The Björkö geothermal energy project

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Impact crater formation results in changes in the physical properties of rocks that can be geophysically determined and therefore are of importance for the mapping of impact structures at depth. Especially electrical properties have a direct bearing on the remaining porosity found in impact structures in crystalline target rocks. Several studies made in the Dellen, Siljan and Lockne craters show typical changes in rock physical properties. Although a significantly increased porosity in the crater basement seems to occur, the hydraulic conductivity appears to be rather small. The total volume of brecciated rocks in impact structures may be very large and that volume could, after reactivation of the fractures, be used as a heat exchange structure for geothermal energy retrieval, exploiting the normal geothermal gradient at greater depths.
The ***Björkö*** structure is a c. 10 km-diameter impact crater located just west of Stockholm in lake Mälaren. Studies made so far on islands show the characteristic features of intense brecciation and increased porosity known from other craters. The ***Björkö Energy Project*** is designed to assess the potential for geothermal energy retrieval by mapping the structure at depth with geophysical methods and by drilling. The project is financed by the Swedish National Energy Administration and runs for 2 years, starting in October 2000.

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Introduction

Impact craters are caused by bodies in the solar system whose orbits have been disturbed, either by the gravity of Jupiter, namely asteroids, or by the gravity of stellar encounters, namely comets. When their new orbits cross that of the Earth, they may eventually collide with our planet, resulting in a catastrophic explosion where the kinetic energy of the projectile is transferred to the Earth as thermal and mechanical energy. The cratering event transforms terrestrial materials into various shock-metamorphic states. Theoretically, it is envisaged that the shock-induced transformations occur in a hemispherical region around the point of impact, with outward decreasing intensity. The shock-induced transformations of the target material thus grade from the formation of vapour through melting to brecciation. An extensive account of impact cratering has been presented by Melosh (1989). Large impacts result in impact craters, which in the active geological system at the Earth's surface are soon eroded or buried beneath sediments. Craters larger than c. 4 km in diameter evolve as complex structures with an elevated central rise. The transition to this complex final crater structure involves massive radial flow of material, which will add to the shock-induced fracturing of the target material. In Fennoscandia, some 20 large (Cretaceous and older) and 4 small (postglacial) impact craters are presently known. An even larger number of such structures is suspected to occur but remain to be confirmed as impact craters. In the map (Fig. 1), from Henkel & Pesonen (1992), an overview is given of the situation 10 years ago.

This vast fracturing in connection with a large impact crater in a crystalline environment is the research target for the Björkö energy project.

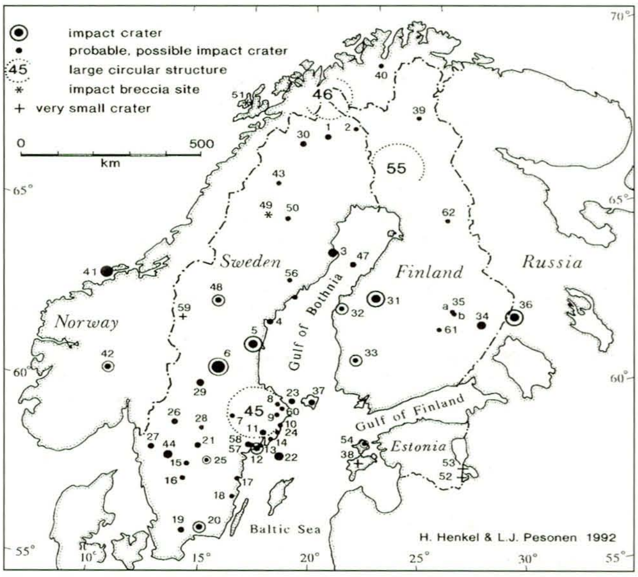

Fig.1. Impact structures in Fennoscandia (from Henkel & Pesonen 1992). Since 1992, a few more impact craters have been confirmed in Finland.

