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RESULTS FROM A DISCRETE FRACTURE NETWORK MODEL OF A HOT DRY ROCK SYSTEM

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INTRODUCTION

The dream of clean, economic power derived from the huge volumes of naturally hot rock that lie beneath us (Parsons, 1904) is as yet unfulfilled. The technical difficulties in engineering heat-exchangers of sufficient area and volume at depth have not yet been solved (Garnish et al, 1992).

In the mid 1970s and early 1980s models of HDR systems assumed "penny-shaped" hydraulic fractures (for example MAGES 1979), which were assumed to have been created by hydraulic fracturing of a homogeneous, isotropic, impermeable, elastic crystalline host-rock. Even at this time some authors were drawing attention to the importance of natural fracture systems (Batchelor, 1976, 1977). Subsequent experience during all large scale field tests has shown that the interaction between the in-situ stress field and the natural fracture system is of supreme importance and new models such as FRIP (Pine and Cundall, 1985) were developed. These models were vital for the understanding of field experiments such as those performed at Rosemanowes (Parker, 1989). However, these models only considered a gross idealisation of the natural fracture system. The work described in the Summary of the Work section represents a move towards better representations of the natural fracture system.

The discrete fracture network model used during the study was the NAPSAC code (Grindrod et al, 1992). NAPSAC has been developed as part of the OECD/NEA Stripa Project.

OBJECTIVES

The goals of the work were to investigate the application of discrete fracture network models to Hot Dry Rock systems, increase the understanding of the basic thermal extraction process and more specifically the understanding of the Rosemanowes Phase 2B system. The aims of the work were:

a estimation of the area, extent and aperture of the hydraulically important natural fractures using pre-stimulation permeability measurements;

b estimation of the effective properties of porous media equivalents of the natural fracture system including directional permeabilities;

c examination of a model of reservoir creation due to aperture enhancement of natural fractures;

d application of the tools developed to the fracture system at Rosemanowes and comparison with field data from that site.

The aim in applying the work to the Rosemanowes site was to use the discrete fracture network approach to integrate a diverse set of field measurements into as simple a model as possible.

CONCEPTUAL MODELS

The limited nature of measurements of natural fracture system properties at depth forces the use of many simplifying assumptions. These assumptions were chosen to simplify the model while still being compatible with experimental observation.

Natural fracture system

The natural fracture system was idealised as a stochastic process with fracture properties such as orientation, size and hydraulic aperture described by probability distributions. Realisations are instances of the stochastic process. In NAPSAC the probability distributions are approximated by "random number" generators and a realisation is specified by the random number seed used to initialise the generator.

The models that have been used in the study assume that the basic fracture properties are independent of each other. Correlations may exist in nature, for example between fracture length and transmissivity, but they have not been included in the models because of the difficulty in deriving estimates of the strengths of such correlations. The probability distributions used to specify fracture orientation, transmissivity and size have been chosen to fit the limited observations available. This means that the models are compatible with observation but are not uniquely so.

It has also been necessary to limit the fractures that are included within the models. Discontinuities within the granite exist on many scales from micro-cracks to major faults extending tens of kilometres. The models have assumed that features not visible by borehole televiewer (BHTV) are hydraulically unimportant. Measurements from core or Formation MicroScanner (FMS) show many more features than the BHTV but experimental evidence suggests that these features are hydraulically unimportant. In fact only a small percentage of those features identified by the BHTV show any appreciable flow (see Summary of the Work section).

Flow within fractures and boreholes

It has been assumed throughout the study that flow in fractures can be approximated as laminar flow within a parallel plate. It has been suggested that flow is in fact "channelled". If this is the case at the pore pressures and stresses of interest, the thermal performance of the underground heat-exchanger may be markedly worse than that predicted here. In this way the models described here are optimistic. Similarly the assumption of laminar flow within the fracture system may underestimate the resistance to flow at the inflows and outflows to boreholes.

It has been assumed that flow through sufficiently large volumes of the fracture network can be treated as flow through an equivalent porous medium. In such a medium the mass flowrate $\underline{q}$ through an area A is related to the non-hydrostatic pressure P by Darcy's Law:

$$\underline{q} = -\frac{KA}{\mu}\nabla P \qquad \text{Eq 1}$$

where μ is the fluid viscosity and **K** is the effective permeability tensor of the equivalent porous medium. For a given network **K** is estimated by calculating the flow through several realisations of volumes of the network under unit pressure gradients. The network volumes used should be sufficiently large that **K** is independent of realisation. Values of **K** derived in this way can be used in porous medium models of fluid-flow to describe the large-scale behaviour of flow within the fracture network.

