increase are three further tests held at flow rates of 32.8, 29.5 and 33.4l/s respectively (Richards et al., 1994). In all cases injection pressure is within the range 9.5 – 11.1MPa (Richards et al., 1994).

Results of the tests confirm the findings of the Phase 2B work (Parker 1989b). At injection rates below the minimum lithostatic stress (~10MPa) there is a roughly linear relation between decreasing impedance and increasing injection pressure/flow rate (Parker, 1989b). The overall minimum achieved is around 0.5MPa/(l/s) at a flow rate of 32.8l/s (Richards et al., 1994). Likewise, a proportional, roughly linear relationship is observed between increasing injection and increasing production flow rates (Parker, 1989b). Maximum production flow rate in RH15 is around 21.5l/s, recorded at both 33.2 and 32.8l/s injection (Richards et al., 1994). Use of injection pressures greater than 10MPa result in a marked increase in microseismic activity signaling reservoir growth and increased water loss (Parker, 1989b). Optimum operating conditions thus become a compromise between pressure and flow rate, which are kept as high as possible whilst still remaining below the minimum lithostatic stress (Parker, 1999). In this case best reservoir performance is achieved at an injection rate of around 24l/s and pressure just below 10MPa (Parker, 1999).

In early August of 1987 a downhole pump is installed at depth in RH15 in an attempt to boost production by lowering the downhole pressure in the production well (Parker, 1999). Experiments using the pump last for several months during which time it becomes clear that it provides little real advantage to reservoir performance (Parker, 1999). It appears that the sub-hydrostatic pressure at depth causes a “pinching” of joints near the well bore and actually increases the resistance to flow, triggering a significant rise in impedance from 0.61 to 0.82MPa/(l/s) (Parker, 1999). Any advantage gained in pressure drop across the reservoir is thus expended in overcoming the increased impedance to flow (Parker 1989b). One potential solution to this problem may be the use of proppants within the near-well joints (Parker, 1989b).

The downhole pump is removed from RH15 in late October 1987 and the system returned to normal circulation. A long term flow test is commenced in November 1987 during which injection flow rate is held constant at around 21.5l/s and pressure
around 9.5MPa (Richards et al., 1994). Production flow in RH15 is reasonably constant around 14l/s. Circulation is held constant in this way for four months during which time it becomes apparent that the reservoir is cooling by around 1°C per month (Parker, 1999). Thermal modelling of the drawdown concludes that the heat transfer area of the reservoir is only around 150,000m², far smaller than that which was originally envisioned (Parker, 1989b; Parker 1999). Given the size of the microseismic cloud generated during the original stimulations, it appears that only a relatively small part of the total reservoir is host to the main flow paths (Parker 1989b). It is not clear however “whether these the main flow paths...are being fully swept or whether the flow is being channelled...producing a short circuit” (Parker, 1989b).

In order to answer some of the questions regarding the nature of fluid flow paths through the reservoir a Flow Characterisation Experiment (FCE) is conceived and carried out from March to July 1988. An inert tracer is injected at three different depths in RH12 and sampling is made at three different depths in RH15 (Parker, 1999). Of the nine possible flow paths it is found that only four are carrying more than 1l/s of the total well production (Parker, 1999). Of these four it is found that one path, that with the shortest breakthrough time, is carrying more than half the total flow indicating that it is most likely the short-circuit (Parker, 1999).

In all, the constant injection regime is maintained in the reservoir for nearly nine months until July 1988. During this time a number of tracer tests are conducted and it is found that, over time, the tracer median volume increase is approximately linear with respect to the thermal energy extraction (Parker, 1999). This effect may be linked to thermo-elastic contraction within the cooling reservoir, the presence of which is also suggested by post-circulation cross-hole seismic surveys (Parker, 1999).

The final stage of Phase 2C in September 1988 involves the manipulation of the reservoir by use of a massive oscillation testing in RH15. A series of 1 hour long oscillations are generated over a period of 100 hours with production rates varying from 0 to 45l/s at backpressures between 0 and 5MPa (Parker, 1999). Results of the test are indifferent with only a slight, relatively short lived improvement in reservoir
performance (Parker, 1999). Post-oscillation testing does however reveal a reduction in the near well impedance, most likely as a result of the physical removal of material from fractures around the well (Parker, 1999).

Following completion of the oscillation tests the reservoir was returned to constant circulation to await the commencement of **Phase 3** of the well program.

**1988 – 1991**

The third and final phase of the Rosemanowes project begins in late 1988. The major aim of this phase is “the development of a prototype commercial system for generating electricity” (Parker 1999). Experimental work to be conducted during this period includes that which aims to investigate “methods of manipulating the unsatisfactory Rosemanowes reservoir to improve its thermal performance by reducing the importance of the (known) short circuit” (Parker, 1999). Techniques to be employed in the achievement of this latter aim include the use of proppants to reduce the impedance around the production well (previously determined as comprising around 70% of the total system impedance) and the use of additional targeted viscous stimulations (Parker 1989b; Parker, 1999).

In early 1989 55 tonnes of proppant (sand) are injected into RH15 with 530m³ of high viscosity gel at flow rates up to 85l/s and pressures up to 24MPa (Parker, 1999). Results of initial post-injection pumping indicate both a boost in fluid recovery (85%) and a reduction in near well impedance (Willis-Richards et al., 1995; Parker, 1999). Success has come at the expense of the reservoir’s thermal performance however with the apparent enhancement of the known short-circuit flow path (Parker, 1999).

Following the placement of proppant a downhole pump is again deployed into RH15 (Parker, 1999). The results of subsequent circulation tests are also successful with (non steady-state) fluid recovery in excess of 100% (Parker, 1999). This time the rise in impedance observed during the previous downhole pumping test is arrested, only reaching 0.54MPa/(l/s). The thermal performance of the reservoir remains affected, however, by the newly improved short-circuit.
It is clear that the performance of the reservoir is now being seriously compromised by the presence of the short circuit flow. In order to counter this effect it is decided to mechanically isolate the area of RH15 around the short circuit and thus, hopefully, remove its influence (Parker 1999). To this end, a section of steel drill-pipe is placed at depth in the well and sealed into place by packers (Parker, 1999). A number of tests known as the Low Flow Production Zone Tests (LFPZT) are run in order to evaluate the quality of the packer seal (Parker, 1999). The success of these tests indicate that it is now possible to pressurise the lower regions of the production well whilst isolating the short circuit (Parker, 1999).

Several attempts are made to stimulate the lower portion of RH15. It is hoped that stimulation of this region will improve the flow connection between injection and production wells by connecting the deeper parts of RH15 to areas stimulated during Phase 2B (Parker, 1999). Following an initial, unsuccessful attempt, a successful viscous stimulation is conducted in June 1990 (Parker, 1990). Around “4,000m$^3$ of low viscosity gel is injected into the well, followed by 40m$^3$ of high viscosity gel and 20m$^3$ of high viscosity slurry containing 11 tonnes of bauxite proppant” (Parker, 1999). Seismic monitoring of the injection indicates that the stimulated region is relatively large, running vertically above RH15 and parallel to the Phase 2B reservoir (Parker, 1999). Subsequent circulation testing indicates that the newly formed region intersects neither the injection well nor the stimulated Phase 2B reservoir (Parker, 1999). This rather frustrating result is taken as evidence of the potential for HDR systems based on a multi-cell reservoir model (Parker, 1999). Unfortunately funding to further explore this possibility was not forthcoming (Parker, 1999).

**Footnote**

Although work is completed during Phase 3 to examine the feasibility of a deep, hot, commercial HDR project in Cornwall, a decision is ultimately made not to proceed with development. This is no doubt partly due to the fact that, in order to reach commercial-grade temperatures in this region, it is necessary to drill to depths of around 6km (Parker, 1989b). Instead, in late 1991 the Rosemanowes project is shut down and the team directed to refocus upon the collaborative European HDR project currently underway at Soultz-sous-Forêts in Alsace, France.
A1.3 Falkenberg HDR, Germany

Summary
Located in north-eastern Bavaria, the Falkenberg research site was the product of a collaborative German project managed by the German BGR (Federal Institute for Geosciences and Natural Resources) and sponsored chiefly by the German government. Never intended to create a full-scale heat exchanger, the work at Falkenberg instead aimed to further the understanding of HDR systems by conducting fundamental in-situ hydromechanical experiments with a high degree of observational control. Operating at depths of between 200-300m the Falkenberg team used fluid pressure to create an artificial hydraulic fracture network which was then studied in detail. Important findings at Falkenberg include the observation that the act of injecting fluid into a fracture is sufficient to create a permanent increase in fracture width and hence fracture volume. This result, attributed to the deformation of asperities on the fracture surface, indicated the potential for creating a permanently enhanced permeability at depth. Work at the Falkenberg site was suspended toward the end of 1986, many workers from this site going on to work at the new EU site at Soultz-sous-Forêts.

Detailed Timeline

1977
By the mid to late 1970’s progress in HDR research at the premier Fenton Hill site in the US has generated significant interest in Europe. In 1977 a number of German research groups come together in a collaborative project which aims ‘to understand the mechanical and hydraulic properties of fractures induced by pressure in crystalline rock’ (Kappelmeyer and Jung, 1987). Managed by the BGR (Hanover) the project is sponsored primarily by the BMFT-PLE (German Ministry of Research and Technology) with additional contribution from the EEC (Kappelmeyer and Jung, 1987). The high costs associated with deep drilling convince the researchers to operate at relatively shallow depths where the ‘principle problems of fracture growth in a natural jointed rock mass’ may be investigated relatively cheaply whilst still
being ‘relevant to the understanding of (deep) HDR systems’ (Baria, 2001a; Tenzer, 2001). To this end, a research site is chosen ‘in the northern part of the Falkenberg granite massif in NE Bavaria’ (Tenzer, 2001). Located around 2km west of the village of Falkenberg itself the site is situated in an area where the relatively homogenous granite ‘extends essentially to surface’ and where natural fracture density appears to be relatively low (Baria, 2001a; Tenzer, 2001).

1978 – 1979

Work commences at the test site in 1978 with the coring of three wells, NB1, NB2 and NB3 to respective depths of 296, 302 and 301m (Kappelmeyer and Jung, 1987). Designed to host an array of downhole seismic equipment the three wells are located at the vertices of an equilateral triangle of side length equal to 100m (Kappelmeyer and Jung, 1987). A fourth hole, HB4a is drilled to a depth of 500m and is located approximately in the center of the triangular array (Kappelmeyer and Jung, 1987). Cored from 10 – 342m, it is intended that the new well will be the injection hole for the planned fracturing experiments (Kappelmeyer and Jung, 1987). Data collected from studies of core and downhole logging indicate the presence of three major sub-vertical joint sets, one striking N-S, two E-W (Baria, 2001a). Downhole fracture density appears low but may be related to the sub-vertical nature of the joints (Baria, 2001a). At depths less than 150m fractures are found to be dominantly horizontal (Baria, 2001a).

A series of small hydraulic fracturing experiments are undertaken at various depths in HB4a during 1979 (Smith, 1987; Baria, 2001a). The experiments aim to generate true (artificial) hydraulic fractures by targeting isolated (packed-off) downhole zones determined to be free of existing natural fractures (Baria, 2001a). One such zone, located between 252-255m, breaks down following injection of some 6m³ of fluid at 3.5l/s (Kappelmeyer and Jung, 1987). Breakdown pressure is observed to be 18MPa and is accompanied by a number of detectable seismic events (Baria, 2001a). Later location of these events suggests the fracturing has formed an E-W striking planar structure dipping around 45° to the south (Baria, 2001a). Close alignment of a number of events along what is subsequently determined to be an intersection between this induced fracture and a naturally occurring (vertical) joint plane indicate
that the acoustic events are most likely the product of shear on natural fracture planes rather than tensile fracture formation (Kappelmeyer and Jung, 1987).

Subsequent examination of the HB4a fracture zone with BHTV reveals a complex zone of multiple fractures intersecting the well, including a vertical set striking 120° and an E-W striking set dipping ~60° to the south (Kappelmeyer and Jung, 1987).

1980 – 1986

The remaining active years at the Falkenberg site are devoted to the characterisation of the newly formed artificial fracture system. A total of four new percussion drill holes are completed at the site, all designed to intersect the fracture created in HB4a (Kappelmeyer and Jung, 1987). SB5 and SB6, both 285m deep, are drilled 15m to the west and the east of HB4a respectively (Kappelmeyer and Jung, 1987). PB7 (500m) and PB8 (497m) are inclined, drilled to the south of HB4a (Kappelmeyer and Jung, 1987). Temperature logs indicate SB5 intersects the hydraulic fracture at 260m, 11m away from HB4a (Kappelmeyer and Jung, 1987). PB8 is also found to have a good connection with the injection well, intersecting the artificial fracture around 2m away from its propagation point (Kappelmeyer and Jung, 1987).

The hydraulic fracture is eventually extended by two further injections, the first in 1981 of 33m³ at 3.5l/s followed by a second in 1983 of 52m³ at 3.5l/s (Baria, 2001a). Ultimately the fracture radius reaches around 70m, intersecting 7 out of 8 of the on-site wells, the exception being NB2 to the north (Kappelmeyer and Jung, 1987). Subsequent BHTV analysis reveals that the complexity of the artificial fracture system decreases with distance from the injection well with PB8 intersecting eight distinct fractures, SB5 two and all other wells only one (Kappelmeyer and Jung, 1987). In all cases the fractures intersected away from HB4a prove to be E-W striking, dipping 40-50° to the south, consistent with the located seismic data (Kappelmeyer and Jung, 1987). It is concluded that only one fracture has penetrated a significant distance from HB4a (Kappelmeyer and Jung, 1987).

A number of downhole stress measurements are made using wire-line hydraulic fracturing (Kappelmeyer and Jung, 1987). σH and σh gradients are determined as 3.5 + 0.0127z and 1.2 + 0.015z MPa respectively with σh oriented at ~119° (Kappelmeyer
and Jung, 1987). Interestingly, neither the magnitude nor the orientation of the determined in-situ stress field are consistent with the geometry of the induced fracture (Kappelmeyer and Jung, 1987). Explanations for this discrepancy include the possibility that the principle stress directions may be inclined or that there may have been a significant shear component to the fracture propagation (Kappelmeyer and Jung, 1987).

Circulation tests undertaken on the multi-well system during this period include both ‘constant flow rate, cyclic one and two-borehole injection and huff-puff experiments’ (Kappelmeyer and Jung, 1987). The longest experiment runs for 14 hours at 3.4l/s (injection) and generates a thermal drawdown estimated to be equivalent to 1°C (Baria, 2001a). Fluid loss rates determined from both circulation and injection experiments are found to vary linearly with fluid pressure and do not appear to be affected by the successive fracture extensions (Kappelmeyer and Jung, 1987). There would seem to be relatively few natural joint intersections with the hydraulic fracture (Kappelmeyer and Jung, 1987). Those few structures which do accept water from the artificial system appear not to suffer significant changes in fracture transmissivity across the range of experimental fluid pressures (Kappelmeyer and Jung, 1987).

Detailed studies of the relationship between the hydraulic fracture width and fracture fluid pressure are undertaken (Kappelmeyer and Jung, 1987). Mechanical (caliper) measurements of the fracture response to fluid injection indicate a non-linear relationship between fracture width and fluid pressure which, furthermore, appears not to be fully reversible (Kappelmeyer and Jung, 1987). Subsequent determination of fracture width from transmissivities calculated from a series of constant rate injection tests appear to corroborate this result, as do calculations of total stored volume (Kappelmeyer and Jung, 1987). It appears that the simple act of injecting fluid into the fracture is sufficient to create a permanent increase in fracture width and hence fracture volume. A significant finding, it is concluded that this effect is most likely a result of the deformation of asperities on the fracture surfaces (Kappelmeyer and Jung, 1987). Volume tests conducted during this period also indicate that fracture opening is constant across the entire fracture surface (Kappelmeyer and Jung, 1987).
The general hydraulic properties of the fracture are also investigated. A series of injection and venting tests are conducted during which the inlet (injection) and outlet (venting) pressure drop of a single well is determined as a function of flow rate (Kappelmeyer and Jung, 1987). While the initial relationship between pressure drop and flow rate is found to be linear, it appears to become non-linear above a critical value (Q = 0.5 l/s), behaviour attributed to the onset of turbulent flow at the inlet and outlet points (Kappelmeyer and Jung, 1987). As indicated from the fracture width studies, transmissivity data gathered from the constant injection experiments indicate a non-linear increase with increasing fluid pressure up to the point where the latter is equal to the crack propagation pressure (Kappelmeyer and Jung, 1987). In order to obtain the kind of flow rates required for commercial HDR operation (50 – 100 l/s) from the single fracture system it is necessary to operate at fluid pressures very close to the fracture extension pressure (Kappelmeyer and Jung, 1987). It is concluded that a multi-fracture HDR system is probably preferable as such a system should imply both a higher critical flow rate for the onset of turbulent flow at the inlet and outlet points as well as a greater overall transmissivity (Kappelmeyer and Jung, 1987).

Concurrent with on-site field work during this period are numerous laboratory experiments including fracture mechanical work, geochemical and stress-related studies (Kappelmeyer and Jung, 1987).

**Footnote**

Following completion of the field and experimental program in 1986 the Falkenberg project appears to have been wound up. Smith (1987) refers to the development of a deeper system at the Falkenberg site though no other reference to this work has been found. It appears likely that, like the Rosemanowes project in the UK, much of the Falkenberg expertise was redirected to work on the new European site at Soultz-sous-Forêts.
A1.4 Bad Urach HDR, Germany

Summary
The Bad Urach Geothermal Project, located in the Swabian Jura of south-western Germany, was initiated in the mid-1970’s by a local consortium. The main interest of this group was to investigate the potential for development of a commercial thermal spa within the region, already known to host a low enthalpy thermal anomaly. In 1977 formal research work, financed by the German Ministry for Research and Technology and operated by the Forschungs-Kollegium Physik des Erdkörpers (FKPE) commenced on the same site. This work was part of a national initiative aimed at better understanding the German geothermal resource. Included within the scope of this project was the drilling of a deep well designed to investigate the potential of the local HDR resource. Initial work at Urach focused upon detailed site characterisation and development of a ‘single-well’ circulatory system. Although the basement at Urach appeared to be suitable for development of an HDR reservoir the single-well concept met with little success. As a result, the project was held over for a number of years. During this time the site was revisited repeatedly to gain more data and the original well was eventually deepened to around 4.4km. By 2001 the combined results of field work and feasibility studies, as well as the ongoing successes at the Soultz site, enabled the go-ahead for the drilling of a second well as the first stage in the development of a functional heat-exchanger.

