

## Problems in the development of artificial geothermal energy exploitation in Cornwall

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The granite batholith underlying south-west England offers the possibility of exploitation of a large resource of geothermal energy, provided that an economic method of accessing and transporting that energy to the surface can be developed. The heat flow over the Cornubian batholith is the highest in the United Kingdom, and the jointing system is amenable to the artificial enhancement of the permeability of the granite using high pressure hydraulic injections. The geological factors controlling the development of Hot Dry Rock geothermal energy technology in Cornwall are reviewed and an account is given of the progress made in the last ten years by the Camborne School of Mines Geothermal Energy Project (funded by the Department of Energy) at Rosemanowes Quarry in the Carnmenellis granite. There are serious problems remaining to be resolved before the technology of artificial heat extraction by injection of cold water into hot, deep granite can be demonstrated to be possible on a commercial basis. The most important of these problems is the present inability to design and carry out the stimulation of the natural jointing in the granite to produce a permeable geothermal reservoir from which heat can be extracted. Based on thirteen years of experience of research at Rosemanowes, it is suggested in this paper that a "multi-cell" method of reservoir creation is the best way of assisting the resolution of the major technical uncertainties of HDR technology. Also, the paper outlines a possible programme of research at Rosemanowes for testing this concept

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### Introduction

Like all experimentation in underground systems, the development of Hot Dry Rock (HDR) geothermal energy technology has been expensive and slow. Starting about 1974, work has been carried out in a number of programmes in the USA, the United Kingdom, France, Germany, Japan and Sweden. Only one organisation has remained exclusively working on the technology throughout this period. This is the Camborne School of Mines (CSM) Project, funded by the UK Department of Energy for work in Cornwall. The US team at Los Alamos National Laboratory has carried out very little underground experimental work since 1986 and is mainly working on other projects. The project at Soultz in Alsace, funded by the European community, and the French and German governments, is only at the exploratory stage, producing basic geological data for a feasibility study. The Swedish project is a small operation at shallow depths, and in Japan the various projects are at a comparatively early stage of development.

The work of the CSM project has concentrated on the engineering technology required to create a HDR "reservoir", which is a volume of rock at a suitable depth, whose permeability has been artificially increased in order that cold water, injected from the surface through the borehole (the "injection well"), can pass through the rock volume. During this passage through the reservoir, the water extracts heat from the rock, and the hot water then enters a second borehole (the "production well"), through which it is carried to the surface. The important reservoir performance parameters are impedance, water losses, and thermal drawdown. Impedance is the resistance of the reservoir to flow of water through it. This has a strong influence on the energy required to pump the water through the system. Some of the injected water is lost to the earth surrounding the reservoir, and is not recovered in the operation of the system. The reservoir rock is cooled down by the water at a much higher rate than heat energy is replaced within its volume by natural processes, such as conduction from hotter zones deeper in the earth's crust, or the decay of radioactive elements in the rock.

The "thermal drawdown" caused by this net loss of heat must not be too rapid, otherwise the economic pay back period will be too short. For example, the efficiency of electrical power generation drops off rapidly as the temperature of the production water falls. Drilling techniques and methods of energy conversion in surface plant are important components of HDR technology, but have not been the subject of investigation by the Camborne School of Mines.

The aim of the CSM programme has been to produce a technology which is as widely applicable as possible. Return from investment in HDR technology will not be high enough to pay for high

