Heiko T. Liebel

Influence of Groundwater on Measurements of Thermal Properties in Fractured Aquifers

Thesis for the degree of Philosophiae Doctor

Trondheim, April 2012

Norwegian University of Science and Technology
Faculty of Engineering Science and Technology
Department of Geology and Mineral Resources Engineering

NTNU – Trondheim
Norwegian University of Science and Technology

NTNU
Norwegian University of Science and Technology

Thesis for the degree of Philosophiae Doctor

Faculty of Engineering Science and Technology
Department of Geology and Mineral Resources Engineering

ISBN 978-82-471-3505-1 (printed ver.)
ISBN 978-82-471-3507-5 (electronic ver.)
ISSN 1503-8181

Doctoral theses at NTNU, 2012:113

Printed by NTNU-trykk

For my mother

Abstract

Shallow boreholes equipped with borehole heat exchangers (BHE) connected to ground-coupled heat pumps are used for the heating and cooling of buildings. Accurate estimates of ground properties are essential to properly dimension a ground-coupled heat pump system. For small projects, the ground properties are assumed for different rock types. In large projects, thermal response tests (TRT) are carried out to estimate the actual properties.

Convection and groundwater flow affect the TRT results and the operation of a ground-coupled heat pump system. This thesis investigates the influence of groundwater on measurements of thermal properties such as effective (*in situ*) thermal conductivity (λ_{eff}) and borehole resistance (R_b) in fractured aquifers.

A statistical analysis for selected rock types shows that λ_{eff} is in general higher than rock thermal conductivities measured from rock cores (λ_{rock}). Databases of λ_{eff} and λ_{rock}, hydraulic yield of wells, and driller's well protocols from the Oslo region are used to test if λ_{eff} can be predicted. It is shown that λ_{eff} cannot be predicted accurately: Heterogeneities in rock mineral content, rock types along a borehole, regional groundwater flow and convection due to different heat input rates during TRTs are too large. It is documented that a high thermal conductivity is not necessarily linked to a high quartz content, but rather to the orientation of insulating layers of low conductive materials. Thermal conductivity estimates based on λ_{rock} from mapped bedrock types can give only a vague indication about the thermal conductivity one may find at a site.

The influence of groundwater on λ_{eff} was investigated in a field experiment. Two TRTs were carried out in the same borehole: A first standard TRT and a second TRT with artificially induced groundwater flow. Temperature profiles after both TRTs showed groundwater flow in a few fractures only. The measured λ_{eff} was higher for the case of groundwater flow. The influence of groundwater flow cannot be discovered from the measured λ_{eff} itself if the flow is restricted to limited areas of the borehole. But temperature profiles taken a few hours after a finished TRT allow a proper interpretation of the TRT results.

A multi-injection-rate TRT (MIR-TRT) showed that the measured thermal properties changed with increasing heat input rate. The required borehole length for a ground-coupled heat pump system would be reduced as buoyancy-driven convection increases in the borehole. A second MIR-TRT was carried out with a groundwater pump installed at the base of the same borehole. Groundwater was pumped up to the surface and re-infiltrated into the borehole. The estimate for required borehole lengths was reduced by 9 to 25 % in comparison to the preceding MIR-TRT. Consequently, artificial convection may be used to reduce the required borehole length of a ground-coupled heat pump system.

Keywords: Thermal response test, thermal conductivity, groundwater flow, convection, quartz content, hard rock, ground-coupled heat pump.

Acknowledgements

I want to thank my supervisors Bjørge Brattli (NTNU), Randi K. Ramstad (AsplanViak) and Bjørn S. Frengstad (NGU) for constructive advice during all phases of this PhD. I am grateful for the instructive cooperation with Saqib Javed (Chalmers University of Technology). I am thankful to the Department of Geology and Mineral Resources Engineering and to the Faculty of Engineering Science and Technology at NTNU for giving me financial support.

I appreciated very much the instructive scientific input of my mentor and friend Allan Krill (NTNU). During field work I got very good support from the diploma student Kilian Huber (University of Bayreuth, Germany) and master students Marie Sigmundsdatter Stølen and Gunnar Vistnes (both NTNU, Norway). Together, we solved the problems during the experiments where I would have capitulated if I had been alone.

I am grateful to Bjørn Borgnes (Futurum Energi AS), Kirsti Midttømme (Norwegian Geotechnical Institute, NGI) and Gaute Storrø (NGU) to introduce me to the TRT trailer. Båsum Boring AS, and specifically John Ihlen, provided energy wells in the Oslo region for thermal response testing. Geoenergi AS, NGU, NGI and Futurum Energi AS contributed to this PhD by making data available from earlier TRTs. Gether AS involved me in their energy optimization project at Mære agricultural school and gave financial support which is gratefully acknowledged. I am thankful to the permanent support for field equipment from NGU. Bjørn Willemoes-Wissing (NGU) taught me the technique to measure rock core thermal conductivity. Helge Skarphagen (Gether AS) helped in the field in Bryn and Mære. Frode Haukland (SINTEF, Department of Acoustics) loaned us an accelerometer and helped with the analysis of vibration data. I want to thank my colleagues for giving a good atmosphere at work.

I like to thank my true and loyal friends in Germany (Michi and Susi Weiler, Arnbjörn Rudolph and Christine Pechmann, Michael Sperlein, Christoph and Dini Held, Lukas Gudmundsson and Jan-Peter Daniels). All of you stayed permanently in contact with me and supported me also during difficult periods.

I am grateful to my new friends Cecilie Miljeteig, James Speed, Jane J. Meiforth and Ivonne Teurlings for sharing their freetime with me. We had many joyful times together.

I am thankful to my parents, Iris and Hermann, and brothers, Andreas and Christian, for their support and to accept me leaving home to study in a foreign country.

My wife Rossana Segreto gave me motivation to accomplish this doctoral thesis and supported me throughout the four years with all her love. Our daughter Annika (11.11.11) is the new sunshine in our family.

Symbols and Abbreviations

Latin letters

C_p	specific heat capacity	[J kg^{-1} K^{-1}]
D	diameter	[m]
E	power	[W]
f	friction factor	[-]
k	constant (slope)	[K]
L	length of borehole heat exchanger	[m]
m	constant (axis intercept)	[K]
P	pressure	[Pa]
q	heat exchange rate	[W m^{-1}]
R^2	coefficient of determination	[-]
R_b	thermal borehole resistance	[m K W^{-1}]
r_b	borehole radius	[m]
Re	Reynold's number	[-]
S_{VC}	volumetric heat capacity	[W m^{-3} K^{-1}]
T	temperature	[K]
t	time	[hr] or [s]
u_m	mean fluid velocity	[m s^{-1}]
V	flow rate of heat-carrier fluid	[m^3 s^{-1}]

Greek letters

a	thermal diffusivity	[m^2 s^{-1}]
η	efficiency factor	[-]
λ	thermal conductivity	[W m^{-1} K^{-1}]
μ	dynamic viscosity	[kg m^{-1} s^{-1}]
ρ	density	[kg m^{-3}]

Subscripts

0	initial
b	borehole
eff	effective
f	fluid
Geomap	geological map
gw	groundwater
in	inlet
out	outlet
pump	pump
ref	reference
th	thermal

Abbreviations

asl	above sea-level
DTA	Differential Thermal Analysis
GRANADA	National groundwater database of Norway
HVAC	Heating, Cooling, Ventilation, Air-Condition
IEA	International Energy Agency
IGSHPA	International Ground Source Heat Pump Association
ILS	Infinite Line-Source
MIR-TRT	Multi-Injection-Rate Thermal Response Test
NGI	Norwegian Geotechnical Institute
NGU	Geological Survey of Norway
NOK	Norwegian krone (currency)
NTNU	Norwegian University of Science and Technology
PhD	Philosophiae Doctor
SINTEF	Foundation for industrial and technical research
TRT	Thermal Response Test
XRD	X-ray Diffraction

Contents

Section of Original Papers

Paper 1: H.T. Liebel, K. Huber, B.S. Frengstad, R. Kalskin Ramstad, B. Brattli (2010): Rock core samples cannot replace thermal response tests - A statistical comparison based on thermal conductivity data from the Oslo Region (Norway). Proceedings of "Renewable Energy Research Conference", 7th – 8th June 2010, Trondheim, Norway, pp. 10.

Paper 2: H.T. Liebel, K. Huber, B.S. Frengstad, R.K. Ramstad, B. Brattli (2010): Can rock core thermal conductivity data replace thermal response tests? Proceedings of Water and Energy Conference 2010, Amsterdam, Netherlands, pp. 8.

Paper 3: H.T. Liebel, J. de Beer, B.S. Frengstad, R.K. Ramstad, B. Brattli (2012): Effect of water yield and rock thermal conductivities on TRT results. Accepted at Communicações Geológicas, pp. 7.

Paper 4: H.T. Liebel, M.S. Stølen, B.S. Frengstad, R.K. Ramstad, B. Brattli (2011): Insights into the reliability of different thermal conductivity measurement techniques: a thermo-geological study in Mære (Norway). Bulletin of Engineering Geology and the Environment, DOI 10.1007/s10064-011-0394-3; pp. 9.

Paper 5: H.T. Liebel, K. Huber, B.S. Frengstad, R.K. Ramstad, B. Brattli (2012): Thermal response testing of a fractured hard rock aquifer with and without induced groundwater flow. Bulletin of Engineering Geology and the Environment, DOI 10.1007/s10064-012-0422-y; pp. 11.

Paper 6: H.T. Liebel, K. Huber, B.S. Frengstad, R.K. Ramstad, B. Brattli (2011): Temperature footprint of a thermal response test can help to reveal thermogeological information. Norges geologiske undersøkelse Bulletin 451: 20-31.

Paper 7: H.T. Liebel, S. Javed, G. Vistnes (2012): MIR-TRT with forced convection in a groundwater-filled borehole in hard rock. Accepted at Renewable Energy (Elsevier).

Appendices

1. Introduction

1.1. Motivation

The understanding and use of geoecological linkages between the different spheres on Earth will be essential for the future survival of humanity. Every individual sphere – the atmosphere, biosphere, pedosphere, hydrosphere, lithosphere – is linked to all other spheres in a fragile equilibrium. It is necessary for humans to maintain an ecosystem functioning to be able to use the ”ecosystem services” in a sustainable way. Ecosystem services are for example natural resources like food crops, oil and gas but they contain also processes that provide such things as clean drinking water to humans.

Humans realize more and more that resources are limited and that ecosystems are vulnerable to human activities. The legislation of many countries has started to implement sustainable strategies concerning the use of renewable energy, mostly as a result of the ongoing debate on climate change due to CO_2 emissions (e.g. ”The Renewable Energies Heat Act”, which came into effect in Germany in 2009). The result is a commercialisation of technologies to use renewable energy resources.

The so-called “Stern review”, published in 2006, was the first report focussing on the effect of global warming on the world economy. Among other things, it shows the relative greenhouse gas emissions per sector. The heating and cooling of buildings accounts for 8 % of the total greenhouse gas emissions, or possibly even 20 % if upstream emissions associated with electricity and heat are included (Stern, 2006, see Figure 1.1). Worldwide, the amount of direct and indirect emissions from this sector grew by 75 % in the period 1970 – 1990 (Metz et al., 2007).

Low-temperature geothermal energy applications, also called shallow geothermal energy or ground-coupled heat pump systems, are considered one of the key technologies to reduce greenhouse gas emissions in the buildings sector (Sims et al., 2007). ”The Directive on the Energy Performance of Buildings” of the

European Union has become an important driving force for research and new developments in renewable energy techniques.

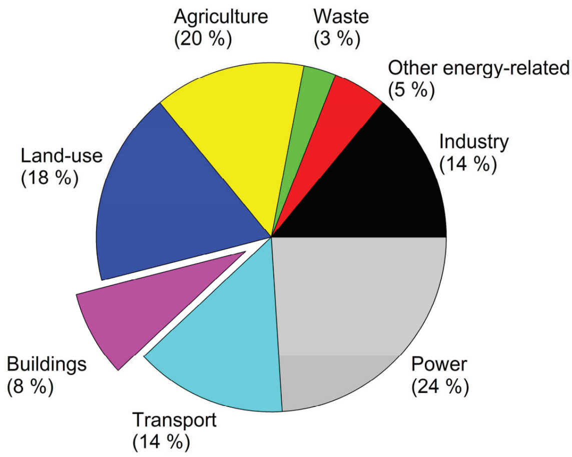


Figure 1.1 Relative greenhouse gas emissions in the year 2000 by source (Stern, 2006 mod.).

One main advantage of a ground-coupled heat pump system is that it is an on-site renewable energy supply system (Norges forskningsråd, 2008). For space heating and cooling, a trend to a regionalisation can be observed where the energy demand is covered almost completely by the ”low-energy building” or ”passive house”. In such buildings, solar panels and wind mills can be installed to produce electricity that may be used to run, for example, a ground-coupled heat pump.

The number of ground-coupled heat pumps in Europe continuously increased until 2008 with Sweden, Germany and France being the countries with most installed units (in 2008: Sweden: 320 689 units, 2 909 MW_{th} capacity; Germany: 150 263 units, 1 653 MW_{th} capacity; France: 121 866 units, 1 341 MW_{th} capacity) according to EurObserv’ER (2009). The fastest growing market in the European Union is Germany with an increase in installed ground-coupled heat pump units of 28 % in 2008 compared to 2007. Sweden, however, is the market with the smallest growth rate in Europe due to a saturating market (40 % of the European Union's ground-coupled heat pumps are installed in Sweden). Norway has approximately 26 000 ground-coupled heat pumps installed (Midttømme, 2010, pers. comm.), which is enough to let Norway be part of the ”top five” countries for installed capacity per population (Lund et al., 2010). The public awareness of the technology is increasing (Hay, 2009) and the potential for the use of ground-stored heat in Norway is large. Ramstad (2011) concludes that the total heating and cooling load could be covered with the help of ground-coupled heat pump systems. Such systems would reduce the electricity demand for heating and cooling by 70 %. The markets of ground-coupled heat pumps have been developing mostly in regions with polar or temperate climate but numbers of installed units are increasing also in southern European countries with Mediterranean climate. Urchueguía and colleagues (2008) show that ground-coupled heat pumps are more efficient than the conventional air-to-water heat pump system also in a warm, cooling-dominated climate.

The story of ground-coupled heat pumps is not an absolute success. There have appeared some issues:

- Thermal ”pollution” in the ground (unnatural ground temperatures)
- Leakage of heat carrier fluids from borehole heat exchangers
- Hydraulic short-circuiting between different aquifers
- Uncontrolled outflow of groundwater through the borehole from artesian aquifers (Sanner, 2011)
- Hydrogeological problems when dehydrated evaporates get in contact with groundwater through energy wells (e.g. Staufen, Germany, see also Goldscheider and Bechtel, 2009).

These problems have been discussed by the media, and especially the case of Staufen made customers in Germany insecure regarding ground-coupled heat pumps as a good choice for heating and cooling of buildings (e.g. Lubbadeh, 2008; Haimann, 2010; Kempf, 2011).

Nevertheless, most of the mentioned problems are preventable through detailed site investigations and installation procedures. Ground-coupled heat pump technology is still an important step towards a sustainable way of life in the future, when environmental aspects are taken into account. For this reason, this research field is motivating to work with.

1.2. General background

Geothermal energy is defined as ”(...) energy stored in form of heat beneath the surface of solid earth” (EU Directive 2009/28/EC on Promotion of Renewable Energy Sources, Art. 2). Shallow geothermal energy deals with temperatures in the range of the mean annual surface temperatures at a given place. The heat used for ground-coupled heat pump systems has two sources, the sun and the earth. A geothermal heat flux from the ground towards the surface opposes heat fluxes in the opposite direction from insolation. The sun is the major heat source for the renewal of heat in shallow depth down to 300 m according to Banks (2008, see Figure 1.2).

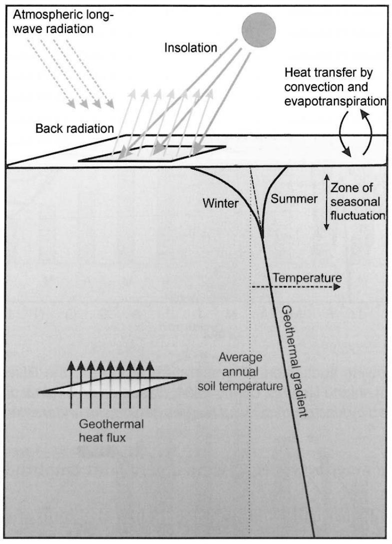


Figure 1.2 Schematic presentation of heat fluxes and temperatures at the ground and atmosphere (Banks, 2008 mod.).

Still, Schiermeier et al. (2008, p. 820) conclude in Nature magazine in their article about the potential of geothermal energy that ”(...) small geothermal heat pumps that warm houses and businesses directly may represent the greatest contribution that Earth’s warmth can make to the world’s energy budget”. This stresses the large potential of ground-coupled heat pump technology in comparison to high-temperature geothermal applications in a global perspective.
The most common type of low temperature geothermal heat applications for space-heating and cooling in Europe is the closed-loop borehole heat exchanger system. Shallow boreholes (< 400 m; Rybach and Sanner, 2000) are drilled for this purpose in different kinds of rocks or unconsolidated sediments. Collector pipes, U-shaped (single or double) or coaxial, are installed in the boreholes and connected to a ground-coupled heat pump, which helps heat to flow from a low-temperature environment to a high-temperature one. To exchange heat with the ground, a heat carrier fluid (often anti-freeze mixtures with ethanole, methanole and glycoles) is pumped through the borehole heat exchangers with the help of a circulation pump (Figure 1.3).

Figure 1.3 Circulation pumps for borehole heat exchangers (left) and ground-coupled heat pump at Nardo school (Trondheim, Norway).

The heat carrier fluid enters the ground-coupled heat pump and delivers heat or cold depending on the mode. A ground-coupled heat pump can easily be switched into reverse, from heating to cooling mode, so that heat from the inside of a building is pumped away to the borehole. This is more efficient than air-to-air or air-to-water heat pumps in warm weather (Banks, 2008; Urchueguía et al., 2008). This type of closed-loop system with a ground-coupled heat pump is widely used in Scandinavia for heating and cooling of single households with one single or a few non-grouted, water-filled boreholes. Large, mostly commercial or public buildings require more boreholes to meet the demands for heating and cooling (Figure 1.4). Free cooling can be used in some cases. In this case the heat-carrier fluid circulates through the ventilation or cooling devices of the building without any heat pump involved.

Figure 1.4 Borehole heat exchangers entering the HVAC (Heating, Ventilation, Air-Condition) centre at Nardo school (Trondheim), 14 boreholes.

The first ground-coupled heat pump using direct expansion in the borehole was installed in 1945 (Indianapolis, USA), while the first borehole heat exchanger with a heat carrier fluid (standard today) in Europe was installed in Germany in 1974 (pers. comm. B. Sanner, 2011). Since then, the numbers of installed ground-coupled heat pumps have increased more or less steadily in several European countries (see also Eugster and Sanner, 2007). The recent market for ground-coupled heat pump systems is still immature in Europe with the exception of Sweden where a stagnation in the number of new installed ground-coupled heat pumps is observed due to market saturation (pers. comm. G. Hellström, 2011). In Sweden, houses traditionally use hot-water heating based on the combustion of oil. The conventional hot-water system can easily be changed into an innovative ground-coupled heat pump system which is one reason for the appeal of the technology in Sweden. In Norway, however, electrical radiators are commonly used for the heating of buildings. A change to ground-coupled heat pump technology is expensive in old Norwegian buildings. New buildings however, are often equipped with ground-coupled heat pump systems for both heating and cooling of buildings. The number of installed units may increase significantly also in Norway in the near future (Ramstad, 2011).

For the estimation of the required borehole length to deliver a certain amount of heating and cooling power, and energy to a building, some ground parameters should be known. If, for example, the thermal conductivity for a certain rock type is assumed and not certain, some extra meters of borehole are usually drilled to avoid underdimensioning the ground-coupled heat pump system. Another possibility is to perform a thermal response test (TRT) in a test well to measure the *in situ* thermal conductivity and thermal borehole resistance (Austin, 1998; Gehlin, 1998) and then drill the required boreholes depending on the measured value. Thermal response tests are often performed for large ground-coupled heat pump projects. The mathematical standard evaluation is based on the line-source theory (Ingersoll et al., 1948) and is closely related to the standard evaluation techniques of hydrogeological pumping tests (Raymond et al., 2011). The Theis equation, for example, is based on the line-source theory for heat transfer as well (Theis, 1935). TRT procedures have been continuously improved as tests with heat injection and extraction were introduced (Witte, 2001, Witte and van Gelder, 2006) to find the most accurate estimates for the ground parameters. New analytical (see e.g. Philippe et al., 2009) and numerical evaluation techniques (e.g. Shonder and Beck, 1999; Austin et al., 2000; Hellström, 2001) are introduced. One disadvantage, however, is that a TRT is a costly procedure (ca. 90 000 NOK which is equivalent to 150 m to 450 m of drilled borehole inclusive borehole heat exchanger installation, depending on the bedrock and the sedimentary cover). Alternatively, thermal conductivity data from rock cores may be used in planning and for the dimensioning of large ground-coupled heat pump installations, if these data are available.

