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Improving Thermal Water Production From Major Fault Zones By Combining Waterfrac And Subsequent Strong Reduction In Pressure

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ABSTRACT

Deep reaching major fault zones respectively structures ("Tiefenstoerungen") hold a vast geothermal potential that is considered to exceed the geothermal potential of aquifers by a factor of four (Jung, 2002). This resource is virtually untapped in Germany, save one attempt in the 1980s at Bruchsal in the central part of the Upper Rhine Graben. It came out as a technical success and was ahead of its time.

At present, with rising fossil fuel prices, an intense debate on climate change, and a growing interest in renewable energies, EGE thinks that attention should be payed to this reservoir type. A a new approach how to harness the potential of such fault zones is described.

EGE plans to use waterfrac to stimulate specific parts of the structure in combination with periodic strong reductions in pressure (pulses). Strong hydraulic currents are created which periodically change their flow direction from the bore-hole into the rock domain and then back to the bore-hole. The applied forces will lead to scouring out channels, reactivating old fractures and fissures, and extract fine particles from the fault zone to the bore-hole from where they will be flushed out.

The aim is to create a high permeability rock zone which surrounds the bore-hole. This zone will connect large volumes of medium to low permeability rock further away from the bore, thus setting the basic drainage system for high production rates.

1. INTRODUCTION

Referring to Jung et al (2002), deep reaching major fault zones ("Tiefenstoerungen") are those which reach to at least 7 km depth. The total length of all such known structures in Germany adds up to 20,000 km. Parallel faults and structures that are less than 5 km apart have been calculated as one. This is based on the fact that structures that close together do generally unite at depth and continue as one.

1.1 The Significance of major Fault Zones in Geothermics

Major fault zones respectively structures have a great significance for geothermal utilization. In many instances they do control zones of increased permeability where they cut through sediments and metamorphic rocks. Frequently they could provide a reservoir of their own.

Citing just a few examples: Major fault zones (structures) have enabled high flowrates of geothermal brines in Hungary. In California, they are a major control of the largest geothermal field "The Geysers". Most of the steam production in the geothermal fields of Tuscany comes from structurally controlled reservoirs. This list could be greatly extended.

When exploiting sedimentary units in Germany for their geothermal energy (mainly Jurassic and Triassic strata), the drilling aims at major fault zones which dissect these sedimentary units which are termed aquifers. Those portions of the aquifers that are close to the fault zone generally have an enhanced permeability. Maximum production rates could be obtained from these structurally privileged zones. Likewise, injectivity is usually higher close to such zones.

1.2 The geothermal Use of Fault Zones as a Reservoir Type of its own.

Except from the aforementioned Bruchsal project, there has been no other high profile attempt for tapping geothermal resources from major deep fault zones in the Upper Rhine Graben nor in Germany, despite of the technical success of Bruchsal.

The project had aimed at the eastern side of the Upper Rhine Graben where the graben and the easterly adjacent Kraichgau region show a vertical displacement in the order of 2.5 – 3.0 km.

With some seismic preparation two bores-holes had been drilled and successfully encountered the fault zones. The brine producing zones in the two bore-holes had cumulative thicknesses of 75 and 64 m respectively. Unstimulated these zones can produce 28 l/s thermal brine. The landing points of the two bores, being approximately 1.4 km apart, were hydraulically connected from the beginning on.

2. PERMEABILITY OF FAULT ZONES

From both theoretical considerations and from observations it becomes evident, that competent rocks are prerequisites for a meaningful thermal water production from fault zones.

Competent rock, when under stress, will react to mechanical force by breaking up, whereas non-competent rock is just being deformed in a more or less plastic mode. In the first instance, the fault zone tends to be open hydraulically, in the latter case it will largely be sealed.

When comparing this to the Bruchsal project again, it does not surprise, that all permeable zones in both Bruchsal bore-holes are hosted by competent rock. These comprise the Lower Triassic Buntsandstein ("Bunter") and the sandy portions of the Lower Permian Rotliegendes (Koziorowski et al, 1975). This has to be kept in mind when prospecting for the geothermal potential of fault zones.

