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Geothermal Energy from Impact Craters? The Björkö Study

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ABSTRACT

The suspected ca 10 km diameter Björkö impact structure has been studied for its potential to retrieve geothermal energy. It has formed in crystalline rocks ca 1.2 Ga ago and is located relatively close to the district heating infrastructure of the Stockholm region, which the largest district heating system in Europe. The region is within a crystalline shield with low geothermal gradient of 15-20 Kkm^{-1}.

Impact structures typically contain fractured rock volumes in the form of allogenic and authigenic breccia formations. This brecciation is the target for geothermal investigations. The low geothermal gradient requires target depths of 3-5 km to obtain sufficiently high temperatures for use in district heating systems. In the Björkö structure therefore both gravity and magnetotelluric (MT) measurements were made to assess the extent of brecciation at such large depth.

A relation between the 3-d-fracture frequency and the electric resistivity was derived based on surface sampling in 19 test areas and two > 900 m deep drill holes. MT measurements were made at 40 stations and a dense net of gravity measurements was located in the area.

Modelling of the resistivity structure indicated that at least 15 km^3 of connected low resistive rock occurs at the target depth between 3 and 5 km. Flow tests made in the wells show a very low permeability confined to a few larger fracture zones. The fracture fill minerals (mainly calcite) are relatively weak and can be re-fractured at relatively low stress. Before further investigations of the energy potential can be made, more comprehensive hydraulic fracturing experiments must be performed. If it is possible to regenerate the vast fracturing, a very large energy potential can be envisaged for the entire 250 km^3 structure.

1. INTRODUCTION AND BACKGROUND

Impact structures have extensively been studied for their occurrence of shock metamorphic features and near surface structure. There is however very little known about the character and extent of the fracturing associated with an impact event. Only very few deep drill holes reveal some of the 3-d-structure of impact carters, the two examples are from the central uplift of the Puchezh-Katunki structure in Russia (Masaitis and Pevzner 1999) and the Siljan structure in Sweden (Juhlin 1991). In these drill holes emphasis has been on the shock metamorphic and physical properties of the rocks. An increased fracture frequency has been estimated for the Puchezh-Katunki deep drill hole and was found to extend to almost 5 km depth. A similar study is however lacking for the Siljan drilling. The intensity of impact induced fracturing is one of the key parameters together with the temperature gradient and the hydraulic conductivity when impact structures in crystalline rocks are targets for geothermal investigations.

Theoretically, the fracturing related to the shock wave, created by an impact extends in a hemispherical volume below the explosion center with outward decreasing intensity of brecciatio. (Melosh 1989). In craters with a diameter larger than ca 4 km, the subsequent collapse of the initially formed crater adds to the impact induced fracturing, which in turn is overprinting existing fracture patterns. After impact, much of the energy from the projectile has been turned into mechanical destruction and some energy remains in the form of impact melt rocks and their heated basement, especially in the central uplift region where previously deeper located rocks at higher temperature are brought closer to the surface (Melosh and Ivanov 1999). The impact structure will thus be a site for more or less extensive hydrothermal changes causing elements to dissolve and precipitate, depending on the local thermal gradients. (Puura and Plado 2004). The hydrothermal activity causes fracture filling where the most typical mineral in a crystalline environment is calcite. The remaining fracturing and the fracture fill will change the physical properties of the affected rocks

To further explore impact structures at depth, remote geophysical techniques are employed (Henkel 1992 and 2002). These depend on the 3-d-distribution of different contrasts in rock physical properties. Their integrated effect can be measured at the surface using gravity, magnetic and electromagnetic methods.

