A COMPARISON OF HDR GEOTHERMAL SITES

J Willis-Richards, A S P Green, A Jupe

CSM Associates Liuited
Rosemanowes, Herniss, Penryn, Cornwall, TR10 9DU, United Kingdon
Tel: **+44 (0) 209 860141;** Fax: **+44 (0) 209 861013**

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ABSTRACT

A review of HDR projects has been carried out to establish the major controls on the performance of HDR reservoirs. The performance of an HDR system is measured in terms of water loss, pressure drop and thermal behaviour and it is clear that the different experimental HDR reservoirs have exhibited different performances. For example the Fenton Hill HDR reservoir at Los Alamos has a minimum water loss when operated at high overpressure whilst the Rosemanowes reservoir has minimum water loss at much lower pressures.

These different results may be explained in terms of the fracture geometry, morphology and material properties, the magnitude of the differential stresc and the magnitude of the least principal stress. These properties together describe the ease with which existing fractures may be opened and kept open by hydraulic stimulation and the extent to which they have been sealed over geological time. Issues of fracture network connectivity and rock material properties appear, in the majority of cases examined, to be of secondary importance.

It is proposed that HDR sites can be categorised by two parameters defined herein, namely their fracture opening potential and fracture closing potential, thus defining a spectrum of HDR behaviour. Using these factors, a simple spectrum capable of predicting appropriate ways of creating and operating HDR reservoirs can be defined.

1 INTROOUCTION

HDR geothermal exploitation requires the development of artificially enhanced permeability through a substantial volume of rock. This defines two phases, reservoir creation and reservoir operation. In practice, reservoir creation is largely identified with hydraulic stimulation, and operation with the strategy for circulation between two or more boreholes.

Experimental HOR programmes involving both reservoir creation and circulation have been carried out at Rosemanowes (UK), Fenton Hill (USA), Hijiori (Japan), Le Mayet-de-Montagne (France) and Fjallbacka (Sweden). The HDR reservoirs at these sites perform differently, however, if HDR technology is to be applied widely, it is important that some underlying general principles be established. The experimental work at these sites is briefly reviewed with the objective of establishing these principles. These reviews draw heavily on the review content of reports by CSMA (1993) and Evans et al., (1992).

1.1 Rosemanowes, Cornwall, UK

Three wells were drilled into a Variscan post-tectonic granite massif and two reservoirs developed, the Phase 2A at about 2000 m and the Phase 2B/2C at 2200 m to 2400 m. This second reservoir, after proppant placement, was termed the Phase 3A reservoir. One well, RH12, acted as injection well for both reservoirs. Two approximately orthogonal sub-vertical joint sets persist with depth with fracture densities between 0.8 and 5 m^{-1}. Less than 10% of these joints contribute measurably to flow into or out of wells in the unstimulated rock mass. Most of the joints appear to be relatively unaltered with chlorite surface coatings common on the older set and limited kaolinization on the younger set. Both sets are planar and rough surfaced and will dilate if sheared under low or moderate normal stress. The undisturbed formation permeability is between 1 and 10 µD.

Stress measurements down to 2600 m indicate a highly anisotropic state of stress with the principal stresses at 2.4 km being 34.8 MPa, 62.4 MPa and 82.2 MPa. The minimum and maximum stresses are horizontal.

The Phase 2A reservoir was developed between two wells (RH11 & RH12) about 250 m apart inclined at 30-40° and deviated in approximately the same direction as the maximum principal stress (NW). The injection well (RH12) was stimulated with a total of 26000 m^3 of water at pressures up to 14 MPa while the recovery well was stimulated with 4000 m^3 of water at pressures up to 11 MPa. The circulation performance of the reservoir was poor with only 30-40% recovery (Table 1).