Stober (1995) reports transmissvities / conductivities from thermal water drilling in the crystalline rock of the Black Forest, that can attain 9.3 10^{-4} m² s^{-1}. These values come close to those of gravel-beds in recent sediments.

3. FACTORS THAT CONTROL THE PERMEABILITY OF FAULT ZONES

Jung et al (2002) mentioned parameters which are likely to influence the permeability of fault zones (likewise, the transmissivity and transmissibilitiy). Apart from its structural setting, thickness, and the adjacent lithology, it is also the extent of past movement along the zone, comprising both the vertical and the horizontal components of the displacement.

In order to have a favourable setting for the fault-zone reservoir type, some, if not all of the following conditions should be met:

- Location in a structural environment that is characterized by a tensional tectonical regime. Tensional forces tend to open fractures and faults or keep them open.

- The right magnitude of tectonic movement, be it vertical, horizontal or oblique.

- Favourable lithology should be present on both sides of the fault zone.

- The fault zone should have a sufficient thickness in order to become a good and long-lasting producer.

3.1 Tensional tectonic Regime

A setting with a tensional tectonic regime is much more favourable than an area governed by compressional tectonics. Tensional regimes do open up plumbing systems that may be closed by mineral precipitates but would continuously be reopened again by the ongoing movements tectonical and subsidence (Illies, 1977).

3.2 Extent of Movement along Fault Zone

It can only be estimated what degree of movement could be favourable and what would be excessive. Fault zones / structures of the type that are looked for here will have vertical movements of up to 4 km in the Upper Rhine Graben. Yet they produce –especially in the tensional regime – thermal water in sufficient quantities to provide large spas. Horizontal movements could make up for displacements of up to 35 km. Such displacements are confined to left-lateral strike-slip movements at the western main fault of the graben. Such order of displacement might already lead to a high degree of rock deformation in the fault zone with negative consequences to hydraulic conductivity.

However, it is very likely that in the northernmost section of the Upper Rhine Graben this lateral displacement as it is known from more central parts of the Graben, is taken up by a number of parallel structures each of which will have a displacement of a few km only.

Specific environments such as long distance thrusting with mylonitic rock deformation, without any economic reservoir potential are absent in the Upper Rhine Graben.

3.3 Lithology adjacent to Fault Zones

It is very important that competent rock is present on both sides of the fault zones. Such rock is required for the development of interesting permeabilities within the fault zone. Crystalline plutonic rocks are considered ideal, gneisses are less favourable, especially if they exhibit a pronounced foliation. Mica schists are considered poor as they are soft and will deform easily. So channelways in the rock would either be closed or just not open at all.

Sedimentary rocks are rated favourably in case quartz-sandstone, quartzites, and conglomerates are involved. Intercalated volcanic rocks – mostly paleo-basalts termed "melaphyres" of Lower Permian age – would be favourable as well.

In the specific geological setting of the northernmost Upper Rhine Graben, the main interest is on sandstones, conglomerates, and basic to intermediate volcanics in the down-faulted graben position, where they are positioned against plutonic and/or gneissic rocks of the uplifted block. Sandstones with carbonate cement may hold a particular advantage over other rocks when it comes to stimulation. Addition of hydrochloric acid could considerably improve the permeability of the fault zone / structure.

All settings with soft, easily deformable Tertiary age rock are considered poor. They are not expected to let fluids pass to any significant extent. A few hydrocarbon drill-holes have intersected such structural positions in other locations. Clayey and marly rocks have thoroughly been mixed with crystalline rock fragments. It must be concluded that fault zones will be tightly sealed whenever soft Tertiary age rocks are present at least on one side of the structure.

This implies, that potential reservoir situations are possible only below the base of the Tertiary sediment sequence. On the other hand, this offers a great advantage as well. Cold water from higher positions could not descend easily into the reservoir proper and lower its temperatures.