Groundwater flow, through and in the vicinity of energy wells, has been shown in practice and in computer simulations to influence the measured effective thermal conductivity as heat or cold is transported away from the borehole using the water as heat-carrier (e.g. Claesson and Hellström, 2000; Witte, 2002; Gehlin and Hellström, 2003; Fan et al., 2007; Wang et al., 2009). In Scandinavia, boreholes in hard rock are normally non-grouted so that groundwater, filling the borehole, alters the thermal properties of the borehole further. In non-grouted water-filled boreholes used for borehole heat exchangers under operation conditions, the effective thermal conductivity can increase 3 to 10 times if the groundwater moves in the borehole due to natural convection (pers. comm. G. Hellström, 2011; thermal conductivity of stagnant water is 0.6 W $m^{-1}K^{-1}$). Related important phenomena during TRTs like thermosiphon effect (i.e. inflow of cold groundwater at a fracture at the base and outflow of warm water at a fracture at the top of the borehole; Gehlin et al., 2003), groundwater flow through open fractures (Gehlin and Hellström, 2003) and density-driven convection inside the borehole (Gustafsson et al., 2010) have been explained and visualized mostly with the help of computer simulations. Experimental data, however, that show the influence of groundwater on TRTs and indirectly on borehole heat exchangers during operation is still scarce, especially for hard rock aquifers.

1.3. Research objectives and hypotheses

The overall research objective of this doctoral thesis is to investigate the influence of groundwater on the determination of thermal properties, in particular, thermal conductivity *via* TRTs in Norwegian crystalline bedrock aquifers. In this context, groundwater plays an important role in two ways:

a) through heat transport with groundwater flow through open fractures.

b) through convective heat transport in the free groundwater column in the energy well (applies to non-grouted boreholes).

In both ways TRT results are altered. To analyze the qualitative and quantitative influence of groundwater on TRT results, four main hypotheses are formulated and tested scientifically:

I.) *Groundwater flow in fractured aquifers has a significant influence on TRTs.*

II.) *Effective thermal conductivities are higher than lab-measured thermal conductivities due to groundwater flow and convection in the borehole.*

III.) *Free convection of water in the borehole during TRTs alters the measured effective thermal conductivity and borehole resistance.*

IV.) *Forced convection induced with a groundwater pump increases the efficiency of a ground-coupled heat pump system.*

By testing these hypotheses, conclusions can be drawn that lead to recommendations on how groundwater should be accounted for in the planning of ground-coupled heat pump projects where non-grouted boreholes are used.

2. Material and Methods

2.1. Study sites

An overview of the study sites is given in Figure 2.1.

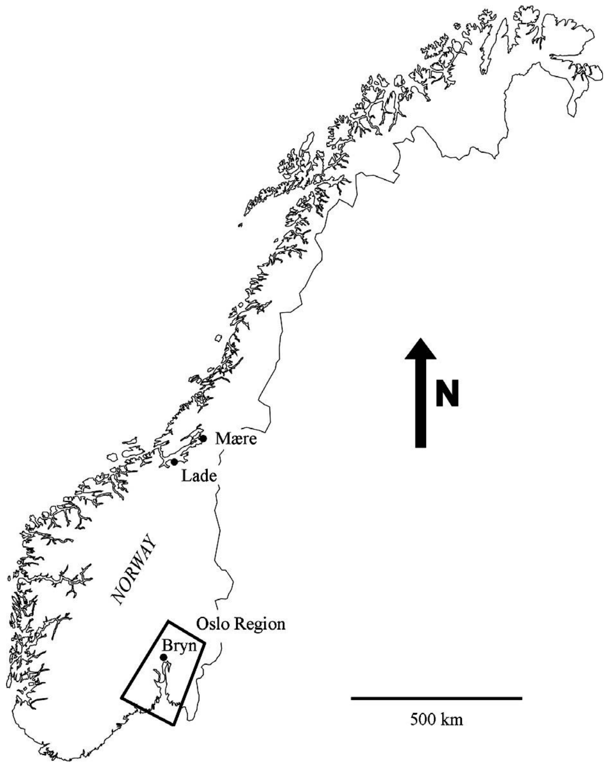


Figure 2.1 Overview of study sites in Norway.

Hypothesis I was tested in a well field consisting of five wells at Bryn (Bærum municipality; UTM: 32 583649E, 6643494N; 60 m asl; see also Figure 2.2) and in a single test well at Mære (Steinkjer municipality; UTM: 32 617243E, 7092403N; 32 m asl).

Figure 2.2 Preparations for the TRT with pumping of groundwater at Bryn.

Hypothesis II was tested with the help of data from 59 TRTs in the Oslo region performed by NGU, NGI and Geoenergi AS. In addition, 7 own TRT measurements were carried out to get a statistically interpretable dataset for some geological units (see Figure 2.3). While the Oslo region is marked only in general on Figure 2.1, the accurate coordinates of the test boreholes can be found in Appendix B. Additional information is given there about surface rock core and *in situ* thermal conductivities, geology and thermal borehole resistances.

Figure 2.3 TRT at Fredrikstad.

Hypotheses III and IV were tested in a research borehole of NGU at Lade (Trondheim municipality; UTM: 32 572044E, 7027070N; 25 m asl; see Figure 2.4).

Figure 2.4 Borehole at Lade equipped with borehole heat exchanger (single U) and tube and electricity cable for the groundwater pump installed at the bottom of the borehole.

All study sites are characterized by fractured hard rocks that are covered with a thin layer of unconsolidated sediments. The boreholes at Lade and Bryn are pure research boreholes while all other boreholes of this study were used for scientific data collection and TRTs before being connected to the ground-coupled heat pumps utilized in commercial or residential buildings. Detailed information about the single study sites is given in the papers.

2.2. Thermal conductivity measurements from rock cores

Surface rock cores from 1398 sample locations within the area of the bedrock map of the Oslo region (based on Lutro and Nordgulen, 2004) were drilled and analyzed for their thermal conductivity by the Geological Survey of Norway. Ramstad et al. (2008a) presented these data as a map showing the thermal conductivity of the different geological units of the Oslo region. 24 out of 50 geological units are represented by 10 to 219 sample locations, and a median thermal conductivity value was calculated for these units. To get a complete map sheet, the thermal conductivity value for the remaining 26 geological units are based on values of geological units with similar mineral composition.

The laboratory procedure to estimate the thermal conductivity of a rock core follows Middleton's approach (1993) where a constant heat source (144 or 300 °C) is applied a few millimeters above the vertically positioned rock core sample at room temperature. The temperature increase at the base of the rock core is measured. From the measurement of the thermal diffusivity (α) of the sample, the thermal conductivity (λ) is calculated according to equation 1.

$$\lambda = \rho C_p \alpha \tag{1}$$

where

λ: Thermal conductivity [W $m^{-1}K^{-1}$]

ρ: Density [kg m^{-3}]

C_p: Specific heat capacity [J $kg^{-1}K^{-1}$]

α: Thermal diffusivity [m^2 s^{-1}]

A detailed description of the method development and quality control routines of the thermal conductivity measurement at the laboratory at the Geological Survey of Norway is given in Ramstad et al. (2008b). The advantage of using this database is that the lab procedure and sampling is well documented and identical for all entries of the database.

One drawback of the method is that fractures and fissures in the rocks are filled with water at the location but they are dry in the lab. Air has a lower thermal conductivity than water so that *in situ* measurements in water-saturated conditions are expected to lead to slightly higher thermal conductivity values

(Ericsson, 1985). Clauser and Huenges (1995, p. 114) report of an increase in measured thermal conductivity with an increase in water saturation from dry to completely water-saturated of around 8 % for a granite with low porosity (1%). Midttømme et al. (2000) conclude that the water saturation is responsible for not more than 10 % increase in rock thermal conductivity for samples from the Oslo region. Further, a strong anisotropic thermal behaviour of some rocks has been shown by among others Clauser and Huenges (1995) and Midttømme et al. (2000; 2004) where the thermal conductivity is high parallel to the foliation and low perpendicular to the foliation. The direction of foliation, however, may vary strongly in folded rocks within the same geological unit. This variation will give varying thermal conductivity values.

One final limitation of the dataset is that only surface bedrock cores are taken into account while several rock types may occur vertically along a borehole used for a ground-coupled heat pump installation. Midttømme et al. (2004) claim however that the variations are small in the main stratigraphy to a depth of 300 m in the study area.

For the study site of Mære, rock cores were drilled from 8 boulders and analyzed for the thermal conductivity. The rock cores were drilled normal and parallel to the foliation direction.

2.3. Thermal conductivity from TRTs

Thermal response tests are often applied in Scandinavia to test the *in situ* or effective thermal conductivity in a borehole which integrates over the thermal conductivity of the bedrock, of the water in the borehole (inclusive effects of convection and from groundwater flow) and the borehole equipment.

For this purpose the TRT equipment is connected to the collector pipes of the energy well. Heating elements in a portable TRT rig warm up the heat-carrier fluid that is circulating through the closed-loop system. The connection between the TRT device and the borehole has to be well insulated, to avoid heat loss in cold weather or heat gain through sun irradiation. The circulation pump creates a turbulent flow in the pipes to get best heat transport from the collector towards the ground.

The undisturbed ground temperature (measured before the TRT) and the temperature increase in the heat-carrier fluid during a test run are used to calculate the effective thermal conductivity of the ground (λ_{eff}) and the borehole resistance (R_b). The thermal borehole resistance depends on the thermal properties of the borehole elements including the collector, grouting and the physical arrangement of the collector in the borehole (Javed, 2010). The calculation of λ_{eff} and R_b follows the suggestions of Gehlin (2002) and Signorelli et al. (2007), which are based on the infinite line-source theory (Ingersoll et al., 1948). The line-source model is based on a linear relationship between the average heat carrier fluid in the collector and the natural logarithm of the time t, if the heat exchange rate per length unit, q, is constant (q is constant if the electric power supply to the heating elements is constant):

$$T_f(t) = k \ln(t) + m \qquad [\mathrm{K}] \qquad (2)$$

where

$$k = \frac{q}{4\pi\lambda} \qquad [\mathrm{K}] \qquad (3)$$

and

$$m = q\left[R_b + \frac{1}{4\pi\lambda}\left(\ln\left(\frac{4\lambda}{r_b^2 S_{VC}}\right) - 0.5722\right)\right] + T_0 \qquad [\mathrm{K}] \qquad (4)$$

r_b is the borehole radius, S_{VC} is the volumetric heat capacity of the rock/sediment, and T_0 is the undisturbed ground temperature. The average heat carrier fluid temperature T_f is calculated from the inlet and outlet temperatures, T_{in} and T_{out}:

$$T_f = \frac{T_{out} + T_{in}}{2} \qquad [\mathrm{K}] \qquad (5)$$

The thermal conductivity λ is found by plotting T_f against the natural logarithm of the time in seconds and by reading off the slope where the conditions have stabilized (Signorelli et al., 2007; normally between 20 (t_1) and 70 hours (t_2)):

$$\lambda = \frac{q}{4\pi} \cdot \frac{\ln(t_2) - \ln(t_1)}{T_f(t_2) - T_f(t_1)} \qquad [\text{W m}^{-1}\ \text{K}^{-1}] \qquad (6)$$

The thermal borehole resistance can be calculated with the help of the obtained λ value.

$$R_b = \frac{m - T_0}{q} - \frac{1}{4\pi\lambda}\left(\ln\left(\frac{4\lambda}{r_b^2 S_{VC}}\right) + 0.5722\right) \qquad [\text{m K W}^{-1}] \qquad (7)$$

A TRT typically lasts 72 hours (Gehlin, 1998). In this time range the analytical solution of the infinite line-source shows a very low error level compared to the alternative solutions of the finite line-source and the infinite cylindrical source theory (Philippe et al., 2009). Different international guidelines recommend durations of at least 36 hours (IGSHPA) or 50 hours (IEA). In Germany, commonly a TRT is considered to be long enough if the estimated thermal conductivity does not change more than 0.1 W $m^{-1}K^{-1}$ within 24 hours (pers. comm. M. Sauer, 2011).

Possible sources of error during a TRT are: 1) heat loss and gain, 2) variable electric power supply, 3) lack of accuracy of the determination of the undisturbed ground temperature, 4) free convection of water in non-grouted boreholes (standard for energy wells in Scandinavia; Gustafsson et al., 2010), 5) gradient-driven horizontal groundwater flow and 6) density-driven vertical groundwater flow (e.g. thermosiphon effect, Gehlin et al., 2003, Gustafsson, 2006). Typical levels of confidence of TRT results are about 9 % for the thermal conductivity and about 14 % for the thermal borehole resistance (Zervantonakis and Reuss, 2006).

Within this study, 15 TRTs were performed, 7 in the Oslo region, 2 in Bryn, 3 in Mære and 3 in Lade. Detailed information is given in the paper section. Videos showing turbulence in the non-grouted borehole at Lade during the TRTs were taken with a special borehole camera borrowed from the Geological Survey of Norway (see Figure 2.5). Three cases are recorded on video and shown in Appendix A: a) No pumping of groundwater, no heating, some groundwater flow at 34 m depth (video 1), b) heat input rate of 83 W m^{-1}, no pumping of groundwater (video 2), c) heat input rate of 94 W m^{-1}, with pumping of groundwater from the bottom and infiltration at the top of the borehole (video 3).

The multi-injection rate TRT (i.e. MIR-TRT) at Lade was evaluated with parameter estimation techniques based on the infinite line-source theory (see Wagner and Clauser, 2005) and with a numerical model of Hellström (2001) which was used and described in detail in an earlier study to evaluate MIR-TRTs (Gustafsson and Westerlund, 2010). A ± 10 % error can be expected for the same TRT results analysed with different methods (Spitler et al., 2000, Witte et al., 2002).

Figure 2.5 Borehole camera used at Lade to visually prove convection in the borehole during TRTs.

2.4. Temperature measurements in wells

Temperature profiles were taken with the help of temperature dataloggers (VEMCO, 8-bit Minilog TDR, Halifax, Canada) with a sinker bound to a 200 m long chord (Figure 2.6).

Temperature profiles were taken inside the collector pipe before each TRT to determine the undisturbed ground temperature and four hours after the end of the TRT. The temperature sensor was lowered to the depth of interest. The datalogger was given two minutes to adapt to the fluid temperature even at steep temperature gradients. The depth interval was two meters for the measurements down to a depth of 40 meters. Below this depth and down to the end of the borehole, the resolution was 4 meters. There, smaller temperature variations can be expected. It is necessary to keep the measurement time of a temperature profile short if it is recorded after a TRT. In this way, a further temperature recovery during the measurement can be minimized. The depth interval was set to four meters. For a 200 m deep borehole the measurement of one temperature profile takes accordingly 70 minutes (30 minutes for the first 40 m and 40 minutes for the next 160 m). This standardized method is necessary to compare the temperature recovery in different wells in different hydro-, thermo- and geological settings.

Figure 2.6 VEMCO minilogger and sinker bound to a chord with two meter marks for manual depth determination (left) and temperature logging inside the collector pipe (right).

For all temperature profiles performed four hours after the TRT, it has to be kept in mind that there is some temperature recovery during the measurement. A permanent temperature log after a TRT in Bryn (see chapter 2.1) in 30 m depth showed a recovery of 0.5 °C between 4 and 5 hours after the test. That is the temperature recovery that can be expected during the temperature measurement under the conditions of the TRT in Bryn.

Temperature data loggers were installed in the borehole at different depths at the borehole in Mære to evaluate the effective thermal conductivity in different depths and the influence of groundwater flow through open fractures on TRT results. The time resolution for the permanent temperature measurements inside the borehole was 10 minutes, equal to the data logging resolution in the TRT trailer.

2.5. Geochemical characterization of rock samples

Rock cores drilled from a boulder from the field site Mære were used to estimate mineral content with x-ray diffraction (XRD) using a Bruker D8 Advance x-ray diffractometer. The sample preparation followed the standard procedure described in Buhrke et al. (2001) with minor adaptations. As the quartz content plays a dominating role for the thermal conductivity of a rock (Sundberg, 1988), it was measured independently with a differential thermal analysis (DTA, Mackenzie, 1970) for each rock core. The measurement equipment used for the DTA was a Mettler Toledo TGA/SDTA851e. Both XRD analyses and DTA were carried out at the Department of Geology and Mineral Resources Engineering at NTNU. The results were used to correlate the quartz content with the lab-measured thermal conductivity depending on the foliation direction of micas contained in the investigated schist.

Thin sections were produced in addition and analysed with plane and double polarized light under the microscope to characterize the rock sample concerning mineral content and mineral orientations.

2.6. Hydrogeological investigations

The influence of groundwater flow through an open fracture on TRT results was investigated at the well field of Bryn (5 boreholes). A TRT was performed in the centre-borehole and groundwater was pumped in the meantime from a close-by well (distance between the two wells: ca. 10 m, pumping rate: 2.2 l s^{-1}). The groundwater level was surveyed in all five boreholes. The groundwater level was lowered in the whole area by about 4 m. The parallel drawdown observed in all wells indicates a hydrological short-circuit by an open fracture that connects all wells to each other. The presence of one main fracture has been investigated with an optical televiewer in an earlier study (Ramstad, 2004). After switching off the groundwater pump, a recovery test was performed to characterize the aquifer and to estimate an overall hydraulic conductivity.

At the research well at Lade a groundwater pump (3"WPS 2-65, Well pumps S.A., Fleurus, Belgium, see Figure 2.7) was lowered directly into the well where the borehole heat exchangers were installed.

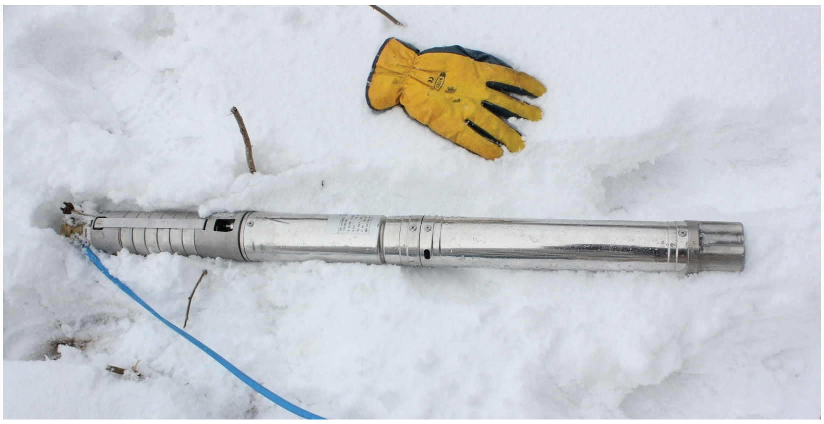


Figure 2.7 Groundwater pump used at Lade.

In this case, a vertical groundwater flow was induced as groundwater was sucked in at the base of the well with a flow rate of 0.62 l s^{-1} and infiltrated at the top of the well. The pump had a measured power consumption of 1.6 kW. All heat produced by the pump was transferred to the water in the borehole (water-cooled pump). The induced artificial convection gives an indication if artificial convection can be used to increase the efficiency of a ground-coupled heat pump system by reducing the thermal borehole resistance and increasing the effective thermal conductivity of a well.

2.7. Vibration and pressure drop measurements

The entire issue of vibration and pressure drop measurements was chosen to be presented in the Materials and Methods section as it focuses on two measurement techniques to compare the performance of different collector types. Preliminary results and interpretations are shown within the chapter as this study is auxiliary to the main topic of this doctoral thesis and the experiments were not successful.

One major expense to run a ground-coupled heat pump is the circulation of brine in the collector pipes. Two different types of collectors are used frequently: Standard and turbulence collector. To achieve turbulent flow, a lower volumetric flow should be needed in the turbulence collector by contrast to the standard collector. The turbulence collector has a grooved inner surface (see Figure 2.8) while the standard collector has a smooth inner surface.

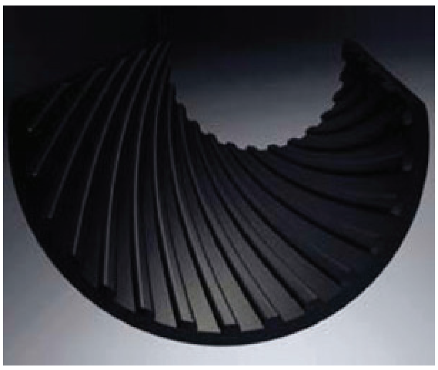


Figure 2.8 Sketch of the inner surface of a grooved turbulence collector (MTV Water Services, 2011).

Two methods were applied to compare the heat extraction performance and fluid flow properties in the two different collector types: a) vibration measurements at the outer surface of the collector and b) pressure drop measurements between the collector shanks. In order to achieve similar conditions during the experiment, both collector types were installed as a double U-collector in one single borehole.

a) Vibration measurements

The vibration at the outer surface of the inward and outward collector was measured at 10 different volumetric flows and Reynold's numbers ranging from ca. 1600 to 16000 for both collector types. The accelerometer used, was a Norsonic Dual Channel Real Time Analyser 840 (Norsonic AS, Lierskogen, Norway) with two sensors glued directly on the collectors with epoxy glue.

Figure 2.9 Vibration measurements performed with an accelerometer (left) and acceleration sensors glued directly on the collectors with epoxy glue (right).

Figure 2.10 shows that a clear difference can be observed only in the lower frequency range, where the turbulence collector vibrates stronger than its standard equivalent. The analysis of the raw data was done by Frode Haukland (SINTEF, Trondheim, Norway).