The Björkö structure

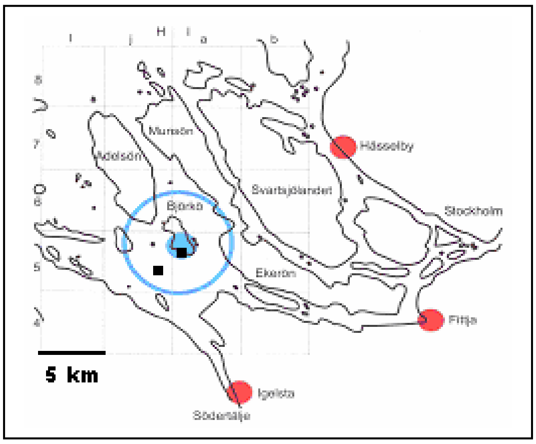

Figure 1. Location and approximate outline of the Björkö structure (encircled) west of Stockholm, Sweden, together with the 3 major district heating plants of the Stockholm region.. The location of two deep drill holes is marked with squares.

The Björkö structure has been suggested as a deep eroded impact crater formed ca 1.2 Ga ago (Flodén et al. 1993). In crystalline rocks with ages from 1.8 Ga and older. Around the central part of the structure, a half-ring shaped occurrence of low porosity sandstone of Jotnian age was suggested to occur based on marine reflection and refraction seismic data (Flodén et al. 1993, Flodén and Bjerkéus 2003). The structure is mainly located within water covered areas (the lake Mälaren). Its central uplift is exposed on the island Björkö, where also more intense fracturing occurs. Preliminary studies of the electric resistivity indicated a generally decreased resistivity, which was interpreted in terms of increased fracturing (Henkel 1992).

The location close to the district heating network in the Stockholm area, Fig. 1, made it a target for studies of its geothermal energy potential. Already with conservative estimates of the remaining fracture induced porosity, the 10 km diameter structure would contain very large amounts of thermal energy. To explore the Björkö structure further for its geothermal energy potential, a project was started with funding from the Swedish Energy Board (Henkel 2002). This project consisted of detailed mapping of fracture frequency, two deep drill holes (in the ring part of the structure and in its central part), gravity and extensive magnetotelluric (MT) measurements.

The project is of particular interest as the demand for heating is considerable during a major part of the year regarded the northern latitudes of Stockholm. The political decisions made in Sweden on restricting CO_2 emissions and phasing out nuclear power, requires efforts to find alternative and sustainable energy resources for the immediate future.

2. GEOPHYSICAL MEASUREMENTS

Rock physical property data were collected from existing outcrops within and around the structure and from drill cores. The in-situ measured electric resistivity was significantly lower for both sandstone and fractured rocks (Bäckström and Henkel 2003), Fig. 2.

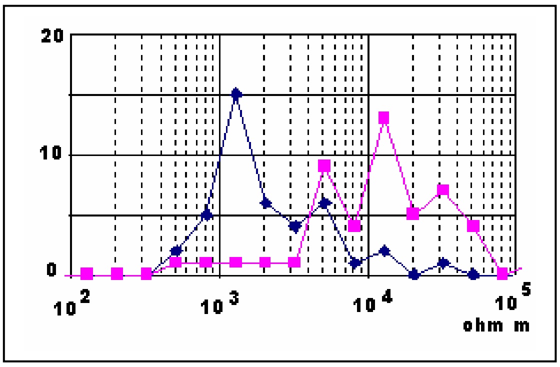

Figure 2. In-situ electric resistivity distribution (number of measurements) of fractured (diamonds) and normal (squares) crystalline rocks. These measurements apply to rocks above the saline – fresh water interface.

The density of fractured crystalline rocks and sandstone was slightly lower compared to normal unfractured rocks. Fig. 3 shows the density measured on drill core samples from the centrally located drill hole. It approaches values at and below the average density of sandstone of 2610 kgm^{-3}.

Gravity measurements, in part made on lake ice in winter periods, thus showed a gravity low of ca – 4.5 mgal, Fig. 4, caused by both the sandstone and the fractured rock volume. A renewed marine geophysical survey (Flodén and Bjerkéus 2003) was the basis to outline in more detail the occurrence of the sandstone in the ring part of the structure. Its depth could however not be resolved as the p-wave velocities of the sandstone were very similar, and in part larger, than the underlying fractured crystalline basement.