3.4 Thickness of Fault Zones

The thicknesses of fault zones should be in the range of several tens of meters. So far, the thickness of the fault zones, where intersected by drilling, had been between 20 and 75 m. It appears, that faults zones will develop certain minimum thicknesses once a certain tectonical displacement and competent rocks are involved.

Even where Tertiary sediments are faulted against crystalline rock, fault zones appear to have a considerable thickness. The bore-hole WIAG 4 had encountered 13 m of true thickness in such a setting, without having intersected the entire fault zone, which in this case had been tight.

4 IDEALIZED STRUCTURAL SETTING AS BASED ON PRESENT KNOWLEDGE

For realizing a geothermal project in fault zones in the northernmost part of the Upper Rhine Graben, EGE presents an idealized scenario, as based on present geological and structural knowledge and understanding:

A fault zone of 40 – 50 m width or more, that is situated below the base of the Tertiary system (approximately set at 2,800 m depth) at a depth of 3,200 – 3,500 m. The expected temperature is 175 °C. Adjacent to the structure and below the base of the Tertiary, the following rock sequences are expected:

<u>Graben position:</u>

Calcareous qtz sandstone with some clayey intercalations and clayey-calcareous cement, paleo-basalts, and conglomerates. This sequence of Lower Permian age can attain a thickness of 1,500 m or more. It unconformably overlies crystalline and metamorphic basement.

Horst position

Granite, granodiorite, amphibolite, ortho- and paragneisses represent the plutonic and metamorphic rocks at the depth of 2,800 to 3,500 m. They are unconformably overlain by Lower Permian rocks, mainly redbeds and volcanics.

5. STIMULATION

Even under favourable conditions it is very unlikely that production rates of 50 – 70 l/s can be achieved from structures without additional stimulation. Such rates, however, are deemed necessary for commercial power generation based on the German subsidized renewable energy pricing system.

As stimulation is a prerequisite for achieving commercial production rates, the most appropiate stimulation methods need to be determined and applied. Fairly simple, yet very effective is the so-called waterfrac that stands for the injection of water at a given rate over a given time at a set pressure. During stimulation, these parameters are usually kept constant until the end of a stimulation phase, after which the success of the method is being evaluated.

The exact parameters need to be determined at a later point in time, once the specifics of the fault zone are better known after having drilled it. The stimulation part should be kept as short as possible since expensive equipent is to be used, thus increasing the project cost as time is spent on the stimulation work. On the other hand, the method must be effective in order to enable high thermal water production rates. Some additional investment during this phase might result in much better economics during the regular production. This could more than just offset the additional efforts for stimulation

The production rate itself is only one side of the medal. High production should be achieved with the lowest possible amount of energy. High production rates might be obtained by a large drawdown but then the running costs of the pumps would be high, thus lowering the possible income from power production.

For economical reasons it will not be feasible to stimulate the reservoir (fault zone) over the entire distance of a later hydraulic cell. Depending on the distance of the landing points between the production and injection bore-hole (that can attain 2 km or more) such a measure would not only consume an excessive amount of time, but might even have negative consequences.

A highly conductive hydraulic cell would inherently be in danger to develop an early thermal short circuit. Then, much of the heat that is contained in the hydraulic cell, could not be recovered anymore.

5.1 Extent and Shape of the Rock Zone to be stimulated

In order to avoid the aforementioned problems, EGE plans to stimulate a rock domain of limited extent around the bore-hole where it intersects the fault zone. This stimulation is to produce a zone of high permeability that extends from the bore-hole into the structure. In case the structure has a relatively even planar shape, the zone to be stimulated would have an overall shallow cylindrical shape.

The rock volume in this zone would be calculated according to the following equation:

$$V = r^2 p \; h \qquad (1)$$

where *V*, *r*, *h* are total volume, radius of stimulation, and thickness of the fault zone. If *r* is set at 100 m and *h* at 40 m, the rock volume to be stimulated would amount to 1,256,000 m³ which is a fairly large mass of rock.

