PROCEEDINGS, Thirty-First Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 30-February 1, 2006
SGP-TR-179

UNDER BALANCED DRILLING AND POSSIBLE WELL BORE DAMAGE IN LOW TEMPERATURE GEOTHERMAL ENVIRONMENTS

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ABSTRACT

During an exploration drilling in Sweden rotary air drilling was used to penetrate the very hard and abrasive gneiss basement right outside the city of Lund. Lund is situated in the southernmost province of Sweden, called Scania. Total drilled depth was 3701.8 m. The project, conducted during 2002 and 2003, was a part of an exploration effort of the Tornquist Zone. TZ is a major basement deformation structure traversing large parts of northern Europe. The aim was to investigate the water production properties of the faulted and fractured deep-seated rock sequences. The reason for using rotary air drilling was mainly to achieve reasonable rate of penetration trough the very resistant basement rock.
The observations made during drilling and testing provide for a framework of discussions if and when underbalanced drilling is applicable in low temperature and low-pressure conditions.

BACKGROUND

The local community owned energy enterprise in Lund in cooperation with Dept. of Engineering Geology (DEG) were given funds to investigate the possibility of extracting hot water (> 100°C) for direct heat transmission to the local district heating net. The project planning started in 2000 and in 2001 the geophysical exploration work was running (Alm et al., 2006). The drilling of the first well, DGE #1, started in 2002 and a second well was drilled during 2004. This article deals only with the first well.
The aim was to increase the already existing geothermal energy production going on since 1984 when a heat pump plant was put in operation. The local community and the National Energy Board (NEB) provided funding. A certain task given by NEB to DEG was to design the drilling program so that technical questions related to deep drilling in crystalline basement rocks were highlighted and evaluated. One of the tasks was the deep drilling capability in hard formations as a function of drilling methods. And of course the exploration of possible deep-seated hot water deposits related to the Tornquist Zone traversing the province of Scania and large parts of Northern Europe.

Figure 1. Sweden and Lund in Europe.

GEOLOGICAL SUMMARY

A summary of the lithology for well DGE #1 is seen in figure 2. The local geological set up provides about 2000 m of sedimentary deposits resting on crystalline basement mainly characterized by quartz rich gneiss/gneiss granite.

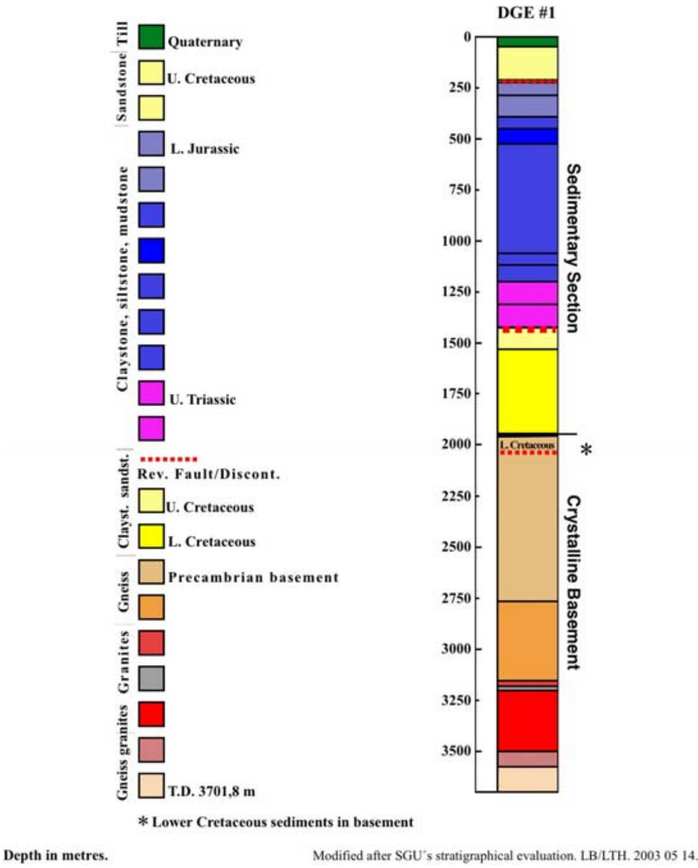

Figure 2. Lithology for Well DGE#1

Granite and along certain parts dolerite, and amphibolites are quite common. Extensive tectonic activities with faulting and shearing of the rock mass has occurred several times during Precambrian, Paleozoic and Mesozoic eras.

