Read at the Annual Conference of the Ussher Society, January 1991

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

H.G. RICHARDS, J. WILLIS-RICHARDS and J. PYE

Richards, H.G., Willis-Richards, J. and Pye, J. 1991. A review of geological investigations associated with the UK Hot Dry Rock programme. *Proceedings of the Ussher Society,* 7, 321-326.

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 Carnmenellis 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.

Hugh Richards, Jonathan Willis-Richards and Jo Pye, Camborne School of Mines Geothermal Energy Project, Rosemanowes Quarry, Herniss, Penryn, Cornwall TR10 9DU.

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 anew 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 haematised, 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 (222Rn) 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}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}Ra parent of ^{222}Rn is taken up from solution on joint surfaces, but not to such an extent as to increase the flux of ^{222}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}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 a1.*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 persuance of HDR geothermal studies. This paper has presented a brief overview and bibliography from which it is hoped future researchers will benefit.

Acknowledgements. The work reviewed in this paper was carried out under contract as part of the DEn Renewable Energy Research and Development programme, managed by the Energy Technology Support Unit (ETSU). The views and judgments expressed in the paper are those of the authors and do not necessarily reflect those of ETSU or DEn.

References

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.

Althaus, E. and Edmunds, W.M. 1987. Geochemical research in relation to hot dry rock geothermal systems. *Geothermics, 16,* 451-458.

Andrews, J.N., Hussain, N., Kwakwa, K.A. and Batchelor, A.S. 1986 ^{222}Rn solution by the circulating fluids an a "hot dry rock" geothermal reservoir. *Applied Geochemistry, 1,* 647-657.

Andrews, J.N. and Hussain, N. 1988. Radon and helium solution in an HDR geothermal reservoir. *In:* Louwrier, K. and Garnish J.K., (eds) /1988/.

Andrews, J.N., Hussain, N., Ford, D., Smith, B. and Youngman, M.J. 1988. Geochemistry of radioelements and noble gases in the HDR reservoir. *In:* Edmunds, W.M. *et al.* (1988), 92-104.

Andrews, J.N., Hussain, N., Ford, D.J. and Youngman, M.J. 1989. The use of natural radioelement and radiogenic noble gas dissolution for modelling the surface area and fracture width of a Hot Dry Rock reservoir. Geochemistry in relation to Hot Dry Rock geothermal development in Cornwall, Vol.3. *Research report SD/89/2, BGS.*

Andrews, J.N. and Hussain, N. 1989. Radon and helium modelling of an HDR geothermal reservoir. *In:* Miles, D.L. (ed.) 1990,19-22.

Armstead, H.C. and Tester, J.W. 1987. *Heat Mining - A new source of energy.* E.F.&.N. Spon, London.

Aschenbrenner, F. 1988. Geochemical modelling of water-rock interactions in a Hot Dry Rock system in the Cornubian batholith, SW England, with EQ3NR/6. *Unpublished MSc dissertation, School of Earth Sciences, University of Birmingham.*

Baria, R. (ed.) 1990. *Proceedings, Camborne School of Mines International Hot Dry Rock, Conference, 27-30 June 1989.* Robertson Scientific Publications, London. ISBN 1-85365-217-2.

Baria, R., Green, A.S.P. and Jones, R.H. 1989. Anomalous seismic events observed at the CSM HDR project. *International Journal of Rock Mechanics Mining Sciences & Geomechanics Abstracts 26,* 257-269.

Baria, R. and Green, A.S.P. 1990. Microseismics: a key to understanding reservoir growth. *In:* Baria, R. (ed.) 1990, 363-377.

Barrow, G.I. 1974. Terrestrial heat flow in South West England. *Unpublished Report, Royal School of Mines, London.*

Batchelor, A.S. 1977. The size of the geothermal resource in the Carnmenellis pluton. *Camborne School of Mines Journal, 77,* 68-69.

Batchelor, A.S. 1979. The engineering properties of the south-western granites related to artificial geothermal exploitation. *Proceedings of the Ussher Society, 4,* 355-361.

Batchelor, A.S. 1979. The granites of South West England and their engineering properties related to possible hot dry rock geothermal exploitation. *In:* Nordic symposium on geothermal energy, Gothenburg, May 1979.

Batchelor, A.S. 1982. The creation of Hot Dry Rock systems by combined explosive and hydraulic fracturing. *In:* International conference on geothermal energy, Florence, May 11-14,1982. BHRA Fluid Engineering, Bedford, England, 321-342.