Fracturing related to impact craters in crystalline environments

The concept of fracturing has not previously attracted impact researchers as much as the shock-metamorphic transitions proper, the crater formation process or the composition of impact-generated rock types. Thus, there are so far only a few studies dealing with this subject. The deep drilling at the ***Puchezh Katunki*** structure (Masaitis et al. 1994) is one example – where impact-induced fracturing is observed to considerable depth along the entire c. 5 km depth of the drillhole in the central rise. The deep drilling at the Siljan structure has not explicitly been devoted to mapping the extent of fracturing, but shock-induced planar deformation features in quartz are reported to occur down to 2.8 km depth (Juhlin 1991).

Fracturing in crystalline rocks normally results in increased porosity, and the additional pore water content decreases the electric resistivity of the material. It would therefore be possible to map the extent of impact-induced fracturing with geophysical methods that rely on electric conductivity, a concept that has a parallel application in fracture zone mapping. The relationship between fracture zones and changes in physical properties has been explored in several contexts, for example in connection with radwaste storage. It is a well established fact that the magnetisation (Henkel & Guzmán 1977) and the electric resistivity both show a decrease in fracture zones (Henkel 1988).

This knowledge has been applied to impact crater structures in four ways: The in-situ measurement of electric resistivity using VLF-R technique; the study of fracture frequency using airborne VLF data; a study of the relationship between in-situ electric resistivity and porosity; and finally a study of the relationship between in-situ resistivity and fracture frequency on a detailed scale.

In the ***Dellen*** impact structure, a traverse with in-situ electric resistivity measurements with the VLF-R technique was performed in connection with regular mapping activities in the area. The impact occurred in a relatively homogeneous gneissic granite (Ljusdalgranite) with numerous outcrops on which the measurement array was located. It was found that the electric resistivity begins to decrease already outside the present erosional (topographic) crater edge. Towards the crater interior, outcrops become scarcer and eventually there is only a glacial till cover. The electric resistivity attains a minimum over the ring of the crater and a relative maximum over the 9 km-diameter region with magnetic impact melt. The resistivity traverse is shown in Fig. 2 (from Henkel 1992).

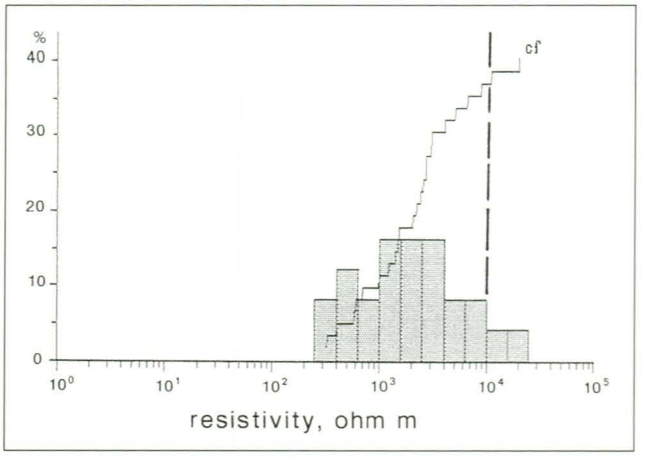

Fig. 3. The resistivity distribution of the central rise of the Björkö structure (after Henkel 1992). The cumulative frequency is marked cf. The broken line indicates the approximate lower resistivity limit of normal crystalline rocks.

The central rise of the then suspected ***Björkö*** impact structure was also studied with respect to the distribution of electric resistivity. It was found that the resistivity systematically is below 10^4 ohm m, which is non-typical for normal low-porosity crystalline rocks such as granite (Fig. 3, from Henkel 1992).