A radius of 50 m might suffice as well. The rock volume to be stimulated would then be 314,000 m³. Estimating a fracture volume of 0.5 percent of the total volume, the voids would make up for 6,280 m³ in the first case and 1,570 m³ in the latter. The 0.5 percent figure in our view is reasonable to conservative. The value could attain 1% as well. This void space is filled with thermal brine.

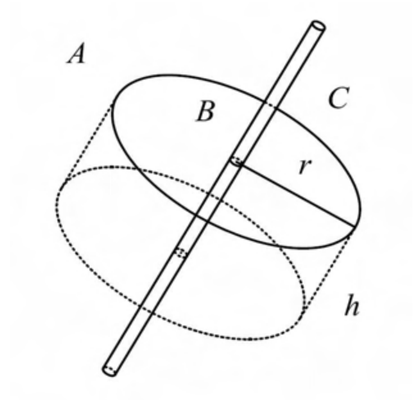

Figure 1: The figure shows a circular section of the fault zone with an overall cylindrical shape. *A* depicts the unstimulated part of the fault zone with low to medium permeability. *B* represents the stimulated and very permeable part of the fault zone. *C* is the central bore-hole with nearly unrestricted flow, while *h* and *r* stand for the thickness of the fault zone and the radius of the stimulated part.

The fluids within the existing voids do not form a liquid reservoir that would warrant an exploitation on its own. The existing liquids in the entire hydraulic cell that is to be set up will only act as a carrier of the thermal energy which will be pumped to the surface, largely stripped from its heat und reinjected into the reservoir by a second bore-hole.

Any stimulation work intends to set up an efficient drainage system, either a completely new one, or enhancing an existing one. Waterfrac is to be applied in order to open up existing fractures and reactivate others that are sealed by (mostly carbonate) precipitates. Existing brine filled voids could be connected and made part of a new or enhanced drainage system. The pressures to be applied can be kept moderate, in the range of 30 – 40 bar (3 – 4 MPa). Standard oil field equipment and pumps could be used for this part of the work.

In the ideal case, a cylindrical rock volume around the bore-hole would be stimulated in such a way that its permeability *k* attains values comparable to fairly good ground water conductors. The transmissivities should be in the range of 10^{-3} m² s^{-1} or better.

The high permeability zone around the bore-hole will connect the bore-hole, that could be likened to a very high permeability conduit, to a zone of moderate permeability. As this zone of moderate permeability is adjoinig the higher permeability zone at a distance of between 50 and 100 m from the bore-hole, there is ample cross sectional area available between the two domains. This ensures high volumetric fluid flow rates, in this case thermal brines.

The following equation is to demonstrate this:

$$q = \frac{k}{\mu} \, A \, (\frac{\Delta p}{L}) \qquad (2)$$

where *q, k, m, A, L, Dp* are volumetric fluid flow rate, absolute permeability, fluid viscosity, cross-sectional area, length and pressure drop over the length *L*, respectively.

The fluid flow rate would increase proportionally with the absolute permeability and the cross sectional area. These factors (*q, k A*) can be influenced by the stimulation work.

The fluid viscosity *m* is given. The length *L* is identical with the radius of the intensely stimulated part of the fault zone and could be influenced by the stimulation work. *DP* is a parameter that could be influenced by stimulation. Increased permeability (transmissivity, transmissibility) could yield higher flow rates with the same *DP* or the same flow rate could be maintained with a lower *DP*.

In principle, raising *DP* will increase the fluid production (by increasing the drawdown) but then energy consumption will go up and make a venture less attractive. So the main efforts are directed at increasing the permeability and the cross-sectional area in order to create a high capacity drainage system around the bore-hole where it intersects the fault zone.

This applies not only for the production bore-hole but also for the injection bore-hole. So the rock around both landing points of a doublet should be stimulated the same way.

5.2 New Approach: adding strong Reflux to Waterfrac

Waterfrac has been the method of choice in most stimulation cases (in geothermics). Even the HDR-Fracturing is a waterfrac, though fairly powerful. In general, fracturing starts from a structure that has been recognized from seismic data and then aims to connect as much aquifer volume as possible to the bore-hole.