Batchelor, A.S. 1983. Hot Dry Rock reservoir stimulation in the UK: an extended summary. *In:* European Geothermal Update: 3rd International

Seminar on EC geothermal energy research, Munich, Nov. 1983, European patent office, Munich (EUR 8853£N), 693-758.
Batchelor, A.S. 1985. Progress in Hot Dry Rock exploitation. *International Journal of Energy Research, 9,* 377-390.
Batchelor, A.S. 1986 Reservoir behaviour in a stimulated hot dry rock system. *In:* Proceedings, 11th annual workshop on geothermal reservoir engineering, Stanford University, California, January 1986.
Batchelor, A.S. and Pine, R.J. 1986. The results of in situ stress determination by seven methods to depths of 2500m in the Carnmenellis granite. *In:* International Society for Rock Mechanics international symposium on rock stress and rock stress measurement, Stockholm, Sweden, 1-3 September 1986.
Beamish, D. 1990. A deep geoelectric survey of the Carnmenellis granite. *Geophysical Journal International, 102,* 679-693.
Beamish, D. and Riddick, J.C. 1989. An audiomagnetotelluric survey of the Carnmenellis granite. *BGS Scientific report SM/89/15.*
Bergin N.K. and Tovey n.P. 1980. A survey of joint orientations in the Rosemanowes area of the Carnmenellis granite. *CSM Geothermal Energy Project, unpublished report (CSM student summer project).*
Black J.H. 1979. Results of a multiple borehole pumping test in low permeability granite. Proceedings of Workshop on low flow, low permeability measurements in largely impermeable rocks, OECD/IAEA Paris 1979.
Bromley, A.V. 1988. The geological setting of the Carnmenellis granite. *In:* Edmunds, W.M. *et al.* 1988, 3-27.
Bromley, A.V. and Thomas, L.J. 1988. Structural controls on the circulation of thermal brines at South Crofty Mine, Cornwall. *In:* Louwrier, K. and Garnish, J.K. , (eds.) 1988.
Brooks, M., Doody, J.J. and Al-Rawi, F.R.J. 1984. Major crustal reflectors beneath SW England. *Journal of the Geological Society of London, 141,* 97-103.
Burgess, W.G., Edmunds, W.M., Andrews, J.N., Kay, R.L.F. and Lee, D.J. 1982. The origin and circulation of groundwater in the Carnmenellis granite: the hydrogeochemical evidence. *Report of the lnstitute of Geological Sciences.*
Burley, A.J., Edmunds, W.M. and Gale, I.N.1984. *Catalogue of geothermal data for the land area of the United Kingdom, Second Revision: April 1984.* BBS.
CSM Report 2A-13. 1981. Hydrofracture stress measurement tests in hole RH12. (Also published as ETSU G 115P1).
CSM Reports 2A-15 - 2A-26 1982. Well drilling and casing, Vols. 1-12. CSM Report 2A-27. 1982. Overcoring stress measurement at South Crofty Mine.
CSM Report 2A-28. 1982. Seismic hazard assessment.
CSM Report 2A-46. 1984. Mechanical properties of the Carnmenellis granite.
CSM Report 2A-47. 1984. In situ stress summary.
CSM Report 2A-52.1984. Low flow rate hydraulic tests (RT2019 - RT2041) 110p.
CSM Report 2A-58. 1986 Lithology, mineralogy and structure. (Also published without Appendices in Parker, 1989b).
CSM Report 2A-59. 1986 Jointing in the Carnmenellis granite. (Also published in Parker 1989b).
CSM Report 2B-20. 1985. RH15 core logs.
CSM Report 2B-23. 1986 Hydrofracture stress measurement in well RH15. (Also published as ETSU G 125 P23).
CSM Report 2B-25. 1986. Heat flow and temperature prediction in the vicinity of the Carnmenellis pluton. Contractor report by M. Sams and A. Thomas-Betts. Geophysics Section. Imperial College. (Also published as ETSU G 137 P3).
CSM Report 2B-27. 1986. The use of differential strain curve analysis in predicting the in situ stress conditions for deep boreholes.
CSM Report 2B-30.1986. Geochemistry results, 1984-1986. (Also published as ETSU G 137 P4 and in Parker 1989b).
CSM Report 2B-34.1986. Viscous stimulation of well RH15. (Also published as ETSU G 137 P13 and in Parker 1989b).
CSM Report 2B-35. 1987. Proprietary logging results. (Also published in Parker 1989b).
CSM Report 2B-38. 1987. Seismic velocity structure, 1984-1986.
CSM Report 2B-39. 1987. Seismic reflection survey field report.
CSM Report 2B-43. 1987. Seismic hazard assessment. (Also published in Parker 1989b).
CSM Report 2C-2. 1987. Current status of HDR technology with reference to further development in South West England. (Also published as ETSU G 137 P11).
CSM Report 2C-3. 1987. Three studies by contractors on: Infrastructure, geology, environment. (See Mount 1987).
CSM Report 2C-5. 1988. Phase 2C Final report, October 1986-September 1988. (Also published as ETSU G 137 F).
CSM Report 2C-7. 1988. Resource evaluation (3 volumes: A Overview, B Seismic reflection survey, C Gravity and heat flow modelling). (Also published as ETSU G 137 P14A,B,C).