Detailed Timeline

1970 – 1974
Located some 35km SE of Stuttgart in the Swabian Alb of southern Germany, the geology of the Urach region comprises thick layers of Mesozoic sediment overlaid unconformably upon ancient crystalline basement (Schadel, 1982a). Regional tectonism, related to the sinking of the Molasse basin at the foot of the Alps to the south, has produced a 1-2° tilt of the sedimentary layers, with subsequent erosion forming a distinctive cuesta (step) landscape (Schadel, 1982a). The presence of a geothermal anomaly within the area has been known for over 150 years (Dietrich,
1982a). Roughly ovoid in shape at surface, the anomaly is centered near the town of Urach from which it extends some 60km along a NE-SW trending axis, covering a total area of approximately 300km² (Schadel, 1982a).

In the early 1970’s a small locally-backed project is commenced with the aim of tapping the known thermal anomaly and producing heated water for direct use (Haenel, 1982). Two 800m deep investigative holes, Urach 1 and 2 are drilled, both of which terminate in ‘warm-water bearing Triassic aquifers’ (Dietrich, 1982a; Baria, 2001c). Ultimately sufficient warm water is sourced from these wells to support a commercial spa project (www.albthermen.de).

1977 – 1980

The energy crisis of the early 1970’s, along with advances being made at the Fenton Hill HDR site in the US have produced an upsurge of interest worldwide in geothermal energy (Haenel, 1982a). In Germany the Forschungs-Kollegium Physik des Erdkorpers (FKPE), a geophysical association involving both government and educational institutions, initiates a geothermal working group to investigate the potential for utilisation of the national resource (Haenel, 1982a). Examination of existing data highlights the Urach area as the best location for a research site and a partnership is forged with the existing local operators (Haenel, 1982a). Aims of the new Urach Geothermal Project include the detailed characterisation of the anomaly and the testing of geophysical methods for geothermal exploration (Haenel, 1982a). Concomitant with this work is a study of the identified aquifers and their uses as well as an examination of the local crystalline basement ‘with a view of future extraction of energy using the hot dry rock concept’ (Haenel, 1982a).

Characterisation of the Urach anomaly includes detailed geological, geophysical, geochemical and hydrological investigations (Haenel, 1982a). Numerous shallow boreholes are drilled to assess the regional heat flow pattern and more closely define the extent of the known anomaly (Behrens et al., 1982; Zoth, 1982). Subsequent determinations indicate a range of values between 67 – 135mWm⁻² and confirm the shape of the surface anomaly (Zoth, 1982). It is found that the anomaly increases in size with depth, its centre shifting slightly to the NNW (Zoth, 1982).
There is much speculation as to the source of the heat anomaly. Close attention is paid to the presence of a tertiary dyke swarm in the region (Maussnest, 1982). Comprised of ultramafic olivine-nepheline tuffs, the volcanic pipes are spread over an area of some 1,600 km² but appear to focus upon the Urach region (Maussnest, 1982). Although the composition of the volcanic material indicates a deep origin for the magma, it is nonetheless postulated that heat conducted from an intermediate chamber or ‘hearth’ located in the upper crust may provide a direct source for the local geothermal anomaly (Wimmenauer, 1982). Gravity data indicates the presence of a local high interpreted as an intrusive body located between 6 - 18 km depth beneath the thermal anomaly (Makris et al., 1982). While this appears to support the magma chamber theory, other data does not. Aeromagnetic surveys show no evidence for a magnetic anomaly that would be expected were a large body of ultramafic material present at depth within the crust (Wimmenauer, 1982). Modelling by Werner (1982) casts further doubt upon the theory that poor thermal conductivity could explain the presence of a present day near-surface anomaly from a deep-seated tertiary-aged magma body.

Seismic surveys identify a large, low velocity region at depths between 5 - 30 km beneath the anomaly which is interpreted as the combined product of thermal effects and large scale alteration of the crust (Bartelsen et al., 1982). Evidence derived from hydrochemical analysis of groundwater is interpreted as indicating the anomaly may be due to the ascent of deep, hot fluids to mix with cooler surface waters (Balke et al., 1982). This theory is supported by the detailed temperature mapping which indicates local areas of high and low temperature correlate well with previously determined regions of ascending and descending surface water (Zoth, 1982). It is found that groundwater movement is also capable of accounting for the NE-SW trend of the anomaly (Villinger, 1982). Postulations that groundwater may be rising from very great depths however become problematic upon examination of the hydraulic conditions of the Urach region (Werner, 1982). Calculations of local hydraulic potential indicate that the ascent of groundwater from very deep regions is highly improbable (Villinger, 1982). Werner (1982) suggests an alternative mechanism for advection related to post-volcanic gas exhalation.

A1-45
In summarising these results Berktold et al., (1982) conclude that there is no single model capable of interpreting all of the observations. On the balance of probability it is concluded that the most likely source for anomaly is the advection of heat from depth by water or gas. Whilst the existence of a mid-level magma body is considered to be unlikely, the possibility of a third alternative hypothesis of heat production at relatively shallow depths by oxidation of hydrocarbons and pyrite in the sedimentary layers, as suggested by Schadel (1982b), cannot be ruled out.

Attendant to the ongoing surface investigations a deep drilling project is engineered to provide access to basement geology and enable in-situ measurements to be made (Haenel, 1982a). Targeting the central part of the known thermal anomaly, the well designated Urach 3 is deliberately located on the edge of the Urach township so as to be proximal to a potential consumer base (Dietrich, 1982a). Originally planned to reach total depth around 2,500m it is ultimately drilled to a final depth of 3,334m and cased to 3,320m (Dietrich, 1982a). Bottom hole temperature recorded in the well is 143°C corresponding to a mean conductive heat flow of 86mWm⁻² (Haenel and Zoth, 1982). Mean temperature gradient is found to decrease with depth from 105°C/km near surface to 30°C/km in basement (Haenel and Zoth, 1982).

Urach 3 intersects crystalline basement at 1,604m (Stenger, 1982). Numerous core samples are recovered from both the sedimentary and basement intersections and standard suites of geophysical logs are run to depth (Dietrich, 1982a). Examination of the available material reveals a basement complex comprised of pelitic gneiss and granodioritic diatexite (Stenger, 1982). Open and healed joints are characterised by calcite + pyrite and quartz fill respectively and are present throughout the intersection where they are often accompanied by halos of retrograde hydrothermal alteration (Stenger, 1982). Joint spacing estimated from core is around 1.3m with most found to be inclined, dipping between 40 –70° (Schadel & Dietrich, 1982). Flow testing in the basement identifies at least one significant productive fracture zone at 1,775m along with numerous smaller scale ‘seeps’ (Dietrich, 1982b). Mean natural permeability of the open hole section is estimated to be around 3µD (Schadel & Dietrich, 1982). Fluid chemistry and structural studies indicate that hydraulic communication between the basement and overlying sediments is likely (Dietrich, 1982b).
Between May and August 1979 a series of hydraulic stimulation and circulation experiments are conducted in Urach 3 (Baria, 2001c). The purpose of these tests is to establish the viability of rock fracture by high hydraulic pressure and consequently the possibility of Hot Dry Rock style energy extraction from a single-well system (Dietrich et al., 1982; Schadel & Dietrich, 1982).

A series of hydraulic fracturing and circulation experiments are undertaken in the interval May – August 1979 (Schadel & Dietrich, 1982). Initial work is focussed upon the open-hole section between 3,320 and 3,334m. Leak off tests indicate fracture opening at wellhead pressures between 17 – 20MPa (Schadel & Dietrich, 1982). Two consecutive high pressure injections pump 11 and 25m³ of water into this region at rates and (wellhead) pressures up to 12.5l/s and 43MPa respectively (Schadel & Dietrich, 1982). Above the opening pressure the formation accepts increasingly greater amounts of water, the relationship between injection rate and pressure apparently linear (Schadel & Dietrich, 1982). The pressure required for opening is noted to be lower than that calculated to be required for the creation of new hydraulic fractures, indicating that pre-existing fractures are opening to accept fluid (Dietrich et al., 1982).

Subsequent fracturing experiments are conducted through 5m perforations in the casing at intervals each separated by 7m (Schadel & Dietrich, 1982). Perforation 1 (P1) 3,259-3,264m is injected with 35.2m³ of water and gel with maximum flow rate of around 16.5l/s at wellhead pressure of 55MPa (Schadel & Dietrich, 1982). Perforation 2 (P2) 3,271-3,276m is treated in a similar manner with 87m³ of water and 16m³ of gel at flow rates between 6 and 16.5l/s corresponding to wellhead pressures of between 10 and 35MPa (Schadel & Dietrich, 1982). Circulation tests are conducted both from P1 to P2 and then P2 to P1. Injection rates up to 20l/s fail to establish any hydraulic link between the two zones although a pressure connection is noted (Schadel & Dietrich, 1982).

An attempt to improve the connectivity of the fracture zones is made through application of proppant to both P1 and P2 (Schadel & Dietrich, 1982). Injection of 40m³ of water/gel/proppant at 9-14.5l/s and 59MPa (wellhead) into P2 is followed by 50m³ of gel/proppant at 6-13l/s and 65MPa (wellhead) into P1 (Schadel & Dietrich,
A third perforation (P3) 3,293-3,298 is fractured using 41.2m³ of water/gel/proppant at 1-13l/s and maximum wellhead pressure 67MPa (Schadel & Dietrich, 1982).

Twelve more circulation experiments are conducted between the newly propped fracture zones (Schadel & Dietrich, 1982). Two initial tests targeting circulation between the upper cased fractures both prove unsuccessful with P1 appearing unconnected to the lower fractures and P2 at best poorly connected (Dietrich et al., 1982). It becomes clear that a pressure relation exists between these zones whereby the interaction of fluid movement and in-situ stress field in one zone causes a reduction of fracture width in the other(s), thereby impeding the circular flow (Schadel & Dietrich, 1982). Subsequent attempts focus upon circulation between the two most distal injection points (Schadel & Dietrich, 1982). A circulation loop is established between P3 and the open hole and is confirmed by tracer tests (Schadel & Dietrich, 1982). A typical test (#11) injects 19.6m³ at 0.7l/s (reducing to 0.5l/s) and 35MPa over a period of 12 hours (Schadel & Dietrich, 1982). Production rates remain steady at around 0.5l/s and recovery is 87% (17m³) (Schadel & Dietrich, 1982). Flow resistance is noted to increase with time during most experiments and is put down to the effect of gradual fluid accumulation in the rock (Schadel & Dietrich, 1982). The closed nature of the system is demonstrated clearly during the post-test venting which continues at low rates for some time, a pressure increase due to water injection still detectable over two years after the end of injection (Schadel & Dietrich, 1982).

1982 – 1983

Whilst initial circulation experiments on Urach 3 demonstrated the possibility of single hole circulation, the relatively poor circulation results lead to the conclusion that a dual well system is preferable (Schadel & Dietrich, 1982). Despite the problems encountered in the initial tests the prospect of HDR-style energy extraction from a deep geothermal well is nonetheless considered feasible (Schadel & Dietrich, 1982). For Urach, where a deep geothermal well has already been drilled, the economics of possible HDR development appear particularly attractive (Haenel, 1982b).
In 1982, following a two year-hiatus, a second phase of work commences at the Urach well site. In an apparent attempt at further characterising the crystalline basement Urach 3 is extended from its original depth 154m to 3,488m. Bottom hole temperature is recorded as 147°C (Tenzer et al., 2001). Data gathered from new drill core and BHTV logging carried out across the interval 3,340-3,412m reveals detailed information concerning the natural fracture network (Baria, 2001c). Total fracture density determined from the core is 6-7 m\(^{-1}\) with open fractures occurring every 0.5-1.5m (Baria, 2001c). Overall the fracture network appears random with a possibility of two steeply dipping sets oriented at 0° and 100° (Baria, 2001c). Borehole breakouts identified in the newly drilled section are consistently oriented ~82° implying a maximum horizontal stress at around 172°, compatible with the observed strike of drilling induced sub-vertical fractures (Baria, 2001c).

Future plans to follow-up the ongoing work in Urach 3 with the drilling of a second deep well in 1984 are scuttled by ‘amendments in research politics’ (Tenzer et al., 2001). Work at the site appears to be put on hold for some years until the early 1990s.

**1990 – 1996**

Interest in the possibility of utilising the Urach 3 well as part of a HDR energy project is reawakened in the early 1990s. No doubt inspired by the ongoing successes at the nearby Soultz-sous-Forêts research site a new feasibility study is commissioned at Urach. Work included in this program involves both practical empirical studies as well as economic modelling of the ‘infrastructure, user potential and utilisation’ of the resource (Tenzer et al., 2001).

As part of the experimental program Urach 3 is re-opened and hydrofracture stress measurements are undertaken in a packed section at 3,352m depth (Tenzer et al., 2001). Maximum and minimum horizontal stress are estimated to be between 76-102MPa and 41-50MPa respectively (Tenzer et al., 2001). The value of \(\sigma_H\) is noted as being close to the likely value of overburden stress indicating the likely stress regime is strike-slip (Baria, 2001c; Tenzer et al., 2001).

Existing studies of the feasibility of European HDR projects indicate that temperatures in excess of 170°C are necessary for the economic development of a
pilot project (Tenzer et al., 2001). To achieve such temperatures at Urach it will be necessary to drill to depths of around 4,300-4,500m (Tenzer et al., 2001). In view of this requirement a decision is made to further extend Urach 3 to determine whether such depths are attainable and, if so, whether the in-situ rock parameters are such that development of a HDR reservoir is workable (Tenzer et al., 2001). Drilling of the well commences in late 1992 and concludes some 40 days later at a depth of 4,444m (Tenzer et al., 2001). The drilling itself is largely successful but is blighted by problems during post-drilling operations when a large section of drill pipe (fish) is irretrievably lost in the open hole section (Tenzer et al., 2001). Whilst significant, the length of fish is such that it does not occupy all of the open-hole section and interference with future hydraulic operations is considered unlikely (Tenzer et al., 2001).

A disturbed bottom of hole temperature is recorded as 169°C implying an equilibrium or true formation temperature in the range of 172-175°C (Tenzer et al., 2001). Basement temperature gradient below 1600m is shown to be 29°C/km (Tenzer et al., 2001). Basement geology is determined from cuttings as core (Tenzer et al., 2001). Formations encountered by the extension includes pelitic biotite gneiss and migmatite (Tenzer et al., 2001). Brittle deformation is noted in the form of in-situ fractures and joints which are again found to be sealed by clays, carbonates and sulphides and characterised by retrograde hydrothermal haloes (Tenzer et al., 2001).

Borehole imaging data indicates joint set maxima below 3,750m striking roughly north-south at 160-170° and dipping mainly to the west (Tenzer et al., 2001). Estimated stress magnitude from anelastic strain recovery measurement on core from around 4,425m depth indicate values of maximum stress between 99-137MPa (Tenzer et al., 2001). Subsequent hydraulic leak-off tests corroborate the value of $\sigma_h$ estimated by the hydraulic fracturing experiment (Baria, 2001c). It is concluded that the local system ‘is characterised by near left-lateral strike-slip faulting with a NNW-SSE $\sigma_h$’ (Tenzer et al., 2001).

2001 –

Results from previous years feasibility studies are such that a proposal for development of an industrial HDR demonstration project at Urach is made (Tenzer et
In 2001-2003 Urach 3 is again opened for a series of logging and hydraulic injection tests aimed at stimulating the open-hole. Results recorded from these tests, including micro-seismic monitoring of the reservoir formation, are sufficiently encouraging that funding of a second deep well is approved. Drilling of well Urach 4 commences in late 2003.
A1.5 Fjallbacka HDR, Sweden

Summary
Swedish geology is dominated by Pre-Cambrian crystalline bedrock with relatively low heat flow and shallow geotherms. Consequently, the purpose of the Swedish HDR project was not to investigate the potential of the national resource for electrical generation but to study shallow reservoir systems which, linked to heat pumps, could be used for domestic heating. Located at Fjallbacka, 50km North west of Uddervalla on the west coast of Sweden, the Swedish HDR test site was operated by Chalmers University of Technology, Gothenburg. Working at shallow depth (<500m) within an exposed granite the Fjallbacka team successfully stimulated natural joint sets to create the world’s first sub-horizontal reservoir. Although successful in achieving its aims, the project was not expanded beyond the research phase, economic modelling indicating the technology was not yet competitive when compared to available heating technologies.

Detailed Timeline

Pre 1984
The Swedish HDR program is instigated as part of a larger government-sponsored geothermal program designed to investigate the potential of the national resource (Eliasson et al., 1987). The project is focussed primarily upon the use of geothermal as a source of direct heat rather than electrical power (Eliasson et al., 1987; Wallroth et al., 1999). This approach has been formulated for both practical and economic reasons, the dominant geology of Sweden being exposed crystalline basement with relatively low heat flow density and geothermal gradients typically only between 10-18°C/km (Eliasson et al., 1987; Wallroth et al., 1999). The aim of the project is thus to create a shallow heat exchanger that is suitable for circulation and heat extraction and which is capable of producing fluid at temperatures which, when combined with the use of heat pumps, is sufficient for domestic heating (Wallroth et al., 1999).
The HDR arm of the geothermal project is backed by the Energy Research Commission of Sweden (later Swedish Energy Administration) and operated by Chalmers University of Technology, Gothenburg (Eliasson et al., 1987). An experimental site is chosen in the central Bohus granite, approximately 50km north-west of the community of Uddervalla on the west coast of Sweden (Eliasson et al., 1987). An area of rolling hills and steep valleys, previous investigations have identified the Bohus granite as being high heat producing (Eliasson et al., 1987). The Fjallbacka site itself is identified as a local anomaly with a heat production of 7.47μW.m⁻³ (Th 52ppm; U 13ppm) and temperature gradient equal to 17.5°C/km, slightly above the regional average (Eliasson et al., 1987).

Emplaced some 920Ma ago the Bohus Granite Massif is a peraluminous monzogranite and occupies a north-south trending area about 20 x 90km on the West coast of Sweden (Eliasson et al., 1987; Wallroth et al., 1999). Geophysical data indicates the intrusion is flat-lying and sheet like, dipping gently to the east and varying in thickness from around 7km in the south to 0.5-4km in the north (Eliasson et al., 1987). Regional joint patterns are dominated by NE-SW trends with subordinate N-S trends (Eliasson et al., 1987). Within the site area joints are dominantly NE-SW and NW-SE vertical/sub-vertical (with minor N-S) plus one horizontal/sub-horizontal set in a classic ‘cubic’ pattern (Wallroth et al., 1999).