Fracture system stimulation

The use of homogeneous, isotropic, elastic models of the rock mass to describe the effects of Massive Hydraulic Fracturing (MHF) is well established in the oil industry. However, it is believed that they are of only limited utility in modelling the stimulations necessary to create a HDR reservoir in low-permeability pervasively fractured granite. Field observations suggest that flow is controlled by the natural fracture system even after stimulation. It is believed that although axial fractures may be created close to the borehole, fracturing fluid will be quickly diverted into the most transmissive and compliant natural fractures rather than creating new fractures. In this way the major effect of MHF programmes away from the vicinity of the borehole is in the dilation of existing natural fractures.

Fully coupled three-dimensional models of the mechanical interaction between the fluid, the fracture system and the rock mass are only now becoming available and demand substantial computing resources to model even small numbers of random fractures. The scale of the Rosemanowes system made such an approach impractical. Even if sufficient computing resources had been available it is not clear that there is sufficient knowledge of the dynamic properties of fractures and their load-paths to make such an approach viable. Instead it was assumed that all fractures within the stimulated volume had been exposed to similar pressure disturbance and that each fracture could be treated independently. This approach was taken using a range of fracture deformation parameters to calculate effective properties of stimulated networks. Having done this the observed hydraulic performance of the stimulated rock mass was used to identify a range of deformation parameters that were compatible with observation.

Tracer transport in the fracture system

Tracer transport has been modelled as the advective transport of non-reactive particles within the flow-field. It has been assumed that the porosity of a fracture is larger than the fracture volume calculated from fracture area and hydraulic aperture. In reality fracture surfaces are rough and resistance to flow is controlled by bottlenecks within the fracture, resulting in hydraulic apertures considerably smaller than the mechanical aperture of the fracture. Travel times in fractures have therefore been calculated using a delay factor based on a transport aperture to hydraulic aperture ratio.

SUMMARY OF THE WORK

The undisturbed fracture system

The Carnmenellis granite is one surface expression of the Cornubian batholith underlying the the South Western peninsula of England (Whittle and McCartney in Parker, 1989). It is relatively homogeneous in composition and character, with pervasive orthogonal jointing. At the Rosemanowes site three deep boreholes were drilled between 1980 and 1983 at depths between 2000 m and 2600 m. The wireline logging data available from Rosemanowes provided information on the orientation, spacing and percentage of hydraulically active fractures at depth.

The fracture orientations derived from borehole televiewer (BHTV) images from RH12 and RH15 showed two clear fracture sets. Set 1 comprises sub-vertical fractures dipping between 80° and 90° and striking approximately NW-SE. Set 2 fractures are again sub-vertical dipping between 70° and 90° but nominally strike NE-SW. Set 1 fractures are more numerous in all the deep boreholes.

An important parameter that cannot be measured from boreholes is fracture length. Early FRIP models assumed infinite, equally-spaced fractures although subsequent work has used discontinuous fractures. NAPSAC, however, needs estimates of the fracture length distribution. Microseismic source diameters derived from analysis of events generated during hydraulic tests at the Rosemanowes site were therefore used as a basis for fracture length studies. These estimates will be shown to correspond to fracture system geometries that are compatible with the results of hydraulic and tracer data from the site. An alternative would have been to look for suitable out-crop data (Gale et al, 1991).

Although it would have been possible to measure individual fracture transmissivities in the deep boreholes at Rosemanowes, it would have been impractical to perform complete surveys of each borehole. Such surveys were performed at the Carwynnen test site to depths of 700 m using lightweight equipment (Hodgkinson, 1984). This latter data was used as an initial estimate of the fracture transmissivity distribution at Rosemanowes despite the discrepancy in depth and hence normal stress. These fracture transmissivities were used to calculate equivalent hydraulic apertures using the 'cubic law'. At a later point the data was used only as a measure of the variation in hydraulic aperture, the mean aperture being adjusted so that network permeability matched the observed in situ permeability.