CSM Report 3A-10. 1990. Characterisation of the Rosemanowes HDR reservoir.
CSM Report 3A-14. 1990. Progress in Hot Dry Rock technology for application in South West England (1987-1989). (Also published as ETSU G 151 P1).
CSM Bi-monthly Report 2, 1981. Strain rate dependence of the tensile strength of granite.
CSM Bi-monthly Report 8,1982. Initial geological interpretation of the core from RI-112.
CSM Bi-monthly Report 10, 1982. Interpretation of the temperature logs on boreholes RH11 and RH12.
CSM Bi-monthly Report 16, 1984. Evaluation of jointing from dipmeter logs.
CSM Internal Report IR02/01. 1989. Joint mapping at South Crofty Tin Mine, Cornwall.
CSM Internal Report IR05/01. 1988. Study of microencapsulation of tracers and the flow of particulate material in the Rosemanowes system.
CSM Internal Report IR05/03.1990. The use of radon for characterisation of the Rosemanowes HDR Reservoir: An overview and critique.
CSM Internal Technical Note TN02/62. 1990. Estimate of thermal stresses in HDR reservoirs.
CSM Internal Technical Note TN02/64.1990. A discussion of the mechanical/ hydromechanical conditions that result in the shear failure of joints within the CSM HDR reservoir.
CSM Internal Technical Note TN03/15.1987. Combined gravity and seismic analysis of seismic lines HDR86/001 and HDR86/002 across the Cammenellis granite.
CSM Internal Technical Note TN03/22. 1988. Uncertainty in temperature extrapolation to 6km depth.
CSM Internal Technical Note TN03/27. 199. A note on the development of tensile jointing at great depth.
CSM Internal Technical Note TN03/31. 1988. Cooling forces and the formation of joints in the Cornubian granite batholith.
CSM Internal Technical Note TN03/32. 1988. Fault plane solutions for the aftershocks of three large Phase 2C microseismic events.
CSM Internal Technical Note TN03/39. 1989. High resolution, broad band, magnetotelluric survey across the Carnmenellis granite, Cornwall.
CSM Internal Technical Note TN03/50. 1989. Uncertainty in temperature extrapolation to 6km depth: Supplementary information.
CSM Internal Technical Note TN03/54. 1989. Reservoir structure: Which joints are seismically stimulated?
CSM Internal Technical Note TN03/66.1989. A summary of magnetotelluric investigations of the Carnmenellis granite.
CSM International Technical Note TN03/68. 1990. Jointing orientation measurements from local quarries. (See also: Bergin and Tovey 1980).
CSM Internal Technical Note TN03/69. 1990. Relocation of Phase 2A microseismicity.
CSM Internal Technical Note TN03/70.1990. Magnetotelluric investigations of the Carnmenellis granite.
CSM Internal Technical Note TN03/71. 1990. Unusual microseismic events during RT3A018.
CSM Internal Technical Note TN03/81. 1990. Estimating water storage in the microseismic cloud: A second note.
CSM Internal Technical Note TN05/21. 1989. Observations of particulate material in circulation fluids during the massive oscillations (25 September 1988).
CSM Internal Technical Note TN05/22. 1989. Bacterial studies monitoring biological effect of proppant placement.
CSM Internal Technical Note TN05/25. 1990. Geochemical modelling of HDR systems: Philosophy and strategy.
CSM Internal Technical Note TN05/34. 1990. Simple coupled thermalchemical modelling of an HDR system.
CSM Internal Technical Note TN05/38. 1990. The use of chemical kinetic modelling to estimate joint apertures in the Rosemanowes HDR reservoir.
CSM Internal Technical Note TN05/39. 1990. Geochemistry of the Phase 1 HDR reservoir at Rosemanowes (unpublished manuscript by R.A. McCartney).
CSM. Internal Technical Note TN05/49. Investigation of the solubility of some major and minor elements in granite and killas from Pendarves mine.
CSM Internal Technical Note TN05/51.1990. Scanning electron microscope observations of soluble salts in cores from RH15. (A.E. Milodowski, BGS).
CSM Internal Technical Note TN05/52. 1990. An investigation of the behaviour of lithium in the Rosemanowes HDR reservoir: A technical synopsis of the work of C. Faille.
CSM Internal Technical Note TN05/54. 1990. Results of lithium step input experiment.
CSM Internal Memorandum 1984. Evaluation of jointing by dipmeter logs (G.W. Lanyon, Oct. 1984,305/02/00).
CSM Internal Memorandum 1985. Analysis of circulation water during RT2B001 by outside establishments. (R.A. McCartney and C. Wilkins, Feb. 1985, 317/02/04).
CSM Internal Memorandum 1985. Jointing. (G.W. Lanyon, Sept. 1985,305/ 02/00).
Crampin, S. and Booth, D.C., 1989. Shear wave splitting showing

