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THE STIMULATION OF A HOT DRY ROCK GEOTHERMAL RESERVOIR IN THE CORNUBIAN GRANITE, ENGLAND

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ABSTRACT

A Hot Dry Rock geothermal reservoir has been created at a depth of 2000 m in granite. The stimulation was carried out using 40 000 m^3 (10 million US gal) from a 350 m open hole section that had been treated with a purpose-designed explosive tool. On-line seismic mapping has shown that the reservoir has developed in the direction of the maximum principal stress despite the fact that the joint directions are not orientated in that direction. Photographic and television inspection has been used to correlate acoustic seisviewer and conventional wire logging results including observations of fracture width at the wellbore during pressurisation.

Downward growth of the reservoir has been observed despite the fact that the stimulation fluid was fresh water. This has been explained tentatively as predominantly shear growth because the shear stress gradient is sub-hydrostatic due to the highly anisotropic stress field. Preliminary calculations have shown that the reservoir structure has a volume of 100-200 million m^3 but there is no direct, low resistance flow path between the wells and the residence time is in excess of 5 days.

INTRODUCTION

Hot Dry Rock geothermal exploitation has a well established literature (eg, Smith (1975), Smith (1978), Parsons (1919), Batchelor (1978), Armstead (1979), Milora et al (1976), etc, and there is active research in a number of countries. However, only two, USA and Great Britain, have substantial field programmes and only the USA has reached potential production temperatures. The work in the UK by the author has concentrated on developing stimulation techniques to create HDR reservoirs in a jointed, highly stressed granite body heated by natural radioactivity. Figure 1 shows a panoramic view of the site during pumping operations.

A massive hydraulic stimulation commenced on 4 November this year in Cornwall, England, and more than 40 000 m^3 (10 million US gal) has been used to interlink two wells at a depth of 2000 m. The results presented in this paper are from the start of the stimulation to the onset of steady circulation at noon on 21 November 1982. Full interpretation of the data will not be completed for some time but the results form a useful case study for evaluating the potential application of HDR systems in this area of the UK.

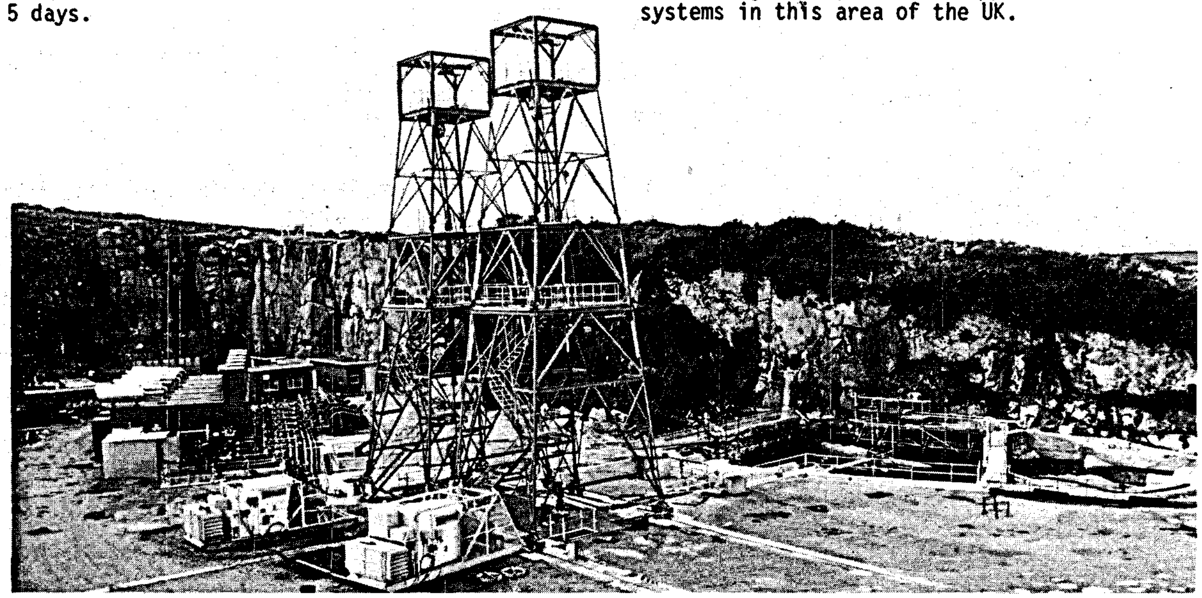

Figure 1: View of site showing tool handling towers and enclosed pump units at the wells

REGIONAL GEOLOGICAL AND THERMAL SETTING

South West England is a peninsula comprising the counties of Devon, Cornwall and part of Somerset, which is bounded by the Atlantic Ocean, the Bristol Channel and the English Channel. The majority of the rocks in the area are shales and mudstones with subordinate bands of grit and conglomerate which have been subjected to varying degrees of metamorphism. These rocks are usually referred to by the local name 'Killas' and they are primarily of Devonian age together with slightly younger Carboniferous rocks to the north east of the area. Towards the end of the Carboniferous period, the thick sedimentary beds were folded along an east-north-east trend by movements of the Armorican orogeny; the intrusions of the granite into this rock mass occurred in the late Carboniferous or early Permian period and formed large cupolas and bosses above a batholith some 200 km in length.

Figure 2 is a sketch plan showing the location and idealised granite structure of the region. The area has been mapped extensively by innumerable authors during the last 200 years because of the interest in the intense mineralisation associated with the granite. Hosking (1949 and 1964) proposed a conjectural mega-structure for the batholith from surface and underground mappings. Bott et al (1958, 1964 and 1970) have confirmed the detailed shape using gravity, magnetic and seismic data. Exley and Stone (1964) have presented the largely definitive survey of its petrography and geochemistry. Bromley (1976) postulated that the whole batholith is the product of crustal thickening providing a uniform melt during intrusion.