In view of the inevitable incompleteness of the data available to characterise the natural fracture system, a parametric approach was taken. The parameter used in the study was fracture length. Experimental uncertainties, together with observations from local mines suggested that the microseismic source diameters might be an overestimate of fracture length. Several different distributions of fracture length were studied; these included distributions estimated from trace-mapping in local mines and scaled versions of the microseismic source diameters. For each distribution the percolation frequency was calculated. This is the frequency at which the fracture network becomes connected over large distances. Below this frequency the network is made up of discrete unconnected clusters of fractures. There is no evidence for such a disconnected fracture system at Rosemanowes and it was assumed that the fracture system was above the threshold, thus limiting the range of fracture lengths that were considered.

Three distributions were used throughout the rest of the study. These were scaled versions of the log-normal fits to the microseismic source diameters. The three distributions had mean fracture lengths of 24 m, 16 m and 11 m respectively. The distribution with a mean length of 24 m was that derived directly from the microseismic data with no scaling reduction.

Equivalent permeability tensors were calculated for networks with the three different fracture length distributions by performing flow simulations on 200 m side cubes of fractured rock. Figure 1 shows a sample 200 m cube for each of the three length distributions.

The permeability was found to increase with fracture-length. All the permeability tensors were anisotropic with the greatest permeability in the vertical and NW-SE directions. Typically permeability in the NE-SW direction corresponding to the set 2 strike direction was a factor of four to seven times lower than the vertical permeability. The permeability tensors were more anisotropic for the smallest fracture length distribution.

Constant-head well tests were also simulated for models including a 200 m length of pressurised borehole for each of the length distributions. Only the 11 m fracture length distribution network had permeabilities close to those measured. However, since there were no measurements of hydraulic aperture at Rosemanowes and the data from Carwynnen had been used as an estimate of the hydraulic aperture distribution, it was not possible to exclude the higher fracture length models. Instead the aperture distribution was scaled by a factor chosen for each length distribution to match the field permeability of 5 x 10^{-17} m^2 (50 μDarcy). In this way a range of fracture aperture and length distributions was identified that were consistent with the well-test observations. The estimated mean hydraulic aperture and anisotropy (given as the ratio of maximum to minimum principal permeability) are given in Table 1.

Geological constraints on the fracture system

In order to assess whether the models of the fracture system were realistic it was essential to consider the geological context of the modern fracture system, and to assess what 'soft' geological information might contribute to the modelling effort.

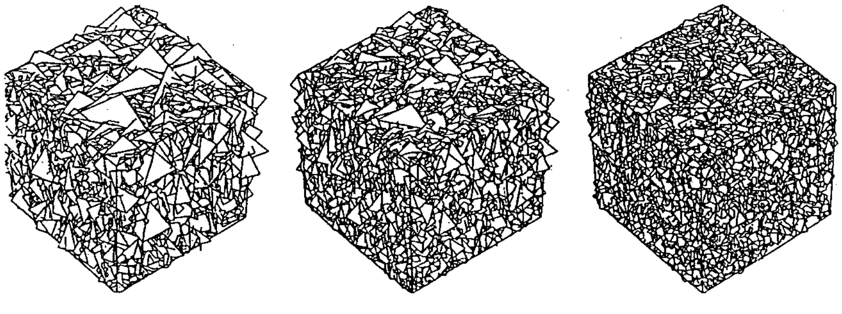

Figure 1 Realisations of 200m cubes of fracture system, for three distributions of fracture length with means of 24, 16 and 11m.

TABLE 1 CALCULATED AND EXPERIMENTAL PERMEABILITIES FOR UNDISTURBED FRACTURE SYSTEM AT ROSEMANOWES

Mean Fracture Length (m)	**Mean Fracture Aperture** (μm)	**Mean principal permeability values** (m^2)			**Ratio of max/min**	**Simulated well-test permeability** (m^2)
		Set 2	**Set 1**	**Vertical**		
24.4	22	$1.3\ 10^{-17}$	$2.8\ 10^{-17}$	$5.0\ 10^{-17}$	4	$1.1 - 6.6\ 10^{-17}$
16.4	27	$1.2\ 10^{-17}$	$2.6\ 10^{-17}$	$5.0\ 10^{-17}$	4	$0.7 - 4.6\ 10^{-17}$
11.0	59	$0.7\ 10^{-17}$	$1.7\ 10^{-17}$	$5.0\ 10^{-17}$	7	$0.9 - 7.0\ 10^{-17}$
Experiment		Falling head tests led to estimates of permeability in the range 1 to 5 10^{-17}				

The scope of this geological study was limited to a review of existing literature. The review indicated that the models described in the previous section were consistent with the overall pattern of fracturing in the Carnmenellis. The major sets identified in BHTV mapping related to "master joint" sets identified by Ghosh (1934). The relationship between fractures and larger scale flow-structures (eg the cross-courses) was also considered.