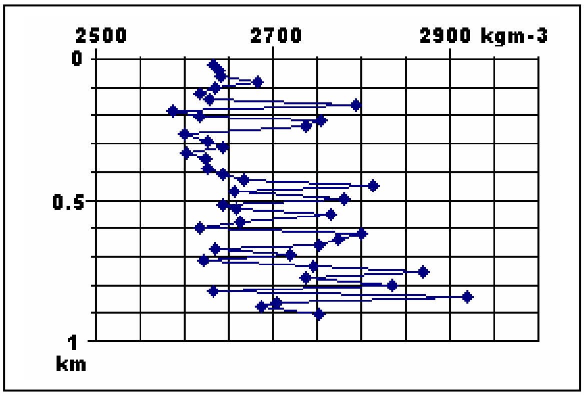

Figure 3. Density distribution with depth in the centrally located drill hole. Densities below 2650 kgm^{-3} are related to brecciation. Densities above 2700 kgm^{-3} are related to rocks with more mafic (than granite) composition.

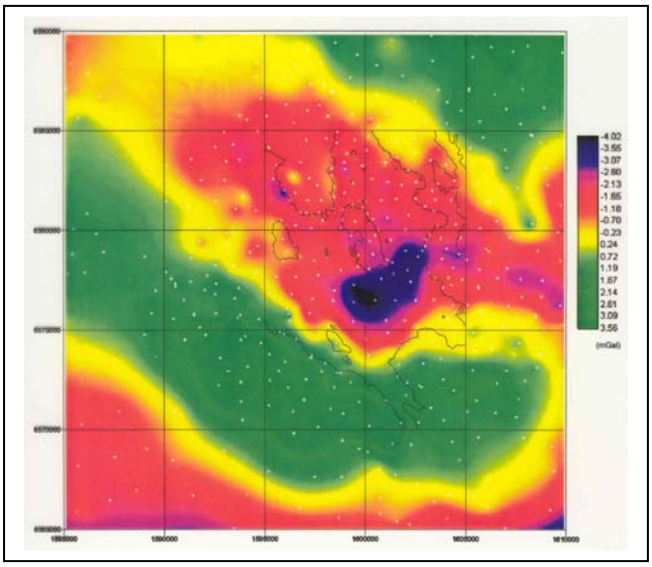

Figure 4. Gravity residual map of the Björkö structure. The lowest anomaly is caused by the combined effect from brecciation and the overlying sandstone thickness. Measurements in water areas were made during winter time on lake ice. Each square is 5x5 km.

Magnetotelluric (MT) measurements

A series of tests were made to study if the MT measurements could be used to discriminate between sandstone and the underlying basement rocks and the occurrence of more intense fracturing within the basement. The results (Fig. 5), were encouraging and a total of 40 stations were subsequently measured, on lake ice and on land within and around the structure (Oskooi and Pedersen 2003). Severe disturbancies from a nearby high voltage power line excluded the eastern edge of the structure from the survey. The obtained results have been compiled in a 3-d-perspective view in Fig. 4 and show that very large volumes of low resistivity crystalline rocks occur at depth in the 3-5 km range.