DRILLING SUMMARY

The drilling operation started in October 2002 and was finished in March 2003. The total drilled depth became 3701.8 m and the well is cased down to 3200 m. Below follows a summary of most of the executed drilling operations for the DGE#1. All the depths given are from Kelly Bushing located 7.1 m above ground level.

The following drilling methods were used:

Conventional rotary drilling with mud
Rotary air drilling
Percussion drilling/Hammer drilling
Mud Hammer drilling

Conventional rotary drilling

The section from *23 m to 160 m* was drilled with a 26" (660 mm) bit. Afterwards opened with a 36" (914 mm) hole opener down to 165 m.

The section from *165 m to 1020 m* was drilled with 26" (660 mm) bits.

The section from *1020 m to 2044 m* was drilled using 17 ½" (445 mm) drillbits. From 1944 m to 1996 m a 12 ¾" mud motor was used. The mud motor was used in an effort to increase the penetration rate near the top of basement but the mud motor was abandoned due to operational problems.

The section from *2044 m to 2119 m* was drilled using 12 ¼" (311 mm) drillbits.

Rotary air drilling

Rotary air drilling was thereafter introduced from *2119 m to 3365 m* using 12 ¼" (311 mm) drillbits. Roller cone bits designed for air drilling with for example different kinds of nozzles and bearings.

The drilling fluid was air but for shorter periods also aerated water. The choice of air drilling was made to increase the penetration rate in the crystalline basement rocks found from about 1950 m depth and downwards. At the end of conventional rotary drilling the penetration rate had gone down to less than 1 m/h. The introduction of air drilling increased the penetration rate about 4 times in the same kind of rock formation. The change in ROP from conventional to air drilling is marked by a circle in figure 3.

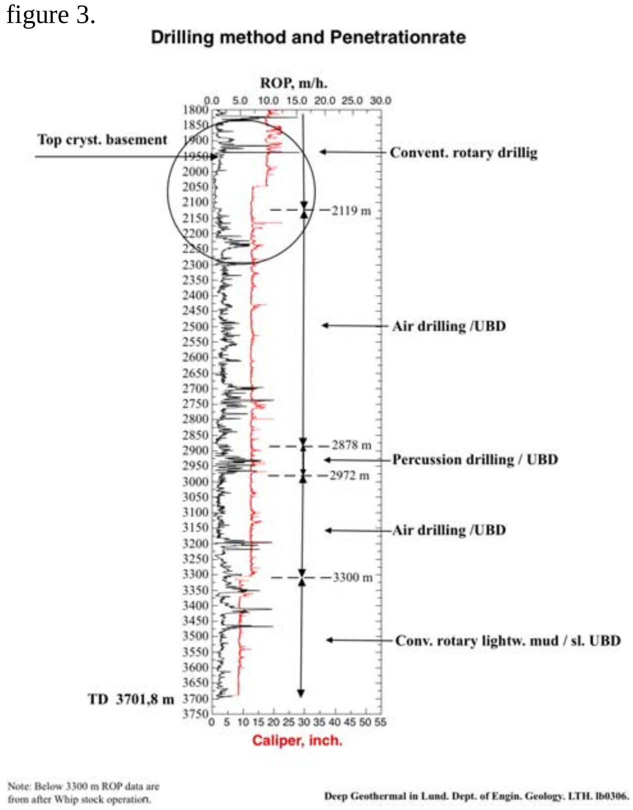

Figure 3. Drilling methods and penetration rate

The shift to rotary air drilling moved the operation from being balanced to being *underbalanced*. The change was also a part of DEG´s task to evaluate different drilling technologies in hard and abrasive formations at great depth.

Percussion drilling/Hammer drilling

As an intermediate test Percussion drilling was carried out between *2878 m and 2972 m*.

A Numa Challenger 125 hammer with a 12 ¼" percussion button bit was used. The test was stopped after almost 100 m drilling due to a loosened main valve in the hammer assembly. The penetration rate was occasionally around 5 m/h and commonly around 4 m/h in the same kind of crystalline basement as for the rotary air drilling. From there on the operation was again rotary air drilling, see figure 4.

