependence. None of these approaches have to the author's knowledge satisfactorily addressed the interactions of rock joints and blocks, fluid pressure transients and in situ stresses.

Conceptual permeability model

The pressure transient analysis, microseismic location and FRIP modelling results indicate that a reasonable conceptual model for the permeability distribution associated with the injection well, RH12, would be as shown in Figure 10. There is an inner highly stimulated core, Zone A, with a permeability of up to 5 md and progressively lower permeabilities in the outer zones B (stimulated) and C (unstimulated). The figure shows a cross section. The lengths of zones A and B, approximately parallel to σ_H could be of the order of 100-200 m and 300-600 m respectively. It will be necessary to establish the main circulation of the system within zones A and B.

This model is applicable where the reservoir pressure is several MPa above hydrostatic. The sizes and permeabilities of these zones are probably smaller at reservoir pressures near hydrostatic.

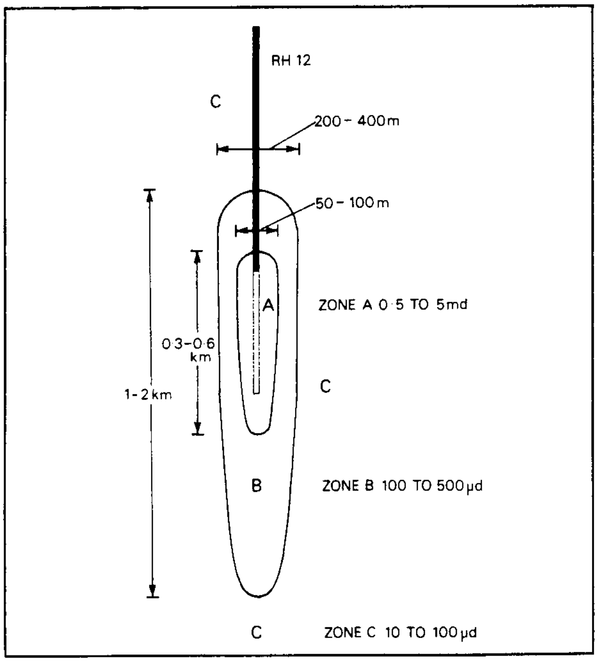

Figure 10: Conceptual model of permeability distribution in the hydraulically stimulated zone

CONCLUSIONS

The use of conventional diffusion theory for pressure transient analysis of the CSM HDR wells has provided a useful index of the changes caused to the rock mass near the wellbores by hydraulic injections. The penetration of the tests has been insufficient to determine hydraulic characteristics beyond about 100 m from the wells, and has more typically given information within about 50 m from the wells.

Reservoir growth as a result of the injections has been predominantly downwards and mostly beyond the range of influence of the pressure transient tests. The downward growth is believed to be due to a shearing mechanism in a significantly anisotropic in situ stress regime.

The effect of the high flow rate injections (up to 90 l/sec) was to increase the lumped permeability of the rock mass from less than 100 µd to greater than 5 md in the vicinity of the wells. Skin values were reduced to about -5 to -6.

The net effect after the reservoir pressure had returned to near hydrostatic was to increase the extent of more permeable fractures by a factor of about 30 compared with early values.

The use of the discrete joint-block model FRIP has given some useful insights into the interactions of rock mechanics and hydraulics in stressed jointed rock during hydraulic injections. Although the model is currently two dimensional and uses significant computer CPU time, it may be possible to develop a more efficient formulation with eventual three dimensional application.

It has been possible to use the results of the transient tests, microseismic locations and FRIP modelling to establish a conceptual permeability model for the reservoir zone adjacent to the injection well, RH12. The model will require further calibration from the results of circulation tests, tracers, well logging and thermal drawdown.

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