GEOPHYSICAL EXPLORATION, DRILLING, WELL COMPLETION AND TESTING OF DEEP-SEATED AQUIFERS

Leif Bjelm
Lund University. Dept. of Engineering Geology
John Ericsons v. 1. Box 118
221 00 Lund, Sweden
ph: +46 46 2228983/2227425. fax: +46 46 2229127
e-mail: leif.bjelm@tg.lth.se

ABSTRACT

Recently two exploration wells were drilled in southern Sweden in order to evaluate the use of direct heat for the local district heating net in the city of Lund. After rather comprehensive geophysical investigations the exploration wells were located. From a technical development point of view the applicability of different drilling methods were also evaluated. Conventional rotary as well as non-conventional rotary air drilling was used. The deep boreholes were drilled in both sedimentary environments as in crystalline basement. Extensive logging operations were conducted as well as injection tests, pumping tests and coiled tubing well stimulation (jetting) was carried out. The exploration procedure is highlighted and results are presented as they become available during the process.

1. INTRODUCTION

This article has an intention to convey to the readers useful experiences encountered during a couple of intensive exploration years. The Department of Engineering Geology (DEG) had the opportunity to test and evaluate rather uncommon solutions in deep exploration drilling. Emphasis is made on the importance of having a structured exploration philosophy and on the methods used in our case.

In conjunction with the latest efforts to gain more knowledge about crystalline basement and its geothermal properties at great depth a rather extensive exploration programme was carried out. The target is an old and major tectonic structure in southern Sweden called the Tornquist zone, Fig1. It is a regional deformation zone crossing large parts of northern Europe, Fig 1. The physical and chemical properties at great depth in that geological feature had never been investigated before so the project was a rather big challenge. In addition to the pure geological exploration aims there was at the time also a national interest in Sweden to investigate different deep drilling techniques in crystalline basement. In the exploration target area, Fig 1, the community of Lund has been using geothermal energy for almost 20 years. A geothermal heat pump plant has successfully produced about 35-40 % of the city's district heat demand. Geothermal water from only about 700 m of depth and around 22°C is used (1,2,3,4).

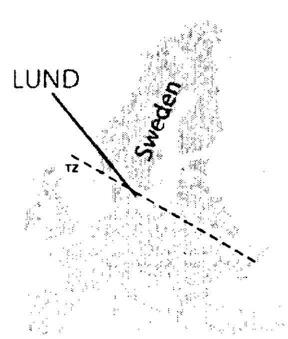

Figure 1. Location of Lund in northern Europe. (TZ) is The Tornquist zone.

At the time for pre-investigating the geological and geophysical conditions for the new project DEG and the community concluded that if the project could provide hot water (around 100°C) that would be of great benefit for the local energy company. They were at the moment looking for an increase of their *direct heat* production. The geological and geophysical exploration work started in 2000 and drilling of the first deep well started in 2002 and the second well in 2004.

2. EXPLORATION - A PHILOSOPHY AND A WORKING PROCEDURE

Exploration as an expression is a very wide concept and seldom means the same to more than a handful of people at any given situation. Nevertheless "exploration" include all there is of governing steps and methods towards a successful result in the very complex process of "searching for something"

Depending on the task and the prospect's character the scheme looks different from time to time. For the Lund project the development of working procedure is shown in Fig. 2.

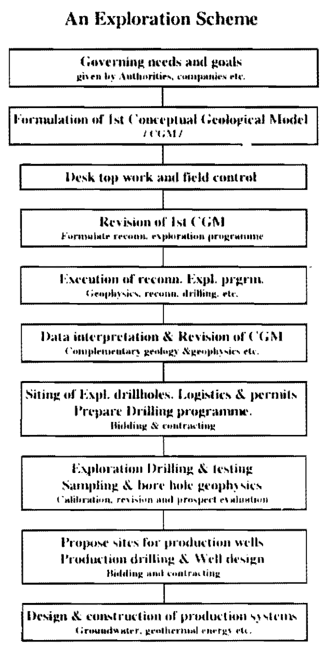

Figure 2. The exploration scheme used for the Lund projects.