Under specific conditions, hydrochloric acid is added to the fracturing fluid. This is important in carbonate environments (as in the karstic Upper Jurassic Malm). However, carbonate precipitates do occur in other settings as well. In all likelihood hydrochloric acid will be used to improve the hydraulic properties of the fault zone.

Waterfrac in general comprises a continuous injection of water at constant rates and pressures into a rock domain. The injected water is generally pumped into an open system. For that reason, a lasting overpressure cannot be built up in the system. The flow direction is normally constant. The success of a waterfrac is usually a function of injected water volumes and applied pressures.

EGE plans to introduce a new system, that could be used for several geothermic applications and that is capable of reducing pressure in the deep of a bore-hole within very short time spans. Such reductions in pressure, when applied to rock, could very well break it up (Hurter & Holl, 2002), likewise healed fissures, connect existing voids and flush out fine rock particles from fault zones.

The new approach will make use of both waterfrac and subsequent strong currents that are induced by artificial strong reductions in pressure. While water frac will inject freshwater into the rock system that is to be stimulated, the use of rapid reduction in pressure will cause the water respectively brine to flow into the opposite direction, i.e. towards the bore-hole (reflux). Such changes of flow direction coupled with considerable force of the currents are expected to produce better results than an one-way steady current as produced by the waterfrac method.

However, a direct comparision between the two methods is not meaningful, as have their specific applications. So does the combination of the two methods. It is expected that the stimulation effects of "current and counter-current" will be restricted to a fairly small zone around the bore-hole as depicted in figure 1. Still, the radius of the intensely stimulated zone is large enough that a continuous flow and a sufficient flowrate of thermal water is ensured.

Ultimately the effect of stimulation should imitate a large diameter bore-hole (100 – 200 m) that unlocks a large rock volume of low to medium permeability and connects it to the bore-hole.

6. STRONG REDUCTIONS IN PRESSURE

In order to make strong reductions in pressure possible at all, high differences in pressure have to be set up in advance and made effective in a controlled way.

Under normal geological conditions – as is the case with the structural settings that had been discussed above – building up and maintaining a stable pressure in the rock that considerably exceeds the hydrostatic pressure, is not feasible. The system looked at is an open one, all the more as it possesses a considerable permeability.

However, strong reductions in pressure need a steep pressure gradient that can only develop if a usable difference in pressure is set up first and then released in a controlled mode. There is one way to set up even high differences in pressure and let the reduction in pressure work on the rock and the hydraulic conduits.

Herr (2002) has described this method which had been developed for In situ-vaporization of thermal waters. The system requires the installation of a pressure-barrier in the lower part of a bore-hole. It consists of a central guiding tube that is locked with the casing by annular packers. Another tube with a valve function is inserted into the guiding tube and depending on its position, there are two "open" functions and one "closed" function. The valve tube has a tight pressure proof fit, yet it is movable still, comparable to a piston in a cylinder.

The difference in pressure will be set up by removing either parts or the entire liquid column above the pressure barrier. For every ten meters of removed liquid column a potential difference in pressure of 1 bar resp. 10 kPa can be provided, as long as the valve tube is in the "closed" position. The desired working pressures resp. differences in pressure can be precisely set by removing a certain amount of the liquid column above the pressure barrier. The difference in pressure can thus be set precisely and then be made working by moving the valve tube into one of the "open" positions.

The differences in pressure could be made effective over a longer lasting time span or as short pulses. The valve tube is being managed from the surface via the tubing string. It is entirely mechanically as in this or other geothermal applications high to very high temperatures prevail and electric equipment may tend to fail.

The pressure-barrier is retrievable and can be removed after stimulation work. At this point in time EGE has no exact figures for differences in pressure that are to be applied.

Likewise the most effective setup of pressure in combination with time needs to be determined by trial work.

Yet, there are clear limitations for a practical use. While it might be technically feasible to set up differences in pressure that could reach 200 bar (≈20 MPa), such values could become a problem of handling and safety, including the safety and stability of the bore-hole.