Table 1: Circulation performance of the Rosemanowes reservoirs

Reservoir	Inj pressures (MPa)	Prod well back pressure (MPa)	Injection flow rates (ls^{-1})	Recovery %	Expt number
2A: 12 --> 11	10.5 - 11	0	17.5 - 20	30 - 40	2A052
2A: 12 --> 11	10.7	3.2	17.5	21	2A053
2A: 12 --> 11	5	0	5	60	2A059
2A: 11 --> 12	10	small	17.5. 12.5	~ >50*	2A064
2B/2C: 12 --> 15	9.8	0.2	23.6'	70 - 75	eg 2C004
2B/2C: 12 --> 15	9.4	-4.0	21.9	75	2C017
3A: 12 --> 15	9.2	0.2	21.5	85	3A008
3A: 12 --> 15	9.2	-4.0	21.5	> 100#	3A009
3A: 15 --> 12	4.2	0	10.0	30 - 40	3A032

* Non steady state, but lower impedance compared to 12 -->11 circulation

\# Non steady state, production from storage?

A third well (RH15) was drilled beneath RH12 with the openhole section inclined approximately 35° to the NNE. The Phase 2B/2C reservoir extended approximately vertically from well RH15 at 2400 m to well RH12 some 200 m above. It was created by a 5500 m^3 viscous gel stimulation from RH15 at pressures up to 14.5 MPa.

Extensive circulation from RH12 to RH15 was carried out for several years with much improved recoveries of about 70 - 75% (Table 1). The circulations became seismogenic if the injection pressure exceeded about 10 MPa with concomitant increase in water loss.

Proppant placement in the production well (RH15) during Phase 3A increased the circulation recovery to 85% and allowed recovery in excess of 100% for several weeks when a downhole pump was deployed. Reverse circulation gave a very poor recovery; this was attributed to the relative geometry of the wells (Table 1).

Rosemanowes is characterised by high fracture opening potential from differential stress and shear dilation properties, a moderate degree of fracturing and relatively little evidence of sealing or alteration processes. It therefore benefits from hydraulic stimulation, production well proppant, and down hole pumps. All significant water loss is associated with seismicity.

1.2 Fenton Hill, New Mexico, USA

Two reservoirs were developed at Fenton Hill, the Phase I reservoir at 2800 m depth in a homogeneous granodiorite and the Phase II reservoir at about 3550 m in faulted/sheared gneiss and schist. Direct observations of the fracture system are rare, a few spot cores being recovered from the gneiss/schist complex between 100 m and 1700 m depth. From these cores two fracture sets were identified, a sub-vertical and one parallel to the metamorphic foliation dipping at 26°. Fracture density is high, approximately 10 m^{-1} and the vast majority of the fractures have tightly sealed with a wide variety of secondary minerals including carbonates, quartz, hematite, clays and some sulphides. The undisturbed permeability of the rock mass is not reported but is thought to be extremely low.

The in situ stress is not as well defined as at Rosemanowes however the magnitude of the principal stresses at 2900 m in the granodiorite is approximately 29 MPa, 40 Mpa and 74 MPa and at 3550 m in the gneiss 35 MPa, 65 MPa and 86 MPa with the maximum stress vertical in both cases.

The Phase I reservoir was initially developed by nearly 200 m^3 of water stimulation injected at up to 12 MPa peak injection pressure. The connection between the wells was inferred to be sub-vertical with a minimum spacing of between 30 and 50 m between inlet and outlet. This small Phase I reservoir was sealed off by cementing and the injection well re-stimulated at 2930 m connecting to the production well some 250-300 m above; this is the enlarged Phase I reservoir. The enlarged reservoir was created by water stimulation (2300 m^3 in three experiments) at peak well head injection pressures of up to 19.5 MPa. The circulation performance of these reservoirs is summarised in Table 2.

The Phase II reservoir was initially developed by a massive water stimulation of 21300 m^3 at pressures up to 48 MPa. 54% of this fluid was recovered on venting, suggesting a well confined reservoir but no hydraulic link to the other well was made. A second water stimulation of 7570 m^3 was made from the second well at pressures up to 41 MPa but again no connection resulted. The second well was then side-tracked into the microseismicity from the original stimulation and stimulated; the circulation performance of the resulting Phase II reservoir is summarised in Table 2.