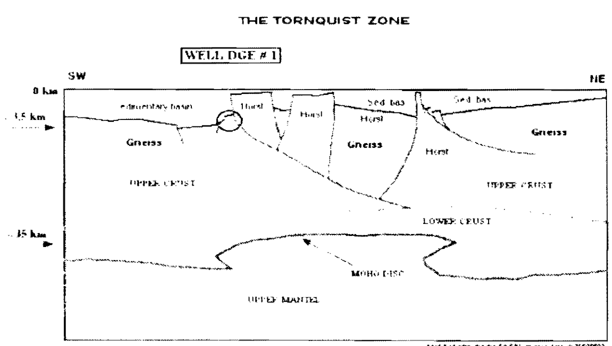

Figure 3. The macro tectonic conditions along a 400 km long section.
(source: The North European seismic traverse)

3. GEOLOGICAL SETTING IN SUMMARY

The target structure is a major tectonic feature developed as a border zone between the Baltic shield and the European sedimentary basins. Its development history has been going on for maybe the last 500 million years. The latest major tectonic activities was during Late Jurassic. -

Early and Middle Cretaceous Eras when regional stress due to the opening of the Atlantic caused compression/shear forces to act over the area. Since long before this Horst and Graben tectonic development had been going on in the area creating a mosaic of large block elements in a large scale (Fig 3).

4. GEOPHYSICAL EXPLORATION BEFORE THE DRILLING OPERATIONS

Having formulated a conceptual model in a very large scale, Fig 2, it was necessary to investigate if the concept could be valid. Therefore both geological and geophysical approaches were executed. The geological task was merely to establish an anticipated stratigrafic section based on former oil exploration data in the area. This was carried out as a final step when all geophysical information was available. But before that the Swedish Geological Survey, se Fig 4, carried out a renewed evaluation of existing gravity data.

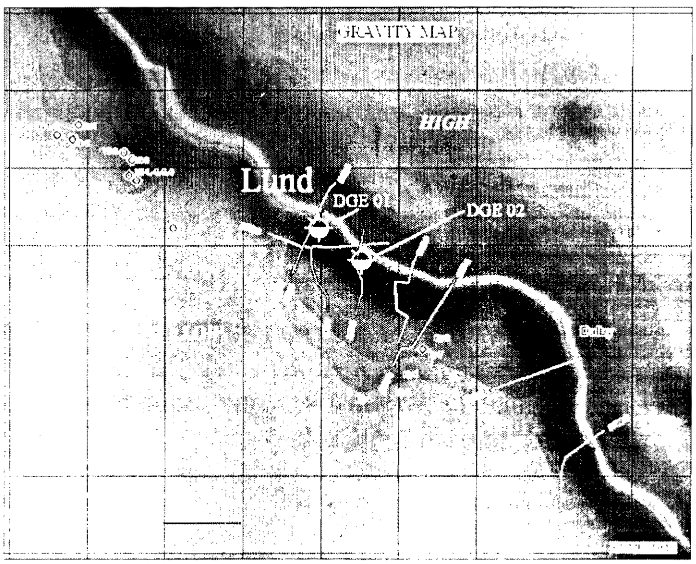

Figure 4. Gravity map of the prospect area.
(source: Swedish Geological Survey, local geophysical map).

Compared to the scale of the macro tectonic interpretation in Fig 3 the perspective of the compiled gravity map is rather a matter of about tenth of kilometres, Fig 4. In other words we are zooming in to the target area step by step. We usually call this the TOP-DOWN approach thereby implying the necessity to go from a large scale towards a smaller one when carrying out exploration work. Before an Anticipated section was ready to be drawn a reflection seismic programme - was carried out (5). The seismic lines are shown in Fig 4 crossing the fault zone revealed by the gravity data. One seismic line, just crossing well DGE 02 in Fig 4, can be seen as a seismic section in Fig 5.