Data from the south west England Seismic Experiment (SWESE, Brooks et al, 1984) suggested that the fracture patterns observed at Rosemanowes and elsewhere in the Carnmenellis might extend to a depth of 6 km or more. The shallowest of the four major reflectors in the granite being estimated to be at approximately 8 km depth. It was also suggested that there might be some medium-scale (200-500 m) block structure within the granite. It was thought that this block structure might be related to the zones of relatively highly fractured rock found in the deep boreholes.

In general the study concluded that most of the assumptions made in the fracture network modelling were reasonable, but that larger scale structures (dykes etc) might be important factors at reservoir scales. This conclusion may prove to be of great significance in the exploitation of the HDR resource.

The stimulated fracture system

A massive stimulation programme was undertaken at Rosemanowes between 1982 and 1985, using a variety of fluids from water to highly viscous gels. The programme could be broadly divided into Phase 2A (attempting to link RH11 and RH12) and Phase 2B (linking RH12 and RH15). In almost all experiments, RH12 was used as the injection well.

It was assumed that away from the immediate vicinity of the wellbore, all permeability enhancement occurred by changes in the hydraulic aperture of existing fractures. Practically all inflows and outflows have been correlated with natural fractures visible on the BHTV (Pearson R A in Parker, 1989). Axial fracturing resulting from the stimulations did not appear to effect flowing locations. No BHTV logs are available for RH11 and RH12 prior to stimulation, so it is not possible to state definitively that only natural fractures flow in this case. However, this hypothesis has been confirmed for RH15.

The stimulation model used represents an upper bound on the performance of the stimulation rather than a prediction of the effects of the various massive hydraulic fracturing tests. The model considered two modes of aperture enhancement:Shear induced dilation and normal dilation. Shear induced dilation was assumed to be a permanent deformation resulting from failure of the fracture, while normal dilation was assumed to be a reversible elastic response to the pore pressure within the fracture. For each of the two modes, permeability tensors were calculated for a range of parameters using 200 m cubes of the largest (mean 24 m) and smallest (mean 11 m) fracture length distributions.

The model used for the in-situ stresses is that given by Pine and Kwakwa (1988) which had been derived from data including a suite of hydro-fracture stress measurements at depth in RH12 and RH15. At reservoir depths the maximum principal stress was horizontal and oriented at approximately 310° N. The intermediate stress was vertical. There was considerable anisotropy in the stress field, with total stresses at 2000 m vertical depth being estimated to be $\sigma_{Hmax} = 71$, $\sigma_V = 52$ and $\sigma_{Hmin} = 30$ MPa. The estimated stresses were used with a simple Mohr-Coulomb failure law for estimating shear failure and a bilinear compliance law for normal dilation.

Figures 2 and 3 show the variation in network permeability with shear induced dilation and fracture normal compliance for the 11 and 24m cases. For the range of values considered, shear induced dilation is the dominant mechanism. It is evident that the smaller fracture length case needs far greater dilations to achieve the same permeability. The very large dilations needed to attain permeabilities of order 10^{-15} m^2 imply that it would be impossible to create viable HDR systems in such networks and that the study of the Rosemanowes system can be limited to cases with either a larger fracture length or a major singular feature that carries the majority of the flow. It is impossible to discriminate between the different length distribution networks until the stimulation properties are considered, suggesting that borehole observations alone will not be able to assess the suitability of the natural fracture system for HDR development.

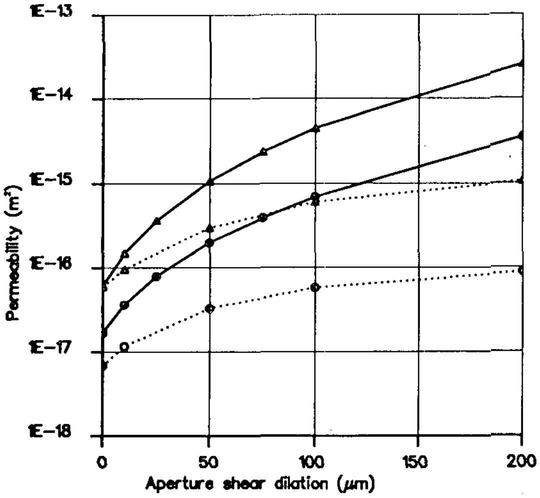

Figure 2 Change in maximum and minimum prinicipal permeability with shear induced dilation. Solid line shows 24m network, dotted line shows 11m network.