Sustained reservoir pressurisation between 7.5 MPa and 19 MPa was carried out for over two years without circulation between the ICFT and LTFT. Very low steady state water losses were found.

Fenton Hill is characterised by extreme fracture alteration and sealing resulting in low in situ permeability and low water losses. Moderate differential stress exists to promote fracture shear and dilation. It therefore benefits from circulation with a high production well back pressure which keeps the reservoir fractures somewhat open but without causing excessive far field water loss. Nevertheless, in the Phase II reservoir, the high minimum principal stresses keep the fractures relatively tightly closed near the production well and the impedance is therefore high.

Table 2: Circulation performance of the Fenton Hill reservoirs

Reservoir	Inj. pressures (MPa)	Prod. well pressure (MPa)	Injection flow rates ( )	Recovery %
I Small (RS2)	10 (dropping)	None	8 --> 14.5	85 --> 99
I Small (RS3)		9.6	6.3 --> 9.5	70 - 80
I		1.1	6.0	84
I Enlarged (RS4)	9.65	~ 1.5	10.6, 18.5	~79, ~67
II (ICFT)	27, 30	3.5		
II (LTFT)*	27.6	9.7	6.5	88

* The impedance dropped remarkable towards the end of this test in response to production well pressure cycling; steady state was not reached so these results are not given

1.3 Hijiori, Yamagata Prefecture, Japan

Experiments have been carried out at depths of about 1800 m, some 300 m beneath the contact between the granodiorite with overlying volcanic rocks. Little core is available and fracture characterisation is based on chippings analysis and logs. Alteration zones with chlorite/sericite and anhydritelgypsum suggest that hydrothermal fracture surface alteration may be extensive in some parts but not in others. Fractures of hydraulic significance appear to be steeply dipping. The minimum earth stress would appear to be horizontal with a magnitude of 26 - 27 MPa. Normal slip fault plane solutions suggest that the overburden weight is the maximum principal stress, about 47 - 48 MPa at 1800 m. Due to temperature considerations (about 250 C at 1800 m) the in situ hydrostatic pressure at 1800 m is somewhat less than 18 MPa.

Four wells have been drilled; SKG-2 for injection and recovery from HDR-1 (40 m S of SKG-2), HDR-2 (40 m SW of SKG-2) and HDR-3 (60 m NE of SKG-2). All stimulations have been performed in the injection well, SKG-2. A total of about 4000 m^3 of water was used at well head pressures of up to 15 MPa.

Circulations at 16.7 1 s^{-1}, producing from HDR-1 and subsequently HDR1 plus HDR-2 achieved 35% recoveries with well head injection pressures of about 5 MPa; these circulations were both seismogenic. Both HDR-1 and HDR-2 were located using microseismicity detected during initial stimulation of SKG-2. Both of these wells approach SKG-2 closely (<50 m); it would seem possible that the microseismic locations (and indeed the well steering) were not sufficiently accurate for proper azimuthal control. Of the two production wells, HDR-2 which was (nominally) in the direction of the maximum principal stress relative to SKG-2 produced most.

HDR-3 was drilled subsequently to the NE of SKG-2, guided by the direction of seismic growth during earlier circulation. Recovery from HDR-1, HDR-2 and HDR-3 of 80% of an injection flow rate of 16.7 1 s^{-1} was achieved using a pumping pressure between 3 to 4 MPa (although as earlier thermal density drive also assists). Thermal draw down was observed but no seismicity recorded.

Moderate fracture opening potential exists due to the relatively large differential stress and limited extent of the alteration zones whose beneficial effects are reduced somewhat by the relatively high effective minimum stress of about 10 MPa. Excessive water loss appears to be related to continued microseismicity in the far field which suggests that no network of extensive naturally open fractures exists. No stimulation of the recovery well or proppant placements have yet been attempted at Hijiori. The small scale of the reservoir, well survey errors and microseismic location errors means that some care should be taken if geometric arguments are to be used to explain reservoir behaviour.

