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## A review of geological investigations associated with the UK Hot Dry Rock programme

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The primary research activity in the UK (Hot Dry Rock) programme has been the engineering of underground heat exchangers (known as HDR reservoirs) by experimentation in a series of boreholes (up to 2.6km deep) at the Rosemanowes research site on the Cammenellis granite in Cornwall. However, extensive geological, geophysical and geochemical research has also been undertaken in support of both the reservoir engineering programme and resource studies. These have included regional geological and geophysical studies, analogue studies in local mines, and studies of the boreholes at the Rosemanowes research site. Much of the research has not been published and remains in contractor and project reports; most of the rest that has reached the public domain is scattered between many conference proceedings and journals. The objective of this paper is to provide a gateway into this research, with emphasis on earth science studies in south-west England, and to provide a reasonably comprehensive bibliography. The studies include observational, experimental and modelling approaches, often with a view to predicting conditions at depths and temperatures in excess of those reached by drilling.

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### Introduction

Geothermal energy extraction schemes range from those with varying degrees of natural recharge to those in which all the extracted fluid is derived from reinjection. The former extreme resembles most conventional geothermal operations, while the latter is the goal of Hot Dry Rock (HDR) geothermal technology.

Detailed local exploration is required for the successful exploitation of conventional geothermal resources. This activity gives rise to a wealth of geological, geophysical and geochemical data, which has contributed much to the understanding of ancient hydrothermal and ore-forming systems. The long-term goal of HDR research is to develop the means to create economically viable geothermal energy extraction schemes in any mass of hot rock with low permeability. Economics (e.g. drilling costs and the value of the energy to be extracted) dictate which resources are viable at any given time. HDR exploration consists of determining the underground rock and temperature distributions on a regional, rather than local scale. The spin-off in terms of the geological sciences is qualitatively different from that arising from conventional geothermal exploration.

The aim of this paper is to provide the reader with an overview and bibliography of the geological aspects of HDR research undertaken in south-west England over the last 15 years. The largest component of the programme has been conducted at the Camborne School of Mines' (CSM) Rosemanowes research site on the Carnmenellis granite outcrop, funded mainly by the UK Department of Energy (DEn). This has been reviewed recently by Parker (1989a). A substantial body of supporting research has been carried out by the British Geological Survey (BGS) and UK universities. Much of the research is to be found in unpublished reports and notes of the project, published contractor reports and conference proceedings and would elude a conventional literature search.

Due to space limitations we cannot cover all aspects of the research within the text. The reference list contains all works cited, together with many others.

### Regional investigations

These aim to delineate the HDR resource (hot granite underlying the land mass of south-west England), to try to quantify and locate any geological hazards to drilling and to estimate the in situ

conditions at the depths of likely HDR reservoirs. Other studies derive from doctoral theses carried out in connection with the HDR Project.

Following the identification of south-west England as a region of high heat flow, a comprehensive programme of shallow heat flow measurement boreholes was started in the late 1970s (Francis 1980). This mapped the heat flow anomaly but included only crude thermal models. Finite-element heat transfer codes, using the 3dimensional gravity model of Tombs (1977) for the granite geometry were applied by Sams (1988), and published by Sams and Thomas-Betts (1988a). Free fluid convection was also included in the models published by Sams and Thomas-Betts (1988b). These models were complemented by a new gravity-based batholith model and finite-difference thermal conduction model (WillisRichards 1990), published in Willis-Richards *et al.* (1990) and CSM (2C-7).

A extensive programme of surface joint mapping (together with downhole televiewer results from the Rosemanowes holes) was reported in CSM (2A-59). Martin Mount, acting as contractor to the project, produced a series of reports on the geological aspects of siting a deep system prototype and on the geological hazards likely to be met with in drilling to 6km (CSM,2C-3). The drilling hazards report brings together historical observations on fractures in the Carnmenellis region into a single report and supplements them with modern field observations and photographs, many of them made underground.