In the central uplift of the ***Siljan*** impact structure, the spacing of a one-directional set of linear airborne VLF anomalies was studied and compared with the spacing of similar exterior anomalies. Such anomalies have previously been found to be caused by water-bearing fracture zones. In the

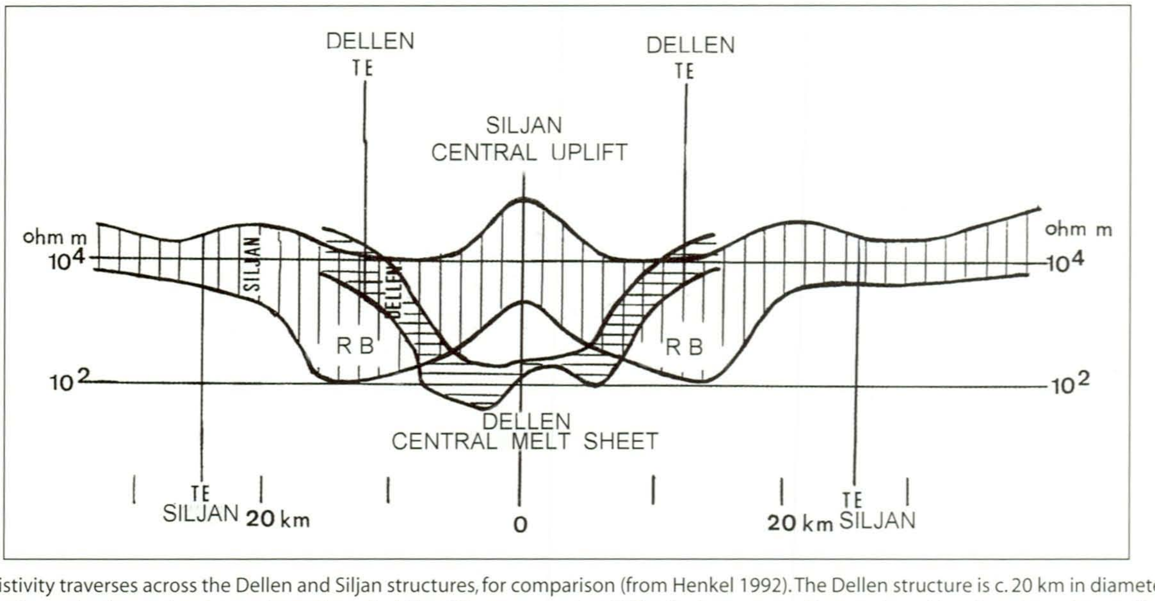

Fig. 2. Resistivity traverses across the Dellen and Siljan structures, for comparison (from Henkel 1992). The Dellen structure is c. 20 km in diameter, has a flat floor and contains impactites (tagamite and suevite). The Siljan structure is c. 75 km in diameter, and is complex with a ring-shaped crystalline uplift which is c. 20 km in diameter. RB denotes the location of the Palaeozoic ring basin of the Siljan structure. TE marks the present topographic (erosional) edge of the structures.

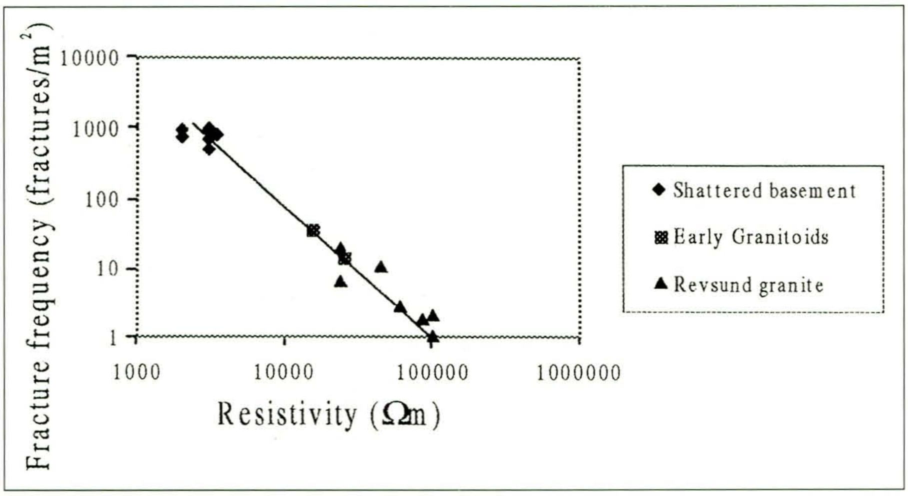

Fig. 4. Correlation between surface fracture frequency and in-situ surface electric resistivity (from Bäckström 2001). The impact brecciated rocks have a c. 100 times higher surface fracture frequency as compared to normal crystalline rocks.

central rise of the Siljan crater, the spacing was found to be on average about 1/5 of that in the exterior areas, indicating a significantly increased fracture frequency (Henkel 1992).