1984 – 1985

Research at the site commences with the percussion drilling of three shallow wells, Fjb0 (200m), Fjb1 (500m) and Fjb2 (70m) (Eliasson et al., 1987). A program of ‘rock mass characterisation’ begins with both surface and downhole geological mapping, cuttings analysis, geophysical logging and hydraulic testing (Wallroth et al., 1999). Downhole fracture mapping (BHTV) in Fjb1 gives a mean fracture density of 0.45m⁻¹ (Eliasson et al., 1987). A number of major natural fracture zones are detected downhole, a proportion of which below 180m are found to be fluid bearing (Eliasson et al., 1987). Transmissivities of these zones determined from injection testing are of the order of 10⁻⁸ to 10⁻⁷ m²/s (Wallroth et al., 1999; Dyer and Wallroth, 1997). Significantly these structures are all found to be horizontal or sub-horizontal (<20°), the rock having very low vertical permeability as evidenced by a compositional
zonation of groundwater with depth (Wallroth et al., 1999). Stress measurements
determined from hydro-fracturing indicate that the minimum stress is vertical at
depths less that around 500m (Eliasson et al., 1987).

1985 – 1986

Small scale shallow water injection tests are conducted at a depth of 200m during two
operations in December 1985 and July 1986 and successfully create systems of sub-
horizontal fractures (Eliasson et al., 1987).

Following the apparent success of small-scale injections a more significant fracturing
experiment is conceived. Sponsored in part by the British Department of Energy
through the Cambridge School of Mines the test is designed to create a shallow high-
permeability heat exchange area through the use of viscous fluid injection (Jupe et al.,
1992). Injection is to take place in a 30m long packer-isolated section of Fjb1
between 450-480m downhole (Wallroth et al., 1999). The effects of injection are to
be monitored on a 15-point 3-pronged seismic surface array radiating up to 450m
away from the injection well (Jupe et al., 1992; Wallroth et al., 1999).

<table>
<thead>
<tr>
<th>Test</th>
<th>Volume (m³)</th>
<th>Duration (min)</th>
<th>Flow Rate (l/s)</th>
<th>P_{inj} Max (MPa)</th>
<th>No. detected seismic events</th>
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<td>180</td>
<td>21</td>
<td>13.2</td>
<td>35</td>
</tr>
</tbody>
</table>

**Table A1.1:** Parameters of 1986 hydraulic stimulation experiment at Fjallbacka HDR site,

The injection test is conducted as a five part process beginning with a small initial
injection of water (Jupe et al., 1992). This is followed initially by two 'mini-frac’
tests involving small volumes of progressively more viscous fluid, then by a larger
water injection before finally the main viscous injection of gel mixed with sand
proppant (Eliasson et al., 1987). Details of all five injection episodes are included in
Table A1.1.
Post-injection temperature logs indicate the major area of fluid inflow is located at a
depth of 455m and corresponds to both a naturally permeable and a seismically active
zone (Eliasson et al., 1987). A second minor inflow zone is located at 472m (Eliasson
et al., 1987). Subsequent hydraulic testing indicates permeability across the 30m test
interval has been enhanced by an order of magnitude from 10μD to 10mD (Jupe et al.,

A total of 72 microseismic events are recorded and, when located, appear to migrate
with time progressively outwards from the injection well to form a relatively planar,
horizontal cloud between 440 and 475m depth (Eliasson et al., 1987; Wallroth et al.,
1999). The most distal event recorded is around 150m from the injection point (Jupe
et al., 1992). A seismically quiet zone extending 40m from the injection point may be
related to the detection limit of the network used (Jupe et al., 1992). Most events are
determined to be shear-related, produced by left-lateral strike-slip movement on
steeply dipping ENE striking fractures (Eliasson et al., 1987). It is concluded that
stimulation has resulted in the aseismic jacking of horizontal fractures, leading to a
cycle of stress build-up and release by shearing on nearby vertical fractures (Eliasson
et al., 1987). Later analysis contradicts this result, using fault-plane solutions
combined with rock mechanics and stress analysis to conclude that the sheared
fractures are most likely sub-horizontal (Jupe et al., 1992).

1987 – 1988

The location of induced seismic events from the 1986 injection testing in Fjb1 are
used to target a new well, 500m deep Fjb3 (Wallroth et al., 1999). Located
approximately 15m distant from Fjb1 at surface, Fjb3 is inclined such that separation
from the injection well at reservoir depth is around 100m (Dyer and Wallroth, 1997;
Wallroth et al., 1999). The new well intersects the stimulated zone at around 470m
depth, encountering remnants of the viscous injection gel whilst drilling and
confirming that seismic data accurately mapped fluid movement during injection
(Wallroth et al., 1999). Information contained in Wallroth et al. (1999) indicates that
Fjb3 is cored enabling direct logging of downhole fracture systems.
Drilling is followed by a second intense period of ‘rock mass characterisation’ this time involving core and borehole logging as well as hydraulic testing. BHTV logging indicates fracture densities and spacing very similar to that recorded in Fjb1 (Jupe et al., 1992). Hydraulic testing reveals that, like Fjb1, the permeability of the stimulated zone intersected by Fjb3 is an order of magnitude greater than that encountered in the well as a whole (Jupe et al., 1992). Around 270m$^3$ of fluid is injected to stimulate Fjb3 and lower impedance in the vicinity of the well (Willis-Richards et al., 1995). This takes place via a number of small scale hydraulic (water) injections plus a viscous gel proppant placement (Willis-Richards et al., 1995).

1989

A 40 day open-loop circulation test is conducted between isolated (straddled) sections of Fjb3-Fjb1 (Wallroth et al., 1999). A total of 5,500m$^3$ of water is injected into Fjb3 at a flow rate of 1.8l/s with recovery reaching a peak value of 51% by the end of the test (Wallroth et al., 1999). Several hundred microseismic events are detected during circulation and are located up to 500m from the injection point indicating water loss is likely to be due to continued reservoir growth (Willis-Richards et al., 1995). The occurrence of such a large number of seismic events at fluid pressures lower than the known minimum effective stress confirms those studies which, based on rock mechanics and stress data, predicted that the most likely orientation of the failing structures is sub-horizontal (Jupe et al., 1992; Dyer and Wallroth, 1997; Wallroth et al., 1999).

1995

Following what appears to be a hiatus in site activity, the Fjallbacka wells are reactivated for a crosshole seismic survey to be conducted between wells Fjb1 and 3. The survey interval is between 400 and 480m depth (Dyer and Wallroth, 1997). Two surveys are recorded, the first of the reservoir at ambient pressure, the second of the reservoir inflated at 3.2-3.4MPa (Dyer and Wallroth, 1997). Images derived from the survey appear to indicate that the hydraulic connection between the two wells is relatively poor. While the stimulated zone in Fjb1 corresponds to an extensive zone of reduced velocity indicating significant permeability the equivalent feature around Fjb3 is noticeably smaller and the two do not appear to be directly linked (Dyer and
Wallroth, 1997). It is concluded that poor connectivity may be a factor causing high reservoir impedance (Dyer and Wallroth, 1997).

Footnote

Economic reviews of the viability of Swedish style HDR heat exchangers as sources of direct heat conclude that they are not yet competitive and the Fjallbacka research project is finally concluded in the mid 1990's.
A1.6 Le Mayet de Montagne HDR, France

Summary
The HDR site at Le Mayet de Montagne, located 25km south-east of Vichy in central France was, like many other sites of its era, a shallow research site used for a series of preliminary experiments which ultimately contributed to the full-scale development at Soultz-sous-Forêt. Work at Le Mayet de Montagne, sponsored by the European Union (formerly European Economic Community, EEC) and the French government was undertaken in two main phases. An initial phase at very shallow depth (<200m) was designed to investigate the mechanics of induced hydraulic fracture within the crust. Several years after completion of this phase the site was re-opened and work commenced examining the stimulation of natural fractures at depths around 800m. No activity is recorded on this site beyond the instigation of on-site work at Soultz in 1987.

Detailed Timeline

1977 – 1978
European interest in the early experimental work conducted at the Fenton Hill site extends to France where a project is created in the late 70’s to investigate the potential for local HDR energy extraction. Supported by both the French government, in the form of the Agence France pour la Maitrise de l’Energy and the Centre National de la Recherche Scientifique and the EEC, work includes both field and laboratory investigations (Smith, 1987; Cornet 1987). An early result of the project work is the identification of a broad heat flow anomaly within the Massif Central region (Smith, 1987). A suitable research site is subsequently located at Le Mayet de Montagne, approximately 25km east-southeast of Vichy on the Northern Fringe of the Massif (Baria, 2001b). Here a relatively homogenous granite extends essentially to surface forming an ‘undulating topography of heights less than 100m’ (Smith, 1987; Baria, 2001b). Surface mapping work identifies four families of sub-vertical fractures, many of which show evidence of past shear displacement (Willis-Richards et al., 1995).
An on-site program of shallow-level feasibility studies for the extraction of heat from the granite commences (Cornet, 1987; Smith 1987). Like many early HDR experiments the main interest of the researchers at this stage appears to be to investigate the potential for the development of a heat exchanger by hydraulic fracturing of competent rock (Cornet, 1987). According to Smith (1987) initial small-scale hydraulic fracturing experiments are conducted in a single shallow well drilled to a depth of 27m. It is unclear whether this well is in fact INAG 3-1 which Cornet (1987) refers to as having been cored, although this does seem likely to be the case.

1979 – 1981

1979 sees the drilling of two new wells, INAG 3-2 and INAG 3-3, both percussion, to total depths of 200m (Cornet, 1987). Sited approximately 30m apart at surface, the wells are neither inclined nor directionally drilled and consequently vary from the vertical by only 2-3° (Cornet, 1987). The precise sequence of events surrounding the drilling of these wells is unclear, according to Smith (1987) INAG 3-3 is not drilled until some time after INAG 3-2, and is specifically targeted to intersect an hydraulic fracture previously created in the older well. It is not clear what method was used to target the well should this have been the case, it does not appear that seismic monitoring techniques were used at this stage.

Hydraulic fracturing experiments are conducted at various depths in INAG 3-2, focussing on areas where the granite is believed to be most homogenous (Smith, 1987). Fracturing of an isolated section at 186m depth using 13m³ of viscous gels and 3t proppant (sand) at injection flow rates around 9l/s successfully produces an hydraulic fracture (Cornet, 1987). Cornet (1987) states that this fracture ‘results in an hydraulic connection between the two wells’ and seems to imply that INAG 3-3 was drilled prior to its creation. At any event, BHTV logging in INAG 3-2 establishes the existence of a propped sub-vertical fracture striking ~55° (Smith, 1987; Cornet, 1987). Subsequent studies indicate that this feature extends no further than 15m to the west and has instead grown upwards about 30m, intersecting an horizontal natural fracture at around 155m depth (Cornet, 1987). It is this feature which intersects INAG 3-3 and provides the hydraulic connection between the two (Cornet, 1987).
Following the establishment of the hydraulic connection between the two wells an extended circulation test is conducted. Again, accounts of the details of this test are conflicting. Cornet (1987) states that a 56 day circulation test with injection flow rate equal to 0.8l/s is conducted. Recovery rates from this test rise to around 60% of the total with the majority of loss occurring ‘through a local short circuit’ (Cornet, 1987). Data from tracer tests and temperature analysis indicates the reservoir heat exchange area is of the order of 6,000m$^2$ (Cornet, 1987). By contrast Smith (1987) quotes an earlier (unavailable) paper by Cornet which appears to state that the same test is 40 days long with a flow rate around 11l/s and total recovery of about 50%.

Following on from this work a fourth hole, INAG 3-4, is drilled approximately 30m south-east of 3-2 and 3-3 with the intention of ‘creating a new heat exchanger’ (Cornet, 1987). Percussion drilled to a total depth of 250m, two attempts at hydraulic fracturing are undertaken at isolated (packed) intervals at 200 and 161m depth within the well (Cornet, 1987). At 200m depth injection of gel and sand at flow rates around 9l/s initiates a vertical fracture, later determined as striking around 155° (Cornet, 1987). Seismic data is collected from four downhole sondes clamped at various depths in INAG 3-2 and 3-3 (Cornet, 1987). Location of the recorded events indicates a progressive flow of injected fluids through a sub-horizontal permeable zone, although individual events themselves appear to be best interpreted as shearing events on sub-vertical planes which intersect this zone (Cornet, 1987). Like the induced fracture in INAG 3-2, it appears that the new hydraulic fracture has propagated a relatively short distance before intersecting with a permeable sub-horizontal natural feature (Cornet, 1987). In this case the natural structure is very close to the injection point and results in a short circuit back into the injection well (Cornet, 1987). It is concluded that ‘flow through the pre-existing fractures is one of the key factors controlling the flow pattern during injection tests’ (Cornet, 1987).

The second injection into INAG 3-4 at 161m depth produces better results, establishing an hydraulic connection with INAG 3-3 that is free of short circuiting (Cornet, 1987). Subsequent circulation testing between the two wells includes 48 days at 1.5l/s with recovery of 95% (Cornet, 1987). Reservoir impedance is calculated as being 5MPa.s/l and effective heat exchange area is 2,000m$^2$ (Cornet, 1987).
1982 – 1983
Following completion of the initial test program in 1981 work at the Montagne appears to have ceased. At the end of 1983 an economic report produced by the French BRGM (Bureau of Geological and Mining Research) concludes that production of electricity from HDR is not likely to be economic in areas where the geothermal gradient is less than 60°C/Km (Gerard and Kappelmeyer, 1987). A decision is made to focus on higher temperature sites, and the “Geothermie Profunde Generalisee” a program designed to combine refined HDR knowledge with a new, high temperature site is launched. Included within the scope of this program is work on both site selection as well as work aimed at improving existing knowledge of HDR and its related technologies (Gerard and Kappelmeyer, 1987).

1984 – 1987
After a three year hiatus the Montagne site is reactivated with the intention of developing a somewhat deeper reservoir at depths around 800m. Although it is not stated explicitly in any of the available literature, the timing of the site reactivation strongly suggests it has come about as part of the newly commenced Geothermie Profunde Generalisee.

Five new percussion wells, INAG 3-5 (?), 3-6, 3-7 (?), 3-8 and 3-9, are drilled at the site (Cornet, 1987). Wells 3-5 and 3-7 are not referred to in the available literature beyond their appearance on a site map and their depth and function are unknown. INAG 3-6 is drilled to 200m depth, its purpose also remains somewhat unclear apart from its use in investigating the nature of the fracture system previously created between 3-2 and 3-3 (Cornet, 1987). INAG 3-8 (783m) and 3-9 (840m), located 100m apart are vertical wells designed to function as the new injection and recovery pair (Cornet, 1987).

Time is devoted to an intense site characterisation study involving downhole logging, surface mapping and re-examination of the Phase 1 reservoirs. Compositional studies of cuttings and cores from various holes reveal no significant variation outside of that which can be explained through the variation in sampling technique (e.g. loss of biotite in cuttings) (Cornet, 1987). Surface mapping reveals a complex pattern of
jointing, dominated by a tightly clustered high-angle set around 170° with a number of lesser sets varying in orientation from 65° to 115° (Baria, 2001b). Fractures exposed in outcrop show evidence of hydrothermal alteration and vein infill formed in voids at depth (Baria, 2001b). Downhole surveys of water chemistry in INAG 3-8 reveal strong anomalies associated with natural fracture zones indicating the percolation of fluid through the in-situ fracture system (Cornet, 1987). This is confirmed by downhole temperature logs in the same well which indicate a number of spike anomalies at depth (Cornet, 1987). Average temperature gradient is found to be ~32.3°C (Cornet, 1987).

Stress measurements are conducted using hydraulic testing of pre-existing fractures (Cornet, 1987; Baria, 2001). Below the planned reservoir depth (650m) \( \sigma_h \) is found to be equivalent in magnitude to the local vertical stress (17-19MPa @ 700m) and is oriented ~140° (Willis-Richards et al., 1995; Baria, 2001). By contrast, \( \sigma_h \) is found to have a magnitude of 9-10MPa at 700m, only around 0.55 times the vertical component (Willis-Richards et al., 1995; Baria, 2001). The value of \( \sigma_h \) is so low in fact that under the prevalent hydrostatic conditions the undisturbed rock is likely verging on failure (Baria, 2001). Fracture orientations determined as most prone to normal failure dip 60° to the NE while those most likely to be strike-slip are sub-vertical striking at 170° and 110° (Baria, 2001). Calculations of stress conditions at reservoir depth indicate that the sub-vertical fractures at 170° experience the lowest normal stress and should be the first to fail (Baria, 2001).

In order to answer questions raised by the Phase 1 seismic data (i.e. the apparent aseismicity of the water-accepting fractures) a new and improved seismic array is emplaced (Cornet, 1987). Ten 3-component downhole geophones are installed at the bottom of 23m deep boreholes, specifically drilled for the purpose and located up to 400m away from INAG 3-8 (Cornet, 1987). An eleventh geophone is placed at 250m depth in INAG 3-4 and a twelfth at 175m in INAG 3-2 (Cornet, 1987). An additional four single (vertical) component stations are spaced outside the three component array (Cornet, 1987).

Stimulation experiments are undertaken in both INAG 3-8 and 3-9. INAG 3-9 is initially designated as the injection well and is stimulated by a number of small
viscous gel treatments at various isolated (packed) depths (Willis-Richards et al., 1995). A small hydraulic connection is established with the as yet untreated INAG 3-8 (Willis-Richards et al., 1995). Circulation with an injection pressure of 8.2MPa and flow rate equal to 8.1l/s results in only 36% recovery (Willis-Richards et al., 1995). Minor seismic activity is recorded near the injection well (Willis-Richards et al., 1995). Next, around 2m$^3$ of proppant is injected into INAG 3-9 and the circulation direction reversed. Injection is targeted at a specific isolated (packed) zone at around 710m in INAG 3-8 and circulation re-commences at injection pressure and flow rate around 9MPa and 8.3l/s (Willis-Richards et al., 1995). Recoveries of around 18% are achieved with a further 33% of fluid returning up the injection well via a vertical short circuit of the type encountered in the earlier experiments (Willis-Richards et al., 1995). Doubling the flow rate at higher injection pressure (11MPa) reduces recovery to 12% and is accompanied by seismic activity (Willis-Richards et al., 1995). Further application of 4MPa back-pressure in the production well drops recovery to only 10% (Willis-Richards et al., 1995).