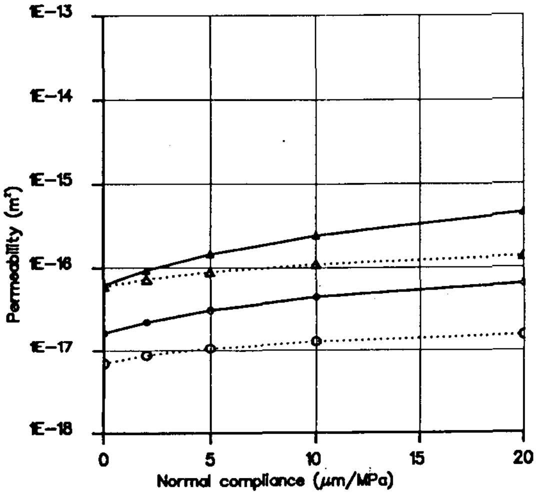

Figure 3 Change in maximum and minimum prinicipal permeability with normal compliance.

In the shearing mode only the set 1 fractures dilate. Similarly, in the normal mode the set 1 fractures are under lower normal stress and hence dilate more. The permeability tensors are therefore more anisotropic in the stimulated system than in the undisturbed fracture system. Typically, the NE-SW enhanced permeability is an order of magnitude lower than that in the vertical direction. The anisotropy in the enhanced permeability is in agreement with the overall shape of the microseismic cloud generated during stimulations. These events are believed to correspond to shear failures on the set 1 fractures.

Circulation performance

The permeability tensors calculated by NAPSAC for the largest fracture length network were used in porous medium models of the entire reservoir using the NAMMU computer code (Rae et al, 1982). Two models were developed: the first assumed a totally homogeneous reservoir bounded by undisturbed rock; the second included a high permeability vertical zone extending between the two wells. This vertical zone was located at the point where the RH12 and RH15 trajectories intersect in the plan view.

The effective permeabilities for the reservoir zones used in the NAMMU models were interpolated from the NAPSAC results and adjusted until the impedance and water loss matched that observed at Rosemanowes during the early low-flow (2-7 l/s) circulation. Table 2 shows the final values of the permeabilities for the two models. The reservoir permeabilities used within the models are between 100 and 1,000 times that of the undisturbed fracture system. Synthetic flow logs were calculated from the models. In both models flow occurs at too shallow a depth compared to the data from Rosemanowes. The logs for the high permeability zone model are ,however, a better match to the observed flow distribution.

The permeabilities derived from the porous medium models were then used to estimate the fracture dilations within the reservoir and to provide boundary conditions to a large NAPSAC model of the reservoir. Two NAPSAC simulations were performed for both the homogeneous and high permeability zone reservoir models. The NAPSAC results were in good agreement with the porous medium models. Preliminary estimates of tracer travel times and effective surface areas derived from the NAPSAC models matched experimental data.

Tracer and heat transport within the reservoir

An important advantage of models like NAPSAC is their direct representation of the fracture system geometry. This means that it is possible to make direct comparisons of predictions of tracer and heat transfer from NAPSAC with experimental data.

Tracer transport within NAPSAC is simulated by tracking large swarms of particles through the calculated flow field. In order to calculate travel times for such particles it is necessary to estimate the flowing porosity of the fractures. In natural fractures cored at approximately 350 m depth in the Stripa mine in Sweden, it was found that the tracer aperture was between two and seven times greater than the hydraulic aperture (Herbert and Lanyon, 1992). It is expected that this factor will be small for large open fractures and higher for more closed fractures. However, this factor is not known for Rosemanowes and was adjusted to get the best possible match to the observed tracer breakthrough.