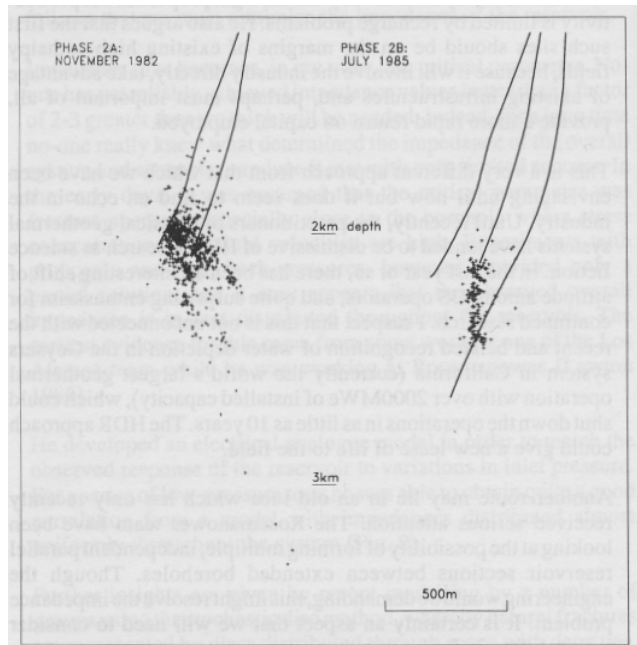


Figure 1. Microseismicity induced during reservoir stimulation.

exploration costs, so that HDR systems will have to adapt to the geological structures in which they are developed. If reservoir development requires specific localised permeable geological structures, high exploration costs will be incurred, and there will be a greater risk of sterile operations. There is also a need to avoid such structures if they could cause unsatisfactory reservoir development, such as preferential flow paths.

It was realised at an early stage in the CSM project that permeability enhancement to create a reservoir would depend on stimulating the natural jointing system, rather than creating new fractures in the granite. In a presentation to the Ussher Society, Batchelor (1979) reviewed the engineering properties of the granites of south-west England. The significant properties were perceived to be thermal and mechanical, joint distribution and permeability and the regional stress field. It is worth pointing out that in 1979 there was no knowledge of the jointing system at depths greater than about 700m, only three shallow stress measurements had been made in Cornwall and Devon, and very little thermal modelling of the batholith had been carried out. Batchelor pointed out that speculation on the regional patterns of jointing and its persistence with depth would be an interesting exercise, but that it was difficult to see how a rational scheme for HDR development could exploit features such as major joint systems and dykes.

Rock at temperatures of the order of 200°C must be accessed if the heat extracted is to be used for electrical power generation - and therefore HDR reservoirs must be created at depths of as much as 6km in this region. CSM experiments so far have been carried out at depths up to 2.6km, with the aim of understanding the technology required for reservoir development, and the geological parameters which control that development.

**The Geological Environment for HDR Development**

Much work has been carried out since Batchelor's paper in 1979, to understand the geological environment in which HDR systems for electrical power development must be installed in south-west England, and to understand the environment in which experimental work has been carried out by CSM at Rosemanowes Quarry since 1977. This quarry was chosen because it was on the exposed Carnmenellis granite, and was not close to a major geological feature at the surface. Richards *et al.* (1991) review these geological investigations, so that it is necessary only to list the findings of major importance to HDR (Parker 1990). It is to be noted that there are no measurements below 2.6km. Only drilling to 6km will give a true indication of the geology at full commercial depth.

The rock is granite, with textures changing from porphyritic nearer the surface to equigranular at about 2km. The base of the granite extends well below a depth of 9km. In situ mechanical properties are:

- Uni-axial compressive strength : 103MPa - 32MPa/km
- Young's modulus : 54GPa + 4GPa/km
- Poisson's ratio : 0.22 - 0.27
- Average Density : 2640kg/m<sup>3</sup>

Two main vertical joint sets (NE-SW, parallel to the trend of tin/copper lode mineralisation, and NW-SE, parallel to tension fractures and strike-slip faults known as "crosscourses") have been identified from surface mapping. These joint sets (although with a broad range of strikes) have been identified on BHTV logs to a depth of 2.6km, and microseismic data indicate the continuation of joints to at least 3.5km.

The relationship of stress distribution to depth has been measured at Rosemanowes in considerable detail to a depth of 2.5km, and these measurements have been complemented by measurements in local tin mines. The relationship for in situ stresses (in MPa) in the Carnmenellis granite with depth (z, in km) is:

$$\begin{aligned} \sigma_H &= 15 + 28z \\ \sigma_h &= 6 + 12z \\ \sigma_v &= 26z. \end{aligned}$$