It is again decided to reverse the circulation direction and INAG 3-8 is treated with 170m$^3$ of gel and 7t of proppant at injection pressures up to 12MPa (Willis-Richards et al., 1995). No seismicity is recorded during this event (Willis-Richards et al., 1995). Circulation is resumed following stimulation and recovery is again found to be low, of the order of 36% with an additional 22% from a third well (INAG 3-3 or 3-4?) equipped with a downhole pump (Willis-Richards et al., 1995). A second, larger stimulation of INAG 3-8 is subsequently attempted with placement of 400m$^3$ of gel and 40t of proppant (Willis-Richards et al., 1995). Once again, no seismicity is recorded (Willis-Richards et al., 1995). The second stimulation is followed by a long-term circulation test which generates recoveries of between 68-82% provided flow rates remain low (<10l/s) and injection pressure is held below $\sigma_h$ (Willis-Richards et al., 1995). Use of higher injection pressures and flow rates result in a rapid increase in water loss with recovery dropping to less than 50% (Willis-Richards et al., 1995).

Cornet (1987) provides a description of two further stimulation experiments in INAG 3-8 at intervals at 443m and below 645m depth. It is unclear from the available literature whether these events proceed or follow those described by Willis-Richards et al. (1995). During the first injection at 443m, 110m$^3$ of water is injected into a sub-
horizontal fracture isolated by packers (Cornet, 1987). Flow rate is increased from 5l/s to 23.3l/s with injection pressures reaching 17.5MPa downhole and 18MPa at surface (Cornet, 1987). No breakdown pressure is observed (Cornet, 1987). An impression taken after shut-in (pressure 12.4MPa) indicates the presence of three sub-horizontal fractures dipping from 10° to 27° and one vertical dipping 87° and striking 073° (Cornet, 1987). (It is noted that the orientation determined for the vertical fracture implies it is nearly parallel to the determined σh implying that the orientation of the impression may be faulty (Cornet, 1987)). Six microseismic events are recorded as a result of this injection and, when located, are found to align with the injection point along a roughly north-south line (Cornet, 1987). This direction is consistent with the determined σH and may be related to the presence of a sub-vertical 170° trending permeable fracture located 30m below the injection point (Cornet, 1987). Once again it is found that individual seismic events most likely represent shear slippages along pre-existing fractures oriented differently to that of the apparent flow direction (north-south) (Cornet, 1987).

The second injection test recorded in Cornet (1987) takes place in the open hole interval between 645m and the end of hole at 783m. Around 100m³ of water is injected at flow rates between 20 and 23.3l/s (Cornet, 1987). Twelve recorded seismic events are associated with this event from which σH is determined as having an orientation of N±15° (Cornet, 1987).

Footnote
Experimental work at Le Mayet de Montagne ceases in 1987, the site effectively made redundant by the switching of the national focus to the new hotter and deeper HDR project at Soultz-sous-Forêts.
A1.7 Soultz-sous-Forêts HDR, France

Summary
Located around 1km west of the town of Soultz-sous-Forêts on the western edge of the Rhine Graben, the Soultz Hot Dry Rock project has an extended history of research and development. Funded under the auspices of the European Union an initial collaboration of French and German researchers has expanded to include workers from many countries including the UK, Italy, Switzerland, Sweden, Japan and the USA. Commencing in 1987 the site has seen the development of three separate reservoir systems, culminating in the current development of a semi-commercial demonstration project at 5km depth. Research conducted at Soultz has been extensive and has seen the rise of an HDR concept more akin to an enhanced geothermal system, that is, one which takes advantage of not only the natural fracture system but also of in-situ fluids to balance flow into and out of the system.

Detailed Timeline

1983 – 1984
European interest in the Hot Dry Rock concept has been strong for nearly a decade by the end of 1983 when an economic report produced by the French Bureau of Geological and Mining Research (BRGM) concludes that production of electricity from HDR cannot be economic in areas where the geothermal gradient is less than 60°C/Km (Gerard and Kappelmeyer, 1987). The consequent decision to focus on high temperature sites results in the launch of the “Geothermie Profunde Generalisee” a program designed to combine site studies with work aimed at the improvement of existing HDR tools and methods (Gerard and Kappelmeyer, 1987). Under this program work is reactivated at the Mayet de Montagne test site whilst site identification studies are undertaken to find a location more suitable for the development of a high temperature HDR prototype (Gerard and Kappelmeyer, 1987).
Studies undertaken during the Geothermie Profunde Generalisee lead to the identification of a prospective geothermal region in the Haguenau-Soultz region of north-eastern France (Gerard and Kappelmeyer, 1987). The area, host to the century Pechelbronn oil-field, already contains around 660 bore holes of which 60 are known to be greater than 800m deep (Gerard and Kappelmeyer, 1987). The exploitation of the oil-field has resulted in the assemblage of a large amount of geological data including a thorough regional sedimentary stratigraphy and detailed geothermal maps (Kappelmeyer et al., 1992).

Situated on the western rim of the Rhine Graben, part of the extensive NNE-SSW trending Cenozoic Western European Rift System, the geology of Haguenau-Soultz comprises some 1,400m of sediment (Triassic – Miocene) overlying mid-Carboniferous (~325Ma) basement granite (Genter & Trainau, 1996). It is known from previous drilling that the basement granite is likely to have been unroofed and eroded sometime during the Permian (Genter & Trainau, 1996). The area is host to a significant regional geothermal anomaly, gradients within the sediment averaging 65°C/km, ranging up to 105°C/km (Schellschmidt & Schulz, 1992). The HDR test site itself is eventually pinpointed around 1km west of the town of Soultz-sous-Forêts thanks to the identification of a particularly strong local geothermal anomaly of dimensions approximately 3 x 7km (Gerard and Kappelmeyer, 1987). Within the area of the anomaly gradient is found to be of the order of 110°C/km for at least the first 1,000m, implying the possibility of temperatures as high as 140-180°C within 2km depth (Gerard and Kappelmeyer, 1987). Basement topography at the test site indicates the presence of a local horst structure (Gerard and Kappelmeyer, 1987).

A collaborative Franco-German project is set up with the primary objective of investigating in detail the potential suitability of the site for future development of a HDR prototype (Gerard and Kappelmeyer, 1987). Funded in part by the European Economic Community (EEC), the initial stage of the project, referred to as ‘pre-feasibility’, is focussed largely on site characterisation (Kappelmeyer et al., 1992). Planning of a two year exploratory program is commenced (www.soultz.net).
1987

An initial exploratory well, GPK-1 is spudded in July 1987 and reaches total depth at 2,000m six months later. The well intersects basement at 1,377m and the granite is sampled by cuttings and occasional core runs (Trainseau et al., 1992). At 140.3°C measured equilibrium bottom of hole temperature is at the lower end of the predicted range (Schellschmidt & Schulz, 1992). Whilst the temperature gradient of the sediments is high (105°C/km), the gradient in the granite is found to be significantly lower at 28°C/km (Baria et al., 1999). Following well completion, a large effort is expended on site characterisation with investigations into geology, basement structure, local stress regime, fracture networks, rock mechanics, hydrology and geochemistry (Kappelmeyer et al., 1992).

A total of 43m of core is recovered from the GPK-1 basement intersection (Trainseau et al., 1992). Detailed petrographic studies of core and cuttings reveal that basement rock is ‘porphyritic granite rich in K-feldspar megacrysts’ (Trainseau et al., 1992). The primary mineral assemblage comprises ‘quartz, plagioclase, K-feldspar, biotite and hornblende plus accessory apatite, titanite and magnetite’ (Trainseau et al., 1992). At least two fine-grained leucogranite phases are noted to intrude the main granite body, these being distinguished from their host by a lack of biotite and from each other by varying degrees of hematization of K-feldspar (Trainseau et al., 1992). A thin biotite-rich layer identified at 1,445m is interpreted as restite (Trainseau et al., 1992).

Varying degrees of hematization of K-feldspar are observed throughout the core and are considered to be a syn-magmatic feature (Trainseau et al., 1992). Pervasive propylitic alteration is evident in the replacement of primary phases biotite and plagioclase by chlorite and corrensite respectively and secondary carbonate, epidote, hydrogarnet, illite, iron oxides and prehnite are observed (Trainseau et al., 1992). Veining and vein-related alteration are also present and suggests five potential ‘major’ fracture zones at 1,618, 1,709, 1,789, 1,812 and 1,857m (Trainseau et al., 1992). Common vein alteration products include sericite and clays, carbonates, iron oxides and occasional quartz (Trainseau et al., 1992). Geochemical analysis of vein alteration indicates removal of Na, Ca, Mg and Fe and concentration of K through clay deposition (Trainseau et al., 1992).
Laboratory analysis of the recovered granitic fluids indicate they are not in equilibrium with granite at 140° and are most likely sourced from deeper, hotter areas within the rock (Pauwels et al., 1992a). Continuous monitoring of the drilling return is able to identify zones of natural fluid influx where formation waters dilute and alter the chemistry of the drilling mud (Pauwels et al., 1992a). A number of distinct fluid entry points are identified on the basis of pH and/or CO₂, Na, Cl and He concentrations and correlate well with the fractured/alterned zones later identified from geological/geophysical logs (Pauwels et al., 1992a). The most productive zone coincides with a fracture identified at 1,812m, a small flow (0.15l/s) of highly saline fluid sufficient to cause a significant anomaly to appear on post-drilling temperature logs (Pauwels et al., 1992a; Schellschmidt & Schulz, 1992).

Extensive downhole logging, utilising both BHTV and FMS is undertaken to assess the nature and distribution of planar structures and discontinuities intersected by GPK-1 (Tenzer et al., 1992). 1,880 individual structures are identified, most steep to vertical E/W dipping joints with a main strike direction around 170° and sub-maxima at 10°, 114°, and 138° (Tenzer et al., 1992). Joint density is on average around 1-2 joints/metre but varies widely (Genter et al., 1992). Other structures identified include a sub-horizontal joint set, most likely formed as a result of stress relief within the massif (Genter et al., 1992). Vertical fractures bisecting the well walls for up to 10m and striking, on average, 169° are identified as drilling induced hydraulic fractures (Tenzer et al., 1992). The strike of these structures very likely reflects the orientation of the maximum horizontal stress, σH (Tenzer et al., 1992).

When compared to core both FMS and BHTV images are shown to underestimate the fracture density within the more altered and disturbed regions (Genter et al., 1992). A study of microcrack directions within a sample of core oriented using BHTV images again indicate a strike maxima around 175° and average dips between 60-85° to both east and west (Tenzer et al., 1992). Microcracks which contain fluid inclusions are noticeably different however, striking 115-135° with sub-maxima at 85° and 55° (Tenzer et al., 1992). Comparison of average strike directions with inferred historical structural trends indicate that fluid filled microfractures are likely reflecting earlier deformation phases (Tenzer et al., 1992). Overall, structures in the upper portion of granite (1,377 – 1,550m) appear to reflect the influence of Miocene (WNW-ESE
tension) stress conditions whilst those lower in the hole reflect current WSW-ESE tension regimes (Tenzer et al., 1992).

A seismic network is set up utilising the existing oil wells (Beauce et al., 1992). Three wells are re-opened and seismic probes emplaced at depths of 843m, 963m and 1,360m (Beauce et al., 1992). Vertical seismic profiles (VSP) of GPK-1 detect fracture zones at 1,560m, 1,640m and 1,812m as well as zones undetected by logging (but later found to respond to hydraulic stimulation) at 1,530m, 1,730m and 1,910m (Beauce et al., 1992). A number of steeply dipping features are observed less than 100m to the east of GPK-1 and several sub-horizontal features identified beneath the well (Beauce et al., 1992). Studies of core indicate seismic velocities are essentially isotropic within the granite although signal transmissions suffer from anisotropic absorption, likely due to the presence of microcracks and fractures with preferred orientations (Rummel, 1992).

Programs undertaken to measure the physical properties of the granite are carried out using both core and cuttings (Rummel, 1992). Density measurements indicate a mean value of $2.66 \pm 0.01 \text{g/cm}^3$ (Rummel, 1992). Areas of intense vein alteration, such as that identified around 1,812m, are noticeably less dense ($2.59 \pm 0.04 \text{g/cm}^3$) (Rummel, 1992). Densities recorded from cuttings are found to be systematically higher than those from core at equivalent depths (Rummel, 1992). Measurements of magnetic susceptibility indicate a decrease, probably related to magnetite destruction, around known fracture zones (Rummel, 1992). Mean thermal conductivity (dry) of the granite is determined to be $2.58 \pm 0.20 \text{Wm}^{-1}\text{K}^{-1}$, diffusivity $0.89 \pm 0.16 \text{10}^{-6} \text{m}^2\text{s}^{-1}$ (Rummel, 1992). Concentrations of U, Th and K are 11.55 ± 4.60ppm, 31.75 ± 3.31ppm and 4.12 ± 0.98% respectively (Rummel, 1992). U is 2-3 times more abundant than the world-wide granite mean. Radioactive heat production rate is calculated as $6.2 \pm 0.7 \mu \text{Wm}^{-3}$, around twice that of the global average (Rummel, 1992). Rb/Sr dating indicate age of intrusion as 325 ± 6Ma (Rummel, 1992).

Hydrogeothermic studies conducted in GPK-1 include measurement of the equilibrium geothermal gradient & BHT (140.3°C) (Schellschmidt & Schulz, 1992). Three distinct stages of temperature gradient are identified: (1) the uppermost sediments containing high gradients (up to 105°C/km) below which lie (2) a distinct
zone with gradient as low as 15°C/km, likely the result of convective influences in the porous Buntsandstein aquifer and below which (3) the curve flexes again, returning to a more average 28°C/km within the granite (Schellschmidt & Schulz, 1992). The surface heat flow anomaly is interpreted as the product of deep upwelling of waters within the Buntsandstein around the local horst structure (Schellschmidt & Schulz, 1992). Water does not penetrate to surface from this system but does convect within the Buntsandstein layer, effectively heating the base of the upper sedimentary layers (Schellschmidt & Schulz, 1992).

1988

A series of hydraulic tests are run in GPK-1 between May and December 1988 with the aim of investigating site specific hydraulic and hydro-mechanical conditions (Jung, 1992). The program commences with a seven-week venting during which some 515 m³ of water is discharged from the well (Jung, 1992). The artesian outflow rises slightly over the test period from 0.12 l/s to 0.16 l/s, an increase believed to result from buoyancy effects accompanying the warming of the hole. Temperature logs run during this test indicate that the naturally altered zone around 1,812 m is the major entry point for fluid in the hole (Jung 1992).

Following long term venting, a number of small injection tests are undertaken to further investigate the distribution of hydraulically significant fractures and observe the influence (if any) of increasing pressure (Jung, 1992). 250 m³ of water is injected in three phases at flow rates of 0.5, 1.5 and 3.5 l/s respectively (Jung, 1992). Monitoring of temperature logs during fluid injection indicates a number of distinct zones are accepting flow, most particularly the 1,812 m fracture zone which takes 73% of the 1.5 l/s injection (Schellschmidt & Schulz, 1992). At higher injection rates (3.5 l/s) a second major flow path opens at 1,728 m accepting 43% of flow and reducing intake at 1,812 m to 57% (Schellschmidt & Schulz, 1992). Opening of the second joint is reflected in pressure versus flow rate curves, which show a strong deviation from initially linear behaviour at around 30-35 MPa overpressure (Jung, 1992). Data from temperature logs recorded during subsequent shut-in identify a series of newly opened joints between 1,700-1,735 m which promptly close when pressure is removed (Schellschmidt & Schulz, 1992).
Combining BHTV logs, petrology and newly identified fluid intake zones it appears that rock sections capable of accepting water are characterised by either vertical fractures or highly altered natural fracture zones (Tenzer et al., 1992). The intake zone at 1,812m is identified as an intersection between an in-situ feature and a vertical drilling induced fracture (Tenzer et al., 1992). By contrast structures around the 1,728m intake zones are steeply dipping N-S striking natural joints (Tenzer et al., 1992). It is clear, however, that the majority of the nearly 800 joints identified within the granite are not hydraulically significant (Jung, 1992).

A series of downhole hydraulic stimulation tests are conducted using packers to isolate individual fractures of specific orientations identified with BHTV (Jung, 1992). Eight tests are completed, three above 1,500m, the rest below 1,900m including two single packer tests above the end of hole (Jung, 1992). During the fifth test run at 1,968m accidental inflation of a packer during pre-experimental flushing results in the initiation of a new fracture, subsequently determined to be a long vertical structure extending down to 1,991m (Jung, 1992). Growth of the fracture appears to have been retarded by intersection with a natural joint set at 1,991m (Jung, 1992). Temperature logs show a strong artesian flow out of the fracture, most of which appears to be sourced from this intersection (Jung, 1992). Subsequent injection tests across the fracture provide evidence for a good connection to a far-field reservoir (Jung, 1992). Larger scale stimulation of the fracture injects 524m$^3$ of water at 3.3l/s over three days and is found to permanently improve local hydraulic conductivity (Jung, 1992). Further injection testing of the full open hole interval indicates that injection rates greater than around 6.5l/s are likely to result in fracture propagation (Jung, 1992).

Seismic monitoring during the three day bottom hole stimulation test detects 58 events (Beauce et al., 1992). Seismic activity initiates after only two hours of injection and peaks shortly thereafter (Beauce et al., 1992). The majority of recorded events are of similar character and spectral content, likely indicating repeated movement of specific planes (Beauce et al., 1992). Travel times of P and S waves point to the existence of at least two focal zones which are found to behave differently with time, one experiencing larger events early in the injection tapering off to smaller over time, the other displaying larger events later in the experiment (Beauce et al.,
Locations determined for 12 events appear to cluster into two distinct groups, one near the top of the injection zone, the other at around 2,090m (Beauce et al., 1992). Nine of these events may be related to a north-south trending sub-vertical structure akin to those identified to the east of the well by the VSP (Beauce et al., 1992). Overall, the decrease of seismic activity with time is believed to reflect the formation of a new steady-state system (Beauce et al., 1992). It is likely that the stimulated fracture has connected to a permeable fault zone (Jung, 1992). Seismicity, the product of pressure induced enlargement of the contact between the borehole and the permeable fault, continuing until the entire fluid flow is able to be accepted into the natural fault system (Jung, 1992).