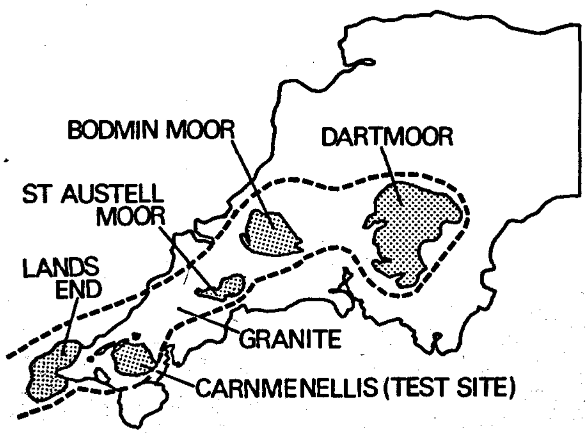

Figure 2: Sketch map of SW England and the Cornubian batholith

The larger plutons are now exposed as elevated moorlands between 200 m and 300 m above sea level and they are circular or elliptical in shape with evidence of multiple intrusion. There is some strong geophysical evidence that the plutons rise on a more or less continuous ridge from Dartmoor to the Isles of Scilly and possibly as far as the rocks of Haig Fras. The model proposed by Bott et al (1970) envisages that granitic material with a seismic velocity of 5850 m/s extends to 12 km depth, although a recent re-interpretation adds 6 km to this figure. It is believed that an intermediate composite lower crust with an average velocity of 6500 m/s continues to the well-defined Moho at 27 km. The bulk of the constituent rocks of the batholith are coarse to fine grained, biotite muscovite granites with and without megacrysts of potash feldspar.

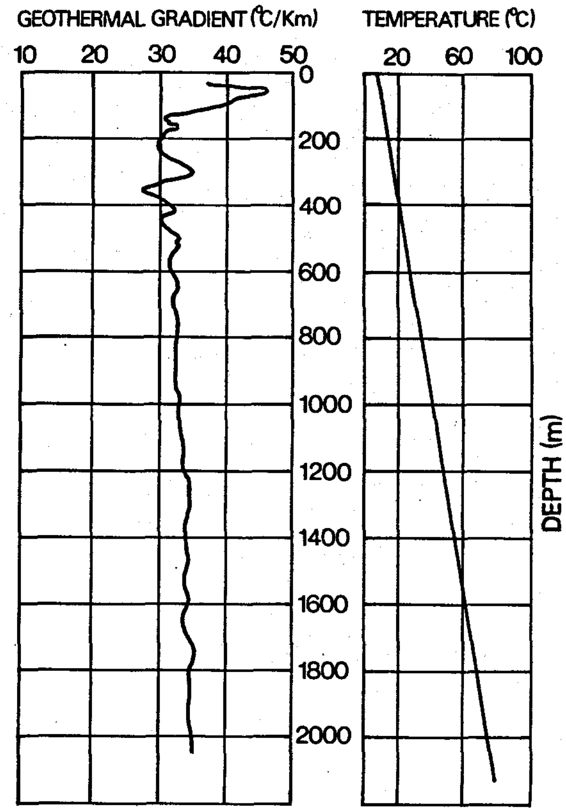

Figure 3: An equilibrium temperature log. Note the increasing gradient.

The HDR research site is located in the centre of the Carnmenellis pluton away from any known mineralisations. The surface area of the Carnmenellis pluton is approximately 300 km^2 and is comprised of a coarse grained porphyritic biotite muscovite granite except in two small areas where the biotite granite is a fine grained porphyry. The south eastern part of the pluton has shown itself to be particularly suitable for hot dry rock experiments because of the massive nature of the granite exposed to the surface. It exhibits well defined vertical jointing which has been extensively mapped at an earlier phase in the Project. The principal rock constituents are:

Quartz	30%
Potash feldspar	30%
Plagioclase feldspar	26%
Biotite	6%
Muscovite	6%
Other minerals	2%

The radioactive element distribution is consistent throughout the batholith:

Uranium	13 ppm (2.5 ppm)
Thorium	8 ppm (2.5 ppm)
Potassium	4.6% (.7%)

Numbers in parentheses are standard deviations.

Wheildon et al (1977) have mapped the heat flow regime in detail and have shown that there is a persistent regional heat flow of 120 mW/m^2 with a surface thermal gradient of 31°C/km. The temperature gradient was observed to increase with depth to 36°C/km at 2000 m, *Figure 3*.

STRESS FIELD AND JOINT STRUCTURE

The geometry and extent of the heat transfer zone created by massive hydraulic stimulation is controlled by the prevailing stress field and its interaction with the natural joint structure, Batchelor et al (1980) and Smith et al (1982).

The surface joint structure within 5 km of the site was mapped by Bergin et al (1980) and the simple, bi-modal distribution of both dip and direction was assumed to persist to depth because of the consistent surface patterns. Limited confirmation of this assumption was possible from observations in the nearest deep mine 10 km away at a depth of 800 m.

The majority of the joints are held shut by the stress field and are thought to be have residual widths of 10 μm to 100 μm. The surfaces have varying thicknesses of hydrothermal alteration and none are completely free of alteration products showing that groundwater circulation has occurred within the granite mass since its emplacement.

The stress field has been measured by both hydraulic fracturing (Pine et al, 1982a) and overcoring (Pine et al, 1982b) and the results are shown in Figure 4. The excellent agreement between the two types of measurement at sites over 9 km apart gave considerable confidence in the results.

Figure 5 shows a stereo plot of the joint strikes with the measured stress field at 2000 m depth superimposed. It can be seen that there is an offset between the joints and the stress field, producing high shear stresses across the joint faces.