1.4 Le Mayet-de-Montagne, France

Two boreholes (111-8 and III-9) were drilled to 750 m TVD into a Variscan granodiorite on the northern fringe of the Massif Central. Four families of sub-vertical fractures were identified from surface mapping while borehole logs with an imaging resistivity tool revealed a wide variety of azimuths of sub-vertical fractures. Fractures examined during surface mapping show evidence of past shear displacement and have extensive surface coatings of silica, occasionally with hydro-muscovite, or calcite/montmorillonite layering up to 2 cm thick. Laboratory studies show the fractures to be highly compliant, with low friction angles and extremely low shear dilation angles; these properties are due to the mechanical properties of the fracture surface coatings. Undisturbed formation permeability is unknown.

At 700 m depth the minimum horizontal principal stress is about 9-10 MPa, the other horizontal principal stress and the overburden weight are about 17-19 MPa. The in situ fluid pressure is assumed to be hydrostatic at about 7 MPa.

The injection well (III-9) was stimulated by several small viscous gel treatments of individual packed off fractures. A small circulation, relying on the unstimulated natural fractures (in well 111-8) for production, gave a recovery of 36% at a flow rate of 8.3 $l\ s^{-1}$. The injection pressure was 8.2 MPa and some microseismicity close to the injection well was recorded.

Subsequently 2 m^3 of proppant was placed around well III-9 and the direction of circulation reversed. A recovery of 18% was achieved. The injection well pressure of 9 MPa was insufficient to cause seismicity during these circulation. Some 33% of the injection water returned up the injection well annulus from a fracture at 550 m, some 160 m above the injection zone isolating packer. Recovery dropped to 12% when the flow rate was doubled to 16.6 $l\ s^{-1}$, and further to 10% when a production well back pressure of 4 MPa was applied. 9 microseismic events were recorded during this phase with an injection well pressure of nearly 11 MPa.

It was decided to return to the original configuration and-to treat the production well by stimulation and proppant placement. A total of 170 m^3 of gel and 7 tonnes of proppant were placed around well III-8. No seismicity was recorded and the peak pressure reached was 12 MPa. The recovery from well 111-8 again amounted to 36% together with some 22% from a shallower well equipped with a downhole pump. A larger stimulation of 111-8 was then carried out with 400 m^3 of gel carrying 40 tonnes of proppant injected at high flow rates. Despite high pressures no microseismicity was detected.

A long term circulation followed from III-9 to 111-8. Recovery at low flow rates, when the injection pressure was below the minimum principal stress, varied from 68% to 82%. At higher flow rates (>10 $l\ s^{-1}$), when the injection pressure was higher than the minimum in situ principal stress, the recovery dropped rapidly to less than 50%. No thermal draw down was observed.

The injection pressure required to cause microseismicity at Le Mayet is inconsistent with the estimated values of the principal stresses and the frictional properties of the fractures. This would suggest that there remains some uncertainty in the stress interpretation.

The Mayet-de-Montagne site appears to offer only moderate fracture opening potential (probable low differential stress, low shear dilation angle, highly altered and compliant fractures) and has a prolonged history of fracture alteration and sealing. Reasonable recoveries were only achieved by repeated stimulation with large amounts of proppant. Low water recovery under aseismic circulation conditions and the emergence of a large fraction of the injection flow from a single fracture 160 m above the injection zone suggests vertically dominant flow and the existence of large conductive natural features.

1.5 Fjallbacka, Sweden

Two shallow wells were drilled into a pre-Cambrian (890 Ma) granite massif. One horizontal and three sub-vertical fracture sets are present; all persist to 500 m depth. Despite a fracture density in the boreholes of between 0.5 m^{-1} and 2.7 m^{-1}, evidence of fluid flow in the unstimulated system appeared only in small groups of fractures about 20 - 30 m apart. Below 200 m all the permeable fractures are believed to be sub-horizontal.

