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

A seismic reflection survey as part of a geophysical investigation of the Carnmenellis Granite

R.H. JONES

Camborne School of Mines Geothermal Energy Project, Rosemanowes Quarry, Herniss, Penryn, Cornwall TR10 9DU.

The seismic reflection survey was shot to elucidate two important topics relating to Hot Dry Rock (HDR) research:

(1) The structure of the granite at depths between 4 and 8 km, as an HDR pilot scheme would require drilling to a depth of about 6km within the granite. The presence of any large scale geological structure within the granite at this depth could affect the behaviour of an HDR reservoir, both in terms of its formation and its long term behaviour. For example, a large scale permeable feature lying within or adjacent to a reservoir could have a significant influence on water losses, initial stimulation, etc. It is therefore desirable to locate any such features before drilling starts. This is the most important question to be addressed by the reflection seismic survey and its design parameters reflect this priority.

(2) Knowledge of the shape of the granite is important if the available thermal resource is to be assessed. The seismic survey was shot not just over granite outcrop, but also over "killas" (Devonian-Carboniferous lower Greenschist fades argillites and arenites with minor basic volcanic and volcaniclastic intercalactions), to try to better determine the shape of the sides of the granite. Understanding the shape of the granite also entails trying to image its base. The main geophysical technique which has been used to assess the overall spaceform of the granite is gravity. A large gravity dataset now exists and 3-dimensional models of the gravity have been produced by the CSM HDR Project as part of a resource evaluation programme. If the shape of the granite below the seismic lines can be determined from the seismic reflection survey data then this can be checked against the gravity model and used to improve it.

A normal-incidence seismic reflection occurs at an impedance contrast. The impedance is defined as being the product of the density and seismic velocity of the rock. This change must be rapid when compared to the dominant wavelength of the seismic signal. The situation for wide-angle reflections is different; a reflection may be caused by the mechanism just outlined but a gradual change in the seismic velocity of the rock can also give an arrival that looks like a reflection. Thus the interpretations produced by the two techniques from surveys over the same area need not necessarily be the same.

In crystalline rocks there are several ways in which a seismic reflection can be caused. Perhaps the most obvious is the juxta-position of rock of differing seismic velocities and densities, eg. basic rocks and acid rocks. Shear zones have also been found to give rise to seismic reflections within crystalline rocks (Jones and Nur 1984).

At shallow depths fractured zones have been found to give reflections (Mair and Green 1981). Offshore seismic reflection profiling around Britain carried out by the British Institutes Reflection Profiling Syndicate (BIRPS) group (Matthews and Cheadle 1986) has shown that the crust around Britain typically consists of sedimentary basins controlled by faults, a seismically transparent upper and middle crust and a seismically reflective lower crust. The reflections from the lower crust are generally short and discontinuous.

Suggestions have been made that there are structures within granites. Although the Variscan tectonism in SW England predates the emplacement of the granite, there are several cases of large permeable fault-related features being encountered within mines (IGS 1982), albeit at relatively shallow depths. Clearly there is a major problem in extrapolating geological observations made near the surface (ie. depths down to several hundred metres) to depths of several kilometers. The increase in the temperature of the rock to around 200°C has an effect on the mechanical properties of the rock (Heuze 1983; Kirby 1983). There is evidence from other crystalline rock bodies which have been investigated that faults can be seismically reflective, but the nature of these faults at large depth and elevated temperatures is not known from direct observation.

A seismic refraction/wide-angle reflection survey has been conducted across the Cornubian Batholith (Brooks *et al.* 1984; Doody 1985). The model produced from these data has two interfaces that