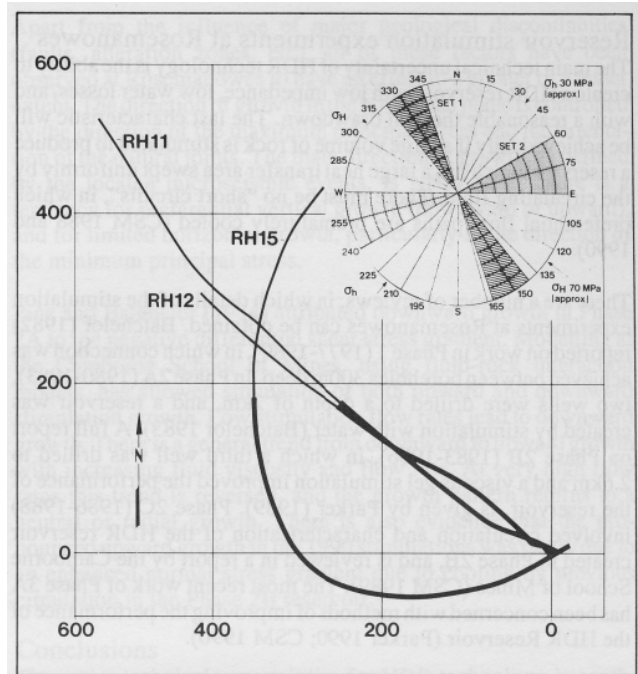


Figure 2. Plan view of well, joint and stress orientations at the Camborne School of Mines Geothermal Energy Project site.

Heat flow at the exposed granite surface is about 120mW/m<sup>2</sup>, which is approximately double the normal heat flow at sites away from the granite's influence. Three-dimensional heat flow models, based on extensive heat flow measurements and gravity surveys, indicate an almost linear dependence of temperature on depth in the upper 7km of crust over large portions of the Cornubian granite batholith. With an average surface temperature of 10°C, this results in a relationship for regions close to Rosemanowes:

$$T = 10 + 35z,$$

where T is the temperature in °C at a depth of z km. These temperature gradients in SW England are the highest in the United Kingdom.

In situ hydraulic properties have been measured at Rosemanowes at depths up to 2km, before major hydraulic injections commenced. Low flow rate hydraulic tests at low injection pressures indicated permeabilities between 1µD and 10µD at up to 0.7MPa fluid overpressure. Then permeabilities rose to 60µD during low pressure injections (3MPa), and microseismicity was first observed during a low flow rate injection (0.51/s), at a wellhead injection pressure of 3.1MPa.

Microseismicity is considered to be the result of shear on joints which are favourably oriented with respect to the anisotropic in situ stress field, when hydraulic stimulation of those joints raises the pore pressure due to fluid in the joint and reduces the joint shear strength to less than the shear stress. The location of microseismic events during hydraulic stimulation of the reservoir has been extensively used to interpret the results of HDR reservoir stimulations at Rosemanowes (Baria and Green 1990). If growth of the reservoir is by tensile failure, new fractures are created or existing joints are opened in the direction of the maximum principal stress by overcoming the minimum in situ stress. Growth of the reservoir by tensile failure requires much higher pore pressures than are required to cause shear failure in a highly anisotropic stress regime, such as that in south-west England. Seismic energy radiated from a tensile failure is very small compared with that from shear failure, so that it is very difficult to follow tensile failure growth of a HDR reservoir. The interaction of the in situ stresses and jointing determine the direction of reservoir growth and the pressures required to reduce growth.

### Reservoir stimulation experiments at Rosemanowes

The main technical uncertainty of HDR technology is the ability to create a HDR reservoir with low impedance, low water losses, and with a reasonable thermal drawdown. The last characteristic will be achieved only if a large volume of rock is stimulated to produce a reservoir which has a large heat transfer area swept uniformly by the circulating fluid. There must be no "short circuits", in which preferential flow paths are prematurely cooled (CSM 1988 and 1990).

There are a number of reviews, in which details of the stimulation experiments at Rosemanowes can be obtained. Batchelor (1982) reported on work in Phase 1(1977-1980), in which connection was achieved between boreholes 300m deep. In Phase 2A (1980-1983), two wells were drilled to a depth of 2km, and a reservoir was created by stimulation with water (Batchelor 1983). A full report on Phase 2B (1983-1986), in which a third well was drilled to 2.6km and a viscous gel stimulation improved the performance of the reservoir, is given by Parker (1989). Phase 2C (1986-1988) involved circulation and characterisation of the HDR reservoir created in Phase 2B, and is reviewed in a report by the Camborne School of Mines (CSM 1989). The most recent work of Phase 3A has been concerned with methods of improving the performance of the HDR Reservoir (Parker 1990; CSM 1990).