Stress measurements suggest that both horizontal principal stresses exceed the overburden weight. Thus the least principal stress is vertical and horizontal fractures open most readily in response to jacking and sub-horizontal fractures in response to shear stimulation. At 460 m the overburden weight is about 12 MPa, the in situ fluid pressure nearly 5 MPa and the maximum horizontal stress about 20.5 MPa.

The reservoir was developed by hydraulic and viscous gel stimulation with proppant placement (total fluid volume 400 m^3) into a 30 m zone isolated by straddle packers. Most of the injected fluid was accepted by a naturally permeable fracture zone at 455 m depth. The permeability of the stimulated zone increased from about 10 μD to 10 mD. Microseismic monitoring showed growth along a sub-horizontal plane; this was used to target the second well which intersected the seismicity 100 m away.

A number of small scale hydraulic stimulations plus a viscous gel proppant placement were used to lower flow impedance in the immediate vicinity of the second well. The total fluid volume used was about 270 m^3.

Circulation at nearly 2 $l\ s^{-1}$ took place between the two boreholes, 100 m apart at a depth of 460 m. The second well was used for injection. The maximum recovery was 51% with a cross reservoir pressure drop of about 5 MPa. Several hundred microseismic events were detected during the circulation which lasted 35 days. Thermal draw down was not seen.

The Fjallbacka site has good fracture opening potential (fresh fractures, reasonably large differential stress, moderate effective minimum stress) and little sign of extensive fracture sealing or alteration which would let them close again after stimulation. The moderate recovery achieved seems to be linked to continued rock mass stimulation due to the high circulation fluid injection pressure. This, in turn, is probably the result of inadequate stimulation volumes (total 670 m^3 for 100 m well separation).

2 DISCUSSION

The following general points may be noted from the reviews:

1 Microseismic locations show regions of high transmitted fluid pressure; these regions form good targets for fluid flow connections. Major permeable flow paths connected to an 'infinite storativity' far field may not be seismogenic although this point is as yet unresolved.

2 Fluid flow in stimulated basement is anisotropic; the main directions of fluid flow (and of microseismic development) are broadly normal to the direction of least principal rock stress.

3 Abundant fractures approximately normal to the present day least principal stress are found at most sites.

4 Fractures of a given set are not exactly parallel with each other but often intersect at acute angles; this is roughly equivalent to saying that a single fracture set commonly shows a range of fracture orientations within which connected flow may take place.

5 Measurable flow in both stimulated and unstimulated reservoirs takes place on a much smaller proportion of fractures than purely geometric arguments would suggest; this implies that tectonic and flow histories have interacted over time to produced a concentrated or channelled flow pattern.

6 Where natural fractures exist it appears to be difficult to create new hydraulic fractures; where observed new fractures probably do not penetrate far although interaction with natural fractures may give an impression of a large fracture in well test responses.

7 Near well bore thermoelastic fracturing of injection wells is common.

8 All the shallow sites (<1 km) have low differential stress magnitudes, often by a factor of 5 or 10 less than is found in the deeper sites (>2 km) which more closely reflect likely commercial conditions. The amount of shear displacement and hence shear dilation that can be induced during stimulation is smaller at the shallower sites.

9 High effective normal stress near the production well can reduce fracture apertures and contribute significantly to reservoir impedance. This can be counteracted successfully by proppant placement.

10 High circulation fluid loss rates are characteristically associated with continued microseismicity.

11 Fluid recovery is characteristically poor where production well stimulation or proppant placement is ignored.

The points above appear to be common to all large scale HDR experimental sites in basement rock. The major difference differences between the sites is based on the nature of the natural fracture network and the in situ stress conditions. Table **3** list a number of factors from the review of HDR projects that can be seen to be important in determining the response of a fractured rock mass to hydraulic stimulation and circulation.

Table **3:** Relative importance of site characterisation data for distinguishing HDR behaviour at different sites.