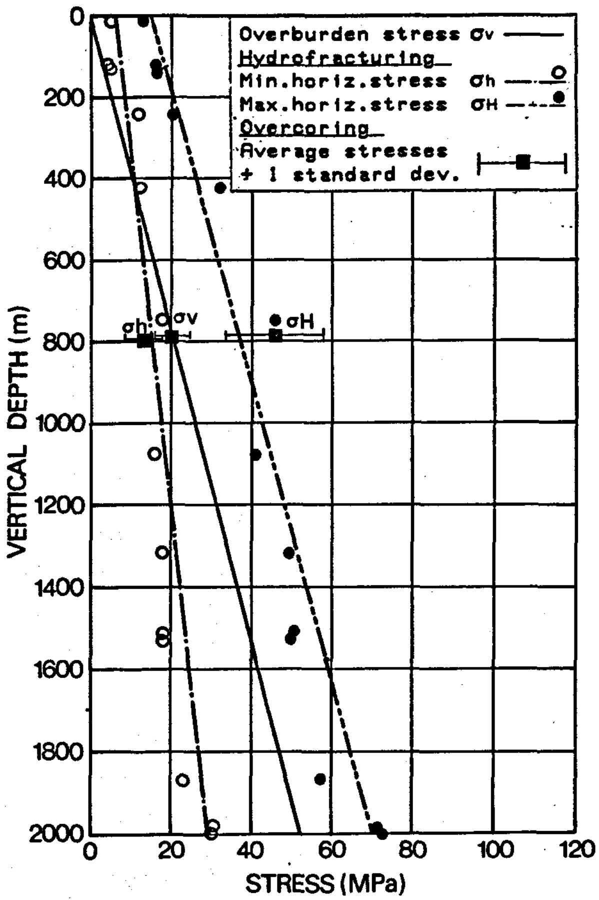

Figure 4: The stress measurement results from hydraulic fracturing and overcoring

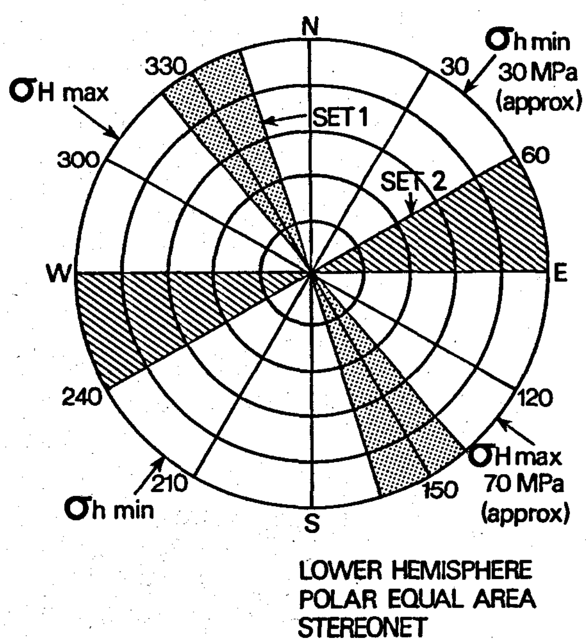

Figure 5: The observed joint strike directions in relation to the measured stresses

THE WELL DIRECTIONS

The boreholes were drilled to give an inclined access to the joint sets within the reservoir. The majority of the joints have dips steeper than 70° to the horizontal so an inclination of 30° was chosen to give as good an access as possible without excessively high torque requirements during drilling. Both wells were completed within a total of 125 days, an average of 32 m/day. The drilling programme has been described by Beswick (1982) and Beswick et al (1982).

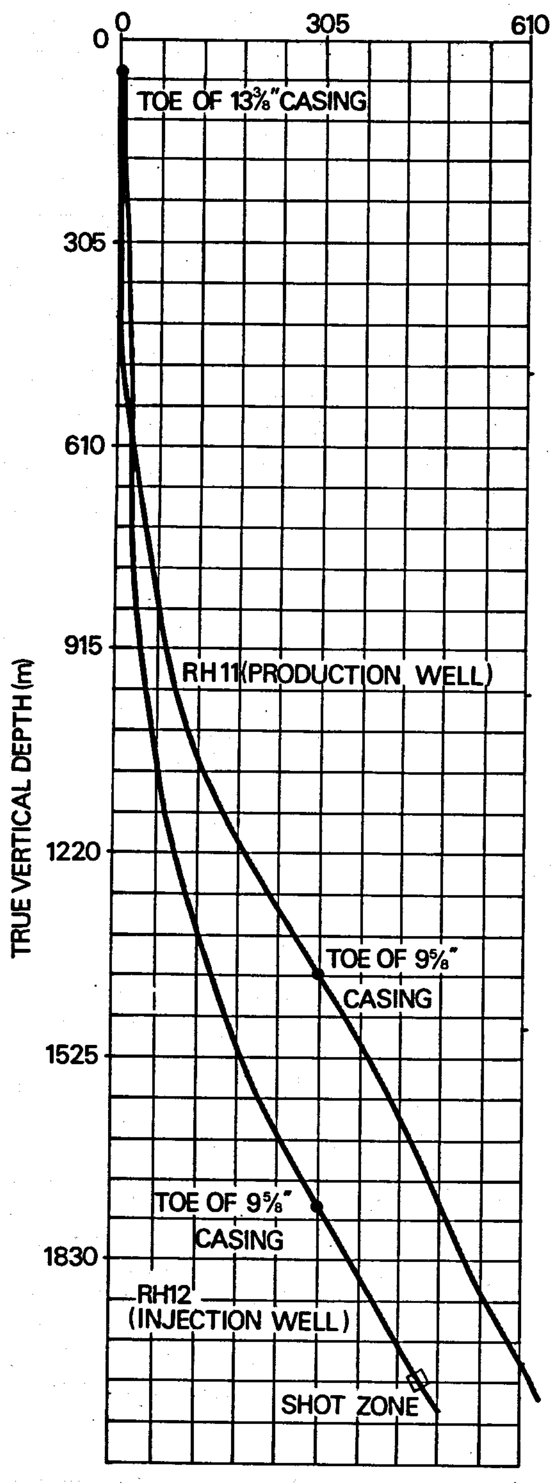

Figure 6: Vertical projection of the wells.

Figure 6 & 7 show the projections of the wells and the two casing points can be seen to be vertically aligned. The production well, RH11, was extended to a similar vertical depth as the injection well, RH12, to ensure that the maximum opportunity existed for the interwell connection during fracturing.