hydraulic dilation of pre-existing joints in granite. *Scientific Drilling 1,* 21-26.

Dodson, LG.1979. Thermal conductivity of granite from Cornwall, England, *Internal memorandum 2-15-79 G-3 981, LosAlamos Scientific La boratory.*

Doody, J.J. 1985. Deep crustal seismic studies of South-West Britain. *Unpublished thesis, PhD, University of Wales.*

Downing, R.A. and Gray, D.A. 1986 Geothermal resources of the United Kingdom. *Journal of the Geological Society of London, 143,* 499-507.

Edmunds, W.M., Andrews, J.N., Burgess, W.G., Kay, R.L.F. and Lee, D.J. 1984. The evolution of saline and thermal groundwaters in the Carnmenellis granite. *Mineralogical Magazine, 48,* 407-424.

Edmunds, W.M., Kay, R.L.F. and McCartney, R.A. 1985. Origin of saline groundwaters in the Carnmenellis granite: natural processes and reaction during Hot Dry Rock reservoir circulation. *Chemical Geology, 49, 287*301.

Edmunds, W.M., Kay, R.L.F., Miles, D.L. and Cook, J.M., 1987. The origin of saline groundwaters in the Carnmenellis granite, Cornwall (U.K.): Further evidence from minor and trace elements. *In:* Fritz, P. and Frape, S.K., (eds), Saline water and gases in crystalline rocks, *Geological Association of Canada Special Paper 33,* 127-143.

Edmunds, W.M., Andrews, J.N., Bromley, A.V., Kay, R.L.F., Milodowski, A.E. Savage, D. and Thomas L.J. 1988. Granite - water interactions in relation to Hot Dry Rock geothermal development. *In: Investigation of the Geothermal Potential of the U.K.,* BGS.

Edmunds, W.M., Andrews, J.N., Bromley, A. V., Richards, H.G., Savage, D. and Smedley, P.L. 1989. Applications of geochemistry to Hot Dry Rock geothermal development: An overview. Geochemistry in relation to Hot Dry Rock geothermal development in Cornwall, Vol.1. *BGS Research report SD/89/2.*

Elliott, G.M. 1985. An investigation of the mechanical and thermal properties of a Cornish granite, Part B (Thermal properties) and C (Hydromechanical Properties). *Report of the Department of Mineral Resources Engineering, Royal School of Mines, Imperial College, London.*

Evans, C.J. 1987. Crustal stress in the United Kingdom. *In: Investigation of the Geothermal potential of the U.K.,* BGS.

Falck, W.E. and Savage D. 1988. Computer simulation of granitewater interactions using EQ3NR/EQ6. *BGS Report WE/88/44.*

Francis, M.F. 1980. Investigation of the south-west England thermal anomaly zone. *PhD thesis, Imperial College, London.* (Also published as Wheildon *et al.* 1981).

Gale, I.N., Rollin, K.E., Downing, R.A., Allen, D.J. and Burgess, W.G. 1984. An assessment of the geothermal resources of the United Kingdom. *In: Investigation of the geothermal potential of the U.K.* BGS.