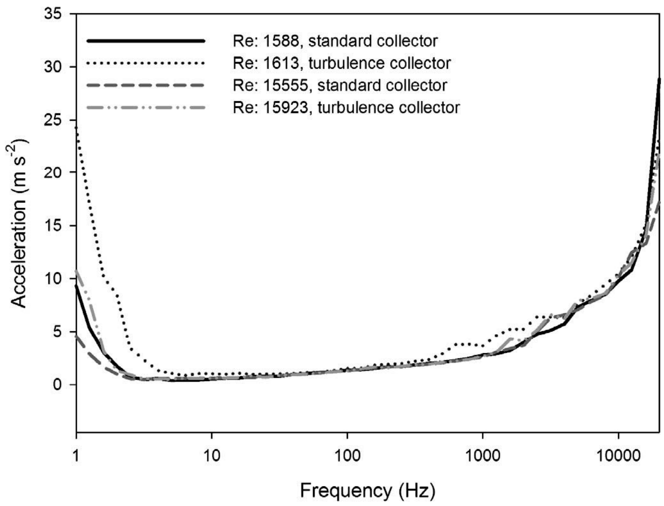


Figure 2.10 Acceleration *versus* frequency in vibration measurements in the outward collector side for the lowest and the highest Reynold's number (flow rate) for both standard and turbulence collector.

After the experiment was finished, a temperature profile was intended to be measured. At 92 m depth the temperature logger did not slide further down which indicates that the standard collector was damaged. Further interpretations of the data are therefore not done. It is recommended to carry out the same experiment in another borehole with undamaged collector tubes of the different types installed in the same borehole.

b) Pressure drop measurements

The methodology and aim of pressure drop measurements are presented at this place as the measurements can be applied in another occasion in the future. In the case of the borehole heat exchangers at Mære, the data could not be interpreted in a proper way due to the problem of the damaged standard collector.

The pressure drop in the borehole heat exchanger was measured with the help of a differential pressure transmitter installed on the TRT trailer (see Figure 2.11). The pressure drop was measured depending on the volumetric flow rate through the borehole heat exchanger, first for the turbulence collector and then for the standard collector. The approach is the same as suggested by Acuña and Palm (2008) except that their borehole heat exchangers were not tested in the same borehole. By using a double U-shaped borehole heat exchanger with both collector types installed in the same borehole, the informative value of the results would have been increased significantly.

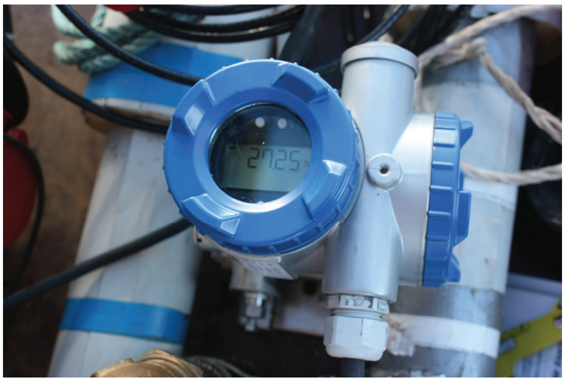


Figure 2.11 Differential pressure transmitter installed on the TRT trailer.

The aim of the pressure drop measurements is to investigate the energy used for the pump to circulate the heat-carrier fluid:

$$E_{pump} = \frac{\Delta P \cdot \dot{V}}{\eta_{pump}} \qquad [W] \qquad (8)$$

where E_{pump} is the pumping power [W], ΔP is the pressure drop [Pa], $\dot{V}$ is the heat-carrier volumetric flow rate [m³ s⁻¹] and η_{pump} is the pump efficiency [-].

The pressure drop is a result of friction in the borehole heat exchanger and it increases with higher flow velocities. With the help of the measured pressure drop, a dimensionless friction factor f can be calculated:

$$f = \Delta P_f \cdot \frac{2}{\rho u_m^2} \cdot \frac{D}{L} \qquad [-] \qquad (9)$$

where ΔP_f is the pressure drop [Pa], ρ is the density [kg m-3], D is the inner pipe diameter [m], L is the total pipe length [m] and u_m is the mean fluid velocity [m s-1].

In addition, the Reynolds number has to be known to find out if the flow in the tube is laminar or turbulent and can be calculated:

$$\mathrm{Re} = \frac{u_m \rho D}{\mu} \qquad [-] \qquad (10)$$

where μ is the dynamic viscosity of the heat-carrier fluid [kg m-1 s-1].

The flow regime can be determined by plotting the friction factor based on the pressure drop measurement against the Reynolds number in a Moody diagram (see Figure 2.12).

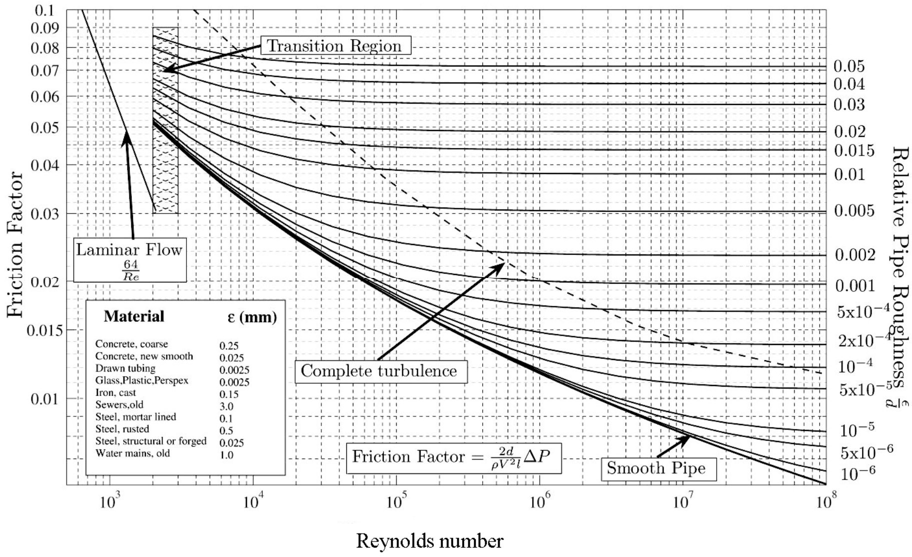


Figure 2.12 Moody diagram showing areas of laminar and turbulent flow depending on friction factor and Reynolds number (Beck and Collins, 2008).

This project is an attempt to define the physical properties of different collector types. Pressure drop measurements as suggested in this thesis, with a double U-shaped borehole heat exchanger consisting of a standard and turbulence single U installed in one single borehole, should be used to compare different collectors.

Major questions that could be answered in this way include: When is turbulent flow reached in different collector types? Which implications has the different behaviour for the use of different borehole heat exchangers? The approach was not followed up further in this thesis as the research question is not directly related to the main focus of this thesis.

3. Summary of Papers and Discussion

Figure 3.0 shows the overall structure of the thesis. It gives an overview over hypotheses addressed in the different papers.

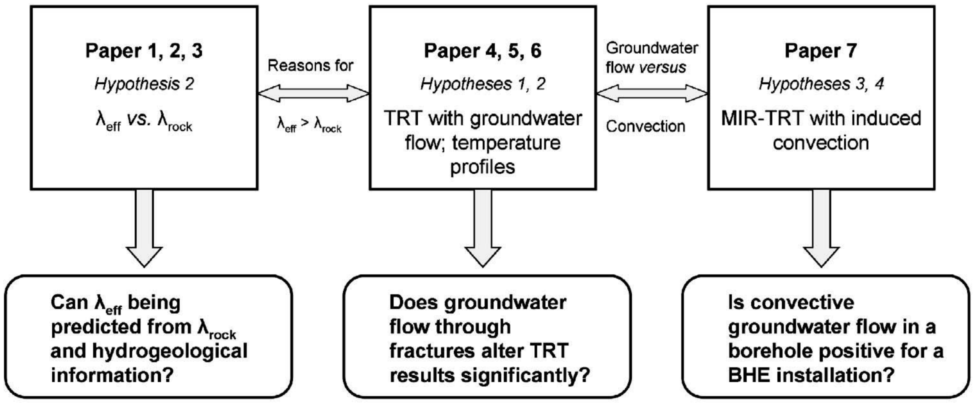


Figure 3.0 Structure of the doctoral thesis.

Short summaries of the papers presented in this PhD are given in the following. The full-length original papers are attached after the synthesis section.

3.1. **Paper 1:** H.T. Liebel, K. Huber, B.S. Frengstad, R. Kalskin Ramstad, B. Brattli (2010): *Rock core samples cannot replace thermal response tests - A statistical comparison based on thermal conductivity data from the Oslo Region (Norway).* Proceedings of "Renewable Energy Research Conference", 7th – 8th June 2010, Trondheim, Norway, pp. 10.

Motivation

The influence of groundwater flow was investigated statistically by comparing databases of thermal conductivities. An extensive database of rock core thermal conductivities from surface samples (1398 entries) exists at the Geological Survey of Norway for the Oslo region (Norway). For comparison, a database was created based on all TRTs performed by different companies and institutions in the same area (67 entries). The motivation for this study was to find an equation that allows a prediction of the effective thermal conductivity in an energy well based on the rock core thermal conductivity database.

Already Jessop (1990) concluded that thermal conductivity data from rock cores cannot be used as generally valid values for different rock types within an error range of 25 %. However, a trial was undertaken in this study as the database of rock core thermal conductivities for the Oslo region is large and as thermal conductivity maps were produced by the Geological Survey of Norway that have the intention to be used as a basis for dimensioning a ground-coupled heat pump installation.

Results

Median thermal conductivities for 14 different rock types in the Oslo region are in a similar range for both rock core samples, 2.3 – 3.5 W m^{-1} K^{-1}, and TRTs, 2.6 – 3.7 W m^{-1} K^{-1}. In rock core samples, the quartz content is decisive for the thermal conductivity. Quartz-poor monzonites and monzodiorites show the lowest, quartz-rich Silurian sandstones the highest thermal conductivities. The highest effective thermal conductivity was measured in granitic to tonalitic gneisses. Borehole resistances varied for all rock types between 0.06 and 0.07 K W^{-1} m^{-1} (except alum shale: 0.09 K W^{-1} m^{-1}).

Plots of the median effective and rock core thermal conductivity values show that all median effective thermal conductivity values are higher than the median values from rock cores (see Figure 3.1). However, no significant correlation between the two thermal conductivity datasets could be found. Consequently, a prediction of effective thermal conductivities based on the rock core database is not feasible.

Whenever enough data were available, the results of the two different thermal conductivity measurements were compared for single rock types. Significant differences were found between the values from TRTs and rock cores in syenites, Silurian and Ordovician sediments. Wells drilled in syenites in Norway are known to have the highest water yields in average according to a study of Morland (1997). Groundwater flow may be the reason for the 15 % higher effective thermal conductivity compared to the thermal conductivity from rock cores (median values). Another reason may be that the rock cores are not water-saturated when measured in the lab. If the porosity of the sample is very low (e.g. granite with 1% porosity) the measured thermal conductivity will be 8 % lower than in a water-saturated sample (Clauser and Huenges, 1995). The median effective thermal conductivity in Ordovician and Silurian sedimentary rocks were 16 and 19 % higher than the median rock core thermal conductivity as well. Taking into account that the rocks are water-saturated, around 8 % can be subtracted from the increase in thermal conductivity. Again, groundwater flow can be expected through fractures and karst systems in the limestones which might be responsible for the increase in thermal conductivity of 8 to 11 %.

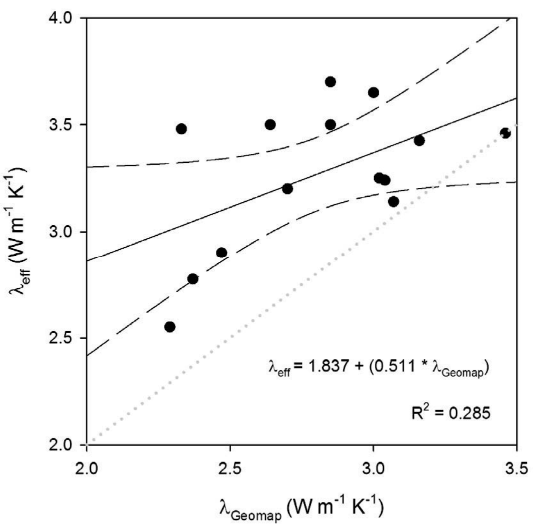


Figure 3.1 Median values of the thermal conductivity from TRTs ("eff") versus values from rock core samples ("Geomap") for 14 different geological units. The linear regression (solid line) is shown with 95 % confidence intervals (dashed line).

No significant difference was observed in mica gneisses. There, the variation due to anisotropy masks possible effects of groundwater flow.

Finally, an inverse approach to search statistically for groups was performed (e.g. a cluster of entries belonging to a geological unit). A hierarchical cluster analysis was carried out based on the two different thermal conductivity datasets. However, no clear pattern could be found.

As the regression between the two different thermal conductivity data shown in Figure 3.1 was not significant, the data analysis was extended and presented in Paper 2.

3.2. **Paper 2:** H.T. Liebel, K. Huber, B.S. Frengstad, R.K. Ramstad, B. Brattli (2010): *Can rock core thermal conductivity data replace thermal response tests?* Proceedings of Water and Energy Conference 2010, Amsterdam, Netherlands, pp. 8.

Motivation

Paper 2 is a direct continuation of the study presented in Paper 1. Even if some of the content is repeated, the study was chosen to be presented in the thesis as it investigates further if rock core thermal conductivity data have the potential to replace TRTs. In addition to the data analyses and the thermal conductivity map shown in Paper 1, a relationship was searched for between the effective and the rock core thermal conductivity from the rock core sample closest to the TRT site. Around every known TRT site in the Oslo region the closest rock core sample within the same geological unit was chosen and compared to the effective thermal conductivity. The research question to be answered was if the ratio between rock core and effective thermal conductivity varies stronger the farther away the rock core sample is taken from the TRT site.

Results

Figure 3.2 shows however, that the deviation of the effective thermal conductivity from rock core thermal conductivity of the closest rock core sample varies over a large range independently from the distance to the actual TRT site.

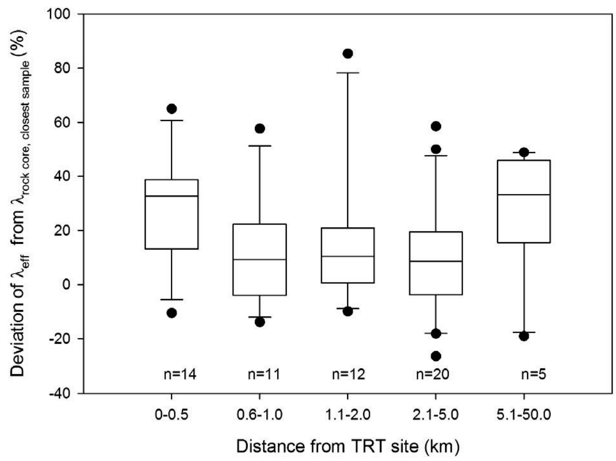


Figure 3.2 Deviation of the effective thermal conductivity from the closest rock core sample thermal conductivity for different distance groups.

The data analysis of this study does not prove an increase in variation and uncertainty concerning the effective thermal conductivity estimate based on the closest rock core sample. By contrast, the uncertainty is high even if the closest rock core sample is located less than 500 meters away from the borehole where the TRT was carried out. As the variation in the thermal conductivity ratio may be explained with groundwater flow in some boreholes, an analysis combining water yield, rock core and effective thermal conductivity data may help to predict the effective thermal conductivity at a site.

3.3. **Paper 3:** H.T. Liebel, J. de Beer, B.S. Frengstad, R.K. Ramstad, B. Brattli (2012): *Effect of water yield and rock thermal conductivity on TRT results.* Accepted at Communicações Geológicas, pp. 7.

Motivation

Paper 3 attempts to predict the effective thermal conductivity at a site based on a database of rock core thermal conductivity measurements and a water yield database covering different geological units in the Oslo region.

Extensive databases exist for water yield data through the national groundwater database GRANADA at the Geological Survey of Norway (see also Gundersen and de Beer, 2009). Four different rock types from the Oslo region were chosen to be compared to each other: Mica gneiss, syenite and Ordovician and Silurian sediments.

The highest water yield can be expected in syenites (median value of 1000 l hr^{-1}). The lowest water yields are found in mica gneisses (median value of 600 l hr^{-1}). A database of rock core thermal conductivities at the Geological Survey of Norway (the same one as in Paper 1 and 2) was used to investigate the thermal properties of the four rock types. In this case, rock samples from mica gneisses are most likely to have high thermal conductivities (median value of 3.03 W $m^{-1}K^{-1}$). Syenites have the lowest thermal conductivities (median value of 2.38 W $m^{-1}K^{-1}$), while the Ordovician and Silurian sediments lie in between. Wells that show a high water yield during drilling are also most likely to support significant groundwater flow. If groundwater flow is more likely in syenites than in mica gneisses, the effective thermal conductivity measured in TRTs should also be relatively higher in syenites than in mica gneisses.

Results

The ratio between effective and rock core thermal conductivity are 1.17 in syenites and 1.07 in mica gneisses. The dominant weakness of the comparison between the two thermal conductivity values is the number of TRT measurements. Data from only 8 TRTs respectively were available for mica gneisses and syenites.

Heat transfer rates were available for 37 TRTs of the four rock types. The thermal conductivity ratio is shown depending on the heat transfer rate in Figure 3.3.

The datapoints are scattered and no significant trends can be found. A linear regression of the overall dataset shows a slight trend to increasing effective thermal conductivities with increased heat transfer rates as it would be expected according to Gustafsson and Westerlund (2010).

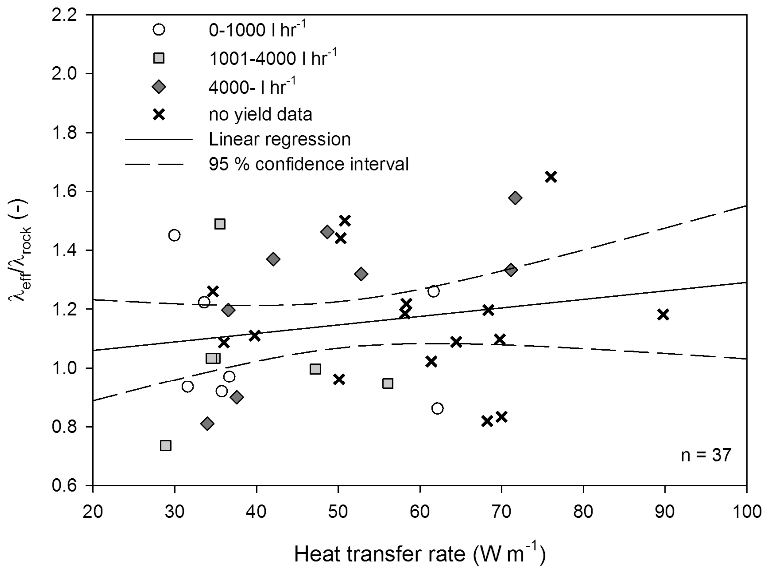


Figure 3.3 Thermal conductivity ratio (TRT/rock core data) *versus* heat transfer rate during TRTs performed in the Oslo region classified after hydraulic yield data from the according well reports. The linear regression and 95 % confidence intervals are based on the whole dataset (own data and data from Geoenergi AS, NGI and NGU).

TRTs with water yields larger than 4000 l hr^{-1} tend to have relatively higher effective thermal conductivities than TRTs with low water yields. Groundwater flow in boreholes with high water yields during drilling can be expected only if regional hydraulic gradients are present that force the groundwater to flow. If low effective thermal conductivities are found in boreholes with high water yields, it can be expected that only minor or no groundwater flow appears through the borehole.

The combined study of databases for water yield, rock core and effective thermal conductivity indicates that no clear overall trends can be found and used for the planning of ground-coupled heat pump projects. However, data about thermal and hydraulic ground properties should be made available to ground-coupled heat pump designers. Data from the closest TRT site in the same geological unit should be available online including hydraulic and thermogeological properties. These data will give an indication about the ground properties at the site of interest.

3.4. **Paper 4:** H.T. Liebel, M.S. Stølen, B.S. Frengstad, R.K. Ramstad, B. Brattli (2011): *Insights into the reliability of different thermal conductivity measurement techniques: a thermo-geological study in Mære (Norway).* Bulletin of Engineering Geology and the Environment, DOI 10.1007/s10064-011-0394-3; pp. 9.

Motivation

The reliability of different thermal conductivity measurement techniques was investigated at Mære agricultural school in the county of northern Trøndelag (Norway). A greenhouse was planned there to be supplied with environmentally friendly ground-stored heat. For the investigation of thermal properties, a test well was drilled (138 m deep) and equipped with a double U-shaped PE borehole heat exchanger and TRTs were performed in different winter weather conditions.

Results

A first TRT was characterized by a cold start with a subsequent period of intense snow melt which led to direct infiltration of surface water through the borehole. Additionaly, an increase in groundwater flow could be detected in the fractured areas of the borehole. Continuous temperature logging was performed in relevant depths where fracture zones were known. The temperature curves from different depths helped to locate areas of groundwater flow and to interpret the TRT results.