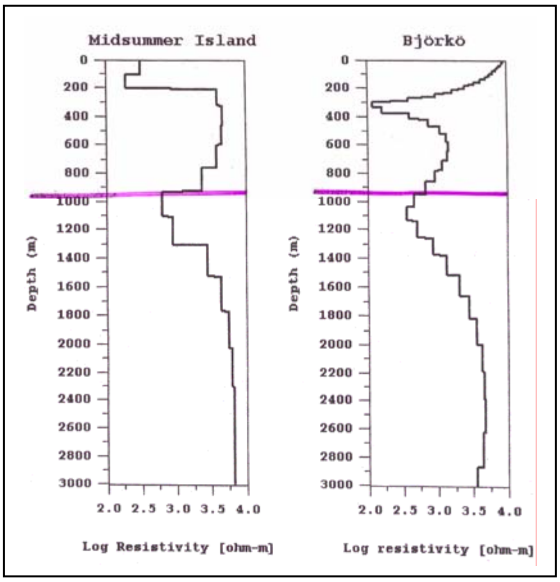

Figure 5. 1-d-models of the electric resistivity based on MT measurements. The lines indicate the drilling depth at each location. Left: ring part of the structure with sandstone in the top 1 km. Right: the central uplift of the structure, where the low resistivity layer at 300 m depth corresponds to a conductive layer in the gneisses. The decreased resistivity just below 1 km depth is the combined effect from increased fracturing and the occurrence of conductive brine.

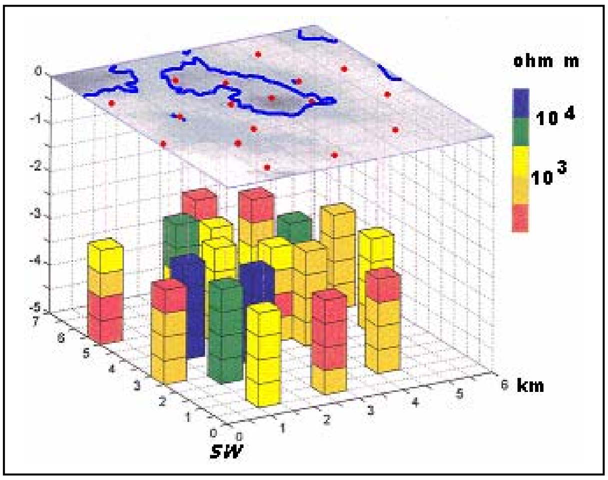

Figure 6. Electric resistivity at 3-5 km depth in the Björkö structure based on MT-data. Each box is 0.125 km^3. The space between the marked volumes has similar properties as the neighbouring volumes. The location of the MT stations are marked on the persåpective view map with the cenmtral part of the structure at the southern part of the island Björkö. In water areas measurement were made during winter time on the lake ice.

3. DRILLING AND LOGGING

Two deep wells were core drilled to allow measurements in-situ in the rock mass and on recovered core samples. The wells were located in the sedimentary ring area (on the island Midsommar) and in the central part (on the island Björkö). The drilling into the sandstone revealed an inward (towards the center) tilted normal sedimentary sequence (Olsson 2003, Viksten 2003) with a vertical thickness exceeding 960 m. At that depth the drilling was stopped for economic and technical reasons as the sandstone not was the primary target for the study. The drilling into the central part of the structure proceeded to 920 m vertical depth through strongly brecciated crystalline rocks (granite and gneisses). From both drillings, almost complete cores could be recovered for the entire depth. Samples every 20 m were measured with respect to porosity, density, magnetic susceptibility, electric resistivity and induced polarization (IP)-effect. The fracture frequency of the entire cores was mapped based on photographs. For 8 sections of the crystalline rock core, the fractures were also characterized by their relative orientation (Bäckström 2004).

Logging results

The temperature of the drill holes was logged, and the drill hole on Björkö was also logged with respect to electric resistivity (several methods), IP-effect, and water inflow. (Ludvigson et al. 2001, Sträng and Wänstedt 2003). The temperature gradient is normal for crystalline shield areas, in the interval 15 – 20 km^{-1}, similar to that found for the Siljan deep drilling (Juhlin 1991). The temperatures at the bottom of the drill holes was close to 20 ^{o}C. The water inflow measured in the brecciated crystalline basement formations was very low (Ludvigsson et al. 2001). The electric resistivity varies with the intensity of fracturing and the occurrence of conductive minerals (mainly sulphides and graphite) in parts of the gneisses.