TABLE 2 PERMEABILITIES AND FLOWS FROM POROUS MEDIA RESERVOIR MODELS

	Far-field (m^2)	**Reservoir** (m^2)	**Inner zone** (m^2)	**RH12 flow** (l/s)	**RH15 flow** (l/s)	**Recovery**
Observed				7.0	5.0	70%
Model 1	5.0 10^{-17}	6.0 10^{-15}	6.0 10^{-15}	7.1	5.0	72%
Model 2	5.0 10^{-17}	2.4 10^{-15}	3.4 10^{-14}	7.0	5.1	73%

It was necessary to implement a heat-transfer solution method within NAPSAC. It would be computationally intensive to solve the heat flow in the rock by discretisation of the blocks between the fractures. Instead, an approximate solution has been implemented based on that used by Cacas (Cacas and Bruel, 1990). Heat transfer is modelled using a one-dimensional finite difference scheme in a block of rock associated with each fracture. This scheme will work well where cooling is dominated by fluid flow in the fracture system rather than conduction within the rock. This method has been verified against analytical solutions for very simple geometries. Heat transport was not coupled to fluid or rock mass properties such as viscosity or thermal expansion/contraction.

As part of the testing of the tracer and heat transport facilities a parameter study was conducted to consider the performance of a single heat-exchanger module 150 x 150 m in plan and 250 m high. To simplify the calculations no wells were included and no account was made for the geothermal gradient. The rock within the model was assumed to be at a constant 80°C and fluid was injected at 20°C at the top surface with an overpressure of 5 MPa. It was also assumed that hydraulic aperture and tracer aperture were equal.

Six different configurations were considered for the fracture system within the block (see Table 3) and heat and tracer transport was modelled for each. The heat transport calculations were for a six-year circulation. The tracer simulations assumed a 1.4kg pulse injection of conservative tracer. A wide variety of thermal and tracer responses were predicted by the models. Only three realisations of each of the six configurations were analysed and so only a very approximate estimate of the variability within each configuration can be made. In all configurations the long-term thermal behaviour was dominated by variations in the mass flowrate.

The results from the study indicate that a well connected evenly stimulated volume is needed for good thermal performance. Part sealing of throughgoing high permeability features (zones or discrete features) provided some delay in thermal breakthrough but long-term performance was still compromised by the concentration of flow within the unsealed portion of the feature.

The thermal responses of the homogeneous heat-exchangers (models 1 and 2) were analysed in terms of the analytical model commonly used to estimate system lifetime (Armstead and Tester 1987). In all cases the effective heat-transfer area estimates represented only about 20% of the total area of hydraulically active fractures in the models. Since it has been estimated that only 10-15% of observed fractures will be hydraulically active, this suggests that only 2-3% of the observed fracture surface area can be used in analytic models of reservoir thermal performance.

In order to investigate the links between tracer and heat transport responses of a reservoir, cross-plots of thermal and tracer breakthrough volumes were produced. Figure 4 shows a plot of the produced volume at the time when production temperature drops by 1°C (T_1) against the volume produced when 5% of the tracer mass has been recovered (C_5) for all the models used in the study. There is a simple linear relationship between the breaktrhough volumes. The relationship would be complicated by the presence of a geothermal gradient. However, these results suggest that if fracture transport properties are known, the early time tracer response can be used to estimate system longevity.

The results of this study, combined with the results of the earlier NAPSAC models of the Phase 2B system, suggested that the Rosemanowes thermal and tracer responses could be modelled by considering only a very small volume of rock, little larger than those used in the study. The tracer and thermal curves for models 3 and 5 were similar in form to those from the Rosemanowes site.

TABLE 3 HEAT EXCHANGER STUDY CONFIGURATIONS

Model	**Mean Fracture Length**	**Shear Induced Dilation**	**High permeability feature**	**Flowrate** l/s
1	24m	100 μm	Absent	7.1 - 7.6
2	16m	110 μm	Absent	6.0 - 10.0
3	24m	80 μm	Vertical zone	7.0 - 7.6
4	24m	80 μm	Discrete vertical feature	4.9 - 8.7
5	Model 3 with zone extending to 50 m of base			6.0 - 7.1
6	Model 4 with feature extending to 50 m of base			5.9 - 6.0

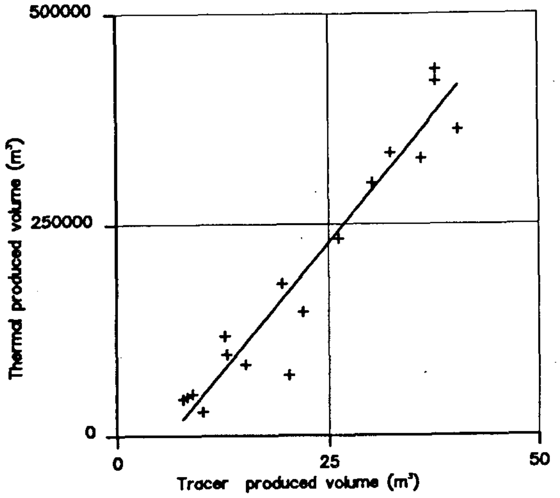

Figure 4 Thermal breakthrough volume versus tracer breakthrough volume.