Gravity and seismic investigations (CSM, 2C-7) show that granitic lithologies are likely to be found to near mid-crustal depths. Uncertainties in the in situ conditions hinge around stresses, jointing, and fluid pressures. Stress extrapolations have been made by Pine and Kwakwa (1988) and Willis-Richards (1989). The chief interest hinges on whether or not creep processes are likely to modify the deep stress field within any proposed HDR system. The depth distribution of natural microseismicity has a bearing on this matter (Walker 1987; Willis-Richards 1989).

The persistence of jointing to depth has been investigated by magnetotelluric surveys (Beamish 1990). This suggests that joint closure is complete by about 6km, and below this depth the resistivity profile is characterised by non-connected porosity rather than a linked network.

A synthesis and interpretation of the stress and magnetotelluric data may be found in CSM (TN03/70). This suggests that the brittle/ductile transition takes place over the depth range 6-8km and is marked by the R1 reflector of Brooks *et al.* (1984). The velocity reduction below R1 is attributed to a rapid increase in pore pressure separating hydrostatic fluid pressures above (high seismic velocities) from near lithostatic pressures below (low seismic velocities).

Willis-Richards (1990) has developed models of the evolution of the Cornubian orefield in relation to the high heat productivity and stress history of the granite batholith. The models account for the two-stage magmatic evolution of the batholith established by radiometric dating, and the associated high-temperature mineralisation events. Much of this work is published in Willis-Richards (1989), Willis-Richards and Jackson (1989) and Jackson *et al.* (1989).

### Natural analogue studies

The difficulty of observing rock mass geotechnical properties from boreholes means that studies conducted in local mines have been used as analogues for the rockmass at 2 - 2.5km depth below Rosemanowes. Most of these have been done in the deeper levels of South Crofty mine, which lie within the Cam Brea granite which is contiguous at depth with the Carnmenellis granite.

Joint mapping in the deep levels of South Crofty mine has permitted investigations of joint orientations, spacing and continuity, down to 790m (Randall *et al.* 1990; CSM, IR02/01). The deep mine workings have also been used to measure the rock stresses using the overcoring technique, complementing the hydrofracture method used in the 2km boreholes (Pine *et al.* 1983a,b).

The existence of hot, saline groundwaters in South Crofty and some other deep mines is well known, their chemistry has been studied in detail (Edmunds *et al.* 1984, 1985, 1987; Smedley *et al.* 1989) on the basis that they may have evolved from fresh meteoric water by the operation of reactions similar to those in the 2km HDR reservoir at Rosemanowes. Stable isotopic data have revealed more complexity in the compositions and possible origins of the saline waters (Kay *et al.* 1988; Smedley *et al.* 1989) than the earlier studies recognised. Underground observations by Bromley and Thomas (1988), summarised in Smedley *et al.* (1989), suggested the presence of intermediate salinity circulating water in crosscourse fractures, distinct from high salinity waters trapped in cavities along the lodes. The ultimate origin of these mineralised waters remains unresolved. An exogranitic origin has recently been proposed on the basis of chemical and stable isotopic similarities to fluid inclusions in the cross-courses that transect south-west England (Smedley *et al.* 1989). Another aspect of the work at South Crofty was to study ongoing alteration phenomena associated with the circulation of warm saline water (up to 45°C). These included iron oxy-hydroxide and calcium silicate gels (Thomas and Milodowski 1988).

In parallel with the studies of the saline minewaters, a detailed hydrogeological and hydrogeochemical study of the shallow groundwaters of the Carnmenellis granite and its country rocks has been undertaken, resulting in a hydrogeological and hydrogeochemical map of an area that includes St Agnes, Helston and Penryn (Smedley *et al.* 1989). Particular emphasis was placed upon the geochemistry of the trace alkali metals, Li, Rb and Cs (Smedley 1989).

### Rosemanowes site investigations

#### *Lithology and mineralogy*

In Phase 1 of the Rosemanowes research programme, four wells were drilled to 300m depth (Pearson 1980; Batchelor 1983). Cores were taken at the bottoms of two of the wells (RH7 and RH9). Visual core descriptions were given by Pearson (1980).