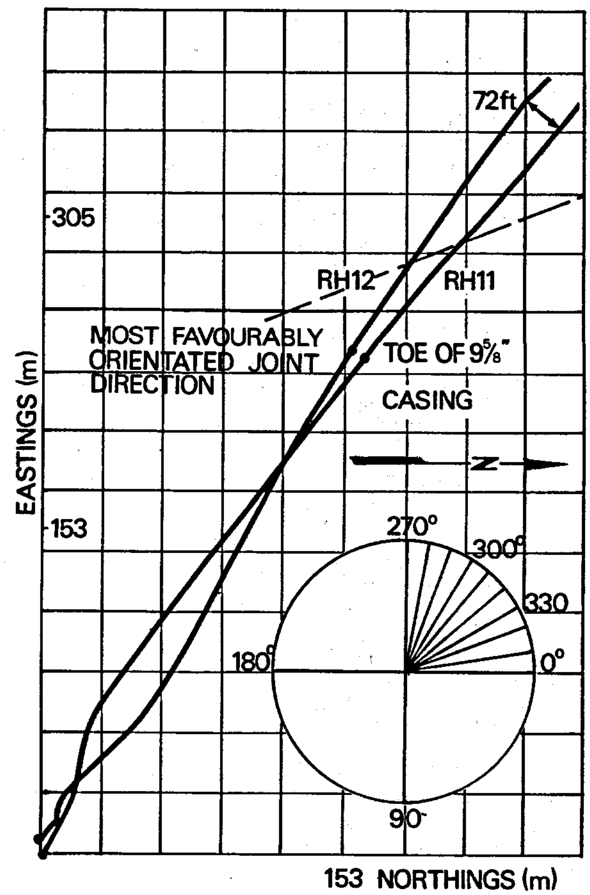

Figure 7: Plan projection of the wells

The stress directions were not known before drilling commenced, so the borehole directions were chosen to be at approximately 40° to both joint directions. This would maximise the chance of interconnection from either set of joints depending on the confinement in each case. However, it was not expected that the plane of the boreholes would be aligned virtually normal to the minimum principal stress.

These were the first two deep wells in this area and were treated as "wildcats" from the point of view of stresses. Intuitively, it would have been better to orient the wells at 90° to their actual trajectory to give more planar connections along the axis of the well but the early reservoir results indicate that the stimulated zone is sufficiently large for adequate heat extraction.

LOGGING RESULTS

An extensive suite of geophysical logs was run at the end of drilling and before the hole was cased. Figure 8 shows the coverage of the logs versus depth. The principal objective of the logging was to determine the pre-stimulation joint characteristics at the wellbore. Joint aperture, intersection length and orientation are all relevant to any HDR stimulation procedure and it was hoped to identify likely flow connections from the wells. The data is virtually impossible to reproduce for a paper such as this but it did show that the natural fracturing did persist to depth and was orientated in similar directions to the joints at the surface. There were zones of extensive fracturing (spacing 100-500 mm) with long intact zones (30 m), irregularly spaced in the open hole section.

However, it was not possible to identify any particular characteristics that were associated with the joints that eventually accepted the water during injection. Low flow rate injections (3 l/s) were used in conjunction with continuous temperature logs to find the naturally flowing joints at pressures very much lower than the eventual fracturing pressures and these were used to select the explosively stimulated zone.

A television and photographic survey was eventually completed after all the logs had been run and work is still continuing to correlate the logs and the TV results.

The flowing temperature logs showed five exit points from the open hole section with one major connection (30% of the flow) and the four others reasonably uniformly distributed. Figure 9 shows two flow meter logs taken during stimulation and the early one shows a very similar flow distribution to the logs derived from the temperature surveys.