Garnish, J.D., (ed) 1987. Proceedings, 1st EEC/US workshop on Hot Dry Rock geothermal energy, Brussels, 1986. *Geothermics, 16.*

Green, A.S.P., Baria, R., Madge, A. and Jones R.H. 1988. Fault plane solutions of microseismicity induced by fluid injections into granite. *In:* Bell F.G., Culshaw M.G., Cripps J.C. and Lovell M.A. (eds) Engineering geology of underground movements, *Geological Society Engineering Geology Special Publication No. 5,* 415-422.

Green, A.S.P., Jones, R.H. and Baria, R. 1988. A correlation between induced seismicity and fluid flow during injection into the Carnmenellis granite at a depth of 2km. *In: International conference on fluid flow in fractured rock, Atlanta, Georgia, June 1988.*

Green, A.S.P., Baria, R. Jones, R.H. 1989. VSP and cross-hole seismic surveys used to determine reservoir characteristics of a hot dry rock geothermal system. *International Journal of Rock Mechanics Mining Sciences & Geomechanics Abstracts, 26,* 271-280.

Green, A.S.P., Pine, R.J. and Jupe A. 1990. In situ stress measurements in deep wells. *In:* Baria R. (ed.) 1990, 557-574.

Hilton, D.R., Oxburgh, E.R. and O'Nions, R.K. 1985. Fluid flow through a high heat flow granite: constraints imposed by He and Rn data. *In: High Heat Production (HHP) granites, hydrothermal circulation and mineralisation.* Institution of Mining and Metallurgy, London, 135-142.

Hodgson S.P. 1985. Differential strain curve analysis - a technique to predict in situ stresses. *Final year project report, Camborne School of Mines.*

Jackson, N.J., Willis-Richards, J., Manning, D. and Sams, M. 1989. Evolution of the Cornubian ore field, South-West England. Part II: Mineral deposits and ore-forming processes. *Economic Geology, 84,* 1101-1133.

Jackson, P.D., Shedlock, S., Mooney, P., Willis-Richards, J., Green, A.S.P., Smith, D. and Busby., J.P. 1990. Identification of hydraulically connected fractures by electrical resistivity methods. Phase 2: Field experiments. *BGS Technical Report WK/90/23R.*

Jupe, A. 1990. Induced microseismicity and the mechanical behaviour of jointed rock during the development of an HDR geothermal reservoir. *PhD thesis, Camborne School of Mines.*

Kay, R.L.F. 1988. Hydrogeochemistry of the Cammenellis granite. In: Edmunds, W.M. *et al.* 1988, 28-56.

Kay, R.L.F., Andrews, J.N., Savage, D., Edmunds W.M., Cave, M.R., Darbyshire, D.P.F., Hussain, N., Milodowski, A.E. and Reeder, S. 1988. Geochemical studies of the Carnmenellis granite Hot Dry Rock system: Progress during 1987. *In:* Louwrier, K. and Garnish, J.D.(eds) 1988.

Kwakwa, K.A. 1988. Tracer measurements during long-term circulation of the Rosemanowes HDR geothermal system. *In: 13th annual workshop on geothermal reservoir engineering, Stanford University, California,* 245252.

Larkin, J.P.A. 1987. An evaluation of inert tracers for hot dry rock geothermal reservoirs. *Unpublished MSc dissertation, School of Earth Sciences, University of Birmingham.*

Louwrier, K. and Garnish, J.D. (eds) 1988. Proceedings, Contractors meeting on geochemistry, Toulouse, November 1987. *Commission of the European Communities, publication EUR-11669-EN (ISBN 92-825-8975-7).*

Maddock, R. and Lanyon, G.W. 1990. Application of fracture network models to hot dry rock research: Report 2 - Geological constraints on jointing in the Carnmenellis granite. *Contractor report by Geoscience Ltd. to Department of Energy.*

Martell, D.J., O'Nions, R.K., Hilton, D.R., Oxburgh, E.R. 1990. The role of element distribution in production and release of radiogenic helium: the Carnmenellis Granite, South-West England. *Chemical Geology 88, 207*-221.

McCartney, R.A. 1984. A geochemical investigation of two Hot Dry Rock geothermal reservoirs in Cornwall, U.K. *PhD thesis, Camborne School of Mines,* 395pp

McCartney, R.A. 1986. Granite-water interactions at 60-80°C: Results from Hot Dry Rock geothermal system field experiments in the Carnmenellis granite, UK. *Proceedings 5th international symposium on water-rock interaction (WRI-5), Reykjavik, Iceland, August 1986,* 372-375.