From drillholes made in connection with the Siljan Deep Gas Project (Juhlin 1991), observed porosity from drillcores has been correlated with electric resistivity measurements. The result shows a linear relationship between the ^{10}log resistivity and the porosity over a range of several orders of magnitude and up to 5% porosity, respectively, indicating that near surface (within ca 200 m) porosity can be assessed with surface measurements of electric resistivity (Henkel 1992).

At the ***Lockne*** impact structure, a study was performed correlating the fracture frequency seen on outcrops with the electric resistivity measured at the same location. A linear relationship between the ^{10}log of resistivity and the ^{10}log of the areal fracture frequency could be established (Fig. 4, from Bäckström 2001).

In summary, the obtained results clearly show that an increased fracture frequency is typical for impact structures both on an intermediate and a detailed scale, and that this is reflected in the electric resistivity measured over a relatively large area. It also indicates that fracturing seems to increase gradually from the erosional crater edge towards a maximum in the central rise area. It has not yet been possible, however, to document the details of this variation due to the lack of basement outcrops under the ring synform in complex craters. Also, the vertical variation of impact-generated fracturing of the basement is still poorly known. The results obtained so far, however, point towards the option to use deep-penetrating, electromagnetic sounding techniques for the mapping of the fracture frequency / porosity within an entire crater structure.

The assumption of a hemispherical fractured volume of the crater basement combined with the relatively low geothermal gradient of c. 15 K km^{-1} typical for the Baltic Shield, requires a rather large impact structure in order to represent a large heat exchange volume at a depth with elevated temperature. The thermal energy generated by a large impact event is likely to cause significant hydrothermal alterations, resulting in cementation of the created fractures. The heat exchange capacity may thus be achieved first after a re-opening of the fracture system by hydraulic methods.

Geophysical methods relevant for modelling of structures in glaciated crystalline environments

In large parts of the Baltic Shield, only a thin cover of glacial deposits occurs directly upon the crystalline basement, and a complete sedimentary cover is absent. This specific geological situation is favorable with respect to the application of a variety of geophysical methods for a modelling of the subsurface. Furthermore, relatively common outcrops of the crystalline rocks make it possible to sample their rock physical properties at the surface. The applicable methods include measurements of gravity, magnetics and electromagnetics. These methods are mutually interrelated and result in constraining options when used in combination. Some of these features and relations are outlined briefly below:

Gravity anomalies are proportional to the density contrast of rock volumes, which in turn is a function of rock composition and porosity / brecciation.

Magnetic anomalies are proportional to the magnetization contrast, which depends on the content of ferrimagnetic minerals. This content is decreased by oxidation in fractured volumes.

The ***electric conductivity*** can be mapped with several electric or electromagnetic methods and is dependent on rock porosity/brecciation and electrolyte content of the pore water, as well as the content of conductive minerals (sulphides and graphite). Relevant methods are Vertical Electrical Sounding (VES), Very Low Frequency Resistivity (VLF-R) measurements and Magneto-Telluric (MT) measurements.

Electromagnetic (VLF) ***anomalies*** are proportional to the contrast in electric resistivity and the (near-surface) volume of conductive material.

Fault zones can thus be identified by both magnetic and electromagnetic methods directly, and indirectly from their distortion of marker structures. In addition, data on terrain morphology, such as elevation data and radar data, reflect the occurrence of fault scarps/lineaments.

Similarly, ***impact crater structures*** result in gravity, magnetic and electromagnetic anomalies, which can be modelled once the physical property contrasts of the rocks have been constrained by measurements.