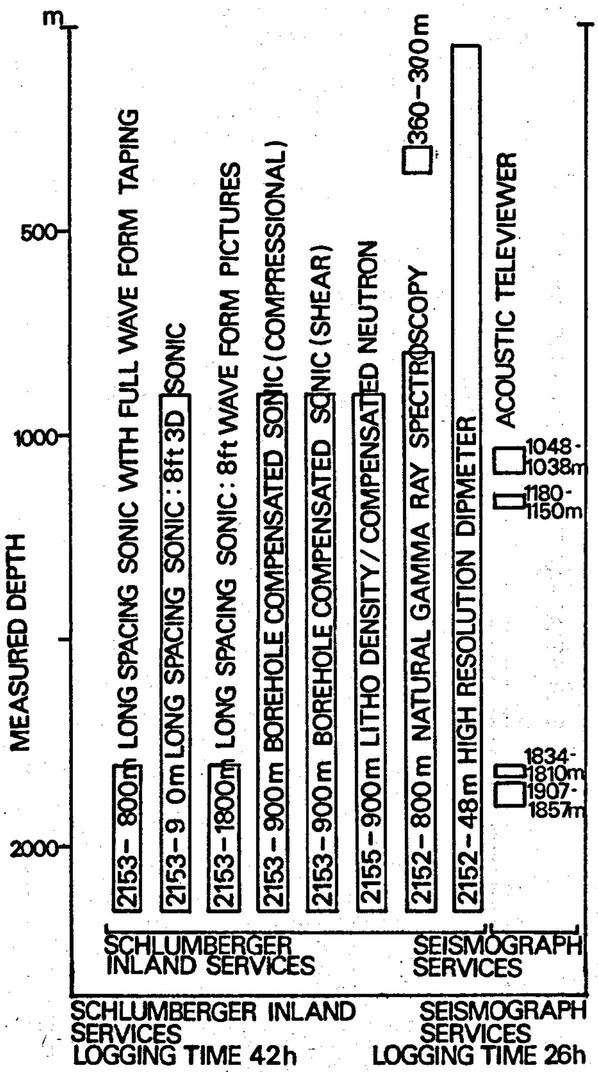

Figure 8: The logging coverage on the injection well

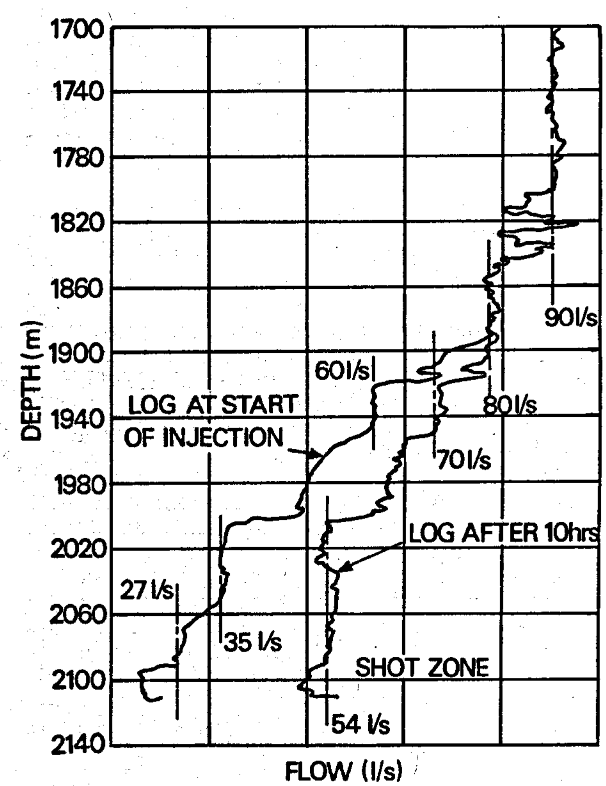

Figure 9: Flow meter logs during stimulation showing the shot zone developing

THE EXPLOSIVE STIMULATION

A depth of 2125 m was chosen for the top of the charge, which was 5 m long. The purpose of the explosive shot is described in detail by Batchelor (1982) but, briefly, it is designed to open self-propped fractures at the wellbore to provide low impedance connections to the natural fracture system prior to hydraulic stimulation.

The complete success of the process is evident in Figure 9, where the second flow meter log, approximately 10 hr after the first, shows more than 60% of the flow is leaving the well in that region. The explosive tool ensures that the minimum pressure loss occurs at the well bore/fracture connection and full pressure can then be applied within the formation.

THE MICROSEISMIC EVENT LOCATION SYSTEM

The only method which can be used to define the extent of a hydraulically stimulated region is microseismic event location mapping. This technique has been used with great success at LANL (for example, Smith et al, 1982) using single sonde, multiaxes geophones. At the site in Cornwall, however, the granite was exposed at the surface and tests had showed that the attenuation factor, Q, was greater than 150 at frequencies up to 1 kHz. This meant that a surface sensor network in shallow boreholes (up to 200 m deep) could be used in conjunction with a downhole system. Vertical axis accelerometers were used in the surface net with three hydrophones deployed on a standard logging cable forming the sub-surface system.

All of the data was collected on the site VAX 11/780 computer via a multi-channel transient digitiser. The signals were then processed via a purpose-written code 'METAL' (Microseismic Event Timing and Location) which used a variety of location algorithms, HYPO (Ref Lee et al (1975)), SPAM (Ref Dechman et al (1977)), and EMI (Ref Thorn-Emi (1981)), to derive locations and rms errors. The system is described more fully in the Project progress reports (1982a and 1982b).

Many thousands of events were detected with one calculated maximum local magnitude of 0.6. Several hundred of the events were large enough to be seen on a surface seismometer network consisting of eight stations at radii of 1 km to 6 km. This surface network was operated by the Global Seismology Unit of the Institute of Geological Sciences.

The event maps are shown in Figures 11 & 12 in the section of the hydraulic stimulation.

THE HYDRAULIC STIMULATION

The purpose of the hydraulic stimulation was to interlink the two wells that were 350 m apart vertically and 200 m horizontally. See Figures 6 and 7. The minimum earth stress was estimated to be 30 MPa at 2000 m, meaning an effective surface pressure of 10 MPa or more would be required to open a favourably orientated joint.

The offset between the joints and the stress direction is shown in Figure 5, meaning that a pressure in excess of the minimum earth stress would be required to open the most favourably orientated set. This pressure was calculated to be 16-18 MPa. Any one joint forming a direct connection between the wells would need 400 m^3 of fluid if it was dilated to a width of 1 mm over a circular area centred on the injection point. There were between 5-10 such joints within the open hole section and a minimum volume of 4000 m^3 was thought necessary to achieve connection with this simple mechanism.

Figure 10 shows the pressure history on the injection well. The pressure peak was reached after 3 hrs but the initial response on the production well, RH11, was a fall in water level and this continued until the point indicated on the figure. The level fell by approximately 150 m in 14 hrs before turning. The water level then began to rise at an ever

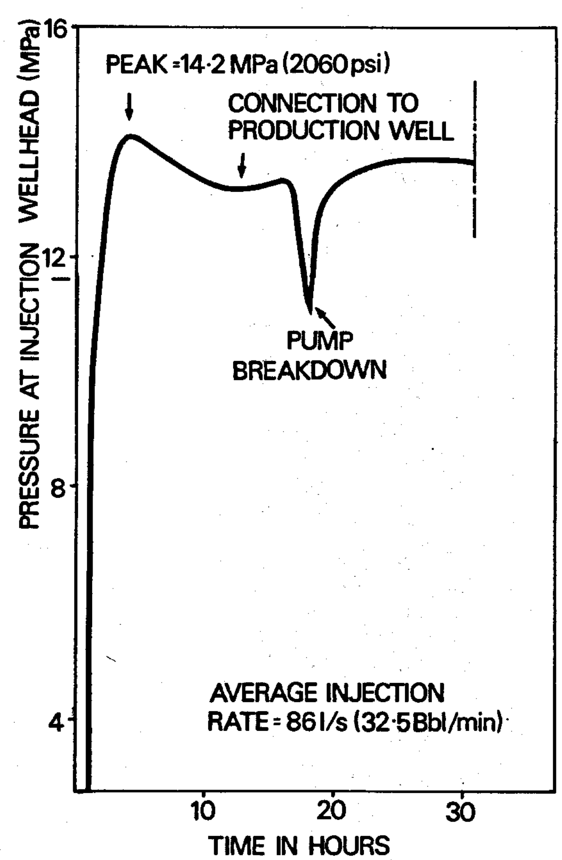

Figure 10: Pressure history on the injection well during stimulation

accelerating rate and the well was filled after the pressure rise was seen to be sustained for 4 hrs.

After 22 hrs of pumping, the production well commenced flowing and the surface pressure control equipment was fitted to enable the pressure to rise on the well. The high injection flow rate was continued until a total of 9000 m^3 (56 600 Bbl) had been injected.

The surface pressure in RH11 rose steadily and production was commenced when it had reached 2.8 MPa (400 psi). The flow declined rapidly and 8 cycles of production and shut-in were used to determine if the connection was improving. Eventually, a sustained 2 l/s was produced for 24 hrs and no further improvement was observed using this procedure. This period lasted 80 hrs and consumed a further 9000 m^3 to maintain a wellhead pressure of 10.5 MPa. There were no significant perturbations in the injection well pressure as the production flow from RH11 was cycled.