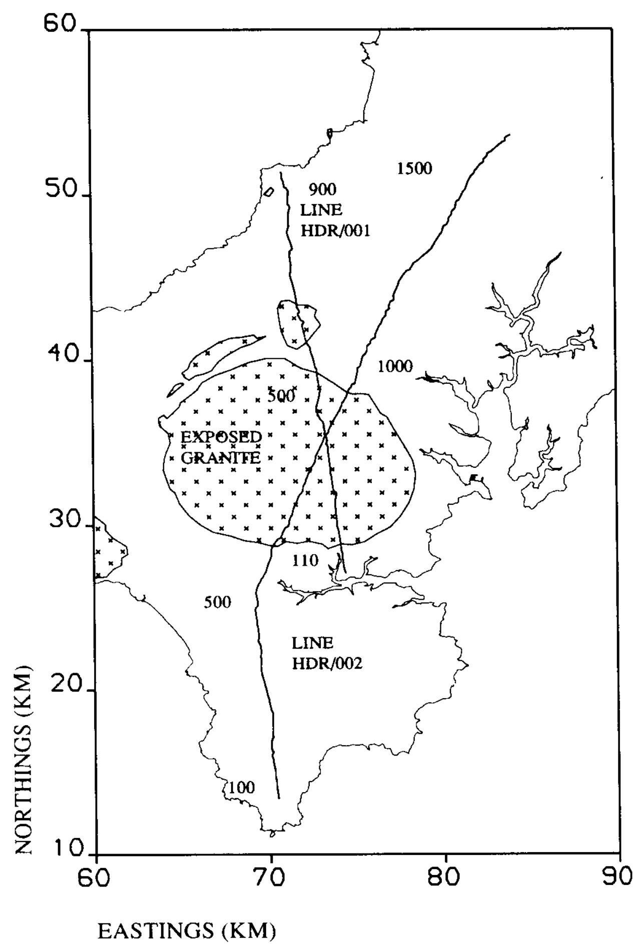

Figure 1. Location of seismic selection lines HDR/001 and HDR/002; number refers to geophone stations.

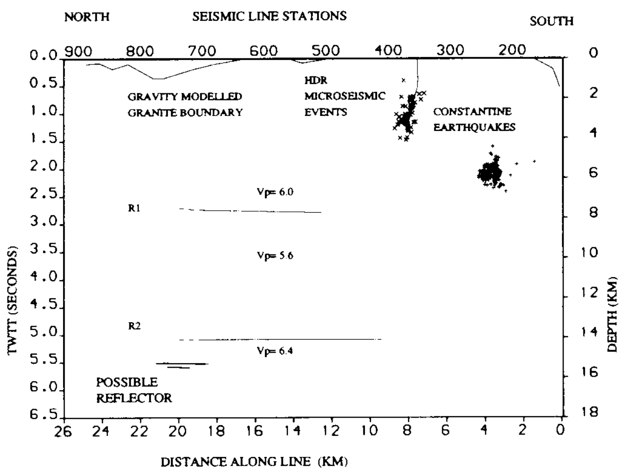

Figure 2. Combined geophysical data on line HDR/001. R1, R2 = velocity interfaces from seismic refraction/wide-angle reflection of Brooks *et al.* (1984). Vp = Velocity in kms^{-1}

are of particular interest in terms of HDR exploration. One of the interfaces of the model, termed R2 (a velocity increase from 5.6 to $6.4kms^{-1}$), was identified as being the bottom of the Cornubian Batholith, and slopes from a depth of about 10km in the north to 15km in the south. The second interface of interest, termed R1 (a velocity decrease from 6.0 to $5.6kms^{-1}$, is within the granite and at a depth of between 6 and 8km. The nature of the feature represented by R1 is thus a primary target for the normal incidence seismic reflection survey.

The geographical location of the seismic lines is shown in relation to the granite outcrop and the coastline in Fig. 1. The two lines cross at the HDR Project Rosemanowes site.

A 1kg explosive source was used for each shot. In all about 400 shots were used for the 71.5 line km of data acquired. The geophone apread was a 60-60 split spread, stations each separated by 30m and the data is nominally 12 fold (CSM 1988).

The results of the seismic reflection survey are presented in the form of line drawings. These line drawings also contain the gravity modelled shape of the granite (CSM 1988), the wide-angle reflection model (Brooks *et al.* 1984) and the microseismicity associated with the HDR reservoir.

The natural seismicity event swarm which occurred beneath Constantine in 1982 has also been projected into the plane of the seismic lines.

Fig. 2 shows a composite gravity, seismic cross-section for line HDR/001. The line drawing is at true scale for a seismic velocity of $5.9kms^{-1}$.There are no imaged reflectors in the seismic section from within the killas or at the gravity-modelled killas/granite interface. The data was also processed using a low-frequency lowpass filter and one tentative short reflector was imaged beneath the northern end of the line with a two way travel time (TWTT) of about 5.6s (a depth of about 17km).

Fig. 3 shows a line drawing made from the processed reflection section of line HDR/002. Many short reflectors are imaged within the killas and on the Lizard Peninsula. These reflectors are in general fairly randomly distributed except for two structures. The structure to the north of the granite lies within the killas and runs parallel to the granite before appearing to come into contact with it and then die out. The region of reflectors to the north correspond well with an interface modelled by Brooks *et al.* (1984) and is here termed RKO. The structures abutting the southern boundary of the granite correlate well with the expected position of the Carrick Thrust (Leveridge *et al* 1984). These events move to lie on the killas/granite interface when they are restored to their correct postition by the process of migration (CSM 1988).