### Developments in the concept of design of HDR stimulation

Work at Rosemanowes since 1980 has attempted to create a HDR reservoir in granite at a depth of between 1.8 and 2.6km. The process of stimulation of the natural joints was carried out at Rosemanowes in 1982, with the aim of creating as large a reservoir volume as possible. 20,000m<sup>3</sup> of water were injected, but the result was a reservoir showing downward vertical growth, and having a high impedance and high water losses (Fig. 1). Analysis of the

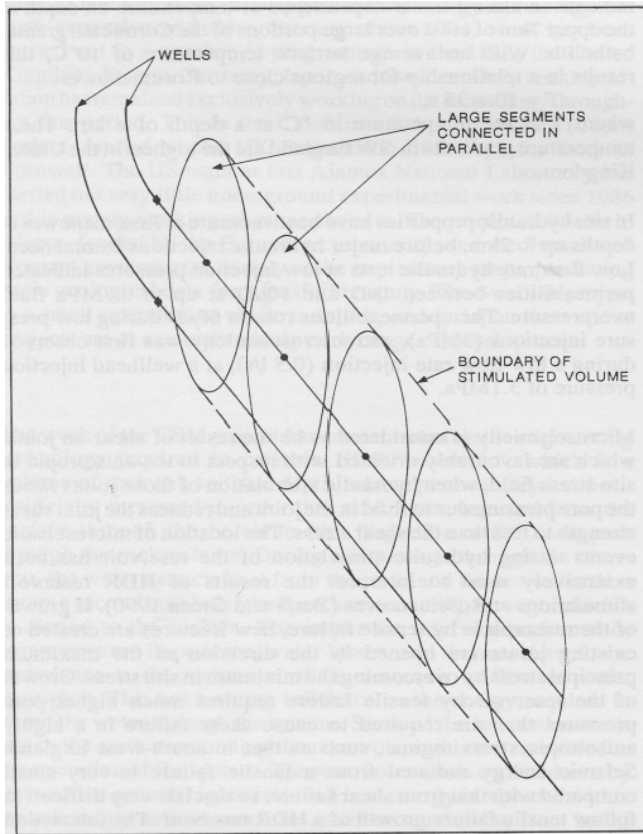


Figure 3. Five large stimulated HDR reservoir segments connected in parallel by two wells.

microseismic data obtained from this early stimulation led to a much better understanding of the process of reservoir stimulation. The two wells (RH11 and RH12) connecting the reservoir to the surface had been drilled at an angle inclined to the vertical, to increase the chance of the wells intersecting vertical joints. Unfortunately, the direction of inclination was to the NW. Studies by the project have shown that the natural jointing system and the earth stresses in the Cornish granite have a significant influence on the direction and characteristics of the stimulation of the reservoir. It is now known that the wells should have been drilled in the NE direction to improve significantly the chance of creation of a suitable reservoir, (Fig. 2). This would have the wells intersecting the major joint set (Set 1) and these joints oriented to the NW opening against the minimum horizontal stress, which is in the NE direction.

In 1984, a third deep well was drilled to a depth of 2.6km, but inclined to the NE as it passed below the two original 2km-deep wells (Fig. 2). In 1985, 5000m<sup>3</sup> of a viscous gel (viscosity 50cp) was injected at high pressure and high flow rate into this new well, to stimulate a region of rock between that well and the well immediately above it. This resulted in a better connection between the wells, with lower impedance and lower water losses than in the original system (Fig. 1). A long period of circulation of this reservoir began in 1985, and the results indicated that it was much smaller in volume and heat transfer area than that which would be needed to give acceptable thermal drawdown for a commercial reservoir. There was also a suggestion of preferential flow restricted to a small region within the Rosemanowes reservoir, this "short circuit" resulting in premature cooling down of that region. In 1987 it was suggested that the concept of using a larger volume of stimulating fluid to produce a larger reservoir volume in a single stimulation operation was wrong (CSM 1988). It would lead to high reservoir impedance, because the wells would have to be drilled to produce large enough interwell distances to allow access to the larger reservoir. It was perceived from cost modelling (Harrison *et al.* 1990) that hydraulic impedance would be an important cost factor. CSM therefore suggested that a commercial reservoir should be created by stimulating about five large segments connecting the injection and production wells in parallel along the lower portion of the two wells. This "parallel" connection of the wells would not lead to an increase in overall reservoir impedance when the overall volume of the reservoir was increased (Fig. 3).