Factor	mportance	Notes
1 Rock elastic properties	2	Small range (x2?) seen in HDR
2 Rock fracture toughness	1	New fracture creation difficult' difficult in presence of existing natural fractures
3 Fracture orientation distributions	2	Fractures near to normal to min principal stress seem to be ubiquitous
4 Fracture length distributions	3	Microseismic source parameter distribution seems similar for many sites
5 Fracture condition/properties	5	Determines whether or not shear dilation will take place as a result of shear wide range seen
6 Differential stress magnitude	4	Determines maximum possible shear displacement when effective fracture lengths are similar
7 Min effective stress magnitude	5	With 5 determines how fractures close up after stimulation
3 Friction angle of fractures	2	Relatively small range. stimulation pressures at or above minimum principal stress are common

The three first order factors are fracture condition (5), differential stress magnitude (6) and minimum effective stress magnitude (7). Figure 1 shows these factors plotted on a 3-dimensional diagram. In addition to the five HDR sites reviewed data from Soultz (France), Falkenberg (Germany), Urach (Germany) and the Gamma Project (Japan) are also included.

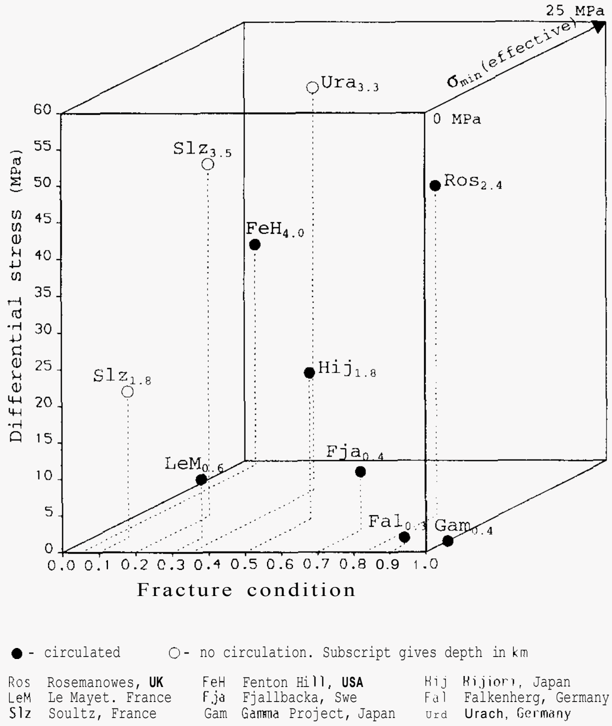


Figure 1 Characterisation of HDR experimental sites by fracture properties and state of stress

In order for any categorisation to be of value it need to have some predictive potential. For HDR development it should suggest reservoir creation and circulation strategies for a potential HDR site. The most important aspects are the fracture opening potential under stimulation conditions and fracture closing potential when fluid pressure is reduced to circulation conditions. Table **4** identifies the factors contributing to fracture opening and closing potential

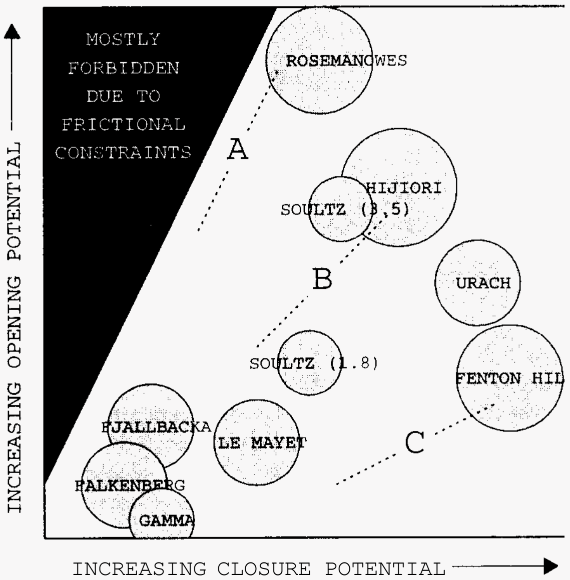
Table **4:** Factors contributing to fracture opening and fracture closing potential