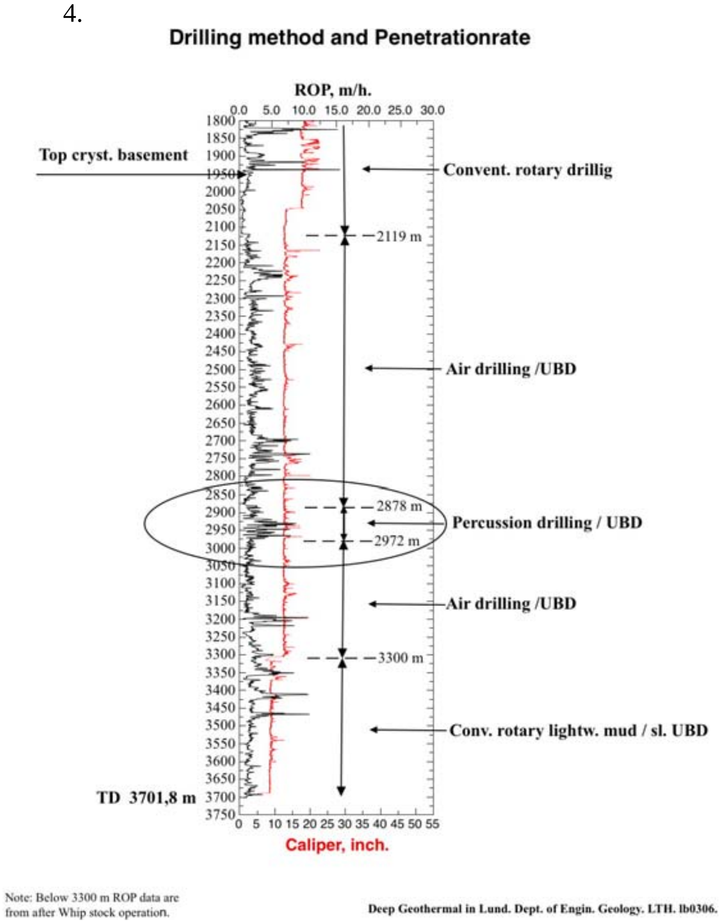

Figure 4. ROP during Percussion drilling

From *3102 m* the drilling was for a while adjusted to an aerated water/water operation. The reason was simply lack of storage space for produced formation water and mud. The penetration rate decreased thereby as the amount of water by volume increased and became soon as low as 0.6 m/h. When new storage ponds had been located the drilling could go back to regular air drilling again and as expected the high penetration rate was back again, see figure 5.

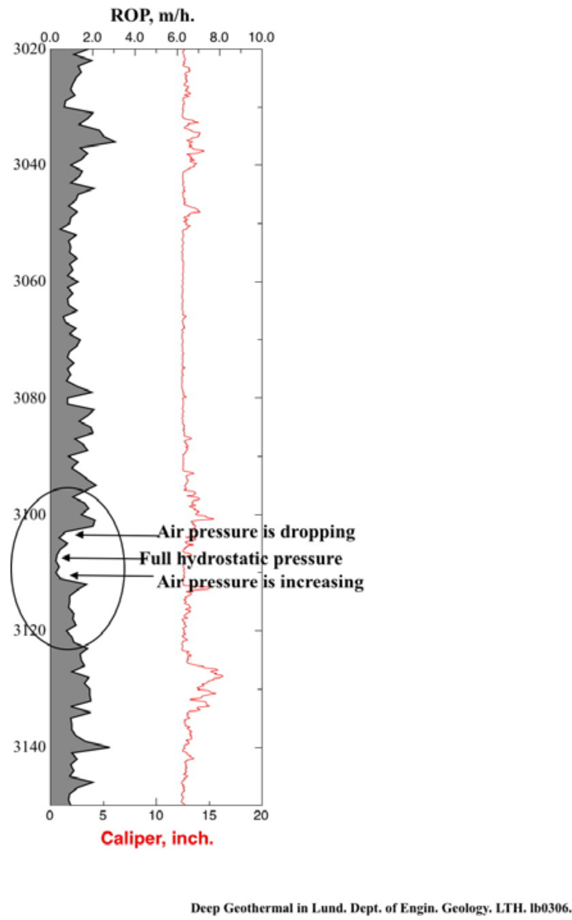

Figure 5. Difference in ROP with or without air

At a depth of *3365 m* the driller failed to clean the hole when the penetration rate was extremely high, 15-20 m/h, and all the bottom hole assembly got stuck. A major fracture zone had been hit.

After having tried to install an open hole Whip stock with no success a casing Whip stock was finally in place and the drilling could start again from a higher level at about 3200 m. From there on the bit size was 8 ½".

After this intermezzo the drilling continued to total depth at 3701.8 m. The final part was drilled with a lightweight polymer mud and was therefore slightly underbalanced.

Mud Hammer drilling

As final short test a Wassara Mud Hammer prototype was tested between *3666 m and 3675 m*. Bit size at this test was also 8 ½". The test was unfortunate to some extent as a wash out of the drill pipes occurred during the test. For shorter whiles the Mud Hammer proved to work in a promising way.