Stress determinations using the results of the hydraulic stimulation testing indicate a stress regime with relatively low horizontal stress, consistent with the presence of recent normal faulting within the basement (Rummel and Baumgartner, 1992). Assuming an average rock density of 244g/cm³ mean stress profiles are obtained for the basement granite between 1,458 and 2,000m (Rummel and Baumgartner, 1992):

\[
\sigma_h = 15.1\text{MPa} + 0.0179\text{MPa/m}^*(z - 1458\text{m})
\]
\[
\sigma_H = 24.8\text{MPa} + 0.0198\text{MPa/m}^*(z - 1458\text{m})
\]
\[
\sigma_v = 0.024\text{MPa/m}^*z
\]

Calculated orientation of \(\sigma_H\) is 155° or 176°, in both cases consistent with the strike of the vertical drilling induced fractures.

Analysis of fluids recovered from both the initial injection and later hydraulic stimulation tests points to the mixing of injected fresh waters with formation fluid (Pauwels et al., 1992b). Most elements act in a conservative manner with Si, F, Ba, SO₄ and CO₂ the only monitored elements to show evidence of added dissolution due to rock-water interaction (Pauwels et al., 1992b). Changes in concentration of these elements are attributed to the dissolution of calcite, biotite, feldspar, sulphides and/or barite (Pauwels et al., 1992b). In the case of calcite, mineral dissolution is not attributable to the action of injected fresh water on granite but rather a consequence of the disequilibrium between the connate fluids and host rock at 140° (Pauwels et al., 1992b). Sulphur dissolution appears to be erratic and may be the result of an
inhomogeneous spread of one or more source minerals along different fluid pathways (Pauwels et al., 1992b). Tracer experiments using both reactive and non-reactive tracers are undertaken during the hydraulic stimulation experiments (Pauwels et al., 1992a). Breakthrough curves suggest the presence of at least one major fracture zone, the dispersion of fluid implying the presence of a large number of fluid pathways within this zone (Pauwels et al., 1992a).

A number of general conclusions are drawn from the hydraulic testing. The upper limit of permeability for the open hole section is determined to be around 35μD, well within the normal range for granite (Jung, 1992). It is concluded that the Soultz granite is not unusually permeable, rather contained within the granite is at least one zone, likely a fault or fracture, of much greater permeability (Jung, 1992). This feature is likely to lie within a 100m or so of GPK-1 and is connected to the borehole via three main crosscutting fractures (Jung, 1992). Propagation pressures of stimulated fractures are very low (3-5MPa), the vertical N-S oriented drilling induced fractures being the least resistant to opening (Jung, 1992). Models of fracture propagation indicate that the coincidence of greatest flow and fracture intersection (between induced vertical fracture and pre-existing joint) is likely a result of spreading of the propagating fracture tip as it intersects the existing discontinuity (Jung, 1992). The existence of these highly permeable preferred flow paths may have significant consequences for the long term thermal behaviour of the reservoir (Jung, 1992).

1989 – 1991

Follow-up injection testing of GPK-1 conducted in early 1989, intended to assess the affects of the three-day stimulation, ends abruptly when failure of a wellhead coupling leads to uncontrolled venting of some 1.5m$^3$ of water (Jung, 1992). This work signals the end of the ‘pre-feasibility’ studies. Overall, results of the project are considered to be very encouraging, the site seeming suitable for development of an operating heat exchanger at a projected depth of around 3-3.5km (Kappelmeyer et al., 1992). The period until 1991 is set aside as a ‘feasibility study’ designed to address issues identified in the development of the deep reservoir (Kappelmeyer et al., 1992). Work to be conducted in this period includes ongoing hydraulic tests at 2000m depth in GPK-1, investigation of the geological conditions at 3.5km depth using a cored well,
and further development of technologies required to realise the project (Kappelmeyer et al., 1992).

The success of the prototype seismic network used during the initial stimulation in GPK-1 proves the viability of recovering existing oil wells (Kappelmeyer et al., 1992). Work now commences on improving the system by deepening three recovered oil wells to 1,400, 1,500 and 1,600m, enabling emplacement of sondes directly within the crystalline basement (Baria et al., 1999). Instruments deployed into the wells are standard three component seismic sensors (Jones et al., 1995).

The seismic network is tested during single well hydraulic injection tests conducted at 2,000m in GPK-1 in 1991 (Elsass et al., 1995). Two 50 hour tests with injection rates of 7 and 15l/s are performed (Jones et al., 1995). Some 370 microseismic events are detected, their location defining an elongated NW-SE trending cloud extending down from 1,800 to 2,250m depth (Jones et al., 1995). Despite relatively low injection pressures stimulation has again resulted in propagation of a sub-vertical fracture striking around 170° (www.soultz.net). The pattern of flow observed in the system further points to connection with a permeable aseismic natural fracture (Elsass et al., 1995).

Parallel to the work in GPK-1 is an investigative project centered on the drilling of a second, fully cored reconnaissance well EPS1. Located about 400m SSE of GPK-1, EPS1 utilises a pre-existing oil well allowing coring to commence at 930m depth (Baria et al., 1995). Granite is intersected at 1,417m and a total of 810m of core is recovered before drilling difficulties result in the termination of the well at 2,227m (Genter & Traineau, 1992; Baria et al., 1995). Recorded bottom hole temperature is given as 150°C (www.soultz.net). Despite failing to reach target depth (3,500m) EPS1 nonetheless provides useful lithological and structural data (Baria et al., 1995).

Basement geology encountered in EPS-1 core is similar to that of GPK-1 (Genter & Traineau, 1992). A detailed study is undertaken into the orientation and distribution of naturally occurring macroscopic fractures within the new core (Genter & Traineau, 1992). Around 3,300 individual structures are identified within the core the majority being natural brittle structures with a lessor amount of magmatic features (Genter &
Structures are initially oriented with respect to an arbitrary core orientation line, the azimuth of which is later estimated using borehole imagery (BHTV) (Genter & Trainseau, 1992). Around 97% of the observed macroscopic structures are successfully oriented in this manner—in spite of the fact that resolution constraints in the BHTV imagery allow identification of only 517 structures within the same 810m section (Genter & Trainseau, 1992).

Overall, fracture orientations are found to describe a bimodal distribution, the majority dipping either westward (270° – 280°) or eastward (70° – 80°) with westward trends becoming more dominant with depth (Genter & Trainseau, 1992). The great majority of all identified fractures are steeply dipping around 70° – 80° (Genter & Trainseau, 1992). In contrast to GPK-1, predominant strike directions identified in microfractures from EPS-1 core at 1,567m are 30-34° and 115-122° with a subset at 165° (Tenzer, 1995). It is concluded that the EPS-1 microfractures primarily preserve the orientation of a palaeo stress field with the current stress regime represented by the sub-maxima (Tenzer, 1995).

Overall, fracture distribution in EPS-1 core is uneven with the majority falling into well defined zones interpreted as the trace of major faults interspersed throughout relatively massive granite (Genter & Trainseau, 1992). Fracture zones in the upper parts of EPS1 correlate well with those observed in GPK-1 (Genter & Trainseau, 1992). Towards the top of the basement fracture density is found to increase with the presence of a greater number of sub-horizontal joints, most likely a result of unroofing during the Permian (Genter & Trainseau, 1992). Subtracting the effect of stress release the fracture population shows neither a net increase nor decrease with depth (Genter & Trainseau, 1992).

Around 80% of all fractures identified in core have widths of less than 1mm, the remainder generally being less than 10mm with only a handful of vein deposits greater than 1cm thick (Genter & Trainseau, 1992). There appears to be a direct correlation between fracture density and fracture width (Genter & Trainseau, 1992). Most observed structures are sealed, noted open features are typically thick quartz veins located within the most fractured zones (Genter & Trainseau, 1992). In at least one case (2,160 – 2,175m) a high density of open fractures is associated with a zone

A1-75
of known fluid flux (Genter & Trainau, 1992). There is evidence of heterogeneity in average fracture orientations between less fractured (massive) granite and the altered fault zones (Genter & Trainau, 1992). Fracture orientations present in both include the dominant N/S striking sets but less fractured zones are characterised by NE/SW fractures whilst faulted zones contain E/W and NW/SE as well as lesser amounts of NE/SW striking sets (Genter & Trainau, 1992).

Comparison of faults orientation between the granite and overlying sediments reveal many similarities suggesting that fault zones within the granite may be extensions of major sedimentary structures (Genter & Trainau, 1992). This in turn suggests that fluids may circulate freely from sediments into granite along more or less continuous pathways (Genter & Trainau, 1992).

1992

Encouraging results from initial stimulation experiments, combined with indications from both GPK-1 and EPS-1 that fracture density within the granite does not decrease with depth, leads to the decision to proceed to deeper areas. Extension of the existing well GPK-1 is undertaken, the hole reaching a final depth of 3,590m, cased to 2,850m (Baria et al., 1995). Around this time the seismic network of three-component sondes is updated to a ‘second generation’ network of permanent four-component instruments (Jones et al., 1992; www.soultz.net). EPS-1 finds eventual use as host for a hydrophone assembly and a surface network of 8 three-component stations is installed (Baria et al., 1995). Equilibrium BHT in the newly drilled GPK-1 is recorded as 160°C, somewhat lower than had been predicted (Pauwels, 1997). Average gradient at total depth is around 13°C/km, significantly less than the 28°C/km determined in the upper granite section.

Extension of GPK-1 is followed by an extensive program of geophysical logging and large-scale hydraulic testing, the latter being accompanied by close microseismic and geochemical monitoring. Newly drilled deep sections of GPK-1 reflect the pattern established in the shallow basement with intervals of massive, unfractured granite interspersed with highly fractured and altered zones (Baria et al., 1995). At least three of these zones (2,815m, 3,386m, 3,485m) are identified as producing fluid (Baria et al., 1995). BHTV and sonic downhole logging systems are applied to study
the deep fracture system (Tenzer, 1995). As before the system is dominated by sub-vertical 170° striking fractures with lesser components striking 10-30°, 90-110° and 140° (Tenzer, 1995). Between 3,300 and 3,570m depth there is an apparent rotation of the maximum strike direction to 100-120°, most likely the result of a disruption to the local stress field by a local fault (Tenzer, 1995). Comparisons of apparent aperture with strike direction indicate wider structures tend to strike SSW-NNE and WNW-ESE (Tenzer, 1995). Features identified as open or flowing structures are found to have predominantly NE-SW strikes in the upper logged region (3,190-3,340m) and predominantly WNW-ESE in the lower logged region (3,340-3,490m) (Tenzer, 1995). The rotation in orientation of these features is consistent with that noted in the general fracture orientations (Tenzer, 1995).

Stress measurements are undertaken using a new aluminium packer technology designed specifically for the hostile high temperature environment encountered at great depths (Rummel & Klee, 1995). Data confirms that the direction of $\sigma_H$ is NNW-SSE, around 170° (Baria et al., 1995). The magnitude of $\sigma_H$ approaches $\sigma_V$ with depth but does not become significantly greater, $\sigma_H/\sigma_V$ remaining approximately one at 3,500m (Rummel & Klee, 1995). By contrast $\sigma_h$ remains significantly lower than $\sigma_H$ at all times, the strong horizontal stress anisotropy and equality of $\sigma_H$ and $\sigma_V$ indicating the normal faulting regime identified at shallower depths persists to at least 3,500m (Rummel & Klee, 1995). A single hydrofracture measurement within the lower region of GPK-1 indicates a rotation of $\sigma_H$ in line with the apparent rotation of the major fracture strike to 100-120° (Baria et al., 1995). Once again this is considered to be an abnormal result, likely produced by proximity to an unknown fault (Baria et al., 1995). Assuming an average rock density of 2.44g/cm³ new mean stress profiles were calculated for the basement granite between 1,458 and 3,506m (Baria et al., 1995):

$$\sigma_h = 15.8\text{MPa} + 0.0149\text{MPa/m*}(z - 1458\text{m})$$
$$\sigma_H = 23.7\text{MPa} + 0.0336\text{MPa/m*}(z - 1458\text{m})$$
$$\sigma_V = 33.8\text{MPa} + 0.0255\text{MPa/m*}(z - 1377\text{m})$$
Hydraulic testing in GPK-1 re-commences in 1993 with injection of 41m$^3$ of water across the open hole interval (Baria et al., 1995). Subsequent venting produces 1.5l/s decreasing over time to 0.03l/s (Baria et al., 1995). Application of a downhole pump initially improves production to 2l/s but again sees a decrease in time to 0.5l/s (Baria et al., 1995). A total of 525m$^3$ of fluid is recovered (Baria et al., 1995). Downhole flow monitoring during venting indicate, as expected, the existence of discrete zones of fluid output, the most significant of which is at 3,485m (Jung et al., 1995). Geochemical analysis indicates that fluid recovered is of similar composition to that produced in the upper granite (Baria et al., 1995). It is noted that the relation of flow rate to injection pressure is indicative of turbulent flow (Jung et al., 1995).

A second test, aimed at initiating new hydraulic fractures within competent sections isolated by packers, is abandoned due to leakage of fluid into the open hole section (Baria et al., 1995). No new fractures are initiated although microseismic data indicates shearing of a natural joint at wellhead pressure around 6MPa (Baria et al., 1995). It is decided to focus future testing upon areas above the main producing zone at 3,485m and the bottom portion of the well is cased to a depth of 3,400m (Baria et al., 1995). A 17-day stepwise 'massive' injection experiment is commenced on the remaining open hole (Jung et al., 1995). A total of 25,300m$^3$ is injected with injection rate rises periodically from 0.15l/s to a maximum of 36l/s across the test period (Jung et al., 1995). Injection is followed by a day of shut in and two days of venting during which some 1,200m$^3$ of water is returned to surface (Jung et al., 1995). Spinner logs recorded during injection confirm the presence of discrete zones of water acceptance, this time located at 2,850-2,900m, 3,090-3,100m, 3,230-3,240m and 3,320-3,325m (Jung et al., 1995). It is noted that pressure increases at low flow rates are accommodated by the lower 3,230-3,240m intake zone, which gradually increases its percentage intake from 5 (0.3l/s) to 40% (4.8l/s) of the total (Baria et al., 1995). As pressure (flow rate) approaches and exceeds $\sigma_h$ for the upper zone (2,850 – 2,900m) the situation reverses, the lower zone accepting progressively smaller percentages of flow (down to 25%), the upper expanding to take 65% at 23.4l/s (Baria et al., 1995). Once minimum horizontal stress of the upper zone is exceeded new fractures open to accept water and injection pressure remains stable at 10MPa even as injection flow
rate increases (Jung et al., 1995). The direction of fracture propagation appeared to be upwards, a fact later confirmed by microseismic data (Jung et al., 1995).

Geochemical analyses of fluid vented after the massive injection provide interesting insight into the temperature dependent nature of rock-water interactions (Pauwels, 1997). The large volume of water injected into GPK-1 produces significant cooling of the near well environment, similar to that which would be expected around the injection well in a dual or multi-well heat exchanger (Pauwels, 1997). Comparison of the chemical changes observed in production fluid retrieved from the massive single well injection with those seen in dual well experiments at other sites (e.g. Fenton Hill, Rosemanowes, Hijiori) reveal a number of significant differences (Pauwels, 1997). One of the most spectacular of these is a release of Mg into the fluid phase (Pauwels, 1997). Attributed to dissolution of biotite or chlorite, Mg is characteristically deposited at higher temperatures, its dissolution therefore likely due to the relatively low temperatures of the single well environment (Pauwels, 1997). In dual well systems Mg is often found to be depleted indicating uptake must be occurring in the hotter production end of the system (Pauwels, 1997). The implication then is that Mg is likely to be transported across a HDR reservoir from cooler to hotter regions (Pauwels, 1997). Similar relations are found with anhydrite and calcite both of which dissolve and precipitate at lower and higher temperatures respectively (Pauwels, 1997). Temperature differences within a two well HDR system are likely, therefore, to cause mass transfer of certain elements from point to point within the reservoir without necessarily producing a signature in the fluid vented to surface (Pauwels, 1997).

The fourth hydraulic test of 1993, designed to isolate and stimulate the naturally permeable 3,485m fracture system, is unsuccessful due to packer failure (Baria et al., 1995). It is replaced by the fifth and final test for the year, a high rate injection across the entire open hole for which the sand plug is removed (Jung et al., 1995). 19,300m$^3$ of water is injected over five days, four at 40l/s (9.5MPa) the last at 50l/s (10MPa) (Jung et al., 1995). The hole is shut in for two days before venting during which 650m$^3$ of fluid returns to the surface (Jung et al., 1995). Flow logs recorded during injection indicate that only 10% of fluid is accepted by the naturally permeable 3,485m zone, the majority of water (70%) instead taken up by the previously
stimulated 2,850-2,900m section (Baria et al., 1995). During venting the 3,485m structure is found to release 15% of the return flow at around 1.65l/s, most of the remaining balance drawn from the stimulated fracture (Baria et al., 1995).

Seismic monitoring is continuous throughout the 1993 hydraulic testing. Around 19,000 individual events are recorded of which some 16,000 are able to be accurately located (Jones et al., 1995). The sum of all located events define a large tabular shaped seismic cloud (1,200m (h) x 1,000m (l) x 400m (w)) centered on the injection well GPK-1 with a long axis extending NW-SE (Jones et al., 1995; Jung et al., 1995). Distribution of seismic events within the cloud is most concentrated in the immediate vicinity of the well at 2,900m and appears to extend upward as well as outward from the injection point (Jones et al., 1995). Horizontal sections taken at various depths through the cloud indicate the occurrence of a number of features whose strike varies from the average (Jones et al., 1995). Most particularly within the 2,700-2,900m depth range it is found that the cloud north of the bore strikes N-S whereas south of the bore it is NW-SE (Jones et al., 1995). These differences are attributed to variation within the pre-existing joint network (Jones et al., 1995).