The Björkö structure

Björkö is located in the eastern part of Lake Mälaren, and its anomalous character is related to the occurrence of non-metamorphosed sandstone of supposed Jotnian age (Gorbatschev & Kint 1961). In Flodén et al. (1993), the structure was suggested to be caused by a meteorite impact. The structure is ca 10 km in diameter, with a centrally located hill c. 2 km in diameter. Based on seismic mapping, the sandstone was found to encircle the central rise in a ca 170° sector to the southeast of it, with an estimated thickness varying between 40 and 280 m based on refraction seismic interpretations. Drilling on the island of Midsommar, however, revealed a sandstone thickness of over 900 m. The erosion level of the structure is unknown and its age is estimated to about 1.2 Ga based on K-Ar data from a claystone bed immediately above the granitic basement (Flodén et al. 1993). The structure is also tilted down to the southeast. Most of it is covered with water except for the central portion, some islands within the ring, and parts of the edge. The nature of the target at the time of impact is unknown – some sandstone may already have existed. To the south, the crystalline basement is dominated by gneissic rocks (paragneisses and gneissose granites-tonalites) with distinct E-W strike and steep dip. To the north, these rocks are intruded by younger granites (Stockholmgranite) and have a more irregular orientation of their foliation. An ENE-WSW- striking dyke with magnetic signature can be seen cutting through the northern part of the Björkö structure. It is offset in several segments within the structure, and provides a useful marker feature for structural modelling. Inspection of thin-sections from the central rise region reveal numerous imprints that are typical for impact-exposed rocks, like sets of planar deformation features in quartz, kink banding in biotite and feldspars, and a general fragmented appearance on a crystal scale. Similar features were found in sediment clasts overlying the fractured basement. These have therefore been interpreted as re-deposited ejecta.

The entire central part of the structure is intensely fractured on the cm scale. This brecciation is also observed at several localities near the edge of the structure. In the central rise, VLF-R data indicate abundant low resistivity down to a depth of a few hundred metres. VES measurements indicate similar properties down to ca 600 m depth, and MT measurements indicate decreased electric resitivity down to a depth of c. 7 km.

Geothermal energy and the energy situation in Sweden

On a small scale, geothermal energy is frequently used for heating of single family houses in many places in Sweden. On a medium scale, only one production facility is operating. This is located in Lund in southern Sweden and is based on the exploitation of warm water at moderate depth. The heat exchange volume is a sandstone formation at c. 1 km depth. The geothermal gradient in crystalline rocks is c. 15 K km^{-1},