Opening potential axis			Notes
Differential stress	Low	High	High shear stress drives large displacements
Shear dilation angle (roughness / smoothness)	Low	High	High dilation angle creates large apertures
Rock material stiffness	High	Low	Low stiffness allows large shear displacements
Fracture material strength	Weak	Strong	Strong fracture material will create less gouge during shear
Fracture extent	Small	Large	Large fractures have lower shear stiffness
Closure potential axis			
Minimum effective stress	Low	High	High minimum effective stress can greatly reduce aperture ·
Fracture material strength	Strong	Weak	especially if the fracture wall material is weak

A two dimensional representation is needed whereby the two axes relate directly to opening (reservoir creation) and closing (reservoir operation) potential.

In order to construct this two dimensional spectrum the 'fracture condition' from Figure **1** is sub-divided into those aspects relating to acquisition of aperture during stimulation (shear dilation angle) and those relating to how much of the stimulation aperture is retained under circulation pressures. These are respectively combined with the differential stress (which drives the shear movement) and with the minimum effective stress (which drive fracture closure as the fluid pressure is reduced). Thus semi-quantitive measures termed fracture opening potential and fracture closure potential respectively form the two axes.

Figure 2 places the experimental HDR reservoirs of Figure 1 within a spectrum and shows the appropriate reservoir creation and operation strategies.



A High shear stress, fresh rough fractures, low permeability. Large stimulations, proppant at prod. well, downhole pumps?, limit P,

B Moderate shear stress, altered fractures, faults?, heterogenous permeal. Large stimulations, use much proppant, downhole pumps

C High normal stress, altered fractures, very low permeability. High pressure stimulations, use much proppant, high prod. back pressure to help keep propped fractures open

Figure 2 Spectrum of HDR site behaviour

In rock masses characterised by a low degree of fracture opening potential large scale hydraulic stimulation alone is unlikely to be able to create a satisfactory reservoir. In cases where natural permeability is very low, due to sealing, such systems may benefit significantly from large scale proppant placement or operation under high production back pressure without excessive fluid loss. These two operating strategies effectively reduce the closure potential by modifying the fracture material properties (via proppant) or the minimum effective stress (by maintaining high fluid pressure throughout the reservoir). Fenton Hill and Le Mayet de Montagne can be seen to be typical of such sites.

In rock masses characterised by high degrees of fracture opening potential and low fracture closure, large scale stimulations are much more likely to be able to create a reservoir. However, excessive circulation injection pressures may lead to unacceptable water loss associated with continued microseismicity. In the case of moderate to high permeability formations, operation of an HDR system would benefit from draw down of the production well and far field fluids could contribute to production. Soultz at 3.5 km depth and Rosemanowes are representative of this category.

3 CONCLUSIONS

A review of HDR experimental sites shows that the condition of the natural fractures and in site stress are the most important factors affecting the development of an HDR reservoir. An HDR spectrum has been defined based on the fracture opening and closing potential of the natural jointing which relates to reservoir creation and operation as follows:

Reservoir creation --> Fracture opening potential under stimulation conditions

Reservoir operation --> Fracture closing potential when fluid pressure is reduced to circulation conditions

Although this classification of HOR reservoirs is undoubtedly oversimplified, it does highlight a number of fundamentals about HDR reservoir behaviour.

1 There is no such thing as a typical HDR site, but the range of variations can be understood in the light of some simple idealisations.

2 The appropriate operational conditions for an HDR reservoir are governed by the condition of the natural fracture system and in situ stresses.

It is believe that the positioning of a potential HDR reservoir within the spectrum based on rock mass characterisation helps direct attention towards the more significant aspects of the physics and geometry and suggests that distinct strategies for development and operation are required for HDR reservoirs at different positions within the spectrum.

HDR reservoir creation and operation processes are clearly wide ranging and site specific. However it is important to appreciate that the relative success or failure of some reservoir creation or operation technique at any site may therefore reflect the specific conditions at the site rather than the intrinsic characteristics of the technique itself.

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