To the right in the Fig 5 the faulting caused by reverse movement of the local crystalline basement (white) is obvious as so is the deformation of the sedimentary layering indicated in dark. The data acquisition is by the way gathered by a towed array technique using a vibro source as energy. This proved to be a very swift and cost effective approach producing as can be seen high quality information about the geological and structural conditions in the area. About 7000 US$/KM was our costs in Sweden including basic processing. To get deeper penetration conventional fixed cable set up was used in the final seismic exploration step. As the swift and cheaper towed array technique had already located the main features the more costly conventional set up was only used where deeper information was needed in an already known context. The kilometre cost for the conventional set up was around 3 times the "light weight version" mentioned above.

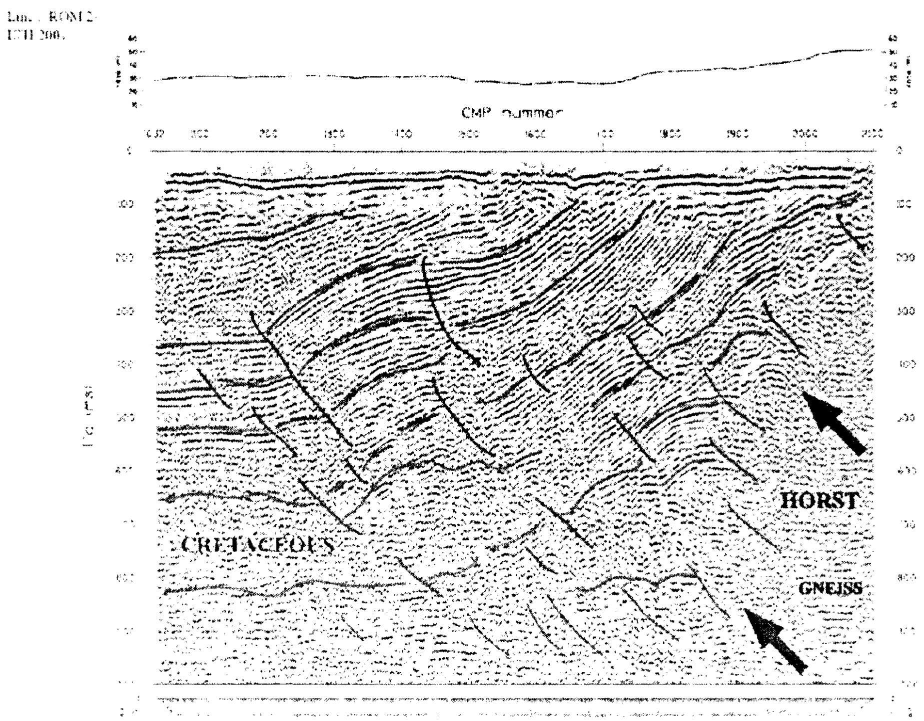

Figure 5. An example of high-resolution reflection seismic data acquisition carried out in order to pinpoint the positions for drill sites and wells. The maximum-recorded depth in this example is roughly 1200 m. Sedimentary features such as pinch out and layering is very obvious as is the structural deformation.

5. DRILLING TECHNOLOGY

The deep 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.

The following drilling methods were used:

-Conventional rotary drilling with mud
-Rotary air drilling – UBD (Underbalanced Drilling)
-Percussion drilling/Hammer drilling - UBD
-Mud Hammer drilling

Figurer 6 shows the use of different drilling methods in the first deep drilling in Lund. In the figure ROP (rate of penetration) and Caliper is shown. The TD was eventually reached at 3701.8 m. The change from conventional rotary mud drilling to rotary air drilling is highlighted with the circle in the upper part of figure 6. As can be seen the ROP increase with air drilling. In general you could say that the increase was about 3 to 4-fold (6).

For the first deep drilling in Lund the emphasis was on using *air drilling* in the crystalline basement section. This was simply because of the good penetration rate performance one has experienced during many years in deep geothermal exploration drilling in western USA (7, 8). The experience has demonstrated a relation between ROP and the degree of being underbalanced, Fig 7. In Lund the basement was hit at around 1950 m.