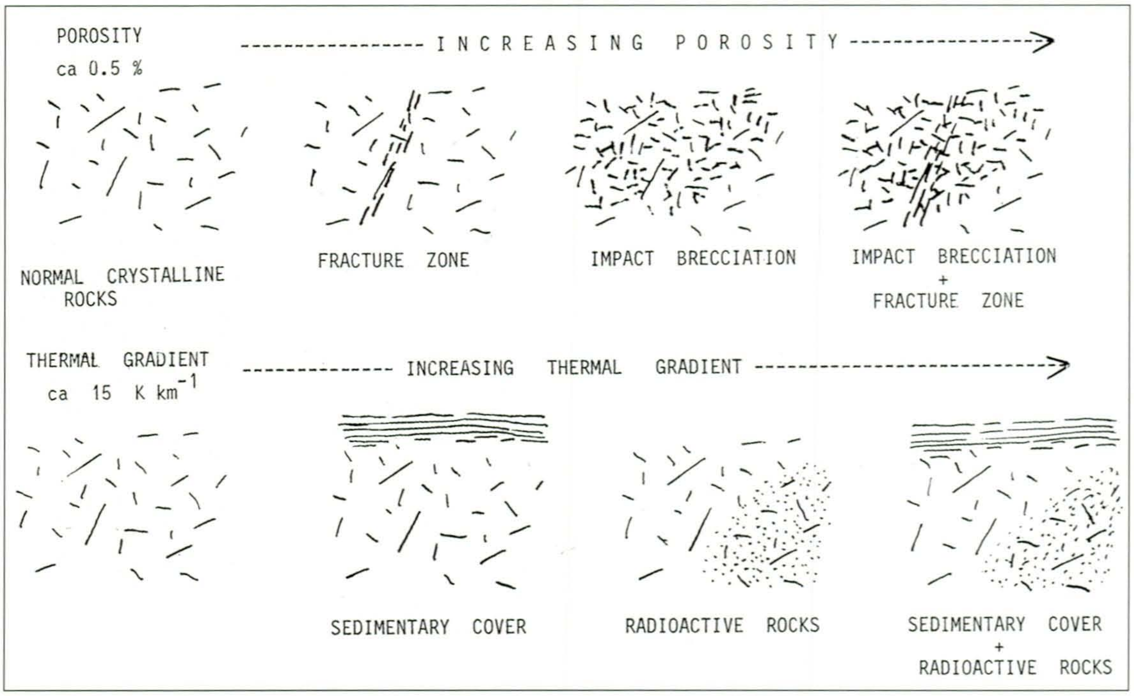

Fig. 5. Cartoon showing the important features representing the potential for geothermal energy in crystalline rocks. The geothermal gradient across sedimentary cover rocks depends on their thermal conductivity. The cited normal geothermal gradient of 15 K km-1 was obtained from the deep drilling at Siljan (Juhlin 1991).

known from the deep drilling at Siljan. There are no anomalous thermal structures known in the Baltic Shield, and therefore geothermal energy has for long been disregarded as an important energy resource. The climatic situation in Sweden causes a large demand for energy for heating during more than 6 months of the year. This demand has been covered by electric energy, oil and gas combustion, and to a lesser extent by the burning of waste and biomass. In many places, a large-scale energy infrastructure with district heating has been established.

Presently, the political decisions to reduce and phase out nuclear power and to reduce CO_2 emissions are not viable as no sufficiently large-scale alternatives have been developed. Geothermal low-temperature energy, however, is present everywhere and would be an obvious resource if an efficient heat exchange structure could be found or created at depth in the crystalline basement. It should also be located close to an existing energy infrastructure.

The extraction of geothermal energy in ordinary crystalline rocks has been tested at Fjällbacka (Wallroth et al. 1999), and included hydraulic fracturing in order to create a heat exchange volume at depth. The exchange efficiency, however, could not be brought to acceptable levels and the project was not developed further. It therefore seems necessary to find already brecciated rock volumes at depth and to explore or increase their hydraulic conductivity. In essence, two such types of structure can be envisaged: ***Fracture zones***, with an essentially planar extent of fractured rock, or ***impact craters***, with an assumed, essentially hemispherical extent of the fractured rock. Geothermal energy prospecting should therefore aim at mapping the extent of brecciation of such structures and to estimate their potential as heat exchange volumes. In addition to the fracturing, which eventually may provide a sufficiently efficient heat exchange volume, the actual geothermal gradient, the radiogenic heat production, and the effect of a shielding cover rock sequence are important factors for the evaluation of the potential for geothermal energy in crystalline environments (Fig. 5).

The Björkö energy project

With this background, the idea was formulated to test the Björkö structure for its potential as a heat exchange volume for geothermal energy retrieval. An application was forwarded to the Swedish National Energy Administration by a research team from the Royal Institute of Technology and the Stockholm University. The project explicitly aims at developing tools for energy prospecting by integrated analysis of relevant surface data and their calibration by drilling. The most important aspect to start with is to find the local relationship between electrical properties and porosity down to several kilometres depth.