The most seismically active injection test of 1993 is the third or massive injection test with over 17,000 events recorded (Jung et al., 1995). Here seismicity initiates at injection pressures around 6MPa (injection flow rate 0.3l/s) (Jung et al., 1995). Initial seismicity is located within the region of the casing shoe but extends downwards across the open hole interval with time, the rate of seismicity increasing significantly as pressure rises to 8MPa (Jones et al., 1995). As the seismic cloud reaches depths equivalent to the lowermost open hole sections, injection pressure stabilises around 10MPa and a reversal is seen, the cloud now growing upwards, elongating to the north of the well in a NW-SE direction. Reservoir growth continues in the fifth injection experiment where initial activity is associated almost exclusively with the newly exposed open hole region, despite the fact that nearly 70% of flow is absorbed by the previously stimulated zone (Jones et al., 1995). It is not until a significant quantity of water (12,000m$^3$) is injected that seismic activity is recorded in the region previously stimulated in test three (Jones et al., 1995).
Production testing is undertaken in GPK-1 in mid-1994 with the aim of further characterising the newly created reservoir system (Jung et al., 1995). A small injection (110m$^3$) of fresh water is followed by a four day shut in and three part production test (Baria et al., 1995). Produced fluid is condensed and re-injected into EPS-1 (Jung et al., 1995). Initial production is unrestricted but flow is throttled to 5l/s after a day due to limitations in the re-injection process (Jung et al., 1995). Throttled production continues for 7.5 days at which point engineering improvements in EPS-1 enable resumption of full flow which is maintained for a further 3 days (Jung et al., 1995). Production rates during this final period slowly decrease from around 10l/s to 7l/s by end of test, a fact attributed to a build up of scale in the surface production line (Jung et al., 1995).

In total 6,200m$^3$ of fluid is vented at flow rates and temperatures up to 18.5l/s and 122°C (Baria et al., 1995). Estimated steady-state flow rate, disregarding the effect of scale in the fluid conduits is 10l/s (Jung et al., 1995). Production flow logs indicate the majority of flow (70%) is sourced from the artificially stimulated zone at 2,850-2,900m (Baria et al., 1995). Surprisingly, the composition of vented fluid indicates that only around 10-15% of the total volume is fresh water, the remainder being natural brines indicating that the large volumes of fluid injected in 1993 have migrated out of the area through what must be a well developed fracture system (Baria et al., 1995). This is consistent with data from shut in pressure curves which indicate connection to a far-field zone of constant pressure/greater transmissivity (Baria et al., 1995).

Following on from the production test a series of injection tests are again undertaken this time with the aim of characterising the injectivity of the reservoir (Jung et al., 1995). Some 9,600m$^3$ of water is injected into the full open hole section at flow rates of 6, 12 and 18l/s for periods of 1.5, 3 and 3.5 days respectively followed by a 3 day shut in period (Baria et al., 1995). In each case care is taken to ensure that injection pressure does not exceed that required for fracture propagation (Jung et al., 1995). It is found that injection pressures required to achieve given flow rates are significantly lower than those recorded in 1993 implying that permeability has been permanently enhanced (Jung et al., 1995). As always the majority of flow (75%) is accepted by the
artificially stimulated zone at 2,850-2,900m, only 10% going into the naturally permeable zone 3485m (Baria et al., 1995). Examination of the flow rate/injection pressure relationship indicates turbulent flow is likely (Jung et al., 1995). It is believed that this may be the result of the fluid focussing along pathways within fractures akin to those noted in the shallower experiments at the intersection of an induced fracture and natural joint set (Jung et al., 1995).

1995

The apparent success of reservoir creation in GPK-1 enables the go-ahead for drilling of a second deep well to create a fully functional paired well heat exchanger. Well GPK-2, positioned approximately 450m to the south of GPK-1 is drilled to a total depth of 3,867m (Baria et al., 1999). The new well is aligned 170° along strike from GPK-1, the decision to move south based upon seismic data from the successive 1993 GPK-1 stimulations and observed temperature trends which indicate an increase in geothermal gradient. The deepest observed temperature in GPK-2 is 168°C at 3,800m (Baria et al., 2000). During the course drilling a permeable fault zone is intersected at a depth of around 2,110m causing total fluid loss (Baria et al., 2000). Subsequent small injection testing measures injectivity in this zone in the order of 50Dm (Baria et al., 2000). The zone is eventually sealed by the casing which extends to a depth of 3,211m (Baria et al., 2000).

Fracture mapping is conducted across the entire granite section of GPK-2 using high resolution image logs (Genter et al., 1996). Around 1,800 natural fractures are identified between 1,425 and 3,800m (Genter et al., 1996). Once again the major fracture set strikes 175°, dipping steeply to both the west and east (Genter et al., 1996). The permeable fault zone recorded at 2,110m is found to be sub-vertical striking 150° (Genter et al., 1996). Fracture density is variable, the granite intersected by GPK-2 identical to that of GPK-1 and EPS-1 in that it may be divided into regions of massive, relatively unaltered rock cut by highly altered fracture zones (Genter et al., 1996). Altogether 52 fracture zones are identified in GPK-2 defining two major tectonic zones (Genter et al., 1996). Piecing together the data from the three wells it is concluded that major alteration zones correspond to major granite faults, the distribution of which is not random but rather regularly spaced at intervals of between 300-400m (Genter et al., 1996).
At some stage during the post-drilling completion and testing of GPK-2 a fish (around 150 metres of 2” tubing and a submersible pump) is lost in the well, limiting access to around 3650m (Baumgartener et al., 2000). Hydraulic testing in GPK-2 is nevertheless commenced with several small scale injection tests across the open hole interval from which the natural injectivity is determined as 0.33-0.38(l/s)/MPa (Baria et al., 2000). This is followed by an extensive stimulation program which begins in GPK-2 in mid-1995 (Gerard et al., 1997). Studies of the previous stimulations in GPK-1 have led to the conclusion that the location and direction of fracture growth, in particular the upward growth of fractures and the formation of a strongly stimulated zone around the casing shoe, are likely to be related to a density contrast between the injected fresh water and the ‘heavy’ in-situ brines (Baria et al., 1999). It is decided that the initial stimulation of GPK-2 should be undertaken using a heavy brine injectate in the hope that this will reduce hydraulic uplift, creating a more even distribution of fractures in the open hole region (Baria et al., 1999).

Stimulation of GPK-2 commences with injection of a 300m³ ‘slug of cold, heavy brine (ρ = 1.18g/cm³) at 30l/s’ across the accessible open-hole interval extending from 3,200 to 3,650m (Gerard et al., 1997). Initial injection is immediately followed by injection of stored natural brine (ρ = 1.06g/cm³) at 12l/s (Gerard et al., 1997). Operations are continued using progressively less saline injectate in a series of flow rate steps from 12 to 18, 24, 38, 44 and finally 56l/s (Gerard et al., 1997). GPK-1 is initially shut-in to monitor pressure response and a rise of 0.06MPa is recorded upon initial injection in GPK-2 (Baria et al., 1999). Following injection of the available stored brine GPK-1 is put onto production to provide brine for the ongoing stimulation (Baria et al., 1999). In total around 30,000m³ of fluid is injected into GPK-2 (Gerard et al., 1997).

Microseismic monitoring is continuous throughout the stimulation and uses the existing network developed in 1992 (Jones et al., 1996). Initial seismicity commences at an injection pressure of 12MPa and is located close to the well (Jones et al., 1996). The apparent need for slightly higher injection pressures than those required for fracture propagation in GPK-1 is considered consistent with the greater depths involved (Gerard et al., 1997). In all, around 6,500 recorded events are located to
form an elliptical cloud approximately 800m high and extending around 800m in a N/S direction (Jones et al., 1996). Two main directions are noted within the cloud, a lower N/S trend and an upper NW/SE trend, both consistent with the known stress regime (Jones et al., 1996).

Whilst initial seismic activity is found to be located near the casing shoe, later events migrate down the hole, eventually reaching around 3,700m depth (Baria et al., 1999). Overall, the distribution of events along the open hole is wider than that observed in GPK-1 and it appears that the use of brine has successfully prevented formation of a system dominated by a single fractured zone (Gerard et al., 1997). Interaction between the GPK-1 and GPK-2 stimulation zones becomes apparent in the later stages of injection with a bifurcation of GPK-2 seismic events around an aseismic region corresponding to the GPK-1 seismic cloud (Jones et al., 1996).

Stimulation of GPK-2 is followed by a series of short term circulation tests conducted over a period of 6 weeks and utilising GPK-1 as the production well (Baria et al., 1996). In an initial test GPK-1 is put on production without any input from GPK-2 (Gerard et al., 1997). Produced flow rates mimic those of the 1994 production tests, commencing around 10l/s and slowly declining thereafter (Gerard et al., 1997). This trend is arrested by the commencement of injection into GPK-2, injection rates of 15l/s causing an immediate increase in production from GPK-1 which re-stabilises around 12l/s (Gerard et al., 1997).

Following establishment of a connection between the two wells subsequent testing employs a downhole pump set at 383m in GPK-1 (Jones et al., 1996). Use of the pump dramatically improves production flow, reducing fluid losses to zero (Gerard et al., 1997). An equilibrated flow balance of around 20l/s and output temperature of 135°C is maintained for several weeks (www.soultz.net). Interestingly, tracer chemicals injected into GPK-2 during this time do not appear in GPK-1 indicating a significant reservoir volume (Aquilina et al., 1996).

1996
Towards the end of the 1995 circulation tests a noticeable reduction is observed in the injectivity of GPK-2 (Baria et al., 1999). Investigations reveal this has most likely
resulted from a build up of fine material contained within the unfiltered injectate (Baria et al., 1999). To ameliorate this problem a second stimulation test commences in 1996 immediately following a well venting designed to remove as much as possible the build up of particulates prior to injection (Baria et al., 1999). 28,000m$^3$ of fluid is subsequently injected into the interval between 3,200m and 3,600m with injection rates increasing in a stepwise manner from 24l/s to 45l/s and 78l/s (Baria et al., 1999). Maximum injection pressure required is 13MPa (Baria et al., 1999).

The effect of the previous 1995 stimulation is apparent both in the low injection pressure required (in spite of higher injection rates) and in an initial lack of microseismic activity (Baria et al., 1999). The commencement of microseismic events near the well coincides with the increase injection rate from 45l/s to 75l/s (Baria et al., 1999). Over time located events again appear to migrate outwards, forming an elongate vertical cloud extending to the north and south of the well (Baria et al., 1999). At least two distinct structures are identified within the seismic cloud, the first appearing to connect GPK-1 and GPK-2 at 3,500m and 3,470m respectively, the second extending NW-SE from GPK-2 at 3,350m and dipping toward GPK-1 (Baria et al., 1999). Flow testing before and after stimulation in GPK-2 indicates only minor changes in the distribution and relative capacity of flow intake zones (Baria et al., 1999). Major intake zones are identified at around 3,220m, 3,250, 3,350m and 3,470m and are able to be correlated with fractures observed both in geophysical logs and, in some cases, in seismic data (Gerard et al., 1997). A hydraulic link between GPK-1 and GPK-2 is evident in the influx of water into the former well via fractures at 3,300 and 3,500m (Gerard et al., 1997). The permanent nature of the enhanced permeability in GPK-2 is subsequently confirmed by a series of stepped injectivity tests where flow rate rises from 6 up to 37.5l/s (Baria et al., 1999).

The 1996 testing program is completed by an 8 day reverse circulation experiment designed to test production in GPK-2 (Gerard et al., 1997). Re-injection of the entire produced volume into GPK-1 enables unassisted (buoyant) equilibrium production of 18l/s from GPK-2 (Gerard et al., 1997). Throttling of re-injection by 40% causes a decline in production rate to 16l/s over two days, indicating both a large storage
capacity in the reservoir and a strong hydraulic connection between the two wells (Gerard et al., 1997).

1997

The ability to produce up to 20l/s of fluid from the existing dual well system with no water loss is an extremely encouraging result and one which enables the go-ahead for a long term circulation test. It is hoped that long term testing will answer questions regarding the ongoing performance of the reservoir under steady state conditions (Gerard et al., 1997). An automated closed-loop surface circuit is designed and requires nearly six months to install (Baumgartner et al., 1998a). A downhole pump is placed at 430m in GPK-2 (production) and is linked to the injection pump in a master-slave relationship such that injection rate is controlled by production (Baumgartner et al., 1998a). The entire circulation loop remains pressurised at all time to minimise the likelihood of disruptions due to scale or corrosion of the surface equipment (Baumgartner et al., 1998a). Heat produced to surface is extracted via a plate heat exchanger and dumped in a nearby (artificial) lagoon (Baumgartner et al., 1998a).

Circulation commences in early July 1997 and is halted less than 24 hours later by a severe electrical storm (Baumgartner et al., 1998a). Following repairs to damaged control systems, which require several days, circulation is recommenced and continues with only minor interruptions for the next four months (Baumgartner et al., 1998a). Initial production rate is 21l/s, raised to 25l/s after around 23 days (Baumgartner et al., 1998a). Re-injection pressure decreases continuously across the course of the test from an initial value of 4.5MPa down to 2MPa (Baumgartner et al., 1998a). The most likely cause for this behaviour is an increase in near-well permeability due to cooling of the formation (Baumgartner et al., 1998a). The opposite effect is seen in GPK-2 where temperature recorded at the production inlet increases continuously, reaching 142°C by the end of the test (Baumgartner et al., 1998a). The effect of warm production fluids heating the near well region (still thermally suppressed from previous injections) appears to be related to a slow decline in production rate (Baumgartner et al., 1998a).
Throughout the four month test period circulation is maintained without any water loss, some 244,000 tons of fluid being produced and re-injected (Baumgartner et al., 1998a). Tracer tests undertaken during the course of the experiment indicate a reservoir volume of the order of several million cubic metres (Aquilina et al., 1998). A total of 10-11MW of thermal power is liberated, most of which is lost to the lagoon which proceeds to steam in a very satisfying way (Baumgartner et al., 1998a). No problems are encountered with scale or corrosion (Baumgartner et al., 1998a). Initial modelling results indicate that the thermal life of the reservoir is likely to be of the order of decades (Baumgartner et al., 1998a).

1998 – 1999

Following the successful demonstration of long-term inter-well circulation in 1997 a decision is made to proceed towards development of a pre-industrial prototype HDR project (Baria et al., 2000). Development of a ‘Scientific Pilot Plant’ is to be undertaken at the temperatures required for commercial electrical generation thereby demonstrating the potential for the HDR concept (Baumgartner et al., 1998b). At this point the project takes on a number of commercial partners with the resulting effect being a significant decrease in the amount of available site data.

The current 3,000-3,500m reservoir is not hot enough for economic electricity production which is considered to need temperatures in excess of 200°C (Baria et al., 2000). In order to achieve this kind of range (±10°C) it is necessary for the current project to be expanded to depths of at least 5km (Baria et al., 2000). Consequently, a new stage of work commences with the decision to extend the newest well, GPK-2, to a depth around 5,000m (Baria et al., 2000).

After considerable planning drilling commences in GPK-2 in early 1999 and is successfully completed 104 days later (Baria et al., 2000). Bottom hole depth is now 5,084m (5,024m vertical) with casing extending to 4,431m (Baumgartner et al., 2000). Near bottom-hole temperature measurements confirm a high temperature, within the expected region of 200°C (Baria et al., 2000). Approximately 1.2m of core is successfully recovered from the bottom hole region (5,048 – 5,051m) (Baria et al., 2000). Information derived from the core along with the continuous monitoring of cuttings indicate that the granite lithology encountered at shallower depths extends to
the new bottom hole depth (Baria et al., 2000). Once again distinct zones of fractured and hydrothermally altered granite are identified, most notably within the region below 4,500m (Baria et al., 2000). Preliminary investigations including geophysical logs (calliper, ultrasonic borehole imager (UBI) etc) indicate that fracture orientation is similar to that encountered in the upper hole regions (Baria et al., 2000).

An injectivity test undertaken across the new open hole interval indicates a natural injectivity of around 0.3(l/s)/MPa and is compatible with previous results from the shallower section of the hole (Baria et al., 2000). Towards the end of the year the newly completed well is placed on production. Assisted by placement of a downhole pump, 500m³ of brine is vented at flow rates of 0.17 – 0.25l/s (www.soultz.net). Initial geochemical results indicate the deep brine is of similar composition to that recovered from the shallower reservoir areas (Baria et al., 2000).

2000
Stimulation and flow testing experimentation continues in GPK-2 deep. Tests include a low flow rate injection (<0.5l/s over 5 days) followed by temperature logging which indicates fluid acceptance at 4,520, 4,770 and 4,980m (www.soultz.net). Stimulation comprises fracture initiation (1,000m³ brine at 30l/s for 9 hours), fracture propagation (21,000m³ brine @ 30l/s for 15hrs, 40l/s for 24hrs then 50l/s for 90hrs), followed by shut-in (3 days), stepwise injection (14,500m³ brine at 3, 6, 15, 25 & 35l/s for 48 hours each) and final shut-in (3 days) (www.soultz.net). Over 31,000 microseismic events are recorded on a network which now includes the recently deepened well OPS4 (1,537m) (www.soultz.net). Location of these events defines an elliptical cloud aligned NNW-SSE of dimensions 1,500 x 1,500 x 500m (H x W x L) (www.soultz.net).

2001 –
Once again project success leads to project expansion, the successful demonstration of deep drilling and stimulation technologies in GPK-2 allowing the go-ahead for further development (www.soultz.net). The Scientific Pilot Project now comprises a deep three-well system utilising GPK-2 as a production well (www.soultz.net). To achieve this vision it is necessary to drill two new deep wells, GPK-3 and GPK-4 (www.soultz.net). Both new wells are to be directionally drilled from the same
platform as GPK-2 with inter-well separation at depth to be of the order of 600m (www.soultz.net). Each new well will be targeted using microseismic data produced during the stimulation of its predecessor (www.soultz.net).

Following an extensive planning phase drilling of GPK-3 commences in mid-2002 (www.soultz.net). Successful well completion is followed by stimulation in May 2003, a ten day circulation test utilising injection rates up to 50l/s with spikes up to 85l/s (www.soultz.net). Simultaneous microseismic monitoring again indicates development of a N-S trending ellipsoidal cloud in this case estimated to be around 3km$^2$ in volume (www.soultz.net). Post stimulation circulation (July 2003) indicates successful connection with the GPK-2 reservoir (www.soultz.net). Drilling of GPK-4, targeted to intersect the seismic cloud generated during the recent stimulation of GPK-3, is commenced in September of the same year (www.soultz.net). Stimulation of this well is anticipated in early to mid 2004 (www.soultz.net).

**Footnote**

Work at the Soultz project remains ongoing. Information on the most recent developments is available at the website www.soultz.net.
A1.8 Deep Heat Mining (DHM), Switzerland

Summary
The Swiss Deep Heat Mining (DHM) project represents the first attempt at creation of a commercial HDR project designed for use both in direct heating and electrical generation. Although only a few years old the project has made considerable advances including the drilling of two wells near the city of Basel on the Swiss-German border.

Detailed Timeline

1996 – 1998
In the early 1990’s the Swiss Government introduces a series of packages designed to encourage the development of indigenous, environmentally benign forms of energy (Rybach and Gorhan, 1997). Technologies targeted by these initiatives include geothermal energy and HDR.