In Phase 2A, two 2km deep deviated wells were drilled (RH11 and RH12). Five core runs were made between 1.4 and 2.0km (true

depth) in RH11 and four at the bottom of RH12 (McCartney 1984). Also in Phase 2A, a sub-horizontal fully-cored hole was drilled across the strike of the mineralised joint swarm that forms the southern boundary of Rosemanowes quarry (McCartney 1984). In Phase 2B, a third deep well (RH15) was drilled to 2.6km depth. Seven cores were taken from between 2.1km and 2.6km true depth (CSM, 2B-20).

A general petrographic description of the deep core samples is found in the appendix to CSM (2A-58), which also contains bulk rock chemical analyses for major and trace elements. McCartney (1984) also gives generalised descriptions. Two textural types of granite were recognised, namely a rather fine-grained, equigranular type below about 1900m (true depth) and a porphyritic type above 1900m. There is little chemical difference between the two types. A detailed geochemical and mineralogical analysis of a sample from the porphyritic type is given by Savage *et al.* (1987). Details of the joint coating mineralogy are given by Thomas and Milodowski (1988).

Natural gamma ray spectroscopy logs were run in the 2km wells (CSM, 2B-35). These reveal little variation in K and U in the granite section, but show zonation in Th.

Chippings samples were collected during the drilling of the deep wells (CSM 2A-15 - 2A-26; Parker 1989b; McCartney 1984). Some of the chippings were intensely haematized, and in one instance consisted of partially oxidised sulphide mineralisation (Thomas 1988).

A summary of the lithology of the rockmass at 2 - 2.6km depth below Rosemanowes, based on cores, gamma logs and chippings samples, is given in Richards *et al.* (1991). Limited amounts of core and a large quantity of drill chippings from the deep wells are still available for research purposes.

#### *Structure and Stress*

The borehole acoustic televiewer (BHTV) logs provide data on the frequency and orientations of joint intersections with the wells, and are summarised in Randall *et al.* (1990).

In situ stresses were measured by the hydrofracture method in all three wells (CSM, 2A-13; Pine *et al.* 1983b; Pine and Kwakwa 1988). Measurements using other methods have also been made (Batchelor and Pine 1986; Green *et al.* 1990).

#### *Initial permeabilities*

The concept of permeability is not readily applicable to jointed rockmasses in which the fracture spacing is of similar order to the scale of the investigation, or in which the fracture properties change in response to applied fluid pressure. The values of undisturbed rockmass permeability obtained from open hole hydraulic tests (CSM, 2A-52; Pine and Ledingham 1983; Pine 1986) must therefore be treated with caution. Packer testing of the hydraulic properties of individual joints was not done in the 2km wells at Rosemanowes, although Randall *et al.* (1990) give some estimates of joint apertures based on joint reopening during attempted hydrofracture stress measurements.

### Use of earth science methods in HDR reservoir characterisation

#### *Microseismic monitoring*

Baria and Green (1990) review the technique of microseismic monitoring. Fluid injection at the Rosemanowes site since 1982 has given rise to one of the largest and most intensively investigated microseismic data sets anywhere. The downward migration of microseismic activity during water injections in 1982 and 1983 is widely known (e.g. Pine and Batchelor 1984). The subvertical structures seen were partly due to location errors. Revisions using a better algorithm and previously unused timings (CSM, 3A-10) now show dense clumps of microseismicity. However, the general pattern of downward migration of the activity remains. The clumps of activity may be due to the existence of

domains in which the dominant joint orientation is such as to allow shear with only a slight increase in pore fluid pressure (CSM, 3A-10). The existence of domains of different joint orientations is supported by joint mapping in quarries (CSM, 2A-59).

Microseismic monitoring has continued throughout the programme of reservoir stimulation and circulation from 1985 to the present. There have not been serious problems with event location errors for this period. The largest observed event occurred at 3.5km depth in July 1987 with ML 2.0 (CSM, 2C-5). Microseismic mechanisms at Rosemanowes have been studied by Jupe (1990) and CSM (TN03/54).

#### Active Seismic Methods

Vertical seismic profiling has been used regularly at Rosemanowes, utilising tube waves (borehole guided waves) to detect the intersections of permeable joints with the wells (Stewart and Jones 1990). Cross-hole seismic surveys have shown that the seismic velocity of parts of the rockmass between the injection and production wells has decreased substantially during circulation. This has been attributed to cooling of the rock (Stewart and Jones 1990).