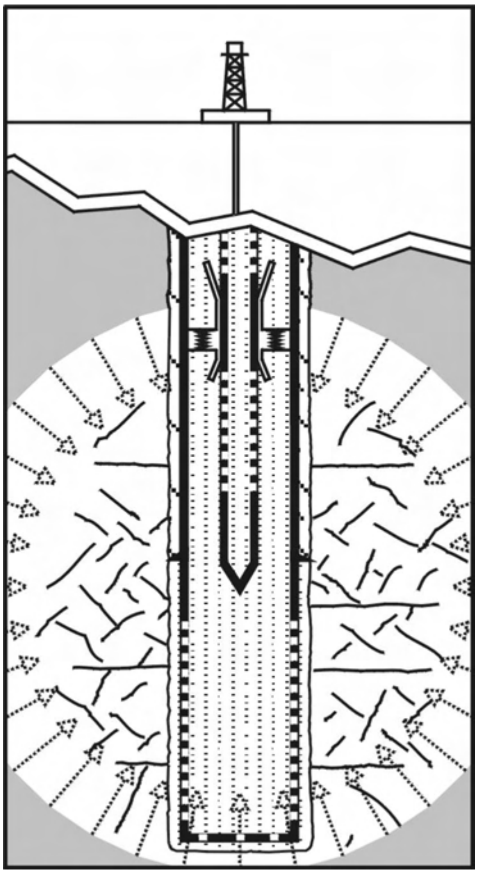

Figure 2: The figure presents one configuration of the pressure barrier in the deep part of a bore-hole. A valve tube is inserted and has just been moved into the "open"-position. The high difference in pressure has initiated a strong current towards the bore-hole. Some fracturing will occur as well.

For specific uses, they might be applied still. Reductions in pressure, once they are applied in an instant, will most likely crush rock. Reductions in pressure would act like strong tensional forces on the rock. The strength of rock to tensional forces is comparatively low, it amounts roughly to only one tenth of the strength to compressional forces (Hurter et al, 2002)

For stimulation work and achieving a strong reflux of previously injected liquids towards the bore-hole, differences in pressure of 40 to 50 bar (≈ 0.4 – 0.5 MPa) would most likely suffice. The difference in pressure is being used up once the formation water rises in the bore-hole to its normal hydrostatic level (equilibrium).

The procedure could then be repeated (possibly alternating with waterfrac) until a satisfactory result of the stimulation work has been achieved. As the strong reflux from the rock domain to the bore-hole is expected to carry mineral particles with it, flushing of the bore-hole is probably required.

The method is also considered being appropiate to reduce at least some of the skin effect cause by the drilling and remove some of the drilling mud that will be lost when drilling intersects the structure.

The method that can generate high differences in pressure and strong reflux to the bore-hole, has been patented by European and US patent law. EGE has an exclusive access to the method and will test this during the course of 2008.

CONCLUSION

The reservoir type fault zones resp. structures ("Tiefenstoerungen") has a large geothermal potential that has got little attention so far. In Germany, the geothermal focus had been mainly on Triassic and Jurassic aquifers.

EGE has concluded that it is worth looking deeper into that potential and selected an area in the Northern part of the Upper Rhine Graben that has a very favourable structural setting and high temperatures. The structures are most likely hydraulic conductors below the Tertiary base. Their permeability is thought to be fair to good when both sides of the fault zone are made up of competent rock.

For successfully drilling the reservoir type "fault zones" the lithology on both sides of the fault zone should be well known. This requires high-resolution seismics but not necessarily 3-D seismic.

Though the reservoir type fault zones even unstimulated could yield very interesting flow rates, stimulation is a prerequisite for high production rates of thermal water.

A new stimulation method has the potential to stimulate the fault zone around the bore-hole in such a way, that a high permeability transition zone is created. This zone connects the large area of non-stimulated fault zone to the bore-hole. A combination of waterfrac and sudden drops in pressure is to treat the fault zone up to 100 m away from the bore-hole. Production rates of 50 – 70 l/s are expected.

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