It was concluded that there was no direct connection between the two wells and that production was controlled by a diffusive zone fed by a "constant pressure" boundary within the main structure.

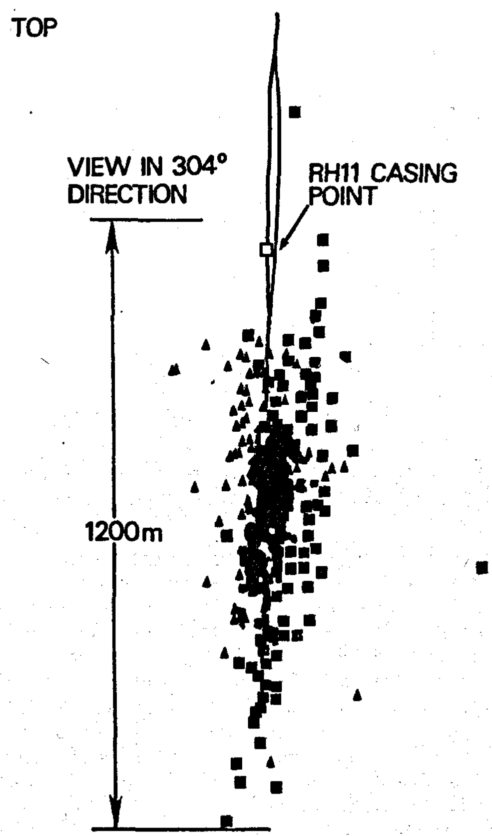

Figure 11: A vertical section through the seismic events at the reservoir

During this period it had been established (see Figure 9) that the majority of the water in the injection well had left the borehole at the shot zone despite the presence of natural fractures elsewhere that had accepted flow at low pressures. The conclusion was that the lower impedance outlet at the shot had enabled a more satisfactory widening of a natural joint set in that vicinity.

The seismic events (see Figures 11 and 12) had been triggering the automatic acquisition system at a rate of one every 5-10 secs and continuous interpretation proved impossible. The two maps were not produced during the fracturing but plan and borehole section plots were used which gave the false impression of an unstructured sphere of events about 350 m in radius. However, it was clear that both wells were completely enveloped by the seismic events and that two thirds of them were from below the reservoir by as much as 600 m.

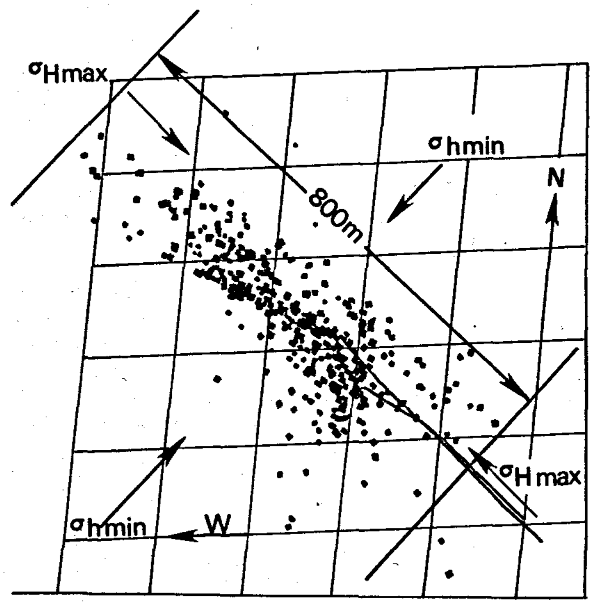

Figure 12: A projection of the seismic events normal to the main structure

When the downward growth was identified, a study of the shear stress gradient showed that shearing would indeed produce downward growth because the gradient was subhydrostatic. The first circulation results showed that water in excess of the TD temperature of the production well was being produced, thus demonstrating that heat transfer was occurring in the deep sections of the region.

The flowing connections to RH11 under injection conditions were know but it was not possible to log in RH11 under initial production because the hydrophone string was positioned in the well. It was decided to try a short (2 hr) high flow rate injection into RH11 in an attempt to form a direct connection to the reservoir and risk the creation of a separate system from RH11.

This injection was completed successfully and the well was put on immediate production flow at 78 l/s (29 Bbl/min) to flush the joints in and around the well. However, it was observed that RH12's shut-in pressure dropped rapidly during the 2 hr pump into RH11 but stabilised immediately the injection to RH11 ceased. This was taken to indicate that no direct connection was formed and, indeed, eventually, a flow of 3.7 l/s could be sustained for 48 hrs, an increase of only 1.7 l/s.

The production well, RH11, was then shut in and a pressure of 2.5 MPa was reached over a 16 hr period with steady pumping into the injection well at 25 l/s. The injection flow rate was then increased rapidly but the rate of pressure increase on RH11 decreased, showing that the perverse influence had not been eradicated. The implication was clear; much more energy was required to break down the final high impedance barrier.

It was decided to pump a nominal 100 l/s into RH11 until a significant change was observed in RH12 or the microseismic data indicated excessive upward growth from RH11.

Figure 13 shows dP/dt of the shut-in pressure on RH12. The ever decreasing fall of dP/dt during the day is evident but, as the injection into RH11 ceased, the pressure started to rise. A total of 3200 m^3 (20 100 Bbl) was injected but the pressure just rose steadily (maximum 11 MPa, 1600 psi) and showed no signs of a breakdown. The injection was terminated because a cluster of microseismic events were received within a few metres of the casing shoe.