McCartney, R.A. 1987. Hot Dry Rock Geothermal systems: geochemical applications of transient field experiments. *Geothermics 16,* 419-429.

McCartney, R.A. 1988. Geochemical modelling of water-rock interactions in hot dry rock geothermal reservoirs. *Report by Geoscience Ltd. Published as ETSU G 137 P18.*

Miles D.L., (ed) 1990. *Proceedings of 6th international symposium on water- rock interaction, Malvern, England (WRI-6).* Balkema, Rotterdam.

Milodowski, A.E., Savage, D., Bateman, K. and Hughes, C.R. 1989. The precipitation of solids from potential heat exchange fluids for use in a HDR geothermal system in granite. *Geothermics, 18,* 233-240.

Moloney, M.J. 1982. Chemical modelling and the Camborne School of Mines Geothermal Energy Project. *Unpublished report, Camborne School of Mines.*

Mount, M. 1987. The geological argument concerning the siting of (A)a 5 to 6km deep hot dry rock geothermal energy system and (B)a 2km deep 'slate' hole. *Report commissioned by the Camborne School of Mines Geothermal Energy Project, 2 vols., unpublished. (Part of CSM Report 2C-3).*

Mount, M. 1988. Assessment of geological drilling hazards on the Carnmenellis Granite. *Report commissioned by the Camborne School of Mines Geothermal Energy Project. (Part of CSM Report 2C-3).*

Newton, K. Resource size estimates for geothermal Hot Dry Rock technology in the UK. *ETSU Report N2/85.*

Nicol, D.A.C. 1990. Cooling of the Rosemanowes HDR reservoir, *In:* Baria, R. (ed) 1990, 477-486.

Nicol, D.A.C. and Robinson, B.A. 1990. Modelling the heat extraction from the Rosemanowes HDR reservoir. *Geothermics, 19,* 247-257.

Parker, R.H. 1989a. The Camborne School of Mines hot dry rock geothermal energy project. *Scientific Drilling, 1,* 34-41.

Parker, R.H. (ed) 1989b. Hot Dry Rock Geothermal Energy - Phase 2B final report of the Camborne School of Mines Project. *CSM Report 2B-45. Commission of the European Communities publication EUR 11840. Department of Energy report ETSU G 125-F. 2 Vols. Pergamon, Oxford, ISBN 0-08-037929-X.*

Pearson C.M. 1980. Permeability enhancement by explosive initiation in the South-West granites, with particular reference to Hot Dry Rock energy systems. *PhD thesis, Camborne School of Mines.*

Pine, R.J. 1986. Rock joint and rock mass behaviour during pressurised hydraulic injections. *PhD thesis, Camborne School of Mines.*

Pine, R.J. and Batchelor, A.S. 1982. In situ stresses and jointing in the Carnmenellis granite and the implications for hydraulic behaviour. *Camborne School of Mines Journal, 82.*

Pine, R.J. and Batchelor, A.S. 1984. Downward migration of shearing in jointed rock during hydraulic injections. *International*

Journal of Rock Mechanics Mining Sciences & Geomechanics Abstracts 21, 249-263.

Pine, R.J. and Kwakwa, K.A. 1988. Experience with hydrofracture stress measurements to depths of 2.6km and implications for measurements to 6km in the Carnmenellis Granite. *In: 2nd International workshop on hydraulic fracturing stress measurements, Minneapolis, Minnesota. June 1988.*

Pine, R.J. and Ledingham, P. 1983. In-situ hydraulic parameters for the Carnmenellis granite Hot Dry Rock geothermal energy research reservoir.
Journal of Petroleum Technology, Nov. 1984 and also in *Society of Petroleum Engineers of AIME, 58th* Annual *Technical Conference, SPE 12020.*

Pine, R.J., Baria, R., Pearson, R.A., Kwakwa, K.A. and McCartney, R.A. 1987. A technical summary of Phase 2B of the Camborne School of Mines HDR Project, 1983-1986. *Geothermics 16,* 341-353.

Pine, R.J., Jupe. A, Tunbridge, L.W, 1990. An evaluation of in situ stress measurements affecting different volumes of rock in the Carnmenellis granite. In: *International Society for Rock Mechanics first international workshop on scale effects in rock masses. Loen. Norway. June 1990.*

Pine, R.J., Tunbridge, L.W. and Kwakwa, K.A. 1983a. In-situ stress measurement in the Carnmenellis granite - L Overcoring tests at South Crofty Mine at a depth of 790m. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 20,* 51-62.