The tracer responses were faster than those observed but this could be due to the discrepancy between tracer and hydraulic apertures and to increased dispersion due to the geometry ofthe injection and production wells.

Review of other data and models of the Phase 2B system suggested that the zone of high permeability extending from the bottom of RH12 does not link directly to RH15. This is similar to case 5 of the heat-exchanger study. Using the locations of microseismic data from the viscous stimulation of RH15 (test RT2B022) to delimit the zone, a NAPSAC model was created to test this hypothesis. Five realisations of approximately 7 l/s steady state flows were calculated. For all except one realisation a good match to the observed tracer was obtained by assuming a ratio of 1.5 between tracer and hydraulic apertures. This small value of the ratio is what might be expected for large planar high transmissivity fractures.

In order to compare the models with the experimental thermal drawdown from the Phase 2B system, thermal calculations were performed for one realisation at a mass flowrate equivalent to 14 l/s. The model and experimental tracer recoveries and drawdowns are shown in Figure 5.

Although a similar drawdown rate is observed, the model temperatures are approximately 10°C higher than the experiment. This can be partially explained by the approximations used to model thermal drawdown in the boreholes. This cannot, however, fully explain the discrepancy. Re-examination of temperature logs from the drilling of RH15 and the work-over of RH12 at the beginning of Phase 2B suggests that the zone below RH12 was already thermally depleted prior to the start of circulation. This was almost certainly due to the large volumes of fluid injected during Phase 2A.

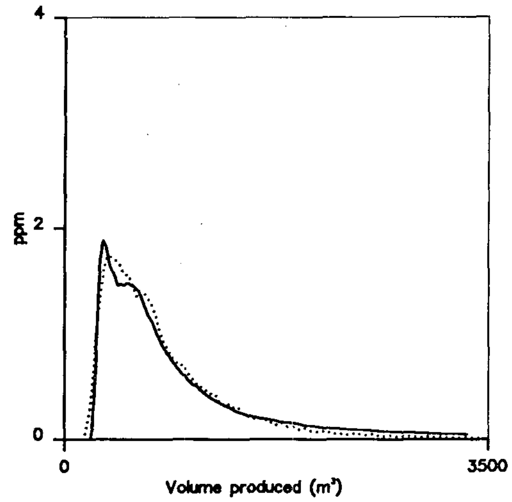

Figure 5a Comparison of experimental (solid line) and calculated tracer response.

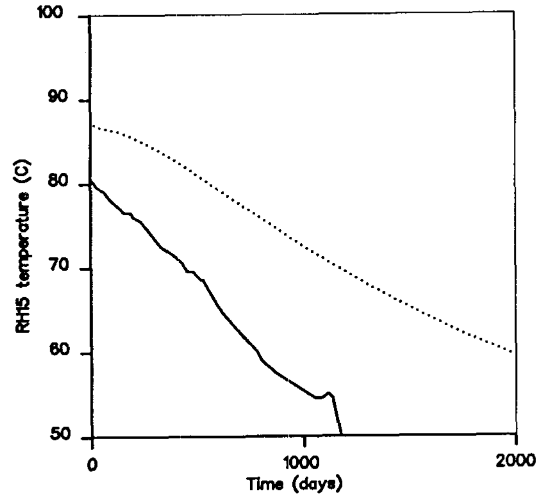

Figure 5b Comparison of experimental (solid line) and calculated thermal response.

Figure 6 shows a sequence of plots illustrating the growth of the thermally depleted zone away from RH12 towards RH15 as calculated by the model. Note that thermal breakthrough to RH15 occurs on a single flow entry, as was observed at Rosemanowes.

DISCUSSION

The work described in this paper represents a geologically realistic approach to the modelling of HDR reservoirs and reflects the progressive movement away from idealised penny-shaped fracture geometries towards systems dominated by natural fractures.