In 1996, after several years of active participation in the European Hot Dry Rock research site at Soultz-sous-Forêts, the Swiss Federal Office of Energy initiates a project called ‘Deep Heat Mining’ (Rybach and Gorhan, 1997). An assemblage of private companies and university institutes, the aim of the consortium is the development of a HDR pilot plant suitable for both electrical generation and/or direct heating applications (Rybach and Gorhan, 1997). The Swiss system is envisaged as a deep (ca. 5km), hot (ca. 200°C) fractured heat exchanger tapped by a multi-well system capable of supporting a flow rate of 70l/s and with power output equal to 3MWe and 20MWt (Haring and Hopkirk, 2001).

Throughout 1997-1998 a series of preliminary studies are undertaken including site evaluation and economic feasibility (Rybach and Gorhan, 1997). Ten potential sites with both favourable geology and surface location are considered (Vuataz and Haring, 2001). A site located upon the edge of the Rhine Graben near the city of Basel is
eventually selected as ‘flagship’ with a second site, the Aire Peninsular 4km west of Geneva, also assigned high priority ( Vuataz and Haring, 2001).

1999 – 2000

The Basel site is located on the SE end of the Rhine Graben, a failed rift system now filled with thick sedimentary sequences (Vuataz and Haring, 2001). In the Basel region no previous drilling had ever penetrated to basement, predicted to lie at a depth of around 2km. In June 1999 drilling commences on the first exploration borehole, DHM-1, located in Otterbach near the German border (Vuataz and Haring, 2001). Unfortunately the drilling runs into difficulties whilst still in the sedimentary cover and is unable to penetrate to basement depth (Vuataz and Haring, 2001). The well is eventually abandoned at 1,537m and is set aside for future use in the envisioned micro-seismic array (Vuataz and Haring, 2001).

2001 –

Temperature logs taken in DHM-1 indicate the geothermal gradient in the sediments is 4.2°C/100m (Vuataz and Haring, 2001). Drilling of a second exploratory well, DHM-2, is successful and penetrates to 2,755m (Vuataz and Haring, 2001). Crystalline basement comprising massive granite is encountered at 2649m (Vuataz and Haring, 2001). Evidence from core indicates the presence of an in-situ fracture network comprising both open and closed fractures (Vuataz and Haring, 2001). Preliminary temperature measurements indicate a geothermal gradient of 40°C/km (Vuataz and Haring, 2001). Following further logging and hydraulic tests it is anticipated that DHM-2, like DHM-1, will be completed and used as a deep seismic monitoring station for the anticipated deep reservoir development.

Coincident with drilling at Basel, ongoing survey work conducted at the Geneva site includes a compilation of existing geological knowledge and some preliminary environmental impact work (www.dhm.ch).
Summary
Experiments at the Yakedake site were amongst the first HDR work completed in Japan. Funded as part of the Japanese Government’s ‘Sunshine Project’, designed to reduce the nation’s dependence on imported fossil fuels, work at Yakedake was sponsored by MITI (Ministry of International Trade and Industry) and operated by NEDO (New Energy Development Corporation). Located in dry wells at the Yakedake geothermal field, Gifu Prefecture, central Honshu, experiments conducted on site were designed to develop techniques for HDR reservoir creation. Operating in sediment at shallow depth results from the work at Yakedake are sufficiently encouraging that NEDO was subsequently able to commence work on a full-scale HDR project at Hijiori.

Detailed Timeline

1976 – 1983
In 1976-77 a geothermal survey hole HSV-1 is drilled into the Yakedake Geothermal field, located about 200km west of Tokyo in the Gifu Prefecture of central Honshu (Kuriyagawa, 1987). The hole reaches a depth of 1,000m and BHT is measured as 180°C but no natural geothermal reservoir is encountered (Kuriyagawa, 1987). The site is subsequently assigned to HDR research as part of a nationwide government initiative known as the ‘Sunshine Project’ which aims to reduce Japan’s dependence on fossil fuels (Kuriyagawa, 1987).

Over the next six years a total of seven additional ~300m deep holes are drilled at the site (Kuriyagawa, 1987). All wells terminate within a shallow sedimentary sequence with BHT of around 60°C (Kuriyagawa, 1987; Matsunaga et al., 1990). Experimental wells HY and HY-2 are drilled in 1980 and 1982 respectively, with drilling in each case being followed by a series of hydraulic fracturing tests (Kuriyagawa, 1987). An array of seismic listening wells S-1, S-2, S-3 and S-4 are also completed, the first pair in 1980 to compliment fracturing in HY, the second in 1981 in preparation for the
experiments in HY-2 (Kuriyagawa, 1987). In 1983 the seventh and final hole, CW, is drilled and a further set of fracturing experiments designed to extend the existing HY-2 fractures to the new well is begun (Kuriyagawa, 1987).

Four injection events take place at isolated intervals in HY-2 between 142 and 283m depth (Kuriyagawa, 1987). At 200m depth a fracture is initiated at an injection flow rate of 200l/s and propagates southwards intersecting first S-2 at a depth of 204m and then CW at 251m (Kuriyagawa, 1987). Subsequent downhole logging indicates that the fracture is parallel to the borehole axis at its initiation point in HY-2 and must therefore have rotated as it grew outward to intersect with S-2 and CW (Kuriyagawa, 1987). The overall structure geometry, determined by its intersection with the three wells, strikes 002° and dips 62° to the west (Kuriyagawa, 1987). Instantaneous shut-in pressure (ISIP) across the fracture is measured at 7.0MPa with initial breakdown or opening pressure equal to 5.3MPa (Kuriyagawa, 1987). The overburden or vertical stress component at 200m depth is calculated as being around 5.3MPa (Kuriyagawa, 1987). Likewise, the principle horizontal stress directions are determined to be N-S and E-W with values of 14.8 and 7.3MPa respectively (Kuriyagawa, 1987). The formation of a vertical fracture under such conditions is interpreted as being the result of the re-opening of a pre-existing fracture or joint (Kuriyagawa, 1987).

Footnote
The results of the experiments at Yakedake in 1983 are sufficiently encouraging that a decision is made to commence further field testing at a deeper, hotter site (Kuriyagawa, 1987). The site chosen for this work is Hijiori located several hundred kilometres to the north of Yakedake, in the Yamagata province. From 1984 onwards this new location becomes the main focus of the Sunshine Project HDR research (Matsunaga et al., 1990).
A1.10 Hijiori HDR, Japan

Summary
Hijiori represents the continuation of NEDO's work at the Yakedake HDR development site. Also funded as part of the Japanese nationwide 'Sunshine Project' and later the 'New Sunshine Project' work at Hijiori has a number of aims, primary amongst which is the creation of a deep, hot, artificial reservoir. Located on the southern edge of a ca. 10,000 year old volcanic caldera the availability of heat is not an issue at Hijiori with bottom hole temperatures in excess of 250°C at less than 2km. Although developed in basement granodiorite underlying the caldera, the influence of the volcanic environment is evident in a high natural permeability. Fluid injection readily creates reservoirs which appear to propagate by stimulation of the existing fracture system. Circulation experiments encounter high fluid losses, largely due to the open nature of the system. To counter this problem the traditional dual-well HDR concept is expanded to a multi-well concept whereby the injection well is surrounded by up to three production points. Fluid loss remains relatively high however, the project eventually put on hold pending review following long-term circulation of a deep reservoir in 2002.

Detailed Timeline

1968 – 1984
Around 200km north of Tokyo in the Yamagata Prefecture of Honshu the Hijiori HDR test site is located within the southern edge of a 2km wide caldera, the Hijiori volcano, last active around 10,000 years ago (Matsunaga et al., 1990; Kitani et al., 1998). First targeted for geothermal exploration in the late 60's and early 70's, initial drilling within the caldera is sponsored by local government and comprises four relatively shallow wells of depth ranging up to 165m (Kitani et al., 1998). Bottom hole temperature recorded in the deepest well is 71°C, and is sufficient to arouse further interest in the regional geothermal potential (Kitani et al., 1998). In 1975 the Geological Survey of Japan drills a 500m deep well within the caldera recording a
bottom hole temperature of 218°C (Kitani et al., 1998). Four years later JAPEX (Japan Petroleum Exploration Company Ltd.) begins a three-year exploratory program involving the drilling of six deep “wildcat” wells (Kitani et al., 1998). Numbered SKG-1 to 6 the wells are scattered throughout the crater and vary in depth from 1,501 to 2,005m (Kitani et al., 1998). Whilst all wells record high BHT (up to 254°C) none produce evidence for the existence of a natural fluid reservoir or in-situ circulatory system (Kuriyagawa and Tenma, 1999). The hottest well, 1,802m deep SKG-2, located within the southern rim of the caldera, intersects some 1,465m of Tertiary and Quaternary pyroclastic rocks before reaching basement in a Cretaceous granodiorite (Kitani et al., 1998).

Concurrent with the JAPEX work inside the caldera, NEDO (New Energy Development Organisation) conducts a geothermal development survey in the region immediately outside the ring structure (Kitani et al., 1998). A series of six, deep (1,005 – 1,802m) wells are drilled, the highest BHT recorded being 247°C at 1,802m in N56-D Z-6 (Kitani et al., 1998). Located around 1km to the southwest of the caldera rim N56-D Z-6, like SKG-2, intersects granodioritic basement at 1,688m (Kitani et al., 1998).

**1984 – 1985**

Following on from the work on shallow HDR reservoirs at the Yakedake research site, part of the national renewable energy Sunshine Project, NEDO undertakes a search for an appropriate site to develop a full size HDR project in a deeper, hotter environment. The search ends with the selection of the southern region of the Hijiori crater, appropriate for both its known high in-situ temperature and crystalline basement as well as the added bonus of pre-existing deep wells (Matsunaga et al., 1990).

Well SKG-2 is ‘selected for hydraulic fracture stimulation’ (Matsunaga et al., 1990). Pressurisation tests of the open hole between 1,298 and 1,800m indicate that the rock is highly permeable (Kuriyagawa, 1987). A 7” casing is installed in the well from surface to a depth of 1,788m isolating a 14m long open-hole section (Matsunaga et al., 1990).
Casing is installed in SKG-2 to a depth of 1,298m and pressurisation tests commenced in the remaining open hole interval. Injection rates of 7.3l/s produce an injection pressure of 6MPa. No breakdown pressure is observed, downhole temperature logs indicating that water is being accepted at a number of points in the well (Kuriyagawa, 1987). It appears that the natural permeability is high and it is decided to extend the casing to 1,788m, isolating a small 14m long open-hole section (Kuriyagawa, 1987). Fracturing experiments are again undertaken in the lower open hole section. This time a flow rate of 0.36l/s results in an injection pressure of 7MPa still with no evidence of breakdown (Kuriyagawa, 1987).

1986

Large scale stimulation of the lower section of SKG-2 commences with injection of around 1,080m$^3$ of water at rates between 33-100l/s (Kuriyagawa and Tenma, 1999). Injection pressures reach a maximum value of around 16MPa at the highest flow rate (Kuriyagawa and Tenma, 1999). Around 35% of the injected fluid is returned to the surface as hot water and steam during post-test venting (Matsunaga et al., 1990). Seismic emissions are monitored using an initial 8-point circular surface array surrounding the injection well plus downhole equipment located nearby in SKG-1 (Matsunaga et al., 1990). Hypocentre locations are found to define an east-west trending near-vertically dipping zone extending from the south side of the injection well (Matsunaga et al., 1990). A teviewer survey identifies two distinct fracture arrays, an inclined set striking 159° dipping 60° to the north east and a near vertical east-west set aligned with the well bore axis (Matsunaga et al., 1990).

1987

The first production well, HDR-1, is drilled. Targeted to intersect a region of seismicity to the south of SKG-2 it reaches a total depth of 1,805m and is cased to 1,513m (Sato et al., 1995; Sasaki, 1998). Several oriented core samples are recovered, and at least one open fracture striking E-W and dipping 70°N is identified (Matsunaga et al., 1990). An interference test confirms the existence of a weak connection between HDR-1 and SKG-2 (Matsunaga et al., 1990; Sasaki, 1998). Downhole temperature logs indicate the presence of two anomalies in HDR-1, one at 1,743m another at 1,786m, which are interpreted to be the likely sites of the hydraulic connection with SKG-2 (Matsunaga et al., 1990).
Stimulation testing commences with injection of 2,000m$^3$ into SKG-2 at step flow rates up to 103l/s (Sasaki, 1998). Injection pressure reaches 16MPa at the maximum flow rate and is associated with seismic activity (Sasaki, 1998). Significantly, microseismic activity is not noted until after around 900m$^3$ of water has been injected however indicating the re-inflation of the original fracture system prior to the creation of new flow paths (Sasaki, 1998). The distribution of seismic events is found to be consistent with that observed in 1986 and forms a relatively tight cluster trending ENE-WSW (Sasaki, 1998). This orientation ‘is essentially co-planar with the local caldera ring-fault structure’ a fact which, along with the relatively low injection pressures, is considered to provide good evidence that existing fractures are being stimulated rather than new fractures created (Sasaki, 1998).

Following the stimulation testing a 16-day circulation test is conducted between SKG-2 (injection) and HDR-1 (production). A total of 13,430m$^3$ of water is injected at flow rates kept constant at 8l/s for the first 10.5 days and thereafter raised to 17l/s (Matsunaga et al., 1990). Production from HDR-1 is intermittent steam and water, the total volume estimated to be around 33% of that injected into SKG-2 (Matsunaga et al., 1990; Kuriyagawa and Tenma, 1999). It is concluded that the fracture connection remains poor (Kuriyagawa and Tenma, 1999). A large number of seismic events are recorded during the circulation and are again found to be consistent with the measurements recorded in 1986 (Matsunaga et al., 1990). Following the circulation testing HDR-1 is deepened to 2,205m in anticipation of the future development of a deeper reservoir (Sato et al., 1995).

The poor nature of the connectivity between HDR-1 and SKG-2 raises doubts about the accuracy of the located microseismic event cloud which the new well was designed to intersect. To minimise the chance of poor data impacting upon future well design, downhole velocity surveys are conducted in SKG-2 and the seismic surface array is expanded to a 10 point array (Sato and Abe, 1996).
1989

Studies of reprocessed seismic data produced during the SKG-2 to HDR-1 circulation indicates that the mapped fracture extends mainly toward the west-southwest of SKG-2. It is decided to target a second production well, HDR-2, to intersect this zone (Matsunaga et al., 1990). HDR-2 is drilled to a total depth of 1,910m, intersecting granodiorite at 1,480m and is cased to 1,504m (Matsunaga et al., 1990). Core recovered is not oriented but comparison with HDR-1 core indicates two distinct fracture sets – an open vertical set characterised by quartz veining and inclined possibly conjugate shear fractures characterised by chlorite veining (Matsunaga et al., 1990). A number of alteration zones (sericite-Mn) are noted downhole at depths around 1,580, 1,655 and 1,760m (Matsunaga et al., 1990).

Interference testing establishes that a good connection exists between SKG-2 and HDR-2 and a 29-day circulation test is commenced between the three wells (Matsunaga et al., 1990). A total of 44,500m$^3$ of water is injected at a constant flow rate of 17l/s with the exception of three short periods when it is raised to 33l/s (Matsunaga et al., 1990; Sasaki, 1998). Injection pressure, initially 6MPa decreases to 4.5MPa over the course of the experiment (Kuriyagawa and Tenma, 1999). Production flow rate from HDR-1 is 1.5-1.6l/s, less than that of HDR-2 at 4.2-4.9l/s (Kuriyagawa and Tenma, 1999). Production temperature at HDR-1 increases gradually and continuously to reach 150°C (Kuriyagawa and Tenma, 1999). By contrast production temperature of HDR-2 shows an initial increase to 170°C before decreasing to 150°C (Kuriyagawa and Tenma, 1999). Total fluid recovery for the test is between 35-40% (Kuriyagawa and Tenma, 1999).

Tracer tests and fluid geochemistry both indicate that the connection between SKG-2 and HDR-2 is shorter and more direct than that between the injection well and HDR-1 (Matsunaga et al., 1990; Kuriyagawa and Tenma, 1999). Not only is travel time found to be shorter between SKG-2 and HDR-2 but the volume of tracer recovered from this path is greater (Kuriyagawa and Tenma, 1999).

Circulation is again accompanied by microseismic activity, the rate of which clearly increases during the periods of raised injection pressure (Matsunaga et al., 1990). The new activity again defines an ENE-WSW trending zone although it is noted that this
time the zone is larger and more diffuse, lying deeper and further to the east than that associated with the earlier hydraulic stimulation (Matsunaga et al., 1990; Sasaki, 1998). The greater size of the induced seismic cloud is attributed to the longer period of injection allowing better fluid penetration throughout the rock (Sasaki, 1998).

Temperature logging in the production wells indicates the presence of four draw points in HDR-2 at 1,570m, 1,660m, 1,760m and 1,770m (Matsunaga et al., 1990). These are estimated to produce respectively 11%, 16%, 31% and 42% of the total production flow in this well (Matsunaga et al., 1990). Temperature logs also indicate reservoir cooling within the region of HDR-2 but not around HDR-1 (Matsunaga et al., 1990). Borehole televiewer observations of HDR-2 are consistent with those from HDR-1 with the presence of an E-W vertical fracture set, an inclined fracture set and a third set of asymmetric fractures interpreted as borehole breakouts (Matsunaga et al., 1990).

1990

A third production well HDR-3 is drilled to the south-east of SKG-2 to access the remaining portion of untapped reservoir in the hope of boosting recovery (Kuriyagawa and Tenma, 1999). The inter-well distances from SKG-2 to HDR1, 2 & 3 respectively are around 40, 50 and 55m (Kuriyagawa and Tenma, 1999). HDR-3 reaches a depth of 1,907m, five oriented cores sections are recovered from between 1,627m and 1,907m. Differential strain curve analysis (DSCA) undertaken on the core produces results consistent with those determined from hydraulic fracturing (Oikawa et al., 1993).