The geothermal energy potential of the 10 km-diameter Björkö structure is dramatic. The porosity variation as estimated from electric resistivity data is 0.5 – 4.5 % and the

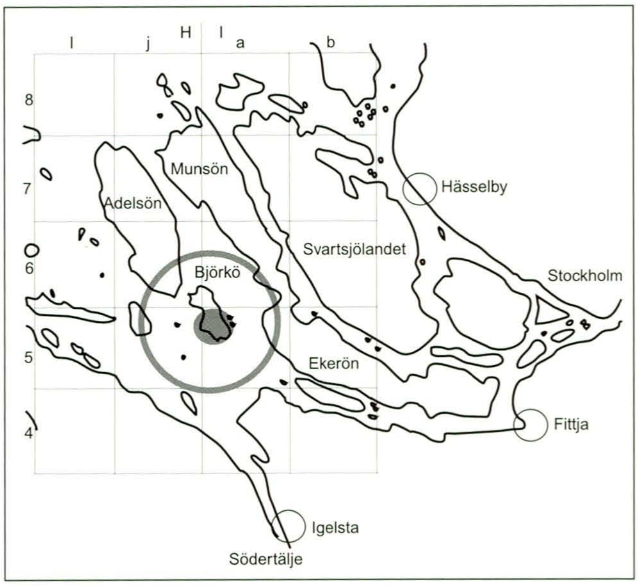

Fig. 6. Location of the Björkö structure in relation to the existing energy infrastructure in the Stockholm region. The approximate edge of the Björkö structure (circle) and its c. 2 km-diameter central uplift are marked. The three small rings NW, S and SW of Stockholm mark the locations of major district heating plants. The study area is west of Stockholm within the coordinate frame with markers every 5 km.

brecciated volume may exceed 250 km^3. Assuming a 1% difference in porosity in a hemispherical volume with 5 km radius and a temperature difference of 40° C, the energy content of the structure is over 4 000 TWh, more than 10 times the annual energy use in Sweden. The structure also lies within the realms of the district heating systems of the Stockholm region (Fig. 6) and its energy potential could cover 70 % of the energy demand for heating on a long-term basis.

In the following, brief descriptions are given of the ongoing activities.

Compilation of existing data and complementary measurements are performed within a 20 km-diameter region around the Björkö structure. These include: *airborne geophysics* (magnetic total intensity, VLF, and gamma radiation), data about the *terrain shape* (elevation and bathymetric data, to form a 50 grid), *gravity* measurements and *petrophysical* measurements on rock samples from outcrops and drillcores (density, magnetic susceptibility, remanent magnetization, electric conductivity).

Measurements of new data, especially on the electrical properties of rocks and rock volumes. These include: VLF-R measurements to estimate the near-surface electric resistivity variation, MT measurements for mapping of the electric resistivity at depth, fracture frequency studies in type regions (central part, ring – edge and exterior) to provide a basis for the correlation between electrical and fracture properties.

Drilling of 2 or 3 drillholes down to markers observed in MT measurements and accompanying tests. These include: chemical analysis of the water in drillholes, estimation of the hydraulic conductivity around drillholes, measurement of the local geothermal gradient and the components of the stress field.

Modelling of the collected data to provide information on the thermal and hydraulic potential of the structure. This includes: estimation of the radiogenic heat production, modelling of gravity, magnetic VES, MT and fracture frequency data.

The expected results of this energy prospecting project are to describe the Björkö structure in 3-d, estimate its potential for geothermal energy retrieval, identify possible relationships between surface data and hydraulic properties at depth, and suggest further approaches to verify the obtained modelling results.

Conclusions

Geothermal energy resources must be a target for renewed research, even in regions with low geothermal gradient. This is motivated by two factors: the need for heating at high latitudes and the local nature of this energy resource (apart from the political goals to reduce both CO_2 emissions and the use of nuclear energy).

Meteorite impact structures are suggested to be suitable targets for geothermal energy studies as they may provide a very large volume of fractured rock in comparison to fracture zones.

The physical property that is most likely a key factor in mapping the extent of fracturing at depth is the electric resistivity, and therefore efforts are directed towards establishing and modelling the relations between the volume fracture frequency and the electrical properties that are measurable from the surface.

The physical condition that is necessary in order to establish a heat exchange system at depth is the hydraulic conductivity that can be created and maintained with artificial methods. How large volumes of fractured rock react involves issues that demand further experiments and research.

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