Since 1987, the CSM project has continued its investigation of the performance of the Rosemanowes reservoir, and of methods of improving it. Stimulation experiments carried out in February and June 1990 have led to a further reassessment of the requirements for stimulation design. Low to medium viscosity gels (10-20cp viscosity) were injected in relatively small volumes (90-350m<sup>3</sup>) in the lower part of well RH15, with the aim of linking that part of the well to the microseismic volume stimulated in the 1985 (Phase 2B) stimulation. Fig. 4 shows that the microseismic events ran in a vertical plane from the point of injection, alongside those for the 1985 injection. Subsequent circulation of the reservoir indicated only a very poor connection between the two stimulated volumes. There seem to be two important characteristics of stimulation operations. The stimulating fluid tends to leave the well to enter the rock mass over a very restricted length of the wellbore (possibly through a single joint). Although the stimulation process spreads out from this point, growth of the reservoir is restricted largely to a vertical plane, and does not spread very much in the direction normal to that plane. The chance of large enough segments being created by a single stimulation spreading out from five positions along the wellbore (Fig. 3) is therefore perceived to be very small.

The Camborne School of Mines proposes that HDR reservoir creation could be achieved by carrying out larger numbers of relatively small stimulations, leading to a reservoir consisting of at least 20 cells connecting the two wells in parallel. This "multi-cell" concept of HDR reservoir creation needs testing.

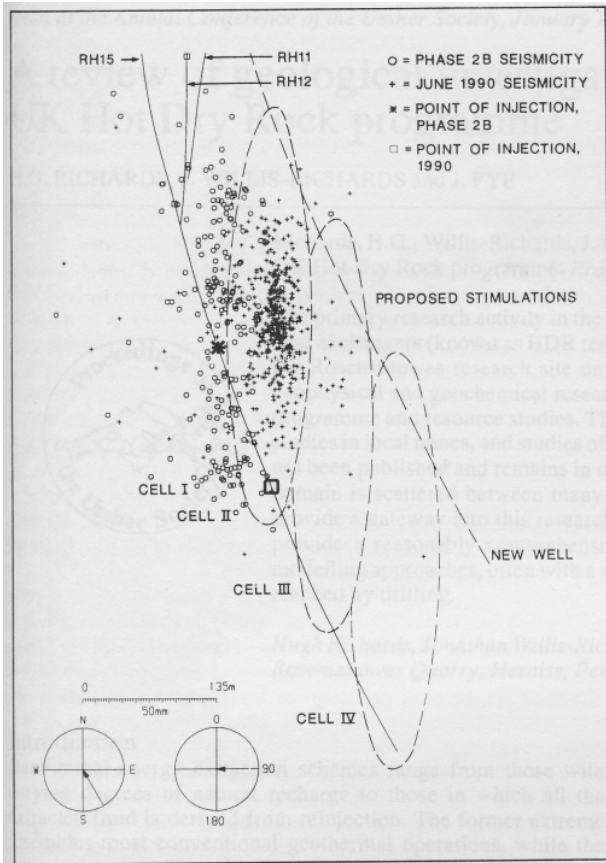


Figure 4. Vertical section showing proposed test multi-cell reservoir system at Rosemanowes in relation to microseismicity from previous stimulations.

CSM's proposal is to use the deepest of the present Rosemanowes wells (RH15) to produce two more "cells" alongside the cell produced in the June 1990 experiment (Fig. 4). No further capital expenditure (other than the cost of the fluids and the pumping) would be necessary initially to test the ability to produce these parallel cells, as the deepest of the Rosemanowes wells is drilled in the correct orientation to the joint system and to the in situ earth stresses. If the direction and extent of growth of the cells was shown by the CSM microseismic system to be satisfactory, it would then be necessary to examine the hydraulic and thermal performance of the multi-cell reservoir. The two original 2km wells (RH11 and RH12) were drilled in the wrong orientation, and therefore a new well would have to be drilled in a NE direction to connect with the cells. This would allow the hydraulic and thermal performance of this multi-cell reservoir to be measured by circulation accompanied by diagnostic tests (Fig. 4).