Pine, R.J., Merrifield, C.M. and Ledingham, P. 1983b. In situ stress measurement in the Carnmenellis granite: 2 - Hydrofracture tests at Rosemanowes quarry to depths of 2000m. *International Journal of Rock Mechanics and Mining Sciences & Geomechanical Abstracts 20,* 63-72.

Randall, M.M., Lanyon, G.W., Nicholls, J. and Willis-Richards, J. 1990. Evaluation of jointing in the Carnmenellis granite. *In:* Baria, R., (ed.) 1990 108-123.

Richards, H.G. and Savage, D. 1989. Rate of plagioclase dissolution in the Camborne School of Mines experimental Hot Dry Rock geothermal reservoir, Rosemanowes, Cornwall. *In:* Miles D.L. (ed.) 1990, 577-580.

Richards, H.G., Wilkins, C., Kay, R.L.F. and Savage, D. 1989a. Geochemical results from the Rosemanowes HDR system, 1986-1988. Geochemistry in relation to Hot Dry Rock geothermal development in Cornwall, Vo1.2, *BGS Research report SD/89/2.*

Richards, H.G., Savage, D. and Shepherd, T.J. 1989b. Geochemical prognosis for a commercial-depth HDR system in South-West England. Geochemistry in relation to Hot Dry Rock geothermal development in Cornwall, Vol.7, *BGS Research report SD/89/2.*

Richards, H.G., Kwakwa, K.A. and Oskui, G.P. 1990. Flowpath characterisation of the Rosemanowes HDR reservoir using inert tracers. In: Baria R. (ed) 1990, 557-574.

Richards, H.G., Savage, D. and Andrews, J.N. 1991. Granite-meteoric water reactions in an experimental Hot Dry Rock geothermal reservoir at the Rosemanowes test site, Cornwall, *U.K. Applied Geochemistry* (submitted).

Roberts, G. and Crampin, S. 1986. Shear-wave polarizations in a Hot-Dry Rock reservoir: anisotropic effects of fractures. *International Journal of Rock Mechanics and Mining* Sciences & G*eomechical Abstracts, 23,* 291302.

Rollin, K.E. 1983. An estimate of the accessible geothermal resource for the UK. *Applied Geophysics Unit report 143, BGS.*

Rollin, K.E. 1987. Catalogue of geothermal data for the land area of the United Kingdom. Third revision: April 1987. In: *Investigation of the geothermal potential of the UK.* BGS.

Sammut, J.C. and Blake, A.J. 1980. Determination of the effect of confining pressure on the Young's Modulus and Poisson's Ratio of Berkely Blue Granite (Georgia, U.S.A.), Carwynnen Quarry Granite (Troon, Cornwall, England), and Rosemanowes Quarry Granite (Stithians, Cornwall, England). *Camborne School of Mines Geothermal Research Group (unpublished).*

Sams M.S. 1988. Numerical models of the heat flow field in south-west England. *PhD thesis, Imperial College, London.*

Sams, M.S. and Thomas-Betts, A. 1988a. 3-D Numerical modelling of the conductive heat flow of south-west England. *Geophysical Journal, 92,* 323-334.

Sams, M.S. and Thomas-Betts, A. 1988b. Models of convective fluid flow in South-West England. *Journal of the Geological Society of London, 145,* 809-817.

Sartori, A. 1983. A line-source method for the measurement of temperature and pressure dependence of rock thermal conductivity. *PhD thesis, Imperial College, London.*

Savage, D., Cave, M.R., Milodowski, A.E. and George, I. 1987. Hydrothermal alteration of granite by meteoric fluid: an example from the Carnmenellis Granite, United Kingdom. *Contributions to Mineralogy and Petrology,* 96, 391-405.

Savage, D., Bateman, K., Milodowski, A.E., Cave, M.R., Hughes, C.R., Green, K., Reeder, S. and Pearce, J. 1989. Experimental studies of granitewater interactions. Geochemistry in relation to Hot Dry Rock geothermal development in Cornwall, Vol.6. *BGS Research report SD/89/2.*

Savage, D., Bateman, K. and Richards, H.G.1991. A laboratory investigation of granite-meteoric water interactions in a flow-through system at 60-100 C, 30 MPa. *Applied Geochemistry (submitted).*

Shock, R.A.W. 1986. An economic assessment of Hot Dry Rocks as an energy source for the UK. *ETSU Report ETSU-34, ISBN 0-7058-1334-7.*

Smedley, P.L. 1989. Alkali metal enrichments in groundwaters from the Carnmenellis area, Cornwall. In: Miles D.L. (ed) 1989, 647-650.