4. FRACTURE FREQUENCY AND STRESS FIELD

The 2-dimensional fracture frequency was estimated at 19 rock outcrop sites in and around the Björkö structure. Areas of 1 m^2 (strongly fractured outcrops) and 9 m^2 (normal fractured outcrops) were digitally photographed and the images were subsequently analysed with a geographic information system. From these data and from the fracture analysis of the drill cores, the 3-d-fracture frequency was calculated. (Bäckström 2004). The most strongly fractured parts of the crystalline basement have up to 40 times more fracture area as compared to normal crystalline rocks, Fig. 7.

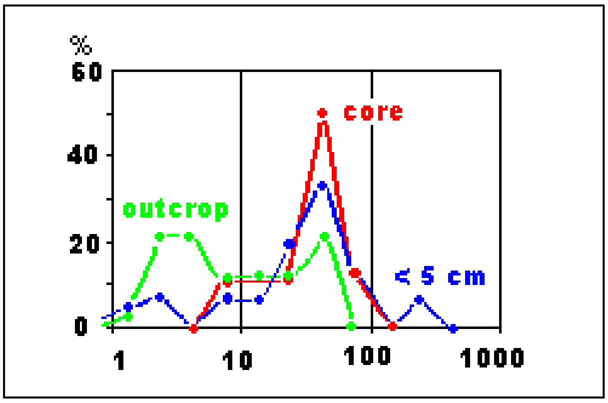

Figure 7. 3-d-fracture frequency (in m^2/m^3) distribution from drill core samples, and surface mapping (including fractures < 5 cm). The high peak represents the most fractured surface near rocks and most fractured part of the drill core, respectively.

The stress field has been assessed with hydraulic fracturing in pre-selected sections of the 920 m deep drill hole in the central part of the structure (on the island Björkö), and are reported in (Ask 2003). The horizontal stress is NW-SE oriented and is slightly lower as compared to other areas in the Baltic shield. During the experiment, new NNW-SSE oriented fractures were induced and fractures at right angles to these were re-activated.

The fracture fill minerals have been studied on core samples from the central part of the structure. The predominant fracture fill mineral is calcite (Broman 2002). Experiments with triaxial testing showed the fractured parts of the rock to have low strength and could easily be re-opened. (Strömhag 2003).

5. DISCUSSION AND CONCLUSIONS

In crystalline rocks, porosity is exclusively linked to fracturing in fracture zones or in impact structures. Impact structures are thus interesting targets for geothermal heat extraction when they approach dimension that provide large volumes of fractured rock to depth where the local geothermal gradient provides high enough temperatures. Several such structures exist in the crystalline shield areas in northern Europe (Puura and Plado 2004).

The geophysical studies confirmed a higher than normal fracturing with the Björkö structure. The calculated temperature based on calculations in Dunwen and Henkel (2004), approach just over ca 105 ^{o}C at 5 km depth and makes the depth interval from 3 to 5 km interesting for geothermal heat extraction. A connected volume of at least 15 km^3 of very low resistivity rocks occur in the eastern, south eastern and southern part of the ring structure. This volume can be assessed by drilling from land at the eastern edge of the structure, where the distance to the nearest district heating plant is ca 13 km.

This kind of relatively low temperature geothermal energy resources could be even better used if the district heating systems are constructed for circulation at lower water temperatures.

The hydraulic conductivity of impact fractured crystalline rocks is very low which has been observed for the Siljan structure and also at Björkö. Such a situation may be a positive factor, preventing the system from being open to uncontrolled in- or outflow. It requires however the application of hydraulic stimulation techniques to create a sufficient large volume for the heat exchange.

Experiments to determine the potential flow after hydraulic stimulation have been planned but remain to be financed. Sites have been selected around the central drill hole for hydraulic fracturing and seismic and acoustic monitoring of such experiments.

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