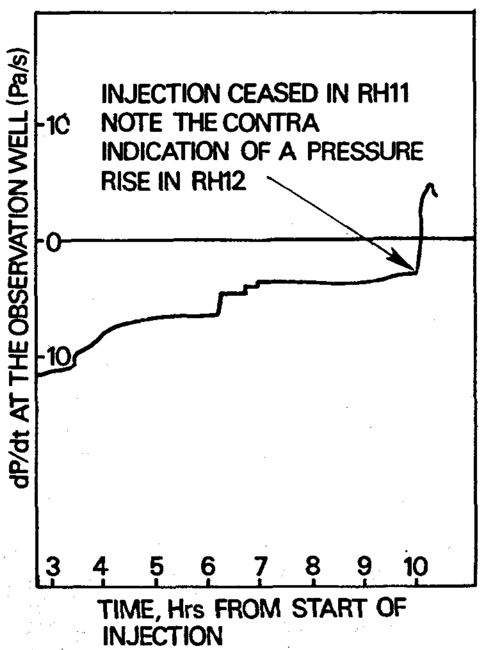

Figure 13: dP/dt at RH12 showing the marked rise when pumping ceased on the other well

RH11 was left shut-in and then pumping commenced again on RH12 at 100 l/s. Figure 14 shows the wellhead pressure in RH11 and note that the pressure falls more slowly from 7.8 MPa. This was just at the point when pumping ceased on the other well because of a weld failure.

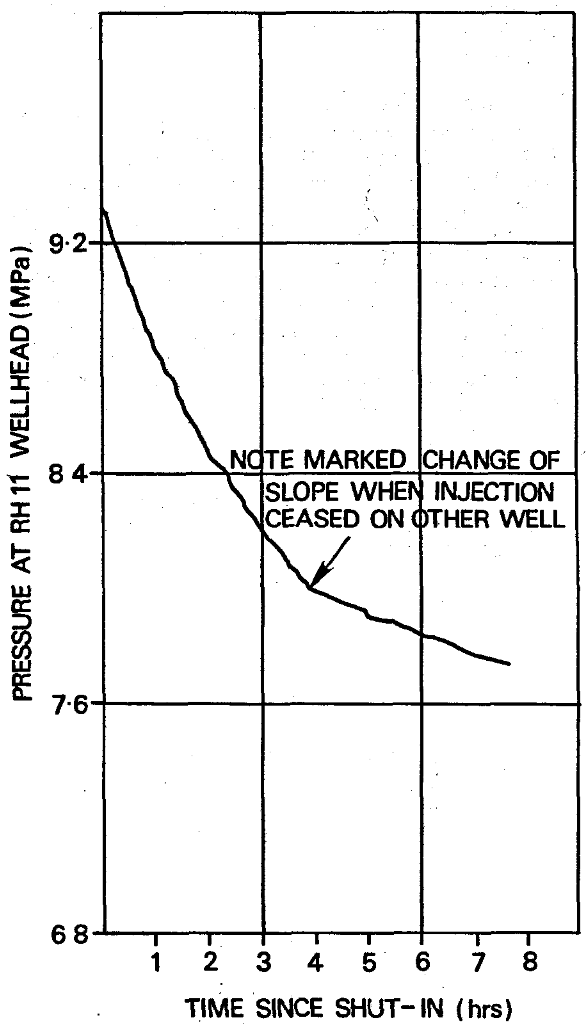

Figure 14: RH11 wellhead pressure after the 3200 m^3 injection and before production

Despite the massive injection into RH11 it was thought that no direct connection could exist because of the perverse nature of the pressure responses and it was decided to commence production on RH11 in an attempt to understand the mechanics of the connection to the well. Figure 15 shows the wellhead pressure during this period; production drew the well pressure down significantly until a pressure of approximately 3.8 MPa was reached. At this point, it proved possible to hold the pressure reasonably steady by increasing the injection flowrate on RH12 and raising its pressure. This was the first time that there was an indication of a flowing connection between the wells that was able to sustain a reasonable and increasing flow rate. The pressure did decline initially during the increase in RH12's pressure but, thereafter, it remained steady.

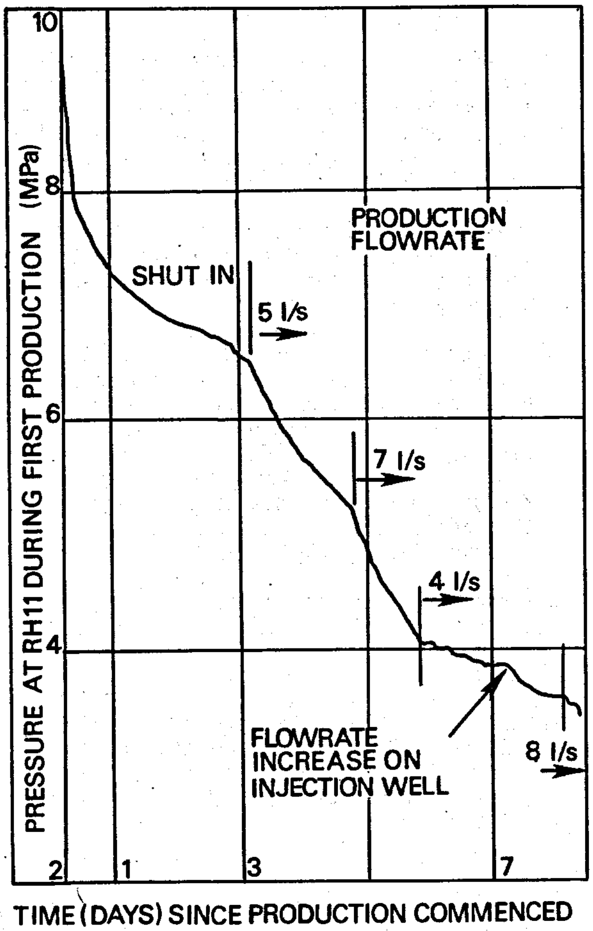

Figure 15: RH11 wellhead pressure during initial production

PRELIMINARY ANALYSIS

a **The stored volume**

The reservoir region delineated by the micro-seismic events is 1200 m high, 800 m wide and 100 m thick, a volume of 96×10^6 m^3. The stored water volume was of the order of 40 000 m^3 which, therefore, would only require a 0.04% porosity change to accommodate it within such a rock volume. This is the equivalent of a 0.4 mm dilation/m, which appears to be a realistic value.

b **The seismicity**

Microseismic activity after massive stimulation has generally declined but the system is apparently pressure-sensitive because the event rate increases rapidly when the injection wellhead pressure on RH12 exceeds 10.5 MPa. It is not clear whether or not the seismicity is related to the absolute pressure value or the differential pressure across the wells.