A second TRT during a period of high atmospheric pressure without precipitation gives the same results for the effective thermal conductivity as for the first TRT. The continuous temperature measurements in four different depths display minimal variations and are not necessary for the interpretation of the TRT results. Directly after the first 72 hours with a heat input rate of 3 kW, the heat input rate was increased to 6 kW. The measured effective thermal conductivity increased then from 4 to 5.8 W m^{-1} K^{-1} probably due to increased convection in the borehole with a better thermal contact to the surrounding bedrock. The study underlines the importance of permanent temperature measurements in depths where groundwater flow can be expected.

Lab measured thermal conductivity values of six rock cores from the local bedrock (a schist) are shown in Figure 3.4.

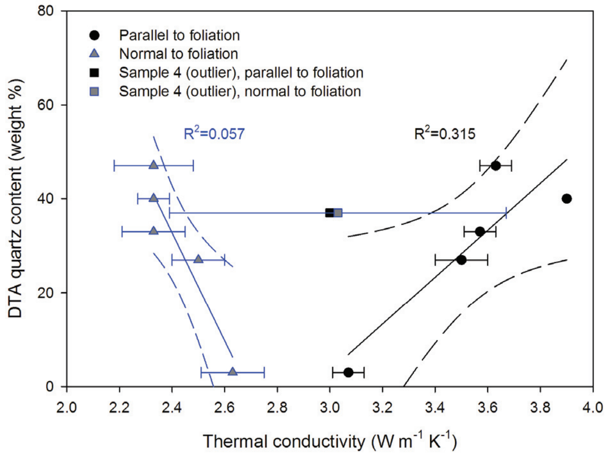


Figure 3.4 Thermal conductivities measured from rock core samples parallel and normal to the foliation direction versus quartz content (DTA). Sample 4 was excluded from the regression as incorrect outlier. For both datasets linear regression lines are drawn and 95 % confidence intervals are shown as dashed lines.

The results indicate an increase of the rock core thermal conductivity with increasing quartz content for a measurement direction parallel to the foliation direction only. Surprisingly, this increase could not be found in the measurement normal to the foliation direction. Thin sections indicate that the schists with high quartz content contain also mica bands, that are relatively thick and continuous, blocking an effective heat transfer.

3.5. **Paper 5:** H.T. Liebel, K. Huber, B.S. Frengstad, R.K. Ramstad, B. Brattli (2012): *Thermal response testing of a fractured hard rock aquifer with and without induced groundwater flow.* Bulletin of Engineering Geology and the Environment, DOI 10.1007/s10064-012-0422-y; pp. 11.

Motivation

The influence of groundwater flow on TRT results and on ground-coupled heat pump installations is a matter of ongoing debate (e.g. Wang et al., 2009). Few TRTs have been performed where groundwater flow through an energy well was controlled. A test performed in a well in unconsolidated sediments by Witte (2002) is frequently referred to in literature. No similar test in fractured rocks is known to the authors of Paper 5.

Results

This paper presents the results of two TRTs carried out in the same borehole at Bryn (Bærum municipality, Norway). The borehole is 100 m deep and located in an unconfined aquifer in fractured metasandstones containing a few diabase dykes. The fracture network was mapped along the river Lomma and data presented in a stereogram.

Groundwater was pumped during a first TRT (TRT_{gw}) from a close-by production well. The induced groundwater flow towards the production well followed the main fracture at approximately 13 meters depth. A hydrogeological recovery test was performed to estimate an overall hydraulic conductivity. The groundwater flow was visualized in a temperature profile taken five hours after the finished TRT. In areas of groundwater flow the temperature recovered much faster than in the rest of the warmed-up borehole. The measured temperature profile was correlated to different geological layers represented in the borehole.

After a recovery time of 24 days, a second TRT was carried out that was used as a reference TRT (TRT_{ref}). No artificial groundwater flow was induced. Data from an earlier PhD thesis of Ramstad (2004) was available and used in addition for the interpretation of the results.

Using the infinite line-source approximation, the measured effective thermal conductivity with groundwater flow was 11 % higher (see Figure 3.5) than without groundwater flow. No clear increase in effective thermal conductivities over time as it was described in Witte (2002, 2007) was discovered during the TRT with groundwater extraction. In a standard TRT it would not have been discovered that groundwater flow was responsible for the high effective thermal conductivity and that a parameter estimation technique should have been used to evaluate the thermal conductivity instead of the infinite line-source or similar approximations. Only with the help of a temperature profile taken after the TRT it is possible to detect the presence of significant groundwater flow.

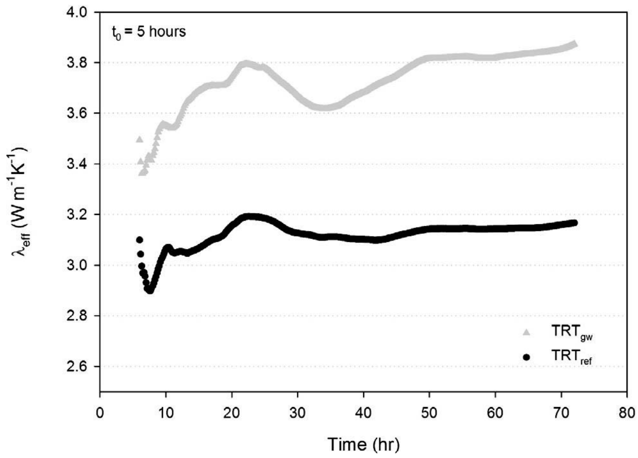


Figure 3.5 Development of the effective thermal conductivity (λ_{eff}) over time during both TRT_{gw} and TRT_{ref} using the method of Signorelli et al. (2007) with a start time (t_0) of 5 hours.

In the paper a finite-element model is presented that was built up to estimate and simulate the groundwater flow through the main fracture. The groundwater simulation in FEFLOW (Diersch, 2009) and the simulation of borehole heat exchangers in Earth Energy Designer (Eskilson et al., 2000) show that a groundwater flow velocity of 130 – 1300 m d^{-1} through one open fracture would reduce the required borehole length by about 7 % to cover the heating demand of a single house. The large range in groundwater flow velocity is a result of the uncertainty of the fracture aperture used as model input.

3.6. **Paper 6:** H.T. Liebel, K. Huber, B.S. Frengstad, R.K. Ramstad, B. Brattli (2011): *Temperature footprint of a thermal response test can help to reveal thermogeological information.* Norges geologiske undersøkelse Bulletin 451: 20-31.

Motivation

In Paper 5 it is shown that temperature profiles after TRTs help to detect groundwater flow. The importance of temperature logs and profiles before and after TRTs in fractured aquifers is investigated further in Paper 6. The experience from about 20 TRTs performed during this PhD work made it possible to draw some conclusions about the use of temperature profiles to better understand the thermal behaviour of the boreholes' thermal energy system.

Results

Four cases are presented showing different phenomena that can be experienced during TRTs.

a) "Perfect" borehole with standard temperature profiles

In rare cases a borehole is characterized by a temperature profile showing seasonal variations in the uppermost 10 to 15 m and a steady temperature increase following the geothermal gradient below this depth. Also a temperature profile taken 4 hours after the TRT will show a smooth curve with increasing temperatures towards the depth. The TRT can be evaluated following standard procedures like the algorithm based on the infinite line-source theory.

b) Thermal "pollution" from buildings or otherwise altered surfaces

Thermal "pollution" from buildings, parking lots, heated swimming pools etc. is visible in the temperature profiles in the ground down to 100 m depth or more depending on the temperature of the source and the duration of increased surface temperatures. An example is shown where the temperature profiles are strongly modified close to a building with decreasing impact on the boreholes farther away from the building (see Figure 3.6).

The anomalous temperature profiles do not implicate a special TRT evaluation. However, it gives valuable information on the expected operation of a ground-coupled heat pump. An increased heat transfer from the surface is positive for the heat extraction from the ground as the extracted heat is replaced faster with heat from the surface.

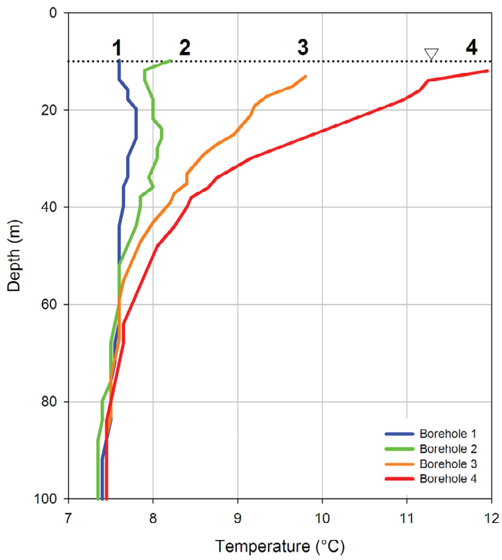


Figure 3.6 Temperature profiles in four boreholes close to a building (borehole 4 directly at the building, borehole 1 farthest away, i.e. ca. 50 m). The dotted line and the triangle show the groundwater level.

c) Groundwater flow through open fractures

Groundwater flow through open fractures passing the borehole can be detected easily with the help of temperature profiles. The temperature profile before the TRT may not show any anomalies if the groundwater has the same temperature as the ground at that depth. The temperature profile after the test however, shows a deviation in the area of the fracture flow. The groundwater is colder than the heated borehole and it cools down the borehole heat exchanger in the area of the water-bearing fracture.

Another possibility for fast cooling in some part of the borehole may also be a layer of the bedrock with high thermal conductivity (e.g. a quartz vein). To distinguish between the two effects, the drillers' reports are helpful as information about water yield in different sections and about drilling mud colour is given.

The effective thermal conductivity estimate may not converge but increase with time in case of groundwater flow (Witte, 2002; 2007) if the infinite line-source theory is applied for evaluation. In this case other evaluation techniques like parameter estimation or numerical combined thermal and hydrological simulations have to be applied to estimate the effective thermal conductivity and the final behaviour of the borehole heat exchanger during operation. The groundwater will transport heat away from the well during operation in cooling mode and towards the well in heating mode.

d) Groundwater up-flow through the borehole connecting two aquifers

Groundwater up-flow through the borehole can be triggered if a confined aquifer gets connected to an unconfined aquifer through the open borehole. The phenomenon of upwards flowing groundwater is easily detected with temperature profiles after a TRT. The section with flowing groundwater will show a faster temperature recovery than the non-affected sections of the borehole. In this case special TRT evaluation techniques have to be applied like parameter estimation or numerical modelling (e.g. Hellström, 1997; Spitler et al., 1999).

Special care has to be taken if dry minerals that have a swelling potential may get in contact with upstreaming water from the confined aquifer as it was the case in Staufen im Breisgau (Germany). The swelling leads to local uplift of the terrain which can result in instability and cracking of buildings (Goldscheider and Bechtel, 2009).

The temperature profiles deliver important hydro- and thermogeological information which supplements other information about the site like data from the TRT, drillers' well reports, rock core thermal conductivity measurements, a geological map and so forth. The combined evaluation of the data allows for a secured dimensioning of the ground-coupled heat pump and the behaviour of the plant in operation can be predicted.

3.7. **Paper 7:** H.T. Liebel, S. Javed, G. Vistnes (2012): *MIR-TRT with forced convection in a groundwater-filled borehole in hard rock.* Accepted at Renewable Energy (Elsevier).

Motivation

The main focus of this paper is to investigate the influence of forced and buoyancy-driven convection on the TRT results and if convective water flow in a borehole reduces the required borehole length for a ground-coupled heat pump system.

Two MIR-TRTs with four different heat input rates were performed at the research well of the Geological Survey of Norway at Lade. At first, a reference MIR-TRT was carried out without any artificial hydrological disturbance of the borehole to have a basis for comparison. Then, a second MIR-TRT was performed after a recovery time that was longer than the recommended waiting time for the borehole to recover from the first thermal disturbance (Javed et al., 2011). A groundwater pump was installed at the base of the borehole. Water was pumped up to the surface during the MIR-TRT and re-infiltrated into the borehole. Video records of the water movement inside the borehole confirm that an artificial convective flow could be established which was larger than pure buoyancy-driven convection in the borehole during a standard (MIR-)TRT.

The obtained fluid temperature developments during both MIR-TRTs were analysed with two different methods: a) A parameter estimation code based on the infinite line-source theory (ILS; see Wagner and Clauser, 2005) and b) numerical 2D finite-difference model of Hellström (2001).

Results

Obtained effective thermal conductivities and borehole resistances were used as input data for an evaluation of required borehole depths in Earth Energy Designer v.3.13 (Eskilson et al., 2000) for a standard single-family house in Sweden (borehole loads derived from Spitler et al., 2010). Figure 3.7 shows that the results of the different models are very similar to each other. A linear relationship of decreasing required borehole lengths with increasing heat input rates was found for the MIR-TRT without pumping of groundwater. The phenomenon can be explained with an increasing influence of free convection in the water-filled borehole (see also Gustafsson et al., 2010).

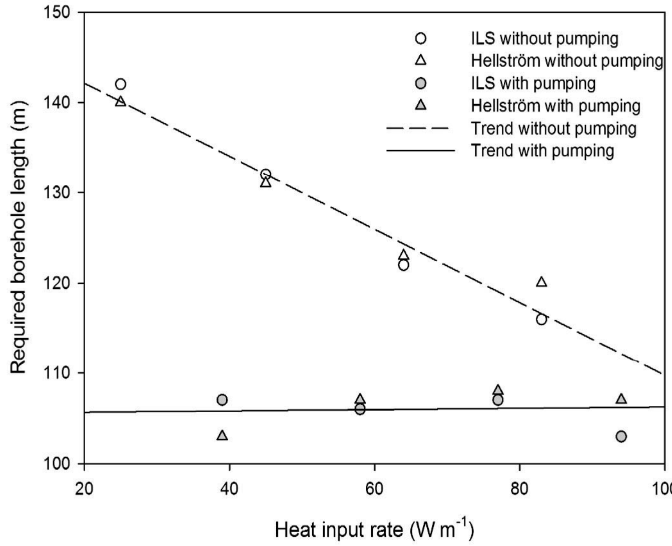


Figure 3.7 Required borehole lengths depending on the heat input rate for the MIR-TRTs with and without pumping of groundwater. The results are based on the ILS parameter estimation technique and the model of Hellström and shown for the case of a Swedish single-family house.

By contrast, the required borehole lengths do not change significantly with increasing heat input rates during the MIR-TRT with pumping of groundwater. The required borehole lengths are significantly shorter, i.e. 9% to 25% shorter than without artificial convection. This effect may be used in operative ground-coupled heat pump systems. Kharseh and Ossiansson (2011) recommend to use air bubbles to create an artificial convection in a borehole to reduce the thermal resistance and to increase the effective thermal conductivity.

More research, however, is needed to determine the long-term performance of a ground-coupled heat pump system where artificial convection is created in the boreholes.

4. Conclusions

Four hypotheses of how groundwater influences the measured thermal properties in a TRT were tested.

I.) Groundwater flow in fractured aquifers has a significant influence on TRTs.

The hypothesis is verified. In fractured aquifers where groundwater flow appears only through limited fracture zones, an increased effective thermal conductivity was calculated. Witte (2002) describes the phenomenon of an increasing non-converging thermal conductivity with time during a TRT. His experiment was performed in a borehole in a porous aquifer in the Netherlands and it was used for comparison with a controlled experiment performed within this thesis. In our study an artificial groundwater flow (pumping of groundwater) was created in a fractured aquifer. The effect of increasing effective thermal conductivities could not be found, however. The reason might be that groundwater flow appears more often over large areas of the borehole in porous aquifers (in the range of several meters) while groundwater flow was limited to few fractures in our study (in the range of several centimeters). Boreholes in fractured rock might show increasing effective thermal conductivities if an upflow of groundwater affects large parts of the borehole. This phenomenon is linked to artesian aquifers.

II.) Effective thermal conductivities are higher than lab-measured thermal conductivities due to groundwater flow and convection in the borehole.

The hypothesis is not fully verified. A systematic study of all thermal conductivity data available from the Oslo region was carried out. TRT results were compared to rock core thermal conductivity values for certain rock types. TRT thermal conductivities are in average 10 to 20 % higher than the lab measured values. This difference in thermal conductivity values can only partly be explained with the fact that rocks are water-saturated in the field and dry in the lab. Low porosity crystalline rocks and rocks from the Oslo region are known to increase their thermal conductivity by less than 10 % when getting water-saturated (Clauser and Huenges, 1995; Midttømme et al., 2000). Large variations within groups of similar rock types prohibit the use of database thermal conductivity values for a site where a ground-coupled heat pump installation is planned. Weaknesses of the measurement techniques are described in the Material and Methods section of this thesis.

III.) Free convection of water in the borehole during TRTs alters the measured effective thermal conductivity and borehole resistance.

The hypothesis is verified. Also in non-fractured hard rock boreholes, TRT thermal conductivities are generally higher than the rock core thermal conductivities would suggest. Free convection in the non-grouted, water-filled borehole is to a large extent responsible for the phenomenon. Free convection during TRTs was proven by video recordings (see Appendix A) and with the help of a MIR-TRT in a fractured borehole with some groundwater flow. Effective thermal conductivity or borehole resistance alone do not give a clear trend for increasing heat input rates. By taking into account the two parameters together, however, it is evident that free convection influences the TRT results strongly. Earth Energy Designer (Eskilson et al., 2000) was used to calculate required borehole lengths for a standard base/peak load profile for a single house. The required borehole lengths decreased linearly by 16 % with increasing heat input from 25 to 83 W m^{-1}, inducing free convection in the borehole.

IV.) Forced convection induced with a groundwater pump increases the efficiency of a ground-coupled heat pump system.

The results from two MIR-TRTs (one with and one without artificial convection in the borehole) indicate that the thermal contact between the borehole heat exchanger and the ground is improved through artificial convection. It could not be concluded that borehole resistances always decrease and effective thermal conductivities always increase with artificial convection. With the help of Earth Energy Designer (Eskilson et al., 2000), however, the effect of the combination of both parameters can be evaluated. A load profile for a modern house in Sweden was used to estimate required borehole lengths (Spitler et al., 2010 mod.). All modelled required borehole lengths were shorter than during the MIR-TRT without pumping of groundwater.

A long-term test of a ground-coupled heat pump system in operation with an additional groundwater pump installed in the borehole should be performed to finally verify the hypothesis.

Main conclusions

- Effective thermal conductivities cannot be predicted from rock core thermal conductivity data and water yields of boreholes because of the large local variation of both thermal and hydraulic conductivity

- Groundwater flow in crystalline rock cannot be detected in ordinary TRTs if the groundwater flow is limited to a few fracture zones (increasing effective thermal conductivity values during the TRT cannot always be found)

- Convective flow in the borehole created by the TRT has a strong effect on the calculated effective thermal conductivity and borehole resistance

- Free convection in energy wells reduces the required borehole length for a ground-coupled heat pump installation

- Convection induced by groundwater pumps installed in energy wells can substantially reduce the required borehole length for a ground-coupled heat pump installation if used for heating and cooling

5. Recommendations for Future Work

In the framework of this thesis it has been investigated the various aspects of groundwater flow and groundwater convection and their influence on TRTs in non-grouted boreholes drilled into fractured hard rock.
It is evident that more work is needed to understand better the processes of convection to find a precise thermal conductivity and borehole resistance estimate through TRTs.

Tracer experiments in combination with TRTs would allow for a more detailed characterization of groundwater flow through fractures and convection inside the non-grouted boreholes. Relevant questions that have not been adressed in this thesis are among others: Which volumetric flow is needed to get increasing effective thermal conductivities in a TRT as reported in an experiment by Witte (2002)? When is the groundwater flow recognizable from the TRT result and where is the border?

MIR-TRTs with and without pumping of groundwater in the test well have been performed in this thesis. It was shown that the required borehole length can be reduced significantly through artificially induced convection inside the borehole. Test runs of borehole heat exchangers with a groundwater pump installed at the bottom for effective convective flow inside the non-grouted boreholes would be a vital test if artificial convection can be a cost-efficient mean to increase the efficiency of the borehole system.

TRT results should be made available to the public in a national database. GRANADA, which is the Norwegian national database for hydrogeological data (maintained by the Geological Survey of Norway) would naturally be the platform to publish TRT results linked to other information available about the borehole such as hydraulic yield, fracture zones, depth of the borehole, sedimentary cover, groundwater chemistry. The database should be enhanced and fed with both thermal conductivity data from TRTs and rock cores and with the thermal borehole resistance. The combination of thermogeological and hydrogeological data gives a good basis for the planning of a ground-coupled heat pump system.

6. References

Acuña, J., B. Palm (2008) *Experimental comparison of four borehole heat exchangers.* Proceedings of the 8th IIR Gustav Lorentzen Conference on Natural Working Fluids, Copenhagen, Denmark.

Austin W.A. (1998) *Development of an in situ system for measuring ground thermal properties.* M.Sc. Thesis, Oklahoma State University, Stillwater, OK, USA.

Austin, W., C. Yavuzturk, J.D. Spitler (2000) Development of an *in-situ* system for measuring ground thermal properties. *ASHRAE Transactions* **106**: 365-379.

Banks, D. (2008) *An introduction to thermogeology – Ground source heating and cooling.* Blackwell Publishing Ltd., Oxford, UK.

Beck, S., R. Collins (2008) Moody diagram. Online: http://commons.wikimedia.org/wiki/File:Moody_diagram.jpg [19.01.2011]

Buhrke, V.E, R. Jenkins, D.K. Smith (eds., 2001) *A practical guide for the preparation of specimens for X-ray fluorescence and X-ray diffraction analysis.* Wiley-VCH, New York, USA, pp. 360.