In a composite graph, figure 3, the drilling methods used for the crystalline part of DGE #1 are shown along with caliper, ROP and depth.

UNDERBALANCED DRILLING IN GENERAL

The reason why Underbalanced drilling (UBD) was used in this project is simply a world wide experience saying that a better penetration rate is most likely when the rock formation is very hard for example a crystalline basement (Leonard et al., 1977, Sheffield et al., 1985). The UDB concept was introduced already during late 19 century. Since then, air drilling (commonly dry air) has been used numerous times in the geothermal industry, for example in California. In oil and gas exploration and production drilling several applications of UBD have become more and more common. In those applications air is replaced with an inert gas in order to avoid ignition of the hydrocarbon deposit. Cunningham et al., already 1958 reports that a 10-fold increase in ROP is possible when a differential pressure of around 3000 psi (about 200 bar) has been established.

Another important reason to use UBD is that the hydraulic gradient towards the well bore will reduce invasion of mud and fine grained cuttings into production zones. A third reason is that an UBD operation makes it possible to detect production zones more or less on fly as the drilling proceeds (Leonard et al., 1977, Sheffield et al., 1985).

The same authors also claim that low cost, longer bit life and limited or no risk for loss of circulation are common advantages. Those conclusions might also in certain cases be valid for geothermal drilling operations.

As always there are drawbacks differing from situation to situation. In geothermal hard rock exploration they might be fewer than otherwise. A couple of examples are given below.

A common concept is that UBD introduce an operational complexity putting extra stress on planning and logistic management.

The fact that multiphase flow regimes have to be managed demands certain skills. An obvious danger is improper hole cleaning if safe flow regimes are not established. The ultimate scenario in such situations could be “stuck in hole”.

Geologists are not always to happy claiming that the cuttings are distorted and mixed making it hard to establish a valid geological interpretation.

And some experts claim that the daily costs increase, as you have to have extra equipment and crews on site. That is maybe the case in oil and gas explorations but not necessarily in geothermal exploration and production drilling.

UNDERBALANCED DRILLING OF DGE #1

In DGE #1 the hydrostatic pressure in the well bore was reduced by means of hooking up 3 air compressors and one booster releasing the compressed air through the drill pipes and back via the annulus. The BOP was arranged so that the air passed by a rotating head with a moving seal. The released air, containing cuttings and some liquid, was then forced to pass through a muffler in order to control the rather violent outbursts occurring in conjunction with slugging. When slugging a mixture of foam and water was used. During the drilling the conditions were close to “dry air” conditions meaning that most of the formation water had been lifted out.
The lifting out of formation water is a stepwise process till you encounter the differential pressure you need for a successful drilling. In this way, at the most, around 3350 m of water column was unloaded forcing the rock mass into an easily broken stage making it easier to drill. The water production from fractured and jointed zones was all the time very limited. This is basic as a high water yield, coming to early, could prevent further deepening of the hole. If such conditions occur it might be necessary to install another casing, which will allow further drilling.

Three compressors, and a booster, had a capacity of delivering around 3600 cfm (100 m^3/min) of air. Maximum pressure delivery was around 140 bar.

The compressive strength for the local gneiss granite and other rock groups encountered during drilling range from about 200 to 350 MPa. The formation fluid is a brine with a TDS of 200 000 – 220 000 ppm and the highest recorded temperature was 85 °C. The static water level in DGE #1 is around 65 m below ground level. And the open section in the basement is between 3200 and 3701.8 m.

The rock mechanical status presumably with critical stress build up of the rock mass is the basis for a swift rock rupture process. This is the main reason why the penetration rate so evidently increases in air drilling. See figure 5 where the drilling went from almost a dry air drilling to full hydrostatic and back to air again. First when the mixture was around 75% air the ROP increased markedly.

WELL BORE DAMAGE RISKS IN UBD-OPERATIONS

Well bore damages can be caused by several different factors depending on the actual situation. In this case the risks are divided in two groups. The hydro mechanical and geological group and the chemical group.

Hydro mechanical and geological considerations

Well bore in this case involves the well and its immediate space in the nearby formation. The perception that an UBD operation can cause aquifer damage such as decrease in hydraulic conductivity is the reason for this discussion.

Damage is brought to attention as that the drilling evidently passed numerous of fractured zones. Occasionally the ROP was very high more than 10 m/h and at a certain level as high as 15-20 m/h(figure 3 and 4). Along those sections the sonic velocity show evident decrease and along the same sections the calculated sonic porosity indicate an increase in porosity. In one occasion the air pressure rose quite markedly during the air drilling indicating water influx. This coincided with the highest ROP measured during the operation. Unfortunately this happened when most of the drilling assembly got stuck and after the Whip stock installation it was not possible to come back to that section again.