Figure 11 shows that the majority of the reservoir has been developed to the North East of RH11, although there is considerable microseismicity at the base of the well. This is in good agreement to the hydraulic data which indicates that the connection has been made by a tortuous path.

c **Geochemistry**

The return water has been sampled for a suite of ions and its radon content has also been monitored. The data is influenced by the cement and drilling additives, but it would appear to imply that the residence time was of the order of 5 days and could be reducing. No tracer tests have yet been run because of the lack of hydraulic equilibrium.

d **Hydraulic data**

The most important observation to explain is the perverse, repeatable and reversible effect that increasing pressure on either well causes the pressure to reduce on the observation well.

There is only one mechanism that can cause a reduction in pressure and that is that an increase in available storage volume occurred that could not be fed by the injection zone.

Figure 16 is a graphical output from a fully explicit computer code, FRIP, (Ref Cundall, 1981), that models the rock mass as discrete blocks that can shear, deform and translate in space. It supports the hypothesis that dilation zones can form within a jointed,

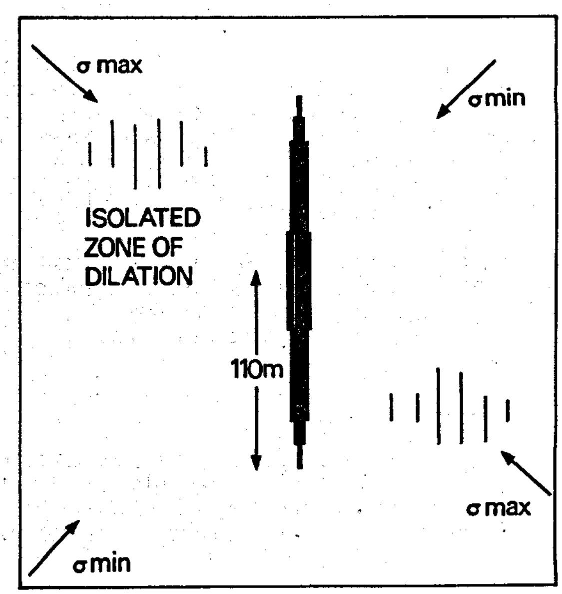

Figure 16: The results of the reservoir simulator code showing isolated dilation zones

discontinuous rock mass simply because the confining stresses are disturbed by the pressurised zone.

The position of RH11 is such that the majority of the openhole section is aligned in this manner with respect to the growing structure from RH12.

The implication of this modelling is that seismicity can be generated in regions not associated with flow from the main structure. However, there is no evidence to support the converse argument that flow could occur without seismicity.

Hydraulic access to these zones is dependent on generating flow normal to the main structure and it will be essentially diffusive through tightly shut joints.

During the circulation trials, it was tentatively concluded that the production well should be kept at sufficient pressure to cause reasonable joint dilation and, hence, a reduction in inlet impedance but not so high that the dilation zones were affected adversely by causing a low differential pressure. It appeared possible to increase the flow rate from the production well with a much smaller decrease in pressure than had been observed at higher total pressures. This confirms an observation of Tester (1981) that the impedance reduction caused by high back pressures was associated with excessively restricted flow and that there was an optimum, but low, back pressure to be found.

e The logging data

The injection well flow distribution changed markedly during the first few hours of operation but it has remained stable since that time.

The return flow pattern has changed both in temperature and flow rate. One of the most interesting observations was that water was entering the well at temperatures in excess of the highest temperature observed in the well (+81°C). Circulation must be occurring below the wells and sweeping through hotter rock.

All the return points are at positions that are known to have accepted water on injection but the reverse is not true; some of the low pressure injection zones did not produce fluid.

CONCLUSIONS

At the time of writing this paper, most of the results are only seven days old and so it follows that any conclusions must be of a tentative nature. However, some of the observations are irrefutable.

- Reservoir growth has proceeded normal to the minimum horizontal stress and not along a known joint direction. This confirms that the stress directions measured 10 km away in a local mine were of regional significance.
- The marked stress anisotropy has been confirmed by the restricted width of the seismically active zone.
- Seismic events were recorded with wellhead pressures as low as 4.5 MPa, although there is a marked increase in events when wellhead pressures in excess of 10.8 MPa are reached. The latter figure corresponds to the measured minimum horizontal stress.
- Two-thirds of the reservoir growth has been downwards and water is circulating through rock that is hotter than the TD temperatures of the wells.
- A mechanism of induced, isolated joint dilation has been observed which caused pressure reductions in the return well when the reservoir structure is pressurized; the reverse effect was also seen when it was depressurized. It takes between 2 and 14 hrs for the effect to diminish, implying that the zones are totally isolated from the reservoir away from the wells.
- Reservoir growth has been contained within a structure 1200 m x 800 m x 100 m and insignificant far field losses have been identified.
- Explosive stimulation provides sufficient self-propped fractures at the wellbore to allow hydraulic stimulation to activate joints more effectively than those which are not treated in this fashion.
- It is essential to predict accurately, or measure, the in situ stress field at any potential HDR site. The stress effects override the actual joint structure in controlling the reservoir zone.
- Seismic event rate is associated with the absolute value of the pressure and its rate of change. Adequate stimulation flow rates appear to be in excess of 90 l/s at this site.
- The majority of the events originate from shear, strike-slip motions within the reservoir and are obviously associated with natural joint activation rather than any fracturing.

Although the reservoir system is supporting a continuing return flow rate (8 l/s on 24 November 1982), with an equally increasing downhole temperature, it may not be possible to achieve the designed 50 l/s because of the suspected unfavourable borehole positions. However, the system will be hydraulically tested to its limits in the programme to understand the heat transfer aspects of the reservoir.

ACKNOWLEDGEMENTS

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The results reported here are the product of a research team. This paper would not have been possible without the dedication and commitment of all concerned, and the author gratefully acknowledges the contributions of the entire staff.

Much of the strategic planning for the programme was based on detailed discussions with the present and past staff at the Los Alamos National Laboratory and the author expresses his thanks for their support.

All the ideas expressed in this paper are personal opinions and are not necessarily endorsed by the UK Secretary of State or the Commission of the European Communities.

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