There is no evidence of any reflecting horizons either from within or from below the granite, as defined by the gravity model and the feature R2.

The main results of the seismic reflection survey are:

(1) Reflectors were imaged in the killas down to depths which are approaching those required for a pilot HDR scheme. It is expected that granite is a better transmitter of seismic energy than killas, and so it seems unlikely that any major, flat-lying structures which could be imaged lie within the granite at these depths. Where the killas achieves thicknesses of about 2km or more then many short reflectors and diffractors are imaged within it, down to depth of 4.5km. There are also some more coherent structures present within the killas.

(2) The actual granite/killas contact is not imaged. It appears from the combined gravity/refection seismic sections (Figs 2 and 3) that the cessation of features with depth in the shallow portion of line HDR/002 corresponds to the granite/killas interface.

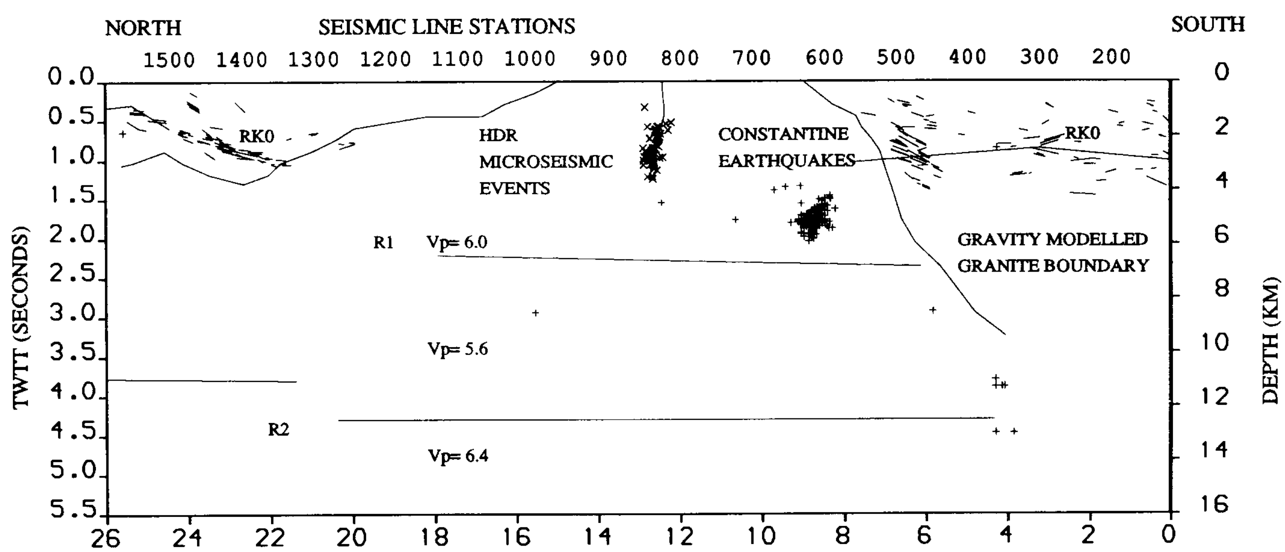

Figure 3. Combined geophysical data on line HDR/002 showing immigrated reflection data. RKO = velocity interface within killas, from Brooks *et al.* (1984).

(3) There is no evidence from this seismic reflection survey of structure within the granite.

(4) Both the seismic lines passed over the current reservoir and the seismic signals from these shots were recorded on the downhole hydrophones deployed for microseismic monitoring. These signals show a good signal-to-noise ratio for the downgoing wave at 2km. However there is no evidence of even incoherent energy returning from the deeper portions of the data.

(5) A single short tentative reflecting horizon is imaged on line HDR/001 at a depth just below the R2 interface of Brooks *et al.* (1984). Seismic data gathered by BIRPS over the Scillies granite (Hobbs and Scheirer 1990) suggests that we do not see a discrete horizon at the base of the granite from normal incidence reflection data, but rather that we might expect to see the layered lower crust, beneath the granite. The top of this characteristic layering is usually imaged at about 5s TWTT on the UK continental shelf but often slightly shallower under granites. Indeed if we had succeeded in clearly imaging lower crustal layering then this would lend further support to the idea of a seismically transparent granite. This would show the granite had been well illuminated by the survey, and hence that lack of reflectors was due to a lack of acoustic structure and not to a lack of penetration on the part of the survey.

In 1988 a contract was placed with the BGS Geomagnetism Research Group to carry out a magnetotelluric (MT) survey of the Carnmenellis Granite. This technique uses natural variations in the earth's electromagnetic field as its source. The way in which this is modified by the rocks being studied is used to give estimates of the resistivity of the rock as a function of depth (Beamish 1990). Granite consists of a highly resistive rock matrix and many fluid filled voids such as joints. The saline solution within these voids dominates the apparent resistivity of the rock.