The cuttings from the fractured intervals show intensive mineral impregnation with calcite, epidote and quartz as veins and as fracture infilling. Signs typical in a deformation zone.

In conjunction with well tests carried out of the basement section of DGE #1 the hydraulic conductivity has been estimated to 9.9 10^{-10} m/s (Rosberg, 2006). An extremely low value, considered being a minimum value. The value is based on fall off data after an injection test. At this occasion around 200 bar and 2.75 l/s was used. This indicates that the basement formation was very tight when the test was carried out in spite of other observations.

Too little of storage capacity also negatively influenced the possibility to separate dirty formation water from cleaner water. As long as a true UBD condition was maintained there was minute risk for invasion of fines into the formation. But this was not always the case. Drilling problems now and then allowed the static level and dirty water to rise all the way up to near ground level. And in conjunction with injection tests the water was never completely cleaned.

In crystalline rock formations virtually all porosity is related to secondary porosity of joints and fractures. The increased load on the rock mass, when lifting out > 3000 m of water, will cause the fine joints to close to some extent. At least temporarily. If the elastic response of the rock mass doesn't lead to secondary fracturing (compaction) the joints and fracture voids will probably go back to its initial aperture when the hydrostatic pressure is restored. In such cases the hydraulic conductivity should also be restored.

To evaluate the risk for mechanical deformation you need information about the in situ rock stress state. Unfortunately no such information is at hand. As stated above the only rock mechanical information available is the compressive strength of the encountered rock groups ranging from 200 to 350 MPa.

Chemical considerations

Apart from mechanical impact on the formation properties there are several chemical scenarios being able to hamper for example the hydraulic conductivity. A couple of them are:

- precipitation of carbonates or silica due to liquid pressure drop
- reactions between mud/foam chemicals, formation water and rock minerals
- release of gas from the formation water changing the pH-conditions

In order to evaluate such risks you need samples with clean formation water. Due to a rather intensive use of foam chemicals while slugging and reuse of formation water it was never possible to get a representative water sample from the basement formation. In situ water sampling was unfortunately not within the budget framework.

The pH was fairly neutral according to measurements but was of course disturbed by all the airlifting and probably also by additives like foam chemicals. The brine composition is a calcium-sodium dominated mixture with around 40 000 mg/l of Calcium and around 90 mg/l of Magnesium. Which is very hard water and under certain circumstances able to precipitate carbonates.

Weather the foam chemicals or the geothermal water composition as such caused clogging or precipitates has not been possible to determine. The forceful unloading of water during drilling and slugging should have had the capability to clean not only the well but also the nearby fractured rock mass from fines and coarser particles.

CONCLUSIONS

As can be seen above there are a number of question marks till today not answered and some of them might never be answered.

In any case there are now in winter 2006 most certainly a vast experience around at the Work Shop in Stanford. Therefore I hereby invite for discussions around the topics promoted by this paper.

However a couple of conclusive remarks are still possible to provide within the concept of UBD operations.

The following s results are advantageous

Air drilling was advantageous regarding penetration rate and drilling performance of the very hard and abrasive crystalline basement rocks.

Testing of fracture zones more or less while drilling is most valuable and saves time and possibly also money.

The borehole walls seamed to be very clean thanks to the air drilling and air lifting activities. This is in favour for electrical logging performance and logging data quality.

The following results were adverse in our case

The hole was not properly cleaned at one occasion during air drilling why we managed to demonstrate that you would get stuck under such conditions.

Too limited storage and cleaning capacity of drilling fluids might have caused material deposition of potential production zones. This can happen when an UBD condition is not possible to maintain or when such water has to be used as injection fluid.

Too limited information about the in situ rock stress state that is valuable to have access to in order to evaluate the risk for rock mass compaction during air drilling.

Lack of undisturbed formation water samples makes it difficult to evaluate the risk for mineral precipitation when the hydrostatic pressure is lowered.

FINAL COMMENTS

It should of course also be stated that one of the most probable explanations for the poor water yield from the crystalline basement is simply lack of suitable geologic and hydrogeologic conditions.

But isn't that why exploration comes before exploitation!

Also we would like to mention that our Drilling Manager in charge during all the operations was *Virgil Welch, USA*, possessing extensive Air drilling experience from for example geothermal operations in California.

Further acknowledgment is directed to *Derek Howard Orchard, England*, reservoir engineer and invaluable in all matters related to drilling engineering.

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