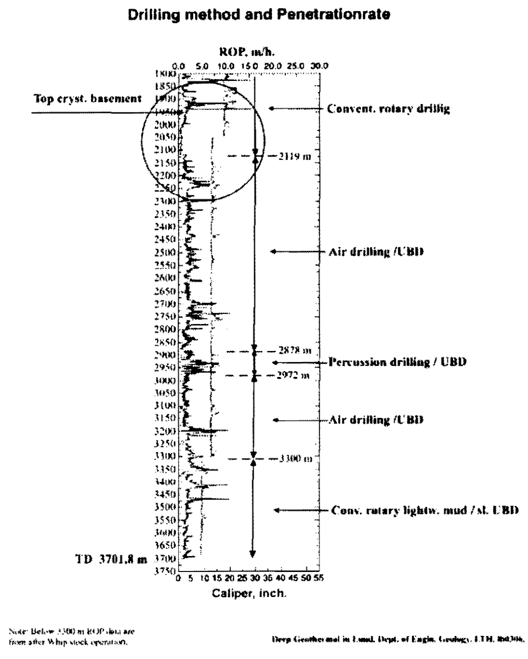

Fig 6. Drilling methods and penetration rate.
The difference in ROP between non-UBD and UBD is seen within the circle.

Basement at this location is a very abrasive gneiss with parts of granite and dolerite included. The quartz content in the gneiss is sometimes way above 30%.

Except for ROP performance there are other advantages with underbalanced drilling/rotary air drilling for example a more or less "automatic cleaning" of the open bore hole and fracture systems close to the well bore. But there are also risks associated with underbalanced drilling for example bad hole cleaning can cause you get stuck in hole with loss of drilling assembly and in the worst case loss of the bore hole/well.

Experienced staff and careful monitoring is necessary in rotary air drilling. If all good parts come together rotary air drilling can be a very cost effective solution and especially in steam dominated geothermal reservoirs it could very well be the best solution.

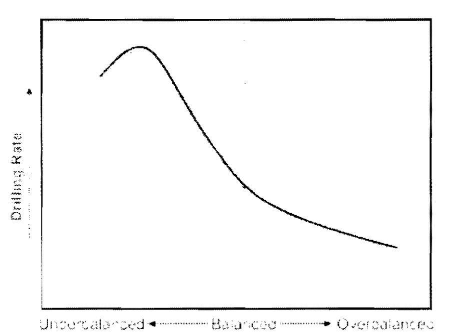

Fig 7. Drilling rate versus the degree of hydrostatic balance.

6. GEOPHYSICAL LOGGING AND WELL COMPLETION

Drilling a borehole is the only way to get access to ground truth information (in situ data) necessary for any qualified interpretation and evaluation of the resource and its properties. The exploration drilling also aims at validating the conceptual geological model which if necessary will be adjusted in accordance to encountered findings. In any aspect the drilling is invaluable as it deliver ground truth information about the subsurface - geological, geophysical and hydraulic conditions. Only with such information anticipations can be turned into confirmations (9).

Geophysical borehole logging provides the most accurate and useful information necessary for a professional well design and construction. In many cases a production test is not possible to carry out before the well is secured with a well construction. Often a productive formation is unstable and can easily collapse when stressed by lowering of the hydrostatic head. Therefore the input for the well design has to come from geological information and geophysical borehole logging data. Based on this information the well completion can be determined.

An example of conducting a well completion process is presented for the second well drilled in the Lund project where the target was the sedimentary formations overlaying the crystalline basement. The total drilling depth was a little less than 1950 m. Due to the heavy faulting in the area there is inverse layering at the target location with parts of Palaeozoic resting on top of parts of Mesozoic deposits. Parts of those Mesozoic sediments are in addition upside down. All this made the drilling prognoses rather uncertain and the online geological interpretation of cuttings was very tricky due to inverse layering and rotated rock sequences. In the first well a couple of sandstone formations of Cretaceous age proved to provide substantial amounts of geothermal water when tested (10). Similar sandstone formations, of Cretaceous or Jurassic age, were encountered in the second borehole. Due to a high degree of unconsolidated parts of the formation it was obvious that a filter screen had to be installed.