#### Geochemical Methods

The release of radon ( $^{222}\text{Rn}$ ) from joint surfaces to the circulating water has been used to infer mean joint apertures and total joint surface areas (Andrews *et al.* 1986, 1988, 1989). The method relies on laboratory measurements of the flux of  $^{222}\text{Rn}$  atoms from granite which have now been made using both cut surfaces and natural joint surfaces (Andrews *et al.* 1989). Andrews *et al.* (1988, 1989) have shown that the  $^{226}\text{Ra}$  parent of  $^{222}\text{Rn}$  is taken up from solution on joint surfaces, but not to such an extent as to increase the flux of  $^{222}\text{Rn}$  significantly. The estimation of surface areas depends upon the estimation of the fluid volume of the reservoir from tracer data. Such estimates however, ignore the possibility of tracer retardation by diffusive interchange with stagnant water in the reservoir (CSM, IR05/03). The mean joint apertures obtained from radon data were of the order of 0.5mm.

The release of helium from the HDR reservoir has also been studied in some detail (Hilton *et al.* 1985; Andrews *et al.* 1988, 1989; Andrews and Hussain 1989), ultimately with a view to constraining the surface area. The caveat expressed above with respect to the tracer interpretation also applies to helium. It should be noted that the  $^{222}\text{Rn}$  data given by Hilton *et al.* (1985) were seriously miscalibrated, being a factor of 2.2 too high (CSM, IR05/03).

Much work has been done to determine the chemical reactivity of the granite, with a view to assessing the effect of water-rock interactions on the hydraulic characteristics of the HDR reservoir. This work has included laboratory experiments (Savage *et al.* 1987, 1989, 1991; McCartney 1984) and studies of the geochemistry of the HDR circulation waters (McCartney 1984, 1986; CSM, 2B-30; Richards *et al.* 1989a, 1991). Earlier interpretations of the HDR geochemistry were largely in terms of mineral dissolution and precipitation reactions. Latterly, the roles of ion exchange reactions and bacterial activity have been recognised as being important (Richards *et al.* 1991). Some work has also been directed towards predicting the effects of chemical reactions on the performance of a full scale HDR system in south-west England (Savage *et al.* 1987, 1989; Milodowski *et al.* 1989; Richards *et al.* 1989b; CSM, 3A-10).

#### Other Methods of Reservoir Characterisation

These include downhole temperature and flowmeter (spinner) logs, inert tracer tests, hydraulic transient well tests and constant flow rate injection/production tests (e.g. Parker 1989a; Nicol and Robinson 1990; Kwakwa 1988; Richards *et al.* 1990).

## Conclusion

A wealth of scientific data exists for the Carnmenellis granite gathered in pursuance of HDR geothermal studies. This paper has presented a brief overview and bibliography from which it is hoped future researchers will benefit.

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To simplify referencing of CSM Geothermal Energy Project reports, these have been cited in the text as "CSM", followed by a report number (e.g. 2B-43). The report numbers refer to the phase of the Project's funding in which the work reported was done: Phase 1: 1977 - 1980; Phase 2A: 1980 - 1983; Phase 2B: 1983 - 1986; Phase 2C: 1986 - 1988; Phase 3A: 1988 - 1991.

Some of the CSM reports have been published by ETSU, as indicated below. They appear in the series "Camborne Geothermal Energy Project" and may have slightly different titles from the CSM reports of which they are copies. They are available from ETSU or through the British Library Document Supply Centre. Other CSM reports are not currently in the public domain. This also applies to "Bi-monthly reports" issued in Phase 2A, and Internal Technical Notes and Reports (prefixed TN and IR, respectively), issued in Phases 2C and 3A. Their citation here does not imply that copies can be released at present.

In 1989, a final report on Phase 2B of the CSM programme was prepared for the Commission of the European Communities (Parker 1989b). This brought together a number of CSM reports, but without their appendices. Where a report cited below is also a chapter of Parker (1989b), this is indicated.

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