Various results from the model demonstrate possible causes of the difficulties encountered by the large scale field experiments, and are potentially highly significant for the development of HDR technology. These are summarised below.

a The hydraulic performance of the Phase 2B Rosemanowes reservoir was controlled by a very small volume of rock.

b The ability of engineers to create regions of enhanced permeability in a controlled manner away from the wellbores is limited by the geometry of the natural fracture system. In particular the stress regime at Rosemanowes leads to stimulated zones with highly anisotropic permeability.

c Large scale geological features in the undisturbed rock might be important at reservoir scales. The high permeability zone needed to fit tracer and heat-transfer results at Rosemanowes may be related to such a feature.

d Heat extraction calculations suggest that fracture systems similar to Rosemanowes may contain insufficient effective heat transfer area for current commercial designs.

e The models have shown that blocking off short circuits close to the production wells would be of limited benefit. In fact the models described here suggest that the Phase 2B system can be considered as a partially blocked short circuit.

The logical conclusion from these findings is that it is necessary to develop reservoir creation concepts which rely on less radical permeability enhancement. One approach would be to engineer reservoirs consisting of multiple cells, each of a similar size to the Rosemanowes reservoir (Green and Parker 1992). One risk attached to the development of such a large overall system would be that zones of differing levels of fracturing would be encountered, making stimulation difficult to control and potentially leading to a small number of very low impedance connections that might severely degrade overall thermal performance.

An alternative approach has been set out by Garnish et al (1992) and involves the study of naturally more permeable systems which require little or no stimulation, but which are able to support sufficient flow. Many naturally fractured geothermal systems are maintained over their lifetimes by reinjection, yet they exhibit little or no thermal drawdown, demonstrating that the flow is evenly distributed or that the systems are very large. Studies of the nature of these successful fractured reservoirs should be used to influence strategy for the creation of artificial (ie HDR) systems, and geologically realistic modelling has a crucial part to play in our understanding of such systems.

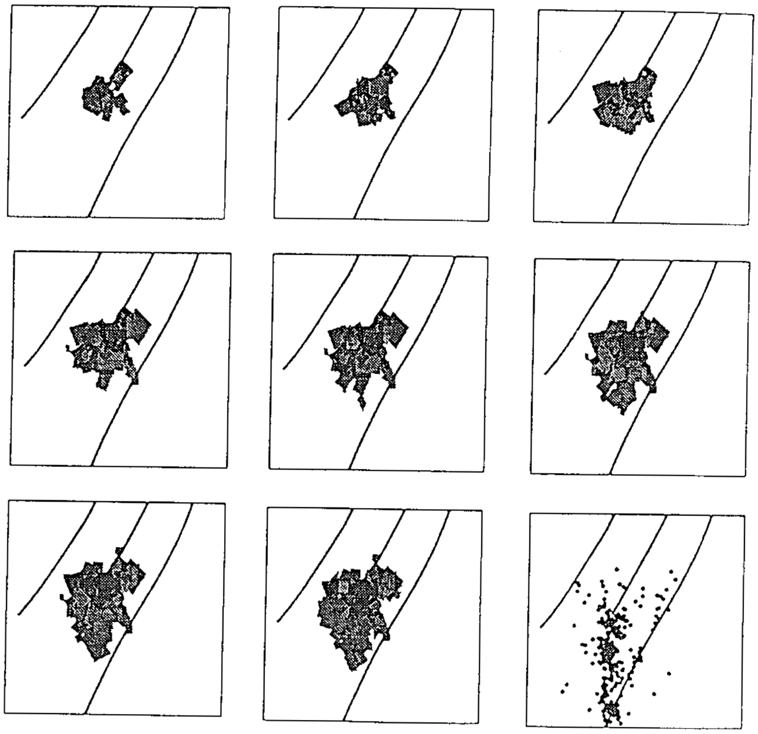

Figure 6 Growth of thermally depleted volume in model of Rosemanowes thermal drawdown. Views at half year intervals, with only fractures with surface drawdowns of 30°C or greater shown. Last view shows microseismic events from stimulation of RH15.

It is the distribution of effective heat-transfer surface area within the reservoir that determines the lifetime of HDR systems and in order to predict the performance of any design it is necessary to have models that adequately represent this. The network models that have been described in this report have resulted in a numerical model of the Rosemanowes system that integrates many of the field observations and has hydraulic, thermal and tracer properties that match the real system. Models of such systems need to be three-dimensional to incorporate the effects of stress and thermal gradients. Such models also need to be based on a geologically realistic fracture system, grid models will be dominated by the orientation of the grid system with regard to the regional stresses and will not be able to account for the large variation in fracture orientation and length found in nature. For these reasons it is important to apply the ideas and tools described in this report to other sites and other HDR concepts.

ACKNOWLEDGEMENTS

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