The geophysical logging programme used to support the well design work included Caliper, NGamma, Full waveform compensated sonic, Density and a set of E-logs. Based on the logs and samples taken during drilling it was concluded that a wire wrapped continuously slotted screen was the best choice providing less hydraulic friction losses. The grain size distribution gave no other alternative than a gravel packed well completion.

A simplified drawing, Fig 8, shows distribution of screens and blanks. As can be seen the well was equipped with two separate screens and a blank section in between.

However, as is often the case, the installed gravel pack was not fully developed and the interface to the formation needed stimulation in order to provide the best rate of performance. A jetting operation was therefore designed and carried out. A coiled tubing unit equipped with proper jetting tools for the actual well screens and gravel pack performed the stimulation and cleaning. The increase in well performance is also seen in Fig 8.

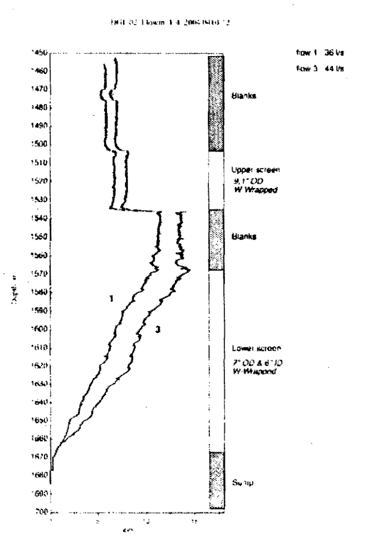

Figure 8. Screen distribution and Flow meter data for DGE 02 measured while pumping before (1) and after (3) jetting operations.

7.TEST PUMPING

As a final step in a rather long chain of exploration activities comes the production and test pumping of the aquifer. The efficiency of the well construction was investigated and analysed by means of short term tests, step-drawdown tests and stimulation efforts mentioned above. With performance and efficiency data from short-term tests it is normally possibly to design a long term pumping programme. Common subjects at this step is selection of flow rate, length of pumping time, data sampling criteria in pump well and observation wells etc. In Fig 9 the difference in drawdown behaviour is seen when comparing properties before and after jetting stimulation.

The pumping well was the only well available for measuring drawdown. The first well, 1500 m away, was at the time used for injection of the pumped fluids and was monitored but no evident interference was noticed during the available pumping time. Unfortunately the pumping did not continue long enough to determine if there ever was a hydraulic interference situation. However it became quite obvious after a couple of days that the aquifer had a limited volume and the drawdown indicated a continuous increase(9).