1991

A three month (90 day) circulation test is undertaken across the new four-hole system. A total of 135,000m$^3$ of water is injected at a constant flow rate of 16l/s following two initial spikes to 50l/s designed to improve the hydraulic conductivity of the fracture system (Matsunaga et al., 1995; Kuriyagawa and Tenma, 1999). After 23 days three 5-day single well production tests are carried out to assess the performance of the individual production wells (Matsunaga et al., 1995). Total recovery for the test is approximately 80% with total thermal output estimated to be around 8.5MWt (Sato et al., 1995; Kuriyagawa and Tenma, 1999).
Initial production rates are found to be highest in HDR-3 but decay over time in favour of HDR-1 and HDR-2 (Kuriyagawa and Tenma, 1999). Ultimately production from HDR-2 and HDR-3 becomes approximately equal and is double that of HDR-1. It is concluded that the connectivity between HDR-2 and 3 and SKG-1 is superior to that of HDR-1 (Matsunaga et al., 1995; Kuriyagawa and Tenma, 1999). Production flow temperatures show an initial rapid increase steadying in the range 160°C to 180°C before experiencing another slight increase in the middle of the test program (Matsunaga et al., 1995; Kuriyagawa and Tenma, 1999). Tracer studies conducted at the beginning and the end of the test program indicate that residence time has increased, inferring an increase in the size of the heat extraction area during the test (Kuriyagawa and Tenma, 1999). Residence times for HDR-2 and 3 are considerably less than that for HDR-1 (2.6, 1.8 and 6.7 hours respectively; Matsunaga et al., 1995). Comparison of the chemistry of produced and injected fluids indicates some fluid-rock interaction (Matsunaga et al., 1995). It appears that differences in the P/T conditions of individual well flow paths may be influencing the chemistry of the produced fluids (Matsunaga et al., 1995).

PTS (pressure, temperature & spinner) logs are conducted once a week in the production wells. A total of 16 feed zones are identified across the production wells, six in HDR-1 and five in both HDR-2 & HDR-3 (Matsunaga et al., 1995). Flow is found to be distributed unevenly across the feed zones within a well, one zone in HDR-3 accounting for around 70% of the total flow and two zones in HDR-2 accounted for 65% of the total (Matsunaga et al., 1995).

1992

The overall success of the four-well 1,800m deep system during the three month circulation test enables the decision to proceed with the creation of the deep reservoir first anticipated in 1988 with the deepening of HDR-1 to 2,200m. Rock temperatures at the new reservoir depth are determined to be around 270°C (Sato et al., 1995). It is decided that SKG-2 will play no role in this deep system with HDR-1 to instead fulfill the role of injection well. Stimulation of the lower section of HDR-1 (2,151-2,205m) is undertaken over two days and uses around 2,120m³ of water at pressures and rates up to 26MPa & 72l/s (Yamaguchi et al., 1998; Kuriyagawa and Tenma, 1999; Tezuka
and Niitsuma 2000). Monitoring of seismic events associated with stimulation indicates a tight, near vertical, E-W trending tabular cluster of focal points around and below the injection point (Yamaguchi et al., 1998; Tezuka and Niitsuma 2000). Post-stimulation injection testing and PTS logging identifies at least five fractures accepting flow, the largest of which at 2,202-2,204m accounts for 30% of the total flow (Yamaguchi et al., 1998).

1993

HDR-3 is deepened to 2,303m to intersect seismicity associated with the reservoir creation in HDR-1 (Kuriyagawa and Tenma, 1999). Distance between the two wells at reservoir depth is estimated to be around 130m (Kuriyagawa and Tenma, 1999). Monitoring of water levels in HDR-1 during drilling enables targeted coring of zones around stimulated fractures (Shinohara and Takasugi, 1996). BHT recorded one week after drilling is 261°C (Sato et al., 1995).

1994

HDR-2a is deviated off the original HDR-2 and drilled to a depth of 2,302m to intersect seismicity associated with the reservoir creation in HDR-1 (Kuriyagawa and Tenma, 1999). Distance between the two wells at reservoir depth is estimated to be around 90m (Kuriyagawa and Tenma, 1999). Monitoring of water levels in HDR-1 during drilling again enables targeted coring of zones around stimulated fractures (Shinohara and Takasugi, 1996). BHT recorded shortly after drilling is 259°C (Kitani et al., 1995). The shallow 1,800m deep fractured zone in HDR-1 is permanently sealed by cementing (Sato et al., 1995).

1995

A 25-day preliminary circulation test (PCT) is conducted in the new three-well system. The purpose of the test is two-fold, to both evaluate and improve the deep reservoir prior to long-term circulation testing (Kuriyagawa and Tenma, 1999). Initial flow rates are varied, peaking at 60l/s (15MPa), in order to improve the hydraulic connections established between the three wells (Kuriyagawa and Tenma, 1999). For the remainder of the test (around 20 days) flow rates are kept at either 16.7l/s or 33.4l/s (Kuriyagawa and Tenma, 1999). In all a total of 51,500m³ of water is injected into HDR-1 of which around 20,100m³ (40%) is recovered with HDR-2a producing
almost twice that of HDR-3 (Nagai and Tenma, 1997). Wellhead temperatures in both HDR-2a and 3 reach 180°C (Nagai and Tenma, 1997). Recovery rates are found to be around 50-55% at the lower flow rate but almost halve to 30% when the higher injection rate is used (Nagai and Tenma, 1997). Total estimated thermal output is around 8.5MW (Nagai and Tenma, 1997).

PTS logging indicates that production in both HDR-2a and 3 is derived from around ten ‘feed zones’ including both deep (2,000-2,200m) and shallow (1,500-1,700m) fractures (Miyairi and Sorimachi, 1996). This is interpreted as indicating a good connection between the new and old stimulated fracture systems (Okabe et al., 2000). Tracer tests and geochemistry confirm that the flow regime in the multi-well system is complex, involving multiple fractures and both new and old reservoir systems (Matsunaga 1997).

Seismicity recorded during the 25-day test is distributed in an E-W trending, north dipping cloud (Tezuka and Miyairi, 1996). Maximum event magnitude is 1.2 (Sasaki, 1997). Hypocentre distribution is similar to that produced by the 1992 stimulation of HDR-1 with the addition of what appears to be a newly created, slightly deeper cluster interpreted as a newly developed reservoir (Tezuka and Miyairi, 1996). As for the upper reservoir, the seismicity associated with the more extended circulation is found to form a larger, more widely distributed zone than that defined during the relatively short stimulation (Sasaki, 1996).

1996

A one month circulation test is undertaken with the aim of improving the underperforming connection between HDR-1 and HDR-3 (Kuriyagawa and Tenma, 1999). HDR-2a is shut-in for 23 days while 32,200m$^3$ of water is injected at a constant rate of 16.7l/s into the dual well HDR-1/HDR-3 system (Kuriyagawa and Tenma, 1999). A total of 6,340m$^3$ (~20%) is recovered from HDR-3 (Kuriyagawa and Tenma, 1999). At the end of 23 days HDR-2a is re-opened and the tri-well system is circulated for a further 8 days (Kuriyagawa and Tenma, 1999). Around 8,700m$^3$ of water is injected at 16.7l/s with a dual well recovery of 72% (Kuriyagawa and Tenma, 1999).
1997 – 1999

Initial circulation tests in the deep reservoir in 1995 and 1996 have revealed complex flow regimes with interactions between the upper and lower stimulated regions. The three years between 1997 and 1999 are spent in preparation for commencement of long term circulation testing of the system. It is envisioned that circulation will last for two years from 2000 to 2002 and is designed to confirm the feasibility of HDR power generation at Hijiori (Kruger et al., 1996; Nagai and Tenma, 1996; Kuriyagawa and Tenma, 1999). A large amount of work is required prior to commencement of the test with construction of a surface plant and power supply capable of surviving through winter (Nagai and Tenma, 1996).

During the hiatus associated with preparation of the surface plant a significant amount of work is undertaken toward compiling and integrating previously collected data (Matsunaga 1997; Sasaki, 1998; Tezuka and Niitsuma, 2000). Also undertaken at this time is extensive modelling of reservoir behaviour in an attempt to better understand the likely effects of long term circulation (Tezuka et al., 1998; Kadowaki, 1998; Yamaguchi et al., 1998; Okabe et al., 2000; Tezuka and Watanabe, 2000; Yamaguchi et al., 2000). Included within this work are compilations of stress measurements made in the reservoir (Yamaguchi et al., 1996). In almost all cases the minimum stress direction is found to be reasonably consistent, horizontal and approximately north-south (Yamaguchi et al., 1996). The direction of maximum principle stress is less consistent, appearing to be E/W in direction but of uncertain inclination (Yamaguchi et al., 1996). More recent modelling based upon examination of focal mechanisms associated with recorded microseismic events indicates that the maximum and intermediate stress axes are more likely to be inclined “about 45° eastward and westward respectively from the vertical direction” (Sasaki and Kaieda, 2000). Tezuka and Niitsuma (2000) use an analysis of microseismic clusters to produce a similar result with maximum principle stress near vertical and ratio $\sigma_1: \sigma_2: \sigma_3$ of 1.8:1.2:1.1.

2000 – 2002

The long-term circulation test of the Hijiori reservoir commences in December 2000 and continues for one year and seven months until August 2002 (NEDO, 2004a). To date relatively little material has been published in the mainstream literature regarding
this test. Information available from the NEDO web site (NEDO, 2004a,b) indicates that the first year of circulation was “deep circulation” designed to evaluate only the deep (ca. 2,200m) reservoir. The final seven months however involve a “dual circulation” with water being injected into both the upper (ca. 1,800m) and lower reservoirs. In both cases HDR-1 serves as injection well and HDR-2a and 3 as production wells. SKG-2 is brought on line as a second injection well for the dual-reservoir test. During the final three months a generator test is conducted to demonstrate the feasibility of the system as a power source (NEDO, 2004a).

For most of the deep circulation test injection is designed to maintain maximum possible continuous production rates. Injection rates into HDR-1 typically vary between 55-60t/hr. The total volume of water injected is 478,336t of which 206,190t (43%) is returned to surface. Maximum wellhead temperatures recorded in HDR-2a and 3 are 167 and 183°C respectively. Initial production return from HDR-2a accounts for around 30% of the injected fluid and is consistently higher than that of HDR-3 at about 20%. Scale problems in HDR-2a cause a gradual decrease in flow which ultimately reduces by around 10% and results in a three week long disruption to circulation in September-October 2001 during which the well is cleaned. This process appears to be successful and the well returns to production rates of around 30%. By contrast, production from HDR-3, which also appears to be suffering a slow decline, drops to little more than 10% of the total (NEDO, 2004b).

Injection into SKG-2 commences in late December 2001. Injection rates into both SKG-2 and HDR-1 are held constant at around 8.3l/s. Use of the dual circulation appears to improve overall recovery rates by around ten percent to just over 50% of injected fluid. The greatest increase appears to come from HDR-2a where production rises to over 40% of the total. Production in HDR-3 stays reasonably steady around 15% but remains considerably hotter than that from HDR-2a (NEDO, 2004b).

Footnote
Activities at the Hijiori site are put on hold following completion of the long term circulation test in 2003. At the present time the future of the site remains under review.
1.11 Ogachi & Akinomiya HDR, Japan

Summary
The project that was to become the Ogachi HDR research site first began at the nearby site of Akinomiya. Located less than 5km away from the eventual Ogachi site in Akita Prefecture, north central Honshu, Akinomiya was home to an initial experimental program implemented and funded by CRIEPI (Central Research Institute of Electric Power Industry), Japan. The purpose of the Akinomiya project was the development of techniques to be used in the creation of a multi-layered or stacked HDR reservoir. CRIEPI’s vision was to significantly improve the economics of HDR by creating a series of layered heat exchangers at different depths, tapped by the same injection-production system. Success at Akinomiya enables expansion to a full scale site at Ogachi. Like its sister site Hijiori, Ogachi was located within a volcanic field, bottom hole temperatures in excess of 220°C obtainable at depths of only 1km. Two reservoirs were created on site at 1,000m and 700m depth respectively using the newly developed casing reamer and sand plug method. Microseismic data indicated that the growth direction of the two reservoirs was almost perpendicular, the lower extending N-S and the upper E-W. This dramatic difference was attributed to interactions between complex natural fracture sets and the in-situ stress regime. Despite the drilling of several production wells, fluid loss at site was exceptionally high, the local system, particularly around the lower reservoir, open and highly permeable. Eventually a series of poor circulation results led to the suspension of work in early 2003.

Detailed Timeline

1986 – 1988
In 1986 Japan’s Central Research Institute of Electric Power Industry (CREIPI) begins work on a comprehensive HDR research project aimed at creating a single injection, multi-layer HDR reservoir suitable for use in commercial electrical generation. Initial research is focussed upon exploration, site identification and
characterisation as well as the development of new techniques required to produce stacked or multi-layered reservoirs (Hori et al., 1995).

Initial fracturing experiments are undertaken at a test site located at Akinomiya, Akita Prefecture, north central Honshu. Here three fractures are created at different depths within two shallow (~400m) deep wells as part of a program designed to develop a new fracturing technique dubbed the Casing Reamer and Sand Plug (CRSP) method (Hori et al., 1995; Yamamoto et al., 1995). Designed specifically to enable the creation of multiple reservoirs at different depths within a single hole, application of CSRP at Akinomiya successfully creates multiple fractures but fails to generate a significant connection between wells (Hori et al., 1995; Duchane, 1998).

CSRP as developed at Akinomyia works from the bottom upwards within a single well and is designed to eliminate the need for downhole packers (Duchane, 1998). First an initial ‘standard’ stimulation is focussed at the open end of hole area (Yamamoto et al., 1995). Upon completion of the initial stimulation the borehole is packed with sand up to a nominated depth at which point the casing is perforated and stimulation is undertaken again, thus creating a new fracture system further up the hole (Yamamoto et al., 1995). The success of the CRSP method at shallow depths at Akinomiya demonstrates the feasibility of the technique (Hori et al., 1999). This, together with encouraging economic studies carried out during the same period enables the decision to proceed to the next project stage, the development of a deeper, hotter site (Hori et al., 1999).

1989 – 1992
Site selection criteria set out by CREIPI for the identification of a suitable deep HDR target require three main features – a granitic basement, obtainable depths of at least 1,000m and temperatures of at least 200°C (Hori et al., 1999). Of three short-listed sites, consultation with the electrical power industry and local communities ultimately leads to the choice of Ogachi, less than 5km NE of Akinomiya (Hori et al., 1999).

Located within the Takamatsu Volcano several kilometres distant from a conventional geothermal field, Ogachi sits at an altitude of around 600m in what is a densely forested mountainous region (Hori et al., 1999; Kitano et al., 2000). The site lies
within a Neogene (2-6Ma) felsic caldera approximately 30km in length and 20km wide (Ito and Kitano, 2000). Basement rock comprises a ca.100Ma granodiorite overlain by around 300m of Quaternary volcanic tuff (Ito and Kitano, 2000). A NNW trending zone of mylonitisation estimated to be around 50-100Ma cuts through the basement granodiorite which, although host to a number of pre-existing joints and fractures, is found to have a relatively low permeability (Ito and Kitano, 2000; Kitano et al., 2000).

Drilling commences at Ogachi in 1990 following completion of initial site preparation work. Injection well OGC-1 is drilled to a depth of 1,000m where BHT is recorded as 228°C and is cased to a depth of 990m (Kitano et al., 2000). Initial well stimulation takes place across the ten metre wide open hole section in 1991 (Kitano et al., 2000). A total of 10,163m³ of water is injected at near-steady wellhead pressure of 18.5MPa and flow rates between 10 and 121/s (Willis-Richards et al., 1996). After stimulation approximately 640m³ of water (6% of injection) is vented from the well over a period of four days (Kiho and Mambo, 1995).

On-site seismic monitoring uses an 8-station shallow well (30-50m) array complimented by a single deep (946m) sonde set into a purpose drilled borehole (Kaieda et al., 1995). Some 1,738 events are detected associated with the initial OGC-1 stimulation (Willis-Richards et al., 1996). Location of the event hypocentres indicates the stimulated area is oval shaped, extending primarily NNE and is estimated to be of the order of 500m wide, up to 1,000m long and 200m high with a cross sectional area up to 500,000m² (Willis-Richards et al., 1996; Hori et al., 1999). Later BHTV surveys reveal that within the lower reservoir permeable fractures cluster around a NE-SW orientation, dipping steeply to the SE and are aligned with mineralised veins and andesite dykes also found at this depth (Ito and Kitano, 2000).

CSRP is applied to OGC-1 in 1992 with perforation of the casing between 711-719m followed by the sanding of the lower hole regions (Kitano, 1997). Some 5,400m³ of water is injected into the perforated interval at pressures and flow rates between 18-22MPa and 6-121/s respectively (Willis-Richards et al., 1996). After stimulation approximately 1,350m³ of water (25% of injection) is vented from the well over a period of twenty days (Kiho and Mambo, 1995). Seismic data is again used to
characterise the stimulated area, this time indicating an oval zone extending primarily to the east and estimated to be of the order of 400m wide, 800m long and 200m high with an estimated cross-sectional area of 300,000m² (Willis-Richards et al., 1996; Hori et al., 1999). Unlike the lower reservoir, subsequent BHTV surveys of the upper stimulated region reveal no dominant orientation to the existing natural fracture set (Ito and Kitano, 2000).

The considerable difference in extension direction between the upper and lower reservoirs is attributed to the influence of pre-existing fracture networks in the highly fractured basement. The lower reservoir fracture orientation is consistent with that of the in-situ fracture system at that depth whereas the upper reservoir appears to be orientated in accordance with the current stress regime (Kiho and Mambo, 1995). That the lower reservoir system is linked to a naturally permeable fracture system is supported by both fluid flow and geochemical evidence (Kiho and Mambo, 1995). The poor recovery during post-stimulation venting of the lower reservoir indicates a connection with far-field flow paths (Kiho and Mambo, 1995). Geochemical data indicates fluid in the lower reservoir experiences a far greater degree of mixing than that in the upper, an observation which also provides evidence for a greater natural permeability (Kiho and Mambo, 1995). Finally, fluid returned from the lower reservoir is found to be characterised by rapid initial increases in Ca and SO₄ (anhydrite dissolution) pointing to the utilisation of naturally permeable fractures as flow paths (Kiho and Mambo, 1995).

1993
In 1993 the first production well OGC-2 is drilled to a depth of 1,100m where BHT is recorded as 240°C (Hori et al., 1999). Spudded to the east of OGC-1, the new hole is directionally drilled to intersect both the upper and lower stimulated zones and is located approximately 80m from the injection well at EOH (Kaieda et al., 1995; Hori et al., 1999).

The first major circulation test between the two wells commences in late 1993 and lasts for 22 days during which some 30,000m³ water is injected into OGC-1 (Hori et al., 1995). Initial injection flow rates and pressures are around 7l/s and 20MPa shifting gradually to a steady state 11.5l/s at 17MPa before being raised to 20l/s and