Because the proposed experiment would use an existing well in which one cell has already been created, it is unlikely that an opportunity will come again to test this multi-cell concept of reservoir stimulation at such relatively low cost and in a geological environment which is so well documented. The problems of well completion in very deep systems are likely to be compounded by the multiplicity of stimulations required, but the demonstration of the concept will make work on completion design worthwhile.

### Progress with the understanding of HDR reservoir stimulation

The following factors affecting the behaviour of the stimulations carried out at Rosemanowes have been considered:

- Variation in stress Orientation distribution of joints
- Injection flow rate and viscosity
- Variations in permeability
- Major geological features.

Apart from the influence of major geological discontinuities (faults, alteration zones, etc), all of these factors have been observed at Rosemanowes to have an effect to a greater or a lesser extent. The direction of growth in the horizontal plane is controlled by the direction of the maximum principal stress and the orientation of the natural joints. The main direction of growth, as defined by the located microseismic events, is NNW-SSE. There is a tendency for preferential vertical growth (downward or upward), and for limited horizontal growth, particularly in the direction of the minimum principal stress.

Pine and Batchelor (1984) attributed downward growth in Phase 2A to the negative differential shear stress gradient. Modelling at the Camborne School of Mines, using fluid-rock interaction models, has allowed simulation of both upward and downward stimulation growth. Low stimulation flow rates lead to downward growth. There is a general trend from downward to upward growth with increasing fluid viscosity and flow rate. At very high flow rates this trend is reversed, and the growth pattern returns to a neutral or radial growth. There is also evidence that the pronounced upward growth in the 1990 stimulations was partly due to an enhanced normal stress gradient due to cooling by previous circulation in the Phase 2B reservoir.

### Conclusions

The major technical uncertainties for HDR technology in south-west England, outlined by CSM in 1987 and 1989 (CSM 1988 and 1990), still remain to be overcome.

- i) The design of an HDR stimulation procedure is based on rock type, temperature, in situ stress distribution, jointing characteristics and in situ hydraulic properties of the rock mass in which the reservoir is to be created. After limited experimental experience, the ability to design and carry out a stimulation procedure to produce a suitable commercial-scale HDR reservoir has not yet been demonstrated, irrespective of the depth of reservoir required.
- ii) The stimulation design data on the rock type, temperature, in situ stress distribution, jointing characteristics and in situ hydraulic properties of the rock mass, at depths necessary in Cornwall to produce water at a temperature which will be required for commercial electricity generation, are not available.

Problem ii is a familiar one to geologists. Although the best efforts have been made to predict data at great depth, using experience at shallow depths, solution of this problem requires drilling to the appropriate depth, approximately 6km in Cornwall.

Problem i is a universal major uncertainty, irrespective of reservoir depth, which all HDR projects have yet to overcome if they are to be successful.

Although the CSM Project has been able to advance towards the possession of models which could aid in stimulation design, and give confidence in the results of that design, there is still a need for more comprehensive experimental experience. Overseas HDR projects have little to add to this experience, as they have carried out few large scale stimulations, and in those few cases, have had no opportunity to characterise the resultant reservoirs properly. Only the Rosemanowes reservoir has been circulated long enough for this purpose.

Whatever the site chosen, the concept of reservoir stimulation to be used in the construction of a HDR system will remain highly speculative unless further experimental work is carried out to establish the design guidelines more clearly. Whilst experimental work on the concept of "multi-cell" reservoir creation put forward in this paper will, in CSM's view, assist in addressing the technical uncertainties of HDR, it is unlikely that current cost estimates of HDR power plants could be reduced markedly as a result, even if the research proved successful. Recent studies (ETSU 1991a and 1991b) have concluded that the generation of electrical power via HDR technology is neither technically nor economically viable in the UK in the short or medium term.

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