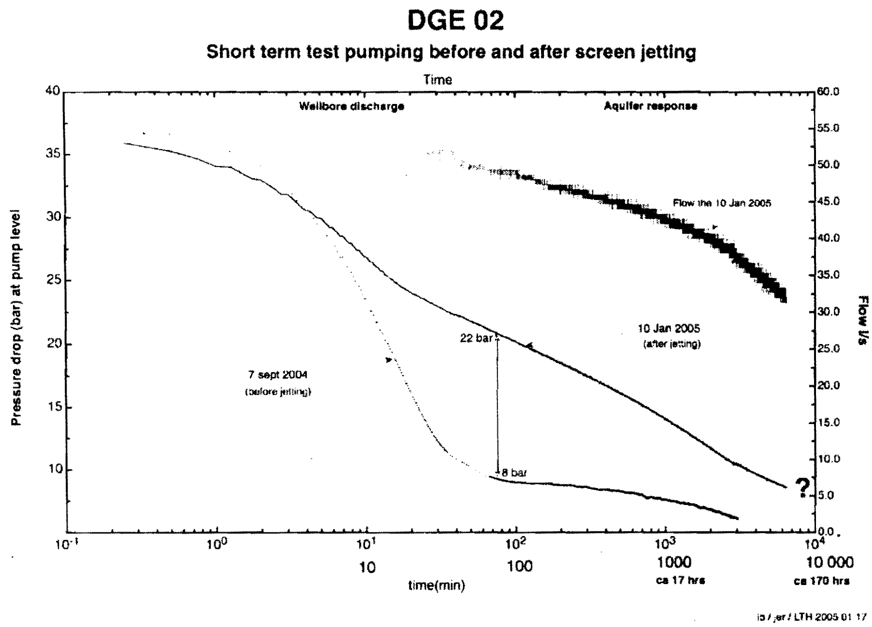

Figure 9. Time-drawdown graph before and after jetting operations. Average flow rate before jetting was 28 l/s and after 38 l/s. The difference in drawdown is a result of jetting and cleaning of screens and nearby parts of formation. The pumping was not carried out long enough to conduct a final interpretation of hydraulic boundaries etc.

It is inevitable and to many maybe somewhat disturbing that useful production information is available at first at the very end of a long and many times exhausting exploration chain. But this is a fact and one must stick to this since there are no short cuts in this business.

8. CONCLUSIONS

By means of a wide angle or a so-called Top-Down approach in exploration a couple of large operations in Sweden are used as an example. A voyage in exploration methods are provided in this article and the conclusion for us, and for everyone else as well should be that a systematic exploration philosophy provides the best possible opportunities to get useful results already at an early stage when opening up a regional exploration programme. It is not given that you will be able to produce the fluids or the energy you were looking for already after the first exploration attempt. But the information have been gathered and evaluated in a systematic way and represents an investment for the future and an invaluable platform for further planning and exploration.

REFERENCES

1. Bjelm, L., Schärnell, L., 1983. Large heat pump plants for district heating utilizing geothermal energy. International symposium on Geothermal Energy. Portland, USA. (Tekniska Högskolan i Lund, Avd. för Teknisk Geologi och STAL LAVAL TURBIN A, Finspong

2. Bjelm, L., 1991. The Geothermal heat pump plant in Lund after six years of experience. Conf. on " Non fossil Energies: Technology trends & development prospect", Sophia Antipolis, France June 26-28, 1991.

3. Bjelm, L., Lindeberg, L., 1995. Long term experience from a heat pump plant in Lund, Sweden, using a low-temperature geothermal aquifer. Conference on Geothermal Energy in Milano 1995.

4. Alm, P-G., 1999. Longterm Study of Geothermal Data from a Low Enthalpy Geothermal
Heat Plant. Proceedings Twenty-Fourth Workshop Geothermal Reservoir Engineering. Stanford
Geothermal Program. Stanford University, Stanford, California.

5. Alm, P-G., and Bjelm, L., 2006. Towed array seismic exploration of the Tornqvist zone. Proceedings. Thirty-First Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, California, January 30-February 1, 2006. SGP-TR-179, p. 459-464.

6. Bjelm, L., 2006. "Under Balanced Drilling and Possible Well Bore Damage in Low Temperature Geothermal Environments", Thirty-First Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 30-February 1, 2006, SGP-TR-179, p. 67-72.

7. Cooper, L.W., Hook, R.A., Payne, B.R., 1977. "Air Drilling Techniques", Deep drilling and production symposium of SPE, Amarillo, Texas, 16 pp.

8. Sheffield, J. S., Sitzman, J. J., 1985. "Air Drilling Practices in the Mid-continent and Rocky Mountain Areas", *SPE/IADC, Drilling conference, New Orleans, Louisiana*, 9 pp.

9. Bjelm, L., and Rosberg, J-E., 2006. Recent geothermal exploration for deep seated sources in Sweden. Engineering Geology, Lund University, Sweden. GRC. Annual Meeting September 10-13, 2006.
San Diego, California, USA.

10. Rosberg, J-E., 2006. Flow Test of a Perforated Deep Dual Cased Well. Thirty-First Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 30-February 1, 2006,
8 pp. SGP-TR-17, p. 123-130.