Smedley, P.L., Bromley, A.V., Shepherd, T.J., Edmunds, W.M. and Kay, R.L.F. 1989. Fluid circulation in the Carnmenellis granite: hydrogeological, hydrogeochemical and palaeofluid evidence. Geochemistry in relation to Hot Dry Rock geothermal development in Cornwall, Vol.4. *BCS Research report SD/89/2.*

Stewart, R. and Jones, R.H. 1990. The use of VSP and cross-hole seismic surveys in the development of HDR reservoirs. *In:* Baria R. (ed) 1990, 509-519.

Thomas-Betts, A., Wheildon, J. and Sams, M.S. 1988. Further heat flow measurements and geothermal modelling in the vicinity of Carnmenellis granite. Final report of a research contract with the Camborne School of Mines, 113p. *(Published as ETSU G137 P16).*

Thomas, L.J. 1988. Report on suspended particulate material from RH12 and RH15 and of surface coatings of RH15 well debris. *Unpublished report, Camborne School of Mines.*

Thomas, L.J. and Bromley, A.V. 1987. Report on the compositions of particulate material in RH15 production water and compositions of haematised drill chippings from RH12. *Unpublished report, Camborne School of Mines.*

Thomas, L.J. and Milodowski, A.E. 1988. Alteration mineralogy. In: Edmunds, W.M. *et al.* 1988, 57-80.

Tombs, J.M.C. 1977. A study of the space form of the Cornubian granite batholith and its application to detailed gravity surveys in Cornwall, *Mineral Reconnaissance Programme Report No. 11, Institute of Geological Sciences.*

Turbitt, T., Walker, A.B., Browitt, C.W.A. and Morgan, S.N.1984. Monitoring the background and induced seismicity for the Hot Dry Rock programme in Cornwall. *BGS Global Seismology Research Unit Report 195.*

Turbitt, T., Walker, A.B. and Browitt, C.W.A.1987. Perceptible hydrofracture seismic events caused by the Hot Dry Rock geothermal research project in Cornwall. *BGS Global Seismology Research Unit Report 339.*

Walker, A.B. 1987. Background and induced seismicity monitoring for the HDR Geothermal programme in Cornwall. *BGS Global Seismology Unit Report 323.*

Walker, A.B., Musson, R.M.W., Turbitt, T. and Browitt, C.W.A. 1988. SW England seismic monitoring: Fourteenth progress report, for the period March to July 1988. *BGS Global Seismology Unit (unpublished).*

Wheildon, J., Francis, M.F., Ellis, J.R.L and Thomas-Betts, A., 1980. Exploration and interpretation of the SW England geothermal anomaly zone, In: *Second international seminar* on *the results of EC geothermal energy* research, *March 1980, Report EUR 6862, D. Reidel, Dordrecht, Holland,* 456-65.

Wheildon, J., Francis, M.F., Ellis, J.R.L and Thomas-Betts, A. 1981. Investigation of the South-West England thermal anomaly zone. *Report EUR 7276EN, Commission of the European Communities, 410p.* ('This is a published version of Francis, 1981).

Willis-Richards, J. 1989. The effect of a high heat production granite batholith on lithospheric stress and strength in South West England, In: Maury, V. and Fourmaintraux, D. (eds) *Proceedings of international* symposium on *`Rock at Great Depth', Pau, France, 28-38 August 1989.* Balkema, Rotterdam (ISBN 90 6191 975 4), 1369-1378.

Willis-Richards, J. 1990. Thermotectonics of the Cornubian batholith and their economic significance. *PhD* thesis, *Camborne School of Mines.*

Willis-Richards, J. and Jackson, N.J. 1989. Evolution of the Cornubian ore field, SW England. Part I: Batholith modelling and ore distribution. *Economic Geology, 84,* 1078-1100. (For Part II see Jackson *et al.* 1989).

Willis-Richards, J., Thomas-Betts, A., Sams M. and Wheildon J. 1990. HDR resource in South West England. In: Baria, R. (ed), 1990, 215-223.