There are two main results from the survey which are of interest here. The first is that on a broad scale the granite appears very homogeneous. The second is that below a depth of 1km the resistivity values are found to increase down to a depth of about 6km, below this depth the resistivity remains fairly constant down to 12 to 14km. Given the high geothermal gradient in the granite a resistivity decrease would be expected if the pore geometry had remained constant as the temperature, and therefore the conductivity of the pore fluid, had increased. This result is interpreted as being consistent with joint closure at a depth of about 7km and a change to a pore dominated resistivity below this depth (Beamish 1990).

A study of the natural seismicity of the area (Willis-Richards 1989) shows that the largest events nucleate at a depth of about 6km, and that there are very few events below 8km within the granite. A model of the granite based on the in-situ stresses and the temperature of the granite which predicts that the brittle-ductile transition will occur within the granite at a depth of about 6km has been proposed (Willis-Richards 1989).

The reflection data found no evidence of structures at depths of between 4 and 8km within the granite, but the wide-angle reflection interpretation does place a feature, R1, at a depth of between 6 and 8km.

If, as suggested by the resistivity (Beamish 1990), this depth represents the change from an interconnected hydrostatic pore network to a system of isolated pores at lithostatic pressure then this could produce a drop in seismic velocity, which is consistent with R1. However, this change would take place over too great a depth range for it to produce a normal-incidence reflection.

The seismic and the MT results discussed here are interpretations and so are non-unique. Thus the proposal that it is the brittle-ductile transition which explains the position of R1 is tentative. However it does have the attraction that it is consistent with the MT data, the seismic reflection data, wide angle and normal incidence, and natural seismicity.

The second aim of the seismic reflection survey was to corroborate the gravity model in areas where the granite is overlain by killas. Fig. 3 shows that where the killas achieves and appreciable thickness there is good agreement between the two methods.

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 judgements expressed in this paper are those of the author and do not necessarily reflect those of ETSU or DEn.

Beamish, D. 1990. A deep geoelectric survey of the Carnmenellis granite. *Geophysical Journal International, 102,* 679-693.

Brooks, M., Doody, J.J. and Al-Rawi, F.R.J. 1984. Major crustal reflectors beneath SW England. *Journal of the Geological Society, London, 141,* 97-103.

CSM Report 2C-7. 1988. Resource evaluation (3 volumes, A: overview, B: seismic reflection survey, C: gravity and heatflow modelling). (also published as ETSU G137 P14A, B, C).

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

Heuze, F.E. 1983. High temperature mechanical, physical and thermal properties of granite rocks - a review. *International Journal of Rock Mechanics, Mining sciences and Geomechanics Abstracts, 23,* 3-10.

Institute of Geological Sciences. 1982. The origin of groundwater in the Carnmenellis granite: The hydrochemical evidence. (Burgess, W.G., Edmunds, W.M., Andrews J.N., Kay, R.L.F., and Lee, D.J.). IGS Geophysics and Hydrology Division, London.

Jones, T.D. and Nut, A. 1984. The nature of seismic reflections from deep crustal fault zones. *Journal of Geophysical Research, 89,* 3153-3173.

Kirby, S.H. 1983. Rheology of the Lithosphere. *Reviews of Geophysics and Space Physics, 21,* 1458-1487.

Leveridge, B.E., Holder, M.T. and Day, G.A. 1984. Thrust-Nappe tectonics in the Devonian of South Cornwall and the western English Channel. *In:* Hutton, D.H.W. and Sanderson, S.J. (eds). *The Variscan Tectonics of the North Atlantic region, S.J.,* Blackwell Scientific Publications, Oxford.

Mair, J.A. and Green, A.G. 1981. High resolution seismic reflection profiles reveal fracture zones within a homogeneous granite batholith. *Nature, 294,* 439-442.

Matthews, D.H. and Cheadle, M.R. 1986. Deep Reflections from the Caledonides and the Variscides of Britain; a comparison with the Himalayas. *In:* Baranzagi, M. and Brown, L. (eds). Reflection seismology: A Global Perspective. *American Geophysical Union, Geodynamics Series, 13,* 297-300.

Scheirer, D.S. and Hobbs, R. 1990. Seismic attenustion in the continental crust SW of England. *Geolphysical Journal International, 103,* 533-540.

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 the International Symposium on `Rock at Great Depth', Pau, France, 28-31 August 1989.* Balkema, Rotterdam, 1369-1378.