Claesson, J., G. Hellström (2000) *Analytical studies of the influence of regional groundwater flow on the performance of borehole heat exchangers.* Proceedings of the 8th International Conference on Thermal Energy Storage, Terrastock 2000, Stuttgart, Germany, 195-200.

Clauser, C., E. Huenges (1995) *Thermal conductivity of rocks and minerals.* In: T.J. Ahrens (ed.): Rock physics and phase relations – A handbook of pysical constants. American Geophysical Union, Washington, USA.

Diersch, H.J.G. (2009) *FEFLOW Reference Manual.* Institute of Water Resources Planning and Systems Research Ltd., Berlin, Germany, pp. 292.

Eskilson, P., G. Hellström, J. Claesson, T. Blomberg, B. Sanner (2000) *Earth Energy Designer version 2.0.* Blocon software, Sweden.

Ericsson, L. O. (1985) *Värmeutbyte mellan berggrund och borrhål vid bergvärme-system (Heat exchange between bedrock and well in ground-stored heat* *systems – in Swedish),* Department of Geology, Chalmers University of Technology and University of Göteborg, Sweden.

Eugster, W.J, B. Sanner (2007) *Technological status of shallow geothermal energy in Europe.* Proceedings of the European Geothermal Congress, Unterhaching, Germany.

EurObserv'ER (2009) *Heat Pumps Barometer.* Systèmes Solaires - le journal des énergies renouvables, No. 193.

Fan, R., Y. Jiang, Y. Yao, D. Shiming, Z. Ma (2007) A study on the performance of a geothermal heat exchanger under coupled heat conduction and groundwater advection. *Energy* **32**: 2199-2209.

Gehlin, S. (1998) *Thermal response test. In situ measurements of thermal properties in hard rock.* Licentiate thesis. Luleå University of Technology, Sweden, 1998:37.

Gehlin, S. (2002) *Thermal response test. Method development and evaluation.* Doctoral thesis. Luleå University of Technology, Sweden, 2002:39.

Gehlin, S.E.A., G. Hellström (2003) Influence on thermal response test by groundwater flow in vertical fractures in hard rock. *Renewable Energy* **28**: 2221-2238.

Gehlin, S.E.A., G. Hellström, B. Nordell (2003) The influence of the thermosiphon effect on the thermal response test. *Renewable Energy* **28**: 2239-2254.

Goldscheider, N., T.D. Bechtel (2009) Editor's message: The housing crisis from the underground – damage to a historic town by geothermal drillings through anhydrite, Staufen, Germany. *Hydrogeology Journal* **17**: 491-493.

Gundersen P., H. de Beer (2009) *Statistikk vanngiverevne i forskjellige bergarter. ForForUT deloppgave 3. Statusrapport 2009 (Statistical water yield in different rock types. ForForUT subtask 3. Status report 2009 – in Norwegian).* Geological Survey of Norway, Report 2009.066, Trondheim, Norway.

Gustafsson, A.M. (2006) *Thermal Response Test – Numerical simulations and analyses.* Licentiate thesis. Luleå University of Technology, Sweden, 2006:14.

Gustafsson, A.M., L. Westerlund (2010) Multi-injection rate thermal response test in groundwater filled borehole heat exchanger. *Renewable Energy* **35**: 1061-1070.

Gustafsson, A.M., L. Westerlund, G. Hellström (2010) CFD-modelling of natural convection in a groundwater-filled borehole heat exchanger. *Applied Thermal Engineering* **30**: 683-691.

Haimann, R. (2010) *Wärmepumpen am Limit – Heizen mit Erdwärme galt lange Zeit als klimafreundlich und günstig. Doch manchem Hausbesitzer kommen Zweifel (Heat pumps face their limits – Heating with ground-stored heat was considered climate-friendly and cheap for a long time. Now some homeowners are starting to doubt – in German),* Welt am Sonntag, 12.12.2010, p.97-99.

Hay, T. (2009): *Kald og varm på grunnvann*, *(Cooled and heated by groundwater – in Norwegian),* Aftenposten Innsikt 20.02.2009, p. 10-11.

Hellström, G. (1997) *Thermal response test of a heat store in clay at Linköping, Sweden*. Proceedings of Megastock '97, Sapporo, Japan, p. 115-120.

Hellström, G. (2001) *Computer program. Numerical evaluation of thermal response test.* Numerical 2D axisymmetric model used for evaluation in Swedish thermal response test measurements 2001.

Ingersoll, L.R., O.J. Zobel, A.C. Ingersoll (1948) *Heat conduction – With engineering and geological application*. McGraw-Hill Book Company, New York, USA, pp. 278.

Javed, S. (2010) *Design of ground source heat pump systems – thermal modelling and evaluation of boreholes.* Licentiate thesis. Chalmers University of Technology, Gothenburg, Sweden.

Javed, S., J. Claesson, R.A. Beier (2011) *Recovery times after thermal response tests on vertical borehole heat exchangers.* Proceedings of "The 23rd IIR International Congress of Refrigeration", 21.-26. August, Prague, Czech Republic, pp. 9.

Jessop, A.M. (1990) *Thermal geophysics.* Elsevier Science Publication Company, Inc., New York, NY, p.45.

Kempf, V. (2011) *Tiefe Risse in der Fauststadt – Geothermiekraftwerk löste Erdbeben aus / Erdwärmebohrungen verursachten in Staufen Millionenschäden, (Deep cracks in the town of Faust – Geothermal power plant triggers earthquake / Ground-stored heat drillings cause damage amounting to millions – in German),* Junge Freiheit, 07.01.2011, p. 22.

Kharseh, M., W. Ossiansson (2011) *Device and method for energy well.* Patent PCT/SE2010/050697.

Lubbadeh, J. (2008) *Nach Erdwärme-Bohrung – Eine Stadt zerreißt, (After ground-stored heat drilling – A town tears apart – in German),* Spiegel Online, http://www.spiegel.de/wissenschaft/natur/0,1518,589944,00.html, 15.11.2008, pp. 3.

Lund, J.W., D.H. Freeston, T.L. Boyd (2010) *Direct utilization of geothermal energy 2010 worldwide review*. Proceedings of "World Geothermal Congress", 25.-29. April, Bali, Indonesia, pp. 23.

Lutro, O., Ø. Nordgulen (2004) *Oslofeltet, berggrunnskart M 1:250 000, (The Oslo field, bedrock map 1:250 000).* Geological Survey of Norway, Trondheim, Norway.

Mackenzie, R.C. (ed., 1970) *Differential Thermal Analysis – Fundamental Aspects*. Volume 1, Academic Press, New York, USA, pp. 497.

Metz, B., O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (2007) *Summary for Policymakers*. In: Climate Change 2007: Mitigation. Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Technical report, IPCC.

Middleton, M.F. (1993) A transient method of measuring the thermal properties of rocks. *Geophysics* **58**: 357-365.

Midttømme, K., B.O. Hilmo, H. Skarphagen, A. Nissen (2000) *Kartlegging av energipotensialet i berggrunnen på kartblad Bekkestua, Bærum kommune: Varmeledningsevnen til bergarter (Mapping of the energy potential in the ground at map sheet Bekkestua, Bærum municipality: Thermal conductivity of rock types).* Geological Survey of Norway, Report 2000.036, Trondheim, Norway, pp. 105.

Midttømme, K., R.K. Ramstad, A. Solli, T. Sørdal, H. Elvebakk (2004) *Grunnvarmekartlegging i Asker og Bærum (Mapping of ground source heat in Asker and Bærum – in Norwegian).* Geological Survey of Norway, Report 2004.013, Trondheim, Norway, pp. 44.

Morland, G. (1997) *Petrology, lithology, bedrock structures, glaciation and sea level. Important factors for groundwater yield and composition of Norwegian bedrock boreholes?* Geological Survey of Norway, Report 97.122, Trondheim, Norway, pp. 274.

MTV Water Services (2011) *Ground loops – Mouvitech turbulence.* Online, http://mtvwaterservices.com/category.php?p=ground_loops, 13.01.2011.

Norges forskningsråd (2008) *Energi21 – Fornybar varme og kjøling. (Energi21 – Renewable heat and cooling – in Norwegian).* Norges forskningsråd, Oslo, Norway, pp. 61.

Philippe, M., M. Bernier, D. Marchio (2009) Validity ranges of three analytical solutions to heat transfer in the vicinity of single boreholes. *Geothermics* **38**: 407-413.

Ramstad, R.K. (2004) *Ground source energy in crystalline bedrock – increased energy extraction by using hydraulic fracturing in boreholes.* Doctoral Thesis at NTNU 2004: 161, Trondheim, Norway.

Ramstad, R.K. (2011) *Grunnvarme i Norge – kartlegging av økonomisk potensial, (Ground-stored heat in Norway – mapping of economical potential – in Norwegian).* Norges vassdrags- og energidirektoratet, NVE, Oslo, Norway, pp. 88.

Ramstad, R.K., H. de Beer, K. Midttømme, J. Koziel, B. Wissing (2008a) *Thermal diffusivity measurement at NGU – Status and method development 2005-2008.* Geological Survey of Norway, Report 2008.050, Trondheim, Norway.

Ramstad, R.K., H. Tiarks, K. Midttømme (2008b) *Ground source energy – Thermal conductivity map in the Oslo region.* Poster shown at NGU's stand at the 33rd International Geologic Congress Oslo, August 6-14th.

Raymond, J., R. Therrien, L. Gosselin, R. Lefebvre (2011) A review of thermal response test analysis using pumping test concepts. *Groundwater*, pp. 14, DOI: 10.1111/j.1745-6584.2010.00791.x.

Rybach, L, B. Sanner (2000) Ground-source heat pump systems – the European experience. *GHC Bulletin March* **2000**: 16-26.

Sanner, B. (2011) *Environmental issues*. In: Mc Corry, M., G.LI. Jones (eds) 2011. Geotrainet Training Manual for Designers of Shallow Geothermal Systems. Geotrainet, European Federation of Geologists, Brussels, p. 185-190.

Schiermeier, Q., J. Tollefson, T. Scully, A. Witze, Oliver Morton (2008) Electricity without carbon. *Nature* **454**: 820.

Shonder, J.A., J.V. Beck (1999) Determining effective soil formation properties from field data using a parameter estimations technique. *ASHRAE Transactions* **105**: 458-466.

Sims, R.E.H., R.N. Schock, A. Adegbululgbe, J. Fenhann, I. Konstantinaviciute, W. Moomaw, H.B. Nimir, B. Schlamadinger, J. Torres-Martínez, C. Turner, Y. Uchiyama, S.J.V. Vuori, N. Wamukonya, X. Zhang (2007) *Energy supply*. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, USA.

Signorelli, S., S. Bassetti, D. Pahud, T. Kohl (2007) Numerical evaluation of thermal response tests. *Geothermics* **36**: 141-166.

Spitler, J.D., P.E.C. Yavuzturk, N.K. Jain (1999) *Refinement and validation of in-situ parameter estimation models*. Short report, Oklahoma State University, Stillwater, OK, USA, pp. 6.

Spitler, J.D., C. Yavuzturk, S.J. Rees (2000) *In situ measurement of ground thermal properties*. Proceedings of Terrastock 2000, vol. 1. 28.08.-01.09.2000, Stuttgart, Germany, p. 165-170.

Spitler, J.D., L. Xing, J. Cullin, D. Fisher, J. Shonder, P. Im (2010) Residential ground source heat pump systems utilizing foundation heat exchangers. Proceedings of Clima 2010, 09.-12.05.2010, Antalya, Turkey.

Stern, N. (2006) *The Stern review report on the economics of climate change*. Cambridge University Press, UK.

Sundberg, J. (1988) *Thermal properties of soils and rocks.* Doctoral thesis, Chalmers University of Technology and University of Göteborg, pp. 310.

Theis, C.V. (1935) The relation between the lowering of the piezometric surface and the rate and duration of a well using groundwater storage. *American Geophysical Union Transactions* **16**: 519-524.

Urchueguía, J., M. Zacarés, J.M. Corberán, Á. Montero, J. Martos, H. Witte (2008) Comparison between the energy performance of a ground coupled water to water heat pump system and and air to water heat pump system for heating and cooling in typical conditions of the European Mediterranean coast. *Energy Conversion and Management* **49**: 2917-2923.

Wagner, R., C. Clauser (2005) Evaluating thermal response tests using parameter estimation for thermal conductivity and thermal capacity. *Journal of Geophysics and Engineering* **2**: 349-356.

Wang, H., C. Qi, H. Du, J. Gu (2009) Thermal performance of borehole heat exchanger under groundwater flow: A case study from Baoding. *Energy and Buildings* **41**: 1368-1373.

Witte, H.J.L. (2001) *Geothermal response test with heat extraction and heat injection: Examples of application in research and design of geothermal heat exchangers.* European workshop on geothermal response tests, 25.-26. October, Lausanne, Switzerland.

Witte, H. (2002) *Ground thermal conductivity testing: Effects of groundwater on the estimate.* Abstract. 3. Kolloquium des Arbeitskreises Geothermik der DGG, Aachen, Germany.

Witte, H. (2007) *Advances in Geothermal Response Testing.* In: Paksoy, H.Ö. (ed.), Thermal energy storage for sustainable energy consumption, Springer Netherlands, p. 177-192.

Witte, H.J.L., G.J. van Gelder, J.D. Spitler (2002) *In situ* measurement of ground thermal conductivity: the Dutch perspective. *ASHRAE Transactions* **108**: 263-272.

Witte, H.J.L., G.J. van Gelder (2006) *Geothermal response test using controlled multi-power level heating and cooling pulses (MPL-HCP): Quantifying ground water effects on heat transport around a borehole heat exchanger.*

Ecostock 2006, 10th International Conference on Thermal Energy Storage, Stocton, New Jersey, USA.

Zervantonakis, I.K., M. Reuss (2006) *Quality requirements of a thermal response test.* Proceedings of the 10th International Conference on Thermal Energy Storage ”Ecostock 2006”, Stockton, NJ, USA.

Paper 1

Reference to the paper

H.T. Liebel, K. Huber, B.S. Frengstad, R. Kalskin Ramstad and B. Brattli (2010): Rock core samples cannot replace thermal response tests - A statistical comparison based on thermal conductivity data from the Oslo Region (Norway). Proceedings of "Renewable Energy Research Conference", 7th – 8th June 2010, Trondheim, Norway, pp. 10.

Note on contributions

The candidate wrote this paper and carried out the field work together with Kilian Huber (diploma student). The candidate collected thermal conductivity data from TRTs and rock cores together with Kilian Huber. The candidate did the data analysis. Ideas and the final manuscript were discussed with the supervisors.

Rock Core Samples Cannot Replace Thermal Response Tests - A Statistical Comparison Based On Thermal Conductivity Data From The Oslo Region (Norway)

H.T. Liebel[1], K. Huber[2], B.S. Frengstad[3], R. Kalskin Ramstad[4] and B. Brattli[1]
[1] Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim; E-mail: heiko.liebel@ntnu.no
[2] Department of Geology, University of Bayreuth, Universitätsstr. 30, D-95440 Bayreuth, Germany
[3] Geological Survey of Norway (NGU), NO-7491 Trondheim
[4] Asplan Viak AS, Postbox 6723, NO-7490 Trondheim

ABSTRACT

Borehole heat exchanger (closed-loop) systems coupled to a ground-source heat pump are applied for space heating and cooling using the ground as energy source or storage medium. For accurate dimensioning of a ground-source heat installation, knowledge of the thermal conductivity of the subsurface is vital.

Thermal response tests (TRT) are widely used to measure the *in situ* thermal conductivity in a well. Alternatively, the thermal conductivity in a borehole is approximated from rock core samples based on lab measurements. Rock core data and thermal conductivity maps are financially more attractive for planning purposes than expensive TRTs. The value of both approaches was statistically tested using data from the geologically diverse Oslo region (Norway).

Effective thermal conductivity data measured *via* TRTs show a clear trend towards higher thermal conductivity values in comparison to lab measured thermal conductivity values from rock cores (in 82 % of cases). The deviation from the rock core samples, however, varies strongly as several geological layers may be represented in one single well. Furthermore, the thermal conductivity of the rock core samples varies strongly within individual geological units.

The comparison of both techniques of thermal conductivity measurement shows that the *in situ* thermal conductivity at a location cannot be predicted from rock core data of a geological unit.

The results of this study indicate that the dimensioning of a large ground-source heat project cannot be based on rock core measurements or thermal conductivity maps only, without analysing the *in situ* thermo-, hydro- and geological conditions in fractured rocks.

Keywords: Thermal response test, thermal conductivity, ground-source heat, hard rock, thermal conductivity map.

1. INTRODUCTION

The so-called "Stern review", published in 2006, was the first report focussing on the effect of global warming on the world economy. Among other things, it shows the relative greenhouse gas emissions per sector. The space-heating and cooling of buildings account for 8 % of the total greenhouse gas emissions, or possibly even 20 % if upstream emissions associated with electricity and heat are included (Stern, 2006).

Low-temperature geothermal energy applications, also called shallow geothermal energy or ground-source heat applications, are considered one of the key technologies to reduce greenhouse gas emissions in the buildings sector (Sims *et al.*, 2007).

The most common type of ground-source heat applications for space-heating and cooling in Europe is the closed-loop borehole heat exchanger system. Shallow boreholes (< 200 m) are drilled for this purpose in different kinds of rocks or unconsolidated sediments. Collector pipes, U-shaped or coaxial, are installed in the boreholes and connected to a ground-source heat pump, which helps heat to flow from a low-temperature environment to a high-temperature one. Ground-source heat pumps can effectively be switched into reverse, from heating to cooling mode, so that heat from the inside of a building is pumped away to the borehole. This is more efficient than air-to-air heat pumps in warm weather (Banks, 2008). This type of closed-loop system with a ground-source heat pump is widely used in Scandinavia for heating and cooling of single households with a single or few non-grouted boreholes. Larger buildings require more boreholes to meet the demands for heating and cooling. For the estimation of the required borehole length to deliver a certain amount of energy to a building, some ground parameters should be known, including the thermal conductivity. If the thermal conductivity for a certain rock type is assumed and not certain, some extra meters of borehole are usually drilled to avoid underdimensioning the system.

Another possibility is to perform a thermal response test (TRT) in a test well to measure the *in situ* thermal conductivity (Austin, 1998; Gehlin, 1998) and then drill the required boreholes depending on the measured value. Thermal response tests are often performed for larger ground-source heat projects. One disadvantage, however, is that it is a costly procedure.Alternatively, thermal conductivity data from rock cores may be used in planning and dimensioning of large ground-source heat installations, if these data are available.

For the Oslo region, the most densely populated area of Norway, such a database, including a thermal conductivity map, exists at the Geological Survey of Norway (NGU).
This study investigates statistically the applicability of such a thermal conductivity map for the dimensioning of large ground-source heat pump projects by comparing its entries with data from TRTs performed in the same geological units.

2. MATERIAL AND METHODS

2.1 Thermal conductivity data from rock cores

Surface rock cores from 1398 sample locations within the area of the bedrock map of the Oslo region (based on Lutro and Nordgulen, 2004) were drilled and analyzed for their thermal conductivity in the laboratory of the Geological Survey of Norway. Ramstad *et al.* (2008a) presented these data as a map showing the thermal conductivity of the different geological units of the Oslo region (Fig.1). For every geological unit a median thermal conductivity value was calculated and then given a colour according to a colour classification code. Each of the 24 geological units is represented with 10 to 219 locations.

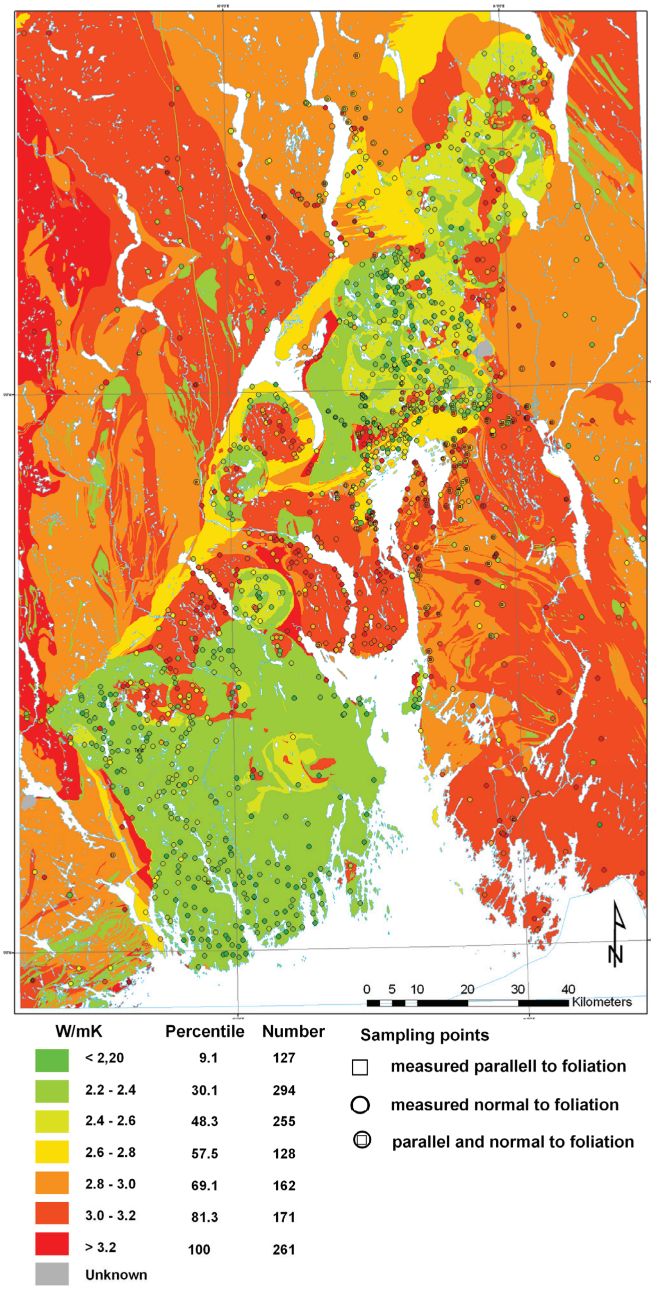


Figure 1: Median values of thermal conductivity of geological units are presented on map sheet "Oslofeltet" where sampling points indicate measured values (Ramstad *et al.* 2008a).

The laboratory procedure to estimate the thermal conductivity of a rock core follows Middleton's approach (1993) where a constant heat source (144 or 300 °C) is applied few millimeters above the vertically positioned rock core sample at room temperature. The temperature increase at the base of the rock core is measured. From the measurement of the thermal diffusivity (α) of the sample, the thermal conductivity (λ) is calculated according to equation 1.

$$\lambda = \rho C_p \alpha \tag{1}$$

where

λ: Thermal conductivity [W m^{-1}K^{-1}]
ρ: Density [kg m^{-3}]
C_p: Specific heat capacity [J kg^{-1}K^{-1}]
α: Thermal diffusivity [m^2 s^{-1}]

A detailed description of the method development and quality control routines of the thermal conductivity measurement at the laboratory at the Geological Survey of Norway is found in Ramstad *et al.* (2008b).

One drawback of the method is that fractures and fissures in the rocks are filled with water at the location but they are dry in the lab. Air has a lower thermal conductivity than water so that *in situ* measurements in water-saturated conditions should lead to slightly higher thermal conductivity values (Ericsson, 1985). Further, a strong anisotropic thermal behaviour of some rocks has been shown by Clauser and Huenges (1995) among others, where the thermal conductivity is high parallel to the foliation and low perpendicular to the foliation. The direction of foliation, however, may vary strongly in folded rocks within the same geological unit, which will give varying thermal conductivity values.

One final limitation of the dataset is that only surface bedrock cores are taken into account while several rock types may occur vertically along a borehole used for a ground-source heat pump installation.

2.2 Thermal conductivity data from thermal response tests

Thermal response tests are often applied in Scandinavia to test the *in situ* or effective thermal conductivity in a borehole. For this purpose the TRT equipment is connected to the collector pipes of the energy well. Heating elements in a portable TRT trailer heat the water that is circulating through the closed-loop system. The connection between the trailer and the borehole has to be well insulated, to avoid heat loss in cold weather or heat gain through sun irradiation. The circulation pump creates a turbulent flow in the pipes to get best heat transport from the collector towards the ground. The undisturbed ground temperature (measured before the TRT) and the temperature increase in the water during a test run are used to calculate the effective thermal conductivity of the ground (λ_{eff}) and the borehole resistance (R_b) which is from contact between the borehole heat exchanger and the well. The calculation of λ_{eff} and R_b follows the suggestions of Gehlin (2002), which are based on the infinite line source theory (Ingersoll, 1948). A TRT typically lasts 72 hours (Gehlin, 1998). In this time range the analytical solution of the infinite line source shows a very low error level compared to the alternative exact solutions of the finite line source and the infinite cylindrical source theory (Philippe *et al.*, 2009).

Possible sources of error during a TRT are: 1) heat loss and gain, 2) variable electric power supply, 3) accuracy of the determination of the undisturbed ground temperature, 4) free convection of water in non-grouted boreholes (standard for energy wells in Scandinavia; Gustafsson *et al.*, 2010), 5) gradient-driven horizontal groundwater flow and 6) density-driven vertical groundwater flow (e.g. thermosiphon effect, Gehlin *et al.*, 2003, Gustafsson, 2006).

Data from 67 standard TRTs from the Oslo region performed with the test equipment of the Geological Survey of Norway and the consulting company Geoenergi AS are statistically evaluated in this study. Statistical analyses were performed with SPSS 17.0

(SPSS, Chicago, IL, USA), box and whisker plots were calculated and drawn with SigmaPlot 11.0 (Systat Software, Chicago, IL, USA).

3. RESULTS

Median thermal conductivities of different rock types from the Oslo region measured in rock cores and in TRTs show a similar range and vary from 2.3 to 3.5 W m^{-1} K^{-1} and 2.6 to 3.7 W m^{-1} K^{-1}, respectively (see Table 1). The lowest thermal conductivity is found in monzonites and monzodiorites (quartz-poor rock). The highest values from rock cores are measured in late Silurian sandstones (quartz-rich rock) while the highest effective thermal conductivity (measured in TRTs) was found in granitic to tonalitic gneisses. The borehole resistance varies from 0.06 to 0.07 K W^{-1} m^{-1}, with the exception of one measurement in an alum shale (0.09 K W^{-1} m^{-1}). Convection occurs in non-grouted, water-filled boreholes during heat injection, which reduces the calculated borehole resistance so that a slightly higher value is expected for a ground-source heat pump system in operation during heating mode (Gustafsson *et al.*, 2010).

Table 1: Mean values for the borehole resistance, R_b, and median values of the thermal conductivity (λ) measured in TRTs ("eff") and from rock core samples ("Geomap") for 14 different rock units (Geomap number) based on the geological map 1:250 000 of Oslo (Lutro and Nordgulen, 2004). Number of analyses shown by (n).

Rock type	**R_b [K W^{-1} m^{-1}] ± SD (n)**	**λ_{eff} [W m^{-1} K^{-1}] (n)**	**λ_{Geomap} [W m^{-1} K^{-1}] (n)**	**Geomap number**
Monzonite, monzodiorite (larvikite and kjelsåsite)	0.07 (2)	2.6 (2)	2.3 (219)	14
Biotite syenite (e.g. Grefsen syenite)	0.06 ± 0.01 (7)	2.8 (8)	2.4 (58)	7
Syenite porphyry (ring-dykes)	0.06 (1)	2.9 (1)	2.5 (18)	9
Dioritic to tonalitic gneiss (in places metagabbro; 1550 Ma)	0.07 ± 0.00 (3)	3.1 (3)	3.1 (11)	42
Shale, marl and limestone, Mid to Late Ordovician age	0.07 ± 0.01 (17)	3.2 (20)	2.7 (79)	26
Mica gneiss, often with garnet, kya-nite or sillimanite (1590-1490 Ma)	0.06 ± 0.01 (8)	3.2 (8)	3.0 (91)	44
Granite, granodiorite	0.06 ± 0.01 (4)	3.3 (4)	3.0 (157)	5
Granite (ca. 925 Ma, Flå- and Iddefjordgranites)	0.07 (2)	3.4 (2)	3.2 (32)	30
Sandstone, Late Silurian age	0.07 ± 0.01 (3)	3.5 (3)	3.5 (24)	24
Latite (rhomb porphyry)	0.06 (2)	3.5 (2)	2.3 (54)	19
Limestone, shale and sandstone, Early Silurian age	0.06 ± 0.01 (8)	3.5 (8)	2.9 (48)	25
Alum shale, sandstone, conglomerate and limestone, Cambrian to Ordovician age	0.09 (1)	3.5 (1)	2.6 (13)	27
Granitic to tonalitic gneiss (1500-1550 Ma)	0.07 ± 0.01 (4)	3.7 (4)	3.0 (95)	41
Mica schist, metasandstone, amphibolite, granitic to tonalitic gneiss	0.07 (1)	3.7 (1)	2.9 (77)	50

The thermal conductivity values from the two different measurement techniques show a significant positive correlation (Pearson product-moment correlation coefficient, normally distributed data) for the 14 different investigated rock types (r = 0.534, P = 0.049, n = 14). A linear regression gives a poor fit to the dataset, however (see Fig. 2).

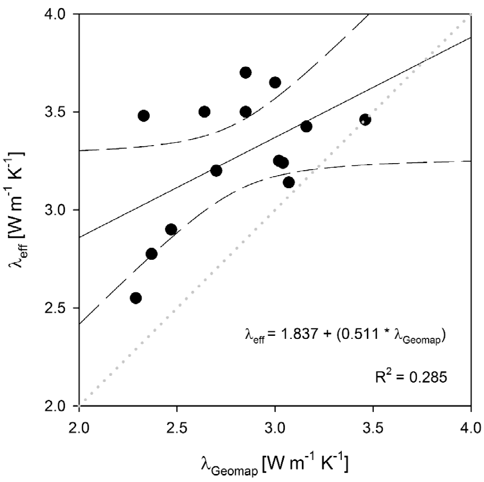


Figure 2: Median values of the thermal conductivity from TRTs (”eff”) *versus* values from rock core samples (“Geomap”) for 14 different geological units. The linear regression (solid line) is shown with 95 % confidence intervals (dashed line).

In all cases the effective thermal conductivity is higher (or equal) than the thermal conductivity measured in rock cores. If thermal conductivities from single TRT results (n = 68) are compared to the median thermal conductivity from rock cores, 82 % plot above the 1:1 line and show accordingly higher thermal conductivities compared to rock cores.

All locations of this study were classified according to the surface bedrock in sedimentary, metamorphic and igneous rocks. The single thermal conductivity measured with TRTs was then compared to the median value from rock cores as a ratio for the according rock type. All median thermal conductivity ratios are higher than 1 (Fig. 3).

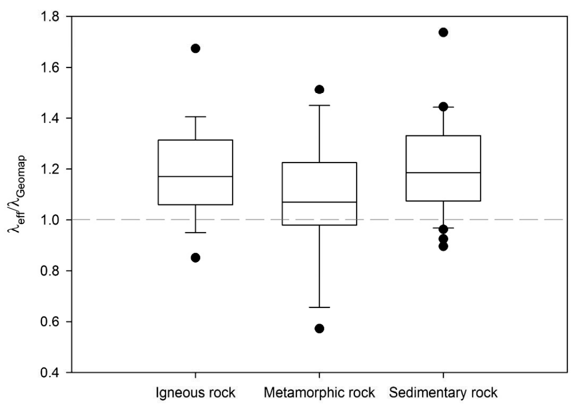


Figure 3: Box and whisker plot for the ratio between the effective thermal conductivity and the median thermal conductivity (rock core samples) for igneous (n = 19), metamorphic (n = 17) and sedimentary rocks (n = 32).

A Kruskal-Wallis nonparametric test (data are not normally distributed) shows that no significant difference (χ^2 = 1.404, df = 2, n = 68, P = 0.496) can be proven in the thermal conductivity ratios between sedimentary, metamorphic and igneous rocks. A remarkable higher variation in its thermal conductivity ratio, however, is found in metamorphic rocks. Also the median thermal conductivity ratio of the metamorphic rocks is lower than the ones of igneous and sedimentary rocks.

The dataset for effective thermal conductivity values in the Oslo region of 68 samples opposes 1843 rock core samples. Statistical comparisons and cautious interpretations are still possible. Box and whisker plots are used as descriptive statistics to compare visually the results from the rock core samples with the thermal conductivity data from TRTs. Sufficient data is available for four different geological units: Syenite (igneous rock), Silurian and Ordovician sediments and mica gneiss (metamorphic rock; Fig. 4).

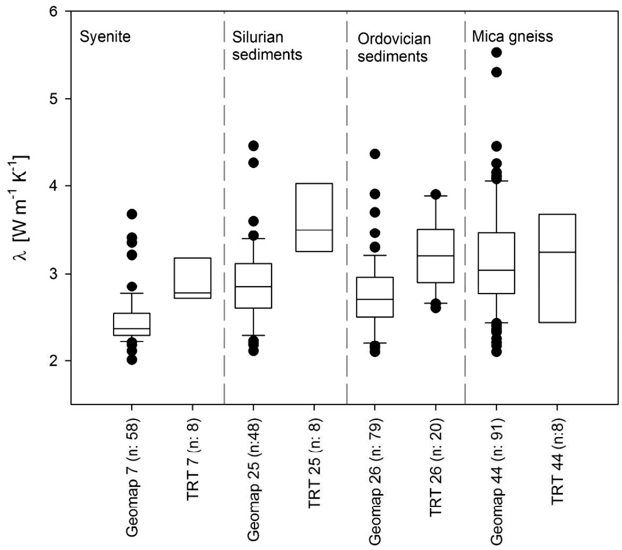


Figure 4: Statistical variations of the thermal conductivity (25 % percentile, median, 75 % percentile, whiskers indicate 10 % and 90 % percentiles if more than 9 samples are available, outliers are dotted) for four geological units of the Oslo region according to the geomap of Lutro and Nordgulen (2004) for data from rock core samples and from TRT data.

Nonparametric Mann-Whitney U tests (no equality of variance in the datasets) show that the thermal conductivities of the rock core samples are significantly different from the values measured in TRTs in syenites (Mann-Whitney U = 83.0, P = 0.003), Silurian (Mann-Whitney U = 37.0, P < 0.001) and Ordovician sediments (Mann-Whitney U = 300.0, P < 0.001). Instead, no significant difference could be found in the data for the mica gneiss (Mann-Whitney U = 322.0, P = 0.590). Large variations within the thermal conductivity measurements appear in all rock types regardless of the measurement type.

The inversed approach to search statistically for groups (e.g. cluster of entries belonging to a geological unit) within the two overall thermal conductivity datasets was done with the help of a hierarchical cluster analysis (Squared Euclidean distance, Ward's Linkage). For this purpose the effective thermal conductivity and the median rock core value of the same geological unit were chosen as input data. No pattern could be found, however.

4. DISCUSSION

Generally, the effective thermal conductivity is higher than the rock core data would suggest. Effective heat transport through groundwater advection has been shown to be the most important cause through field experiments (Witte 2002, 2007) and numerical modelling (e.g. Fujii *et al.*, 2005; Fan *et al.*, 2007). No hydraulic yield or other hydrogeological data is available for the wells of this study.

Morland (1997) however, studied well yields of wells in different geological units throughout Norway.

In syenites, he found a normalised median yield of 22.4 l hr^{-1} per drilled meter, which is one of the highest yields of the different rock types of this study. The median of the effective thermal conductivity measured in syenites is 15 % higher than the thermal conductivity from rock core samples, which may be explained by groundwater flow through fracture networks.

In Ordovician and Silurian sediments, the median of the effective thermal conductivity measured is respectively 16 and 19 % higher than the thermal conductivity from the rock core samples. Groundwater flow through fractures and karst systems in the limestones can be expected. A median normalised yield of 11.4 l hr^{-1} per drilled meter in Cambro-Silurian meta-sediments, however, is a surprisingly low value. One problem of the results of Morland (1997) is, that his group of Cambro-Silurian meta-sediments includes both stronger metamorphosed sedimentary rocks from the Caledonian mountain chain (low yields) and weakly metamorphosed sedimentary rocks of the Oslo region where higher yields are expected.

In micaceous gneisses the median effective thermal conductivity is only 6 % higher than the thermal conductivity from rock cores and the variation within the different samples of the same geological unit is the largest of all rock types of this study. Morland found a median well yield of 16.7 l hr^{-1} for Precambrian gneisses from all over Norway. Groundwater flow is expected in many wells drilled in gneisses as well. The thermal anisotropy of micas may explain the large variation in thermal properties. Clauser and Huenges (1995) investigated the thermal conductivity of biotites. They measured 3.1 W m^{-1} K^{-1} parallel to the sheets and 0.5 W m^{-1} K^{-1} perpendicular to the sheets. The orientation of the foliation in the mica gneisses is not known and it may vary along the boreholes due to folding.

An inverse approach is to classify the thermal conductivity data to find homogeneous groups belonging to one or several rock types with the help of a hierarchical cluster analysis. This approach failed, as it shows that the variability within the geological units is large and that no systematic cluster following the rock type classification can be found.

5. CONCLUSION AND FURTHER WORK

Despite the variations within individual geological units, rock core thermal conductivity values give a good qualitative indication of the effective thermal conductivity expected at a planned ground-source heat pump site. If the linear regression would yield a better fit, the regression equation could be used to predict the effective thermal conductivity of a geological unit. The data of this study, however, shows that the variations are large, due to thermal anisotropic rock properties and variable groundwater influence. The dimensioning of a high-capacity ground-source heat pump installation based on rock core data or the thermal conductivity map of the Oslo region only is not recommended, despite the extensive dataset available.

Further work could test whether a better correlation can be found if only the rock core thermal conductivity from the outcrop closest to the TRT site is used. If this succeeds, a geographic information system (GIS) could be built up that gives information about the thermal conductivity of the closest rock core sample and its distance to the planned ground-source heat site. Additionally, thermal and hydrogeological information can be made available linking relevant databases available at the Geological Survey of Norway.

ACKNOWLEDGEMENTS

The authors are thankful for having gotten access to the GEOS database of the Geological Survey of Norway. TRT data made available by Geoenergi AS, Futurum Energi AS, the Geological Survey of Norway and the Norwegian Geotechnical Institute (NGI) are gratefully acknowledged. We like to thank Båsum Boring AS for their valuable cooperation offering eight energy wells for thermal response testing and Allan Krill (Norwegian University of Science and Technology, NTNU) for giving valuable comments to the manuscript. The study was financed by the Geological Survey of Norway and the Norwegian University of Science and Technology, Trondheim.

REFERENCES

Austin, W.A., 1998, *Development of an in situ system for measuring ground thermal properties*. M.Sc. Thesis. Oklahoma State University, Stillwater. OK, USA, 177 p.

Banks, D., 2008, *An introduction to thermogeology – Ground source heating and cooling*, Blackwell Publishing Ltd., Oxford, UK, 339 p.

Clauser, C., Huenges, E., 1995, Thermal conductivity of rocks and minerals, *In*: Ahrens T.J., Rock *physics and phase relations – A handbook of pysical constants*, Am. Geophys. Union, Washington, USA: p. 105-126.

Ericsson, L.O., 1985, *Värmeutbyte mellan berggrund och borrhål vid bergvärme-system*, Dep. of Geol., Chalmers Univ. of Techn. and Univ. of Göteborg, Publ. A 52, Göteborg, Sweden.

Fan, R., Jiang, Y.Q., Yao, Y., Shiming, D., Ma, Z.L., 2007, A study on the performance of a geothermal heat exchanger under coupled heat conduction and groundwater advection, *Energy* vol. 32: p. 2199-2209.

Fujii, H., Itoi, R., Fujii, J., Uchida, Y., 2005, Optimizing the design of large-scale ground-coupled heat pump systems using groundwater and heat transport modeling. *Geothermics* vol. 34: p. 347-364.

Gehlin, S., 1998, *Thermal response test. In situ measurements of thermal properties in hard rock*, Licentiate thesis, Luleå Univ. of Techn., 1998:37.

Gehlin, S., 2002, *Thermal response test. Method development and evaluation*, Doctoral thesis, Luleå Univ. of Techn., 2002:39.

Gehlin, S.E.A., Hellström, G., Nordell, B., 2003, The influence of the thermosiphon effect on the thermal response test, Renew. *Energy,* vol. 28: p. 2239-2254.

Gustafsson, A.M., 2006. *Thermal Response Test – Numerical simulations and analyses*. Licentiate thesis. Luleå University of Technology, 2006:14, 141 p.

Gustafsson, A.M., Westerlund, L., Hellström, G., 2010, CFD-modelling of natural convection in a groundwater-filled borehole heat exchanger, *Appl. Thermal Eng*., vol. 30: p. 683-691.

Ingersoll, L.R., 1948, *Heat conduction – With engineering and geological application*, McGraw-Hill Book Comp., New York, USA. 278 p.

Lutro, O., Nordgulen, Ø., 2004, *Oslofeltet, berggrunnskart M 1:250 000*, Geol. Surv. of Nor..

Middleton, M.F., 1993, A transient method of measuring the thermal properties of rocks. *Geophysics*, vol. 58: p. 357-365.

Morland, G., 1997, *Petrology, lithology, bedrock structures, glaciation and sea level. Important factors for groundwater yield and composition of Norwegian bedrock boreholes?* Geol. Surv. of Nor., Rep. 97.122, 274 p.

Philippe, M., Bernier, M., Marchio, D., 2009, Validity ranges of three analytical solutions to heat transfer in the vicinity of single boreholes, *Geothermics* vol. 38: p. 407-413.

Ramstad, R.K., Tiarks, H., Midttømme, K., 2008a, Ground source energy – Thermal conductivity map in the Oslo region, Poster shown at the stand of the Geol. Surv. of Nor., *33rd Int. Geol. Congr. Oslo*, August 6-14th.

Ramstad, R.K., de Beer, H., Midttømme, K., Koziel, J., Wissing, B., 2008b, *Thermal diffusivity measurement at NGU – Status and method development 2005-2008*, Geol. Surv. of Nor., rep. 2008.050, 41 p.

Sims, R.E.H., Schock, R.N., Adegbululgbe, A., Fenhann, J., Konstantinaviciute, I., Moomaw, W., Nimir, H.B., Schlamadinger, B., Torres-Martínez, J., Turner, C., Uchiyama, Y., Vuori, S.J.V., Wamukonya, N., Zhang, X., 2007, Energy supply, *In*: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A., *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK and New York, USA, p. 252-322.

Stern, N., 2006, *The Stern review on the economics of climate change*, Cambridge University Press, UK, 692 p.

Witte, H., 2002, Ground thermal conductivity testing: Effects of groundwater on the estimate, Abstract, *3. Kolloquium d. Arbeitskr. Geothermik d. DGG*, Aachen, Germany, October 3rd-4th.

Witte, H., 2007, Advances in Geothermal Response Testing, *In:* Paksoy, H.Ö., *Thermal Energy Storage for Sustainable Energy Consumption*, Springer Netherlands, p. 177-192.

Paper 2

Reference to the paper

H.T. Liebel, K. Huber, B.S. Frengstad, R.K. Ramstad, B. Brattli (2010): Can rock core thermal conductivity data replace thermal response tests? Proceedings of Water and Energy Conference 2010, Amsterdam, Netherlands, 8 p.

Note on contributions

The candidate wrote this paper and collected thermal conductivity data together with Kilian Huber (diploma student). The data analysis was done by the PhD candidate. Ideas and the final manuscript were discussed with the supervisors.

Is not included due to copyright

Paper 3

Reference to the paper

H.T. Liebel, J. de Beer, B.S. Frengstad, R.K. Ramstad, B. Brattli (2012): Effect of water yield and rock thermal conductivities on TRT results. Accepted at Communicações Geológicas.

Note on contributions

The candidate wrote this paper and performed the data analysis. Johannes de Beer made available data from the Norwegian national groundwater database. Ideas and the final manuscript were discussed with the supervisors of this thesis.

Effect of water yield and rock thermal conductivities on TRT results

H.T. Liebel[1], J. de Beer[2], B.S. Frengstad[2], R. Kalskin Ramstad[3], B. Brattli[1]

[1] *Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, heiko.liebel@ntnu.no, +47 73 59 08 98, corresponding author*
[2] *Geological Survey of Norway (NGU), NO-7491 Trondheim, E-mail: hans.debeer@ngu.no, bjorn.frengstad@ngu.no, +47 73 90 40 00*
[3] *Asplan Viak AS, Postbox 6723, NO-7490 Trondheim, randik.ramstad@asplanviak.no, +47 6752 52 00*

The dimensioning of a ground-coupled heat pump project in water-filled hard rock boreholes is dependent on a proper thermal conductivity estimate of the ground.
This study aims to test if thermal conductivities calculated from thermal response tests (TRT) can be predicted with the help of well water yields and thermal conductivity maps based on rock core data. Four different rock types which are widespread in the Oslo region (Norway) were investigated.
Effective thermal conductivities measured with TRTs were higher than rock core thermal conductivities. The quantitative difference between the two thermal conductivity measures failed to be correlated with water yield data for the four rock types. Used databases of water yield, rock core and effective thermal conductivity may not be comprehensive enough and may have methodological weaknesses masking existing patterns. Water yield and effective thermal conductivity may not be related to each other, except for cases with strong local groundwater flow.

Keywords: Ground-coupled heat pump, hard rock, thermal conductivity, thermal response test, water yield.

Introduction

The knowledge of the ground thermal conductivity is a key parameter for the dimensioning of ground-coupled heat pump installations based on closed-loop borehole heat exchangers. Different strategies to obtain reliable thermal conductivity values are applied. Databases with estimates of average thermal conductivities for certain rock types can be found in literature (Horai & Simmons, 1969; Clauser & Huenges, 1995; Verein deutscher Ingenieure, 2010) and in computer simulation softwares (e.g. Earth Energy Designer). These database values rely on lab measurements of different rock types and minerals.
Recent findings, however, show that in-situ (effective) thermal conductivities measured in water-filled, non-grouted boreholes are higher than the database values from rock cores (Liebel et al., 2010). The determination of effective thermal conductivities is not only based on Fourier's law of heat conduction but also on factors that are part of the measurement procedure (e.g. buoyancy-driven conduction in the borehole, heat transfer from a borehole heat exchanger to the surroundings). The standard technique to measure the effective thermal conductivity in a borehole is the "thermal response test" (TRT) which was originally developed parallel in the USA (Austin, 1998) and Sweden (Gehlin, 1998). During the test a borehole is heated up with a heat-carrier fluid circulating through a closed-loop borehole heat exchanger (most common a single U-shaped PE tube). Based on the temperature increase during the heating phase, the thermal conductivity can be

calculated. Higher thermal conductivities measured with a TRT can often be explained with groundwater flow through the borehole or through fractures close to the borehole (Claesson & Hellström, 2000; Witte, 2002; Gehlin & Hellström, 2003; Liebel et al., 2011). The groundwater flow through fractures may be discovered in the TRT data only if large areas of the borehole are affected by the fracture flow e.g. through upwards flowing groundwater when an artesian aquifer was perforated. Then the effective thermal conductivity estimate will increase with time during an ongoing TRT. Significant groundwater flow through limited fracture zones only results in a higher effective thermal conductivity without a pronounced increase of effective thermal conductivities over time. Artefacts linked to the standard test setup occur, e.g. thermosiphon effect (Gehlin et al., 2003) and convection in the borehole due to density differences when the water column in the borehole gets heated up.

Considering that the importance of artefacts is low if only a minor heat input rate is chosen (Gustafsson & Westerlund, 2010), the higher effective thermal conductivities could be linked to the water yield of the wells. Increased water yields measured by pumping of groundwater from a well, increase the likelihood for groundwater flow in the well also during natural, undisturbed conditions.

The hypothesis to be tested is that the difference in rock thermal conductivity and effective thermal conductivity can be predicted if the water yield of wells in a certain geological unit is known. The locations of groundwater flow in the boreholes are not taken into account as these data are not available for the investigated wells. Groundwater temperatures are expected to be similar to the undisturbed ground temperatures. Data on groundwater temperatures are lacking for the investigated wells and are not taken into account.

Datasets of well water yield, effective and rock core thermal conductivity data available for the Oslo region are used for comparison. Rock core thermal conductivities were used to produce a thermal conductivity map for different geological units at the Oslo region (Ramstad et al., 2008). This study tests if effective thermal conductivities can be estimated based on the combination of database values of water yield and rock core thermal conductivities that are the basis for the above-mentioned thermal conductivity map. Predicted values may be appreciated especially in smaller ground-coupled heat pump projects where the budget does not allow for the application of an expensive TRT.

Methods

Water yield data

The Norwegian national database of energy and groundwater wells (GRANADA) is administrated by the Geological Survey of Norway (NGU). By November 2009 the database contained 50000 registered wells of which approximately two thirds included estimates about the water yield of the wells. A statistical analysis of the water yield was carried out for some of the major geological units of Norway and in particular of the region around Oslo. The results are used to improve pre-investigations of tunnel projects (Gundersen & de Beer, 2009).

The estimates of water yield are based on drillers' observations during the drilling of boreholes in hard rock aquifers. Often the water yield of the wells is a rough estimate which should be understood as an indication for the water yield rather than as a precise value. The water yield data is dependent on local conditions like the appearance of water bearing fractures that cross the well and on the groundwater level in the well at the moment of drilling. Igneous Permian dykes intersect several

rock types in the Oslo region. Their presence has been reported to increase groundwater flow in rock types affected by dykes in the Oslo region (Løset, 1981, 2002; Boge et al., 2002; Midttømme et al., 2004). The reason might be fracturing during cooling of intruding rocks.
With the help of the web-based GIS application of GRANADA, information on the water yield for single wells is available for everyone. Data of water yields were gathered of wells in the Oslo region where effective thermal conductivity data were available. For 16 wells the water yield was not reported by the driller or the report had not yet been digitized at the Geological Survey of Norway who maintains the GRANADA database.

Thermal conductivity data from rock cores

Surface rock cores from 1398 sample locations within the area of the bedrock map of the Oslo region were drilled and analyzed for their thermal conductivity in the laboratory of the Geological Survey of Norway. Ramstad et al. (2008a) presented these data as a map showing the thermal conductivity of the different geological units of the Oslo region (based on Lutro & Nordgulen, 2004). The laboratory procedure to estimate the thermal conductivity of a rock core follows Middleton's approach (1993) where a constant heat source (144 or 300 °C) is applied few millimetres above the vertically positioned rock core sample at room temperature. The temperature increase at the base of the rock core is measured. The thermal conductivity (λ) is deduced from the measurement of the thermal diffusivity (α) of the sample according to equation 1.

$$\lambda = \rho C_p \alpha \qquad (1)$$

where

λ: Thermal conductivity [W $m^{-1}K^{-1}$]
ρ: Density [kg m^{-3}]
C_p: Specific heat capacity [J $kg^{-1}K^{-1}$]
α: Thermal diffusivity [m^2 s^{-1}]

A detailed description of the method development and quality control routines of the thermal conductivity measurement at the laboratory of the Geological Survey of Norway is found in Ramstad et al. (2008b). A drawback of the method is that fractures and fissures in the rocks are filled with water at the location but they are dry in the lab. Air has a lower thermal conductivity than water so that in-situ measurements in water-saturated conditions lead to slightly higher thermal conductivity values (Ericsson, 1985). Both Clauser and Huenges (1995) and Midttømme et al. (2000) conclude that the water saturation is responsible for not more than 10 % increase in rock thermal conductivity. Further, a strong anisotropic thermal behaviour of some rocks has been shown by e.g. Clauser and Huenges (1995) and Midttømme et al. (2000; 2004) where the thermal conductivity is high parallel to the foliation and low normal to the foliation. The foliation direction, however, may vary strongly in folded rocks within the same geological unit, which will give varying thermal conductivity values (Liebel et al., 2011).
One final limitation of the dataset is that only surface bedrock cores are taken into account while several rock types may occur vertically along a borehole used for a ground-coupled heat pump installation. Midttømme et al. (2004) claim however that the variations are small in the main stratigraphy to a depth of 300 m in the study area.
For the comparison of rock core with effective thermal conductivities, the thermal conductivity value of the rock core closest to the TRT well was used. 41 % of the rock cores were collected less than 1 km from the TRT site, 52 % between 1 and 5 km and 7 % of the samples were collected farther away than 5 km from the TRT site. The average distance of the closest rock core sample from the next TRT site was 1.4 km for syenites, 2.9 km for Precambrian gneisses, 5.6 km for Silurian sediments and 5.2 km for

Ordovician sediments. It was required that both rock core sampling site and TRT site were located in the same geological unit according to the geological map of the Oslo field (Lutro & Nordgulen, 2004). In a future study rock cores might be drilled directly at the TRT site, analysed for the thermal conductivity and compared to the effective thermal conductivity obtained from TRTs (as it was done for single wells, see e.g. Liebel et al., 2011).

Thermal conductivity data from thermal response tests

Thermal response tests are often applied in Scandinavia to test the in-situ or effective thermal conductivity in a borehole. For this purpose the TRT equipment is connected to the collector pipes of the energy well. Heating elements in a portable TRT trailer warm up the heat-carrier fluid that circulates through the closed-loop system. The connection between the trailer and the borehole has to be well insulated, to avoid heat loss in cold weather or heat gain through sun irradiation. The circulation pump creates a turbulent flow in the pipes to achieve optimal heat transport from the collector towards the ground. The undisturbed ground temperature (measured before the TRT) and the temperature increase of the heat-carrier fluid during a test run are used among others to calculate the effective thermal conductivity of the ground. The calculation of the thermal conductivity follows the suggestions of Gehlin (2002), which are based on the infinite line-source theory (Ingersoll et al., 1948). A TRT typically lasts 72 hours (Gehlin, 1998).

Possible sources of error during a TRT are: 1) heat loss and gain, 2) variable electric power supply, 3) accuracy of the determination of the undisturbed ground temperature, 4) free convection of water in non-grouted boreholes (standard for energy wells in Scandinavia), 5) gradient-driven horizontal groundwater flow and 6) density-driven vertical groundwater flow.

The database of effective thermal conductivities contains data only from the Oslo region (southern Norway) and is the smallest dataset of this study. For comparison, four geological units were chosen where at least a minimum number of 8 TRTs were carried out (numbers of TRTs carried out in the different rock types can be found in Table 1): Precambrian mica gneiss, Ordovician and Silurian sediments, respectively, and Permian syenites. The geological units were chosen to investigate if the thermal conductivity value shown in the map of Ramstad et al. (2008a) can be used together with water yields to predict the effective thermal conductivity.

Results from 44 different TRTs in the Oslo region were used for the direct comparison of rock core and effective thermal conductivities in single wells depending on the water yield of the boreholes. Heat input rates were available only from 37 TRTs. No rock core data was available directly from the TRT sites.

The TRT data available for this study was provided by Geoenergi AS, Futurum Energi AS, the Geological Survey of Norway and the Norwegian Geotechnical Institute (NGI). The measurements were performed with different test equipments, heat input rates and flow rates of the circulating heat-carrier fluid. These factors add some uncertainty to the TRT data. Also the borehole depth has an influence on the TRT results as there is some thermal interaction between the collector shanks. The borehole depth varied around 200 m. Detailed information about borehole properties, however, is available only for few wells of this study.

Results and discussion

Median values of the two thermal conductivity measurements show that in situ tests result in increased thermal conductivity values (Table 1). The ratio of the median thermal conductivities (TRT/rock core) per rock type compared to the median water yield does not show a clear correlation. Mica gneiss, Silurian sediments and Ordovician sediments seem to be linearly correlated (linear regression: R^2: 0.923, n: 3, not significant due to low sample number) with the water yield while syenite would be an outlier.

Table 1. Median values of rock and TRT thermal conductivities, ratio between them and water yield for four rock types from the Oslo region (number of samples).

Rock type	$\lambda_{rock,\ median}$ (W $m^{-1}K^{-1}$)	$\lambda_{TRT,\ median}$ (W $m^{-1}K^{-1}$)	$\lambda_{TRT}/\lambda_{rock}$	Water yield, median (l hr^{-1})
Mica gneiss	3.03 (43)	3.24 (8)	1.07	600 (2655)
Silurian sediments	2.85 (48)	3.50 (8)	1.23	700 (654)
Ordovician sediments	2.70 (79)	3.20 (20)	1.19	650 (1738)
Syenite	2.38 (58)	2.78 (8)	1.17	1000 (525)

The difference in the ratio of thermal conductivities is very small while the difference in water yield of the different rock types is remarkable. The fact that the higher water yield of syenite does not result in higher effective thermal conductivity values may indicate that other phenomena have a stronger influence like the artefacts linked to the TRT procedure mentioned above or that heterogeneities are too large within the different rock types.

Figures 1 to 3 show cumulative frequency distributions for 1) water yield, 2) rock thermal conductivity and 3) effective thermal conductivity.

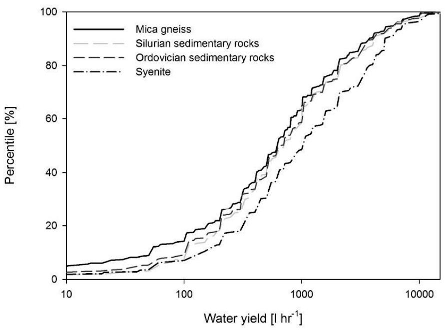


Figure 1. Frequency distribution for the water yield in four different rock types from the Oslo region.

The percentile on the y-axis shows how many values lie below a certain value on the x-axis. Figure 1 shows the probability to find a high water yield in a well in the four different rock types. In syenites the probability is highest and in mica gneisses lowest.

The frequency distributions of the thermal conductivities (figures 2 and 3) are relevant for ground-coupled heat pump projects. The dataset of thermal conductivities from rock cores is large and more representative than the dataset of effective thermal conductivities.

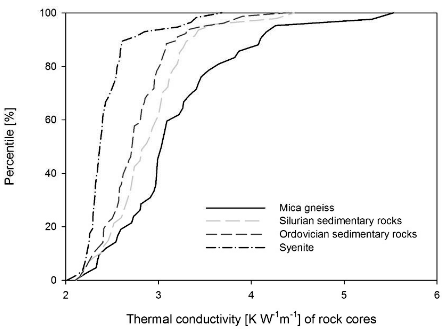


Figure 2. Frequency distribution for the rock core thermal conductivity in four different rock types from the Oslo region.

Some trends can be recognized however. Considering only syenites, Silurian sediments, and Ordovician sediments, the

probability to find high thermal conductivities in a borehole is highest in Silurian sediments and lowest in syenites. This finding is consistent for both frequency distributions (rock core and effective thermal conductivity) which indicate further that different water yields of energy wells play generally a minor role. Mica gneiss, however, shows a large variation in both rock core and TRT thermal conductivities which may be explained with varying quartz contents and anisotropic behaviour of the foliated micas (Clauser & Huenges, 1995).
Figures 1 to 3 indicate that clear trends cannot be found from data classified in geological units. Therefore, a comparison was done of rock core and effective thermal conductivity with water yield and heat transfer rate data for single boreholes at the Oslo region.

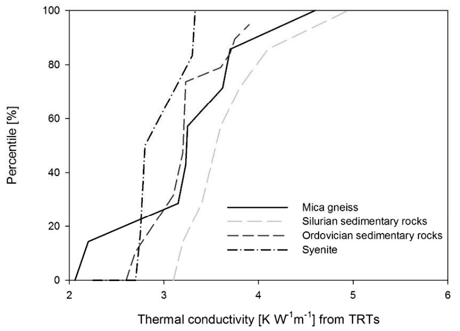


Figure 3. Frequency distribution for the TRT thermal conductivity in four different rock types from the Oslo region.

To obtain a measure with a reduced influence of the geological ground properties, the ratio between effective and rock core thermal conductivity was applied (rock core data from the closest outcrop). About 70 % of the data in figure 4 plot at values larger than one which confirms the former finding of effective thermal conductivities higher than rock core thermal conductivities. The linear regression of the overall dataset indicates an increase in the thermal conductivity ratio with increasing heat transfer rate during the TRT. The trend however is not statistically significant, probably due to a small dataset which includes unavoidable sources of error. Such errors may e.g. include the appearance of different rock types in the same borehole or the possible heterogeneity between the rock thermal conductivity at the borehole and the closest rock core found in the thermal conductivity database. Keeping those limitations in mind, the trend still indicates that the effective thermal conductivities increase with increasing heat transfer rates. The reason for this correlation may be increased convection in the borehole if the temperature difference between the borehole heat exchanger (collector tubes) and the borehole wall is large.

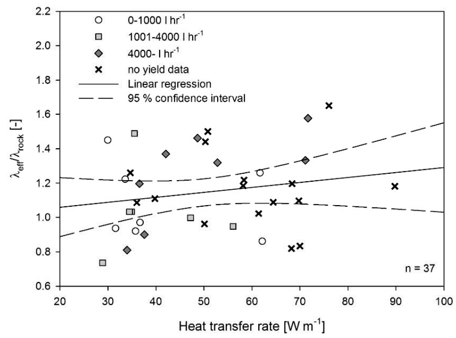


Figure 4. Thermal conductivity ratio (TRT/rock core data) versus heat transfer rate during TRTs performed in the Oslo region classified after hydraulic yield data from the according well reports. The linear regression and 95 % confidence intervals are based on the entire dataset (own data and data from Geoenergi AS, NGI and NGU). Only data are presented where the heat input rates were known, 37 samples.

Water yield classes were chosen in a way that approximately the same number of samples is present in each class (0-1000 l hr^{-1}: n = 7; 1001-4000 l hr^{-1}: n = 6; >4000 l hr^{-1}: n = 8). For the same reasons as above, no clear trends can be detected. However, the average thermal conductivity ratio is highest in the class with large water yields of more than 4000 l hr^{-1} (1.25 in comparison to 1.09 and 1.04 in the groups of 0-1000 l hr^{-1} and 1001-4000 l hr^{-1}, respectively) which may indicate a higher probability of thermosiphon effects and groundwater flow that affect the TRT results.

Conclusions

This study is a continuation of an earlier approach to statistically test if effective thermal conductivities can be predicted with the help of different thermal conductivity databases and water yield data (Liebel et al., 2010). The improvement of this investigation is that a more comprehensive and up-to-date water yield database could be used together with data of different thermal conductivity measurements.

The hypothesis that effective thermal conductivities can be predicted based on water yield and rock core thermal conductivity databases cannot be verified based on the approach of this study. The approach is simplified in terms of following the classification of the data into geological units. The approach is appropriate, however, to show that thermal conductivity maps can serve only as an indication for the effective thermal conductivity.

Different reasons may apply: a) the databases are not comprehensive enough, especially for the TRT thermal conductivities, b) each database has obvious weaknesses (see descriptions of the single measurement methods) and c) water yield and effective thermal conductivity are not related to each other, besides exceptional cases where strong local groundwater flow through open fractures or thermosiphon effects appear. Another aspect is the positive trend of effective thermal conductivities with increased heat input rates during the TRTs. A high heat input rate increases convection and further, the possibility for significant thermosiphon effects.

The study shows that thermal conductivity maps give only an indication about the values to be expected. Effective thermal conductivities measured in close-by wells to the area of interest might contain further useful information. Effective thermal conductivities might be registered centrally and in this way made public and available for drillers, ground-coupled heat pump project designers and researchers if the owners of the data agree on it, as it is the case already for e.g. for water yield data.

Acknowledgements

The authors are thankful for having access to the GEOS database (Geology in the Oslo Region) and GRANADA (national groundwater database) at the Geological Survey of Norway. TRT data made available by Geoenergi AS, Futurum Energi AS, the Geological Survey of Norway and the Norwegian Geotechnical Institute (NGI) are gratefully acknowledged. We like to thank the pre-submission readers and the reviewers of this manuscript for useful comments. The project was funded by the Norwegian University of Science and Technology (NTNU) and the Faculty of Engineering Science.

References

Austin, W.A., 1998. Development of an in situ system for measuring ground thermal properties. *M.Sc. Thesis,* Oklahoma State University, Stillwater, OK, USA, 177.

Boge, K., Åndal, T., Kjølberg, R., 2002. *Final report for the pregrouting at the T-baneringen tunnel (stage one, Ullevål-Nydalen).* Norwegian Public Roads Administration, Tunnels for the citizens, Report No. 16, 1-28.

Claesson, J., Hellström, G., 2000. Analytical studies of the influence of regional groundwater flow on the performance of borehole heat exchangers. *Proceedings of the 8th International Conference on Thermal*

Energy Storage, Terrastock 2000, Stuttgart, Germany, 195-200.

Clauser, C., Huenges, E., 1995. Thermal conductivity of rocks and minerals. In: Ahrens T.J. (Ed) *Rock physics and phase relations – A handbook of Physical Constants*. American Geophysical Union, Washington, USA, 105-126.

Ericsson, L.O., 1985. *Värmeutbyte mellan berggrund och borrhål vid bergvärme-system (Heat exchange between bedrock and well in ground-source heat systems)*. Department of Geology, Chalmers University of Technology and University of Göteborg, Publication A 52, Göteborg, Sweden, 171.

Gehlin, S., 1998. Thermal response test. In situ measurements of thermal properties in hard rock. *Licentiate thesis 1998:37*. Luleå University of Technology, Luleå, Sweden, 73.

Gehlin, S., 2002. Thermal response test. Method development and evaluation. *PhD thesis 2002:39*. Luleå University of Technology, Luleå, Sweden, 191.

Gehlin, S.E.A., Hellström, G., 2003. Influence on thermal response test by groundwater flow in vertical fractures in hard rock. *Renewable Energy,* **28**, 2221-2238.

Gehlin, S.E.A., Hellström, G., Nordell, B., 2003. The influence of the thermosiphon effect on the thermal response test. *Renewable Energy,* **28**, 2239-2254.

Gustafsson, A.-M., Westerlund, L., 2010. Multi-injection rate thermal response test in groundwater filled borehole heat exchanger. *Renewable Energy*, **35**, 1061-1070.

Gundersen, P., Beer, J. de, 2009. *Statistikk vanngiverevne i forskjellige bergarter. ForForUT deloppgave 3. Statusrapport 2009 (Statistical water yield in different rock types. ForForUT subtask 3. Status report 2009).* Geological Survey of Norway, Report 2009.066, Trondheim, Norway, 17.

Horai, K., Simmons, G., 1969. Thermal conductivity of rock-forming minerals. *Earth and Planetary Science Letters*, **6**, 359-368.

Ingersoll, L.R., Zobel, O.J., Ingersoll, A.C., 1948. *Heat conduction – With engineering and geological application*. McGraw-Hill Book Company, New York, USA, 278.

Liebel, H.T., Stølen, M.S., Frengstad, B.S., Ramstad, R.K., Brattli, B., 2011. Insights into the reliability of different thermal conductivity measurement techniques: a thermo-geological study in Mære (Norway). *Bulletin of Engineering Geology and the Environment*. DOI: 10.1007/s10064-011-0394-3, 9.

Liebel, H.T., Huber, K., Frengstad, B.S., Ramstad, R.K., Brattli, B., 2010. Can rock core thermal conductivity data replace thermal response tests? *Proceedings of "Water and Energy 2010" conference*, Amsterdam, Netherlands, 1-8.

Lutro, O., Nordgulen, Ø., 2004. *Oslofeltet, berggrunnskart M 1:250 000 (Oslo region, bedrock geological map 1:250 000).* Geological Survey of Norway, Trondheim.

Løset, F., 1981. Geological engineering experience from the sewage tunnel Lysaker – Slemmestad. *Rock Blasting Conference*, Norwegian Tunneling Association, Oslo, Norway, 31.

Løset, F., 2002. *Geology of the Norwegian tunnels*. Norwegian Geotechnical Institute, 90.

Middleton, M.F., 1993. A transient method of measuring the thermal properties of rocks. *Geophysics,* **58**, 357-365.

Midttømme, K., Hilmo, B.O., Skarphagen, H., Nissen, A., 2000. *Kartlegging av energipotensialet i berggrunnen på kartblad Bekkestua, Bærum kommune: Varmeledningsevnen til bergarter (Mapping of the energy potential in the ground at map sheet*

Bekkestua, Bærum municipality: Thermal conductivity of rock types). Geological Survey of Norway, Report 2000.036, Trondheim, Norway, 105.

Midttømme, K., Ramstad, R. K., Solli, A., Sørdal, T., Elvebakk, H., 2004. *Grunnvarmekartlegging i Asker og Bærum (Mapping of ground source heat in Asker and Bærum).* Geological Survey of Norway, Report 2004.013, Trondheim, Norway, 44.

Ramstad, R.K., Tiarks, H., Midttømme, K., 2008a. Ground source energy – Thermal conductivity map in the Oslo region. Poster shown at the stand of the Geological Survey of Norway. *33rd International Geological Congress,* Oslo, Norway.

Ramstad, R.K., de Beer, J., Midttømme, K., Koziel, J., Wissing, B., 2008b. *Thermal diffusivity measurement at NGU – Status and method development 2005-2008.* Geological Survey of Norway, Report 2008.050, Trondheim, Norway, 41.

Verein deutscher Ingenieure, 2010. *Thermal use of the underground – Fundamentals, approvals, environmental aspects.* Beuth Verlag GmbH, Berlin, Germany.

Witte, H., 2002. Ground thermal conductivity testing: Effects of groundwater on the estimate. *Abstract of "3. Kolloquium des Arbeitskreises Geothermik der DGG"*, Aachen, Germany, 1.

Paper 4

Reference to the paper

H.T. Liebel, M.S. Stølen, B.S. Frengstad, R.K. Ramstad, B. Brattli (2011): Insights into the reliability of different thermal conductivity measurement techniques: a thermo-geological study in Mære (Norway). Published at Bulletin of Engineering Geology and the Environment, DOI: 10.1007/s10064-011-0394-3; pp. 9.

Note on contributions

The candidate wrote this paper and performed the field work together with Marie S. Stølen (master student). He did the data analysis and worked with thin sections. Marie S. Stølen performed most rock core thermal conductivity measurements at the lab of the Geological Survey of Norway. XRD and DTA measurements were carried out by technicians at the Department of Geology and Mineral Resources Engineering (NTNU). Ideas and the final manuscript were discussed with the supervisors.

Is not included due to copyright

Paper 5

Reference to the paper

H.T. Liebel, K. Huber, B.S. Frengstad, R.K. Ramstad, B. Brattli (2012): Thermal response testing of a fractured hard rock aquifer with and without induced groundwater flow. Bulletin of Engineering Geology and the Environment, DOI 10.1007/s10064-012-0422-y; pp. 11.

Note on contributions

The candidate wrote this paper and carried out the field work together with Kilian Huber (diploma student). The data analysis was done by the candidate of the PhD thesis. Ideas and the final manuscript were discussed with the supervisors of this thesis work.

Is not included due to copyright

Paper 6

Reference to the paper

H.T. Liebel, K. Huber, B.S. Frengstad, R.K. Ramstad, B. Brattli (2011): Temperature footprint of a thermal response test can help to reveal thermogeological information. Norges geologiske undersøkelse Bulletin 451: 20-31.

Note on contributions

The candidate wrote this paper based on temperature profiles taken in the field together with Kilian Huber (diploma student). Ideas and the final manuscript were discussed with the supervisors.

RESEARCH ARTICLE

Temperature footprint of a thermal response test can help to reveal thermogeological information

Heiko T. Liebel[1,*], Kilian Huber[2], Bjørn S. Frengstad[3], Randi K. Ramstad[4], Bjørge Brattli[1]

[1] Norwegian University of Science and Technology, Department of Geology and Mineral Resources Engineering, 7491 Trondheim, Norway
[2] University of Bayreuth, Department of Geology, Universitätsstr. 30, 95440 Bayreuth, Germany
[3] Geological Survey of Norway, P.O.Box 6315 Sluppen, 7491 Trondheim, Norway
[4] Asplan Viak AS, Postbox 6723, 7490 Trondheim, Norway
**heiko.liebel@ntnu.no*

Borehole heat exchangers connected to a ground-coupled heat pump extract heat from the ground for the heating of buildings. Heat is transferred to the ground in cooling mode and can be extracted again during the next heating season. To dimension a large borehole field designed to meet the heating and cooling demand of a building, important ground parameters (temperature, volumetric heat capacity of the rocks, thermal conductivity, thermal borehole resistance) are needed. One important parameter is the effective thermal conductivity, which is measured with the help of thermal response tests (TRT). A temperature profile is measured before a TRT to find the undisturbed ground temperature. Rarely, temperature profiles are also measured after a finished TRT. Experience from about twenty TRTs shows, however, that important hydro- and thermogeological characteristics of the borehole may affect the measured ground parameters. These can be detected from temperature profiles after the TRT. Measuring the temperature profile in a well after a TRT can add valuable information to the study and about the nature of a borehole heat exchanger system. Four typical cases are discussed: a standard case of a borehole drilled in homogeneous and non-fractured rocks without any temperature anomaly and three more complicated cases, involving heat loss from buildings, groundwater flow through a single fracture and groundwater up-flow through the borehole from a confined artesian aquifer. Extra information about groundwater flow, open fractures and varying mineral content in the rocks can help to evaluate the TRT results and to suggest a better design of a ground-coupled heat pump installation. Based on the results of our study it is highly recommended to take temperature profiles after TRTs.

Liebel, H.T., Huber, K., Frengstad, B.S., Ramstad, R.K. and Brattli, B. (2011) Temperature footprint of a thermal response test can help to reveal thermogeological information. *Norges geologiske undersøkelse Bulletin*, **451**, 20–31.

Introduction

Geothermal energy is most often understood as heat that is accessible from the Earth's crust. This heat is mainly produced from radioactive decay of minerals but may also include residual heat from the formation of the Earth. Geothermal energy is used for electricity production in areas with an unusually high geothermal gradient (e.g., Iceland, Indonesia, Italy). These areas are mostly restricted to plate boundaries where heat is transported towards the Earth's surface via conductive and convective heat flow. A low-temperature variant of geothermal energy can be used, however, in most places and most effectively in regions with seasonal climate for the heating and cooling of buildings. In this case the energy is not generated in the ground but predominantly stored and renewed with the help of solar irradiation. A term frequently used to distinguish the heat source from pure geothermal heat is 'ground-source heat'. This term may be misleading as the main heat source is not the ground (e.g., average annual geothermal heat flux in Sweden: 0.6 kWh m^{-2}, Andersson 2011). The ground is predominantly a storage medium for the solar irradiative heat (e.g., average annual solar heat flux towards the ground in Sweden: 1500 kWh m^{-2}, Andersson 2011). Therefore, a more precise term should be used: 'ground-stored heat'.

To extract this ground-stored heat, borehole heat exchangers (PE collectors, mostly U-shaped in Scandinavia) are installed in shallow boreholes. A heat-carrier fluid circulates through the borehole heat exchanger and delivers heat to a ground-coupled heat pump which transfers the energy to the building in heating mode. In heating mode heat is removed from the rock. After a considerable removal of heat, a significant heat flow from the surface is established (Figure 1).

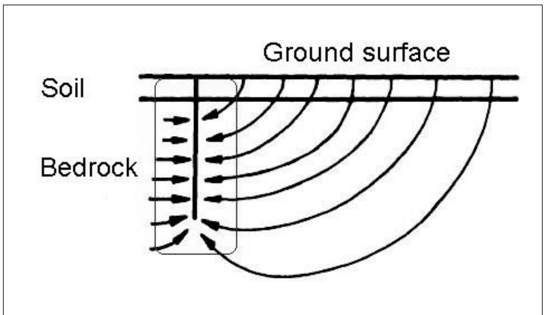


Figure 1. Energy refill around a shallow borehole from solar radiation under stationary conditions (minor geothermal refill is neglected in the figure; Nordell 2008, mod.).

Most commercial buildings have also a need for cooling in the warm season. This applies also to the Nordic countries because of the greenhouse effect of buildings with extensive glass facades or the heat production from computers and other electrical equipment. To satisfy the cooling needs, the heat pump can be reversed and heat can be transferred to the ground. This heat is then available to be brought up again in the next heating period. In this case waste energy is stored in the ground.

Ground-coupled heat pumps are used widely in single houses with a few wells and in commercial buildings or interconnected housing areas with up to 8006 boreholes like in Fort Polk (Louisiana, Hughes 2001). The largest well field in Europe until now is installed at Akershus University Hospital (Norway). There, 228 wells were drilled and furnished with borehole heat exchangers. About 40% of the building's heat load (ca. 20 GWh per year) is expected to be covered with energy mostly from ground-coupled heat pumps (www.fornybar.no, 11.04.2011).

The capacity of ground-coupled heat pumps worldwide has increased from around 1 800 MW (thermal) in 1995 to around 15 000 MW (thermal) in 2005 (Lund et al. 2005) and 35 000 MW (thermal) in 2010 (Lund et al. 2010). The market for ground-coupled heat pumps is also forced to increase in many countries as the use of renewable energy for heating and cooling of buildings is regulated by law. In new buildings in Norway, for example, technical regulation TEK07, § 8–22, requires that after 2007, 40% of the energy required for space and domestic water heating has to be delivered by other energy sources than electricity or fossil fuels.

The decision about how many metres of borehole have to be drilled to meet the heating or cooling load of a building is crucial for the successful and long-lived operation of the ground-coupled heat pump. The needed borehole length can be calculated if the thermal ground and well properties are known. Important parameters are temperature of the rock, volumetric heat capacity, thermal borehole resistance and effective thermal conductivity at a site. The knowledge of them will help to find a good compromise between costs (drilling and operation costs to run the ground-coupled heat pump system) and efficiency (supplying expected heat and cold loads). Thermal borehole resistance and effective thermal conductivity are measured with the help of a thermal response test (TRT, see Austin 1998 and Gehlin 1998). TRTs are applied as a standard procedure before a large well field is dimensioned and the results are considered to be essential for the proper dimensioning.

The objective of this study is to show the importance of temperature profiles before and after TRTs for the interpretation of the TRT results.

Before each TRT, a temperature profile is measured to find the undisturbed ground temperature which is a necessary parameter for the determination of the thermal borehole resistance (e.g., Gehlin 1998). Less attention, however, has been given so far to measure temperature profiles after a TRT. Experience from around 20 TRTs, with temperature profiles taken before and after TRTs, gives us an overview over the most common phenomena that can be observed. The temperature profiles can be grouped into four cases. Four illustrative examples are chosen where observed temperature variations and their implication on the TRT evaluation are discussed.

Materials and methods

Thermal response test

Thermal response tests are often applied in Scandinavia and many countries worldwide to evaluate the in situ or effective thermal conductivity in a borehole. For this purpose the TRT equipment is connected to the borehole heat exchanger of the energy well (PE collector pipes, most commonly U-shaped, see Figure 2).

Heating elements in a portable TRT trailer warm up the heat-carrier fluid that is circulating through the closed-loop system. The connection between the trailer and the borehole has to be well insulated, to avoid heat loss in cold weather or heat gain through sun irradiation. The circulation pump creates a turbulent flow in the pipes to get best heat transport from the collector towards the ground. The undisturbed ground temperature (measured before the TRT) and the temperature increase in the heat-carrier fluid during a test run are used to calculate the effective thermal conductivity of the ground (λ_{eff}) and the borehole thermal resistance (R_b). λ_{eff} is a parameter which integrates a) the ability of the bedrock surrounding the borehole to conduct heat (Fourier's law), b) buoyancy-driven convection in the borehole due to the heat input along the collector tubes (e.g., Gustafsson et al. 2010), and c) groundwater movement in or in the vicinity of the borehole (e.g., Gehlin et al. 2003).

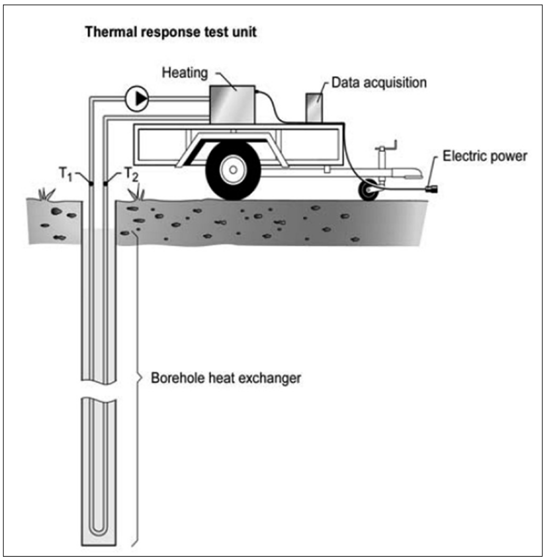


Figure 2. TRT rig connected to a borehole heat exchanger (Gehlin 2002).

The calculation of λ_{eff} follows the suggestions of Gehlin (2002) and Signorelli et al. (2007), which are based on the infinite line-source theory (Ingersoll 1948). The line-source model is based on a linear relationship between the average heat-carrier fluid in the collector and the natural logarithm of the time t, if the heat exchange rate per length unit, q, is constant (q is constant if the electric power supply to the heating elements is constant):

$$T_f(t) = k \ln(t) + m \qquad \text{[K]} \qquad (1)$$

where

$$k = \frac{q}{4\pi\lambda} \qquad \text{[K]} \qquad (2)$$

and

$$m = q\left[R_b + \frac{1}{4\pi\lambda}\left(\ln\left(\frac{4\lambda}{r_b^2 S_{VC}}\right) - 0.5722\right)\right] + T_0 \qquad \text{[K]} \qquad (3)$$

r_b is the borehole radius, S_{VC} is the volumetric heat capacity of the rock/sediment, and T_0 is the undisturbed ground temperature. The average heat carrier-fluid temperature, T_f, is calculated from the inlet and outlet temperatures, T_{in} and T_{out}:

$$T_f = \frac{T_{out} + T_{in}}{2} \qquad \text{[K]} \qquad (4)$$

The thermal conductivity λ is found by plotting T_f against the natural logarithm of the time in seconds and by reading off the slope where the conditions have stabilized (e.g., Signorelli et al. 2007; normally between 20 (t_1) and 70 hours (t_2)):

$$\lambda = \frac{q}{4\pi} \cdot \frac{\ln(t_2) - \ln(t_1)}{T_f(t_2) - T_f(t_1)} \qquad [\text{W m}^{-1}\text{ K}^{-1}] \qquad (5)$$

A TRT typically lasts 72 hours (Gehlin 1998). In this time range the analytical solution of the infinite line-source shows a very low error level compared to the alternative solutions of the finite line-source and the infinite cylindrical-source theory (Philippe et al. 2009). Different international guidelines recommend durations of at least 36 hours (IGSHPA) or 50 hours (IEA). In Germany, commonly a TRT is considered to be long enough if the estimated effective thermal conductivity does not change more than 0.1 W m^{-1}K^{-1} within 24 hours (M. Sauer, pers. comm. 2011).

In case of strong groundwater flow through the borehole, the parameters of interest (in our case: λ_{eff}) can be approximated with a parameter estimation technique which varies the unknown variables in equations 1–3 to find the best fit between calculated and measured data for time-varying heat inputs (see also Shonder and Beck 1999, Wagner and Clauser 2005, Witte 2007).

Possible sources of error during a TRT are: 1) heat loss and gain (affects T_f), 2) variable electric power supply (affects q),

3) accuracy of the determination of the undisturbed ground temperature (affects T_0), 4) free convection of water in non-grouted boreholes (standard for energy wells in Scandinavia; affects λ; Gustafsson et al. 2010), 5) gradient-driven horizontal groundwater flow (affects λ; e.g., Gehlin and Hellström 2003) and 6) density-driven vertical groundwater flow (affects λ; e.g., thermosiphon effect, Gehlin et al. 2003, Gustafsson 2006, Gustafsson and Westerlund 2010). Typical levels of confidence of TRT results are about 9% for the thermal conductivity (Zervantonakis and Reuss 2006). If thermo- or hydrogeological situations are present that alter the effective thermal conductivity measurement, temperature profiles help to interpret the obtained TRT data or help to detect the special situation.

Temperature profiles

Temperature profiles were taken directly in one shank of the single U-shaped borehole heat exchanger before each TRT to determine the undisturbed ground temperature, T_0, and four to five hours after the end of the TRT. The local heat flux is the product of thermal conductivity and temperature gradient (Fourier's law of heat conduction). The heat flux is strongest in areas where the temperature decreased most during the recovery time after the TRT. In these areas a high effective thermal conductivity can be expected due to high thermal conductivity of the bedrock or due to groundwater flow.

The depth interval was two or four metres. It is necessary to keep the measurement time of a temperature profile short to avoid a further temperature recovery during the measurement after a TRT. Measuring a temperature profile for a 200 m long borehole took about 70 minutes. The temperature recovery during the temperature measurement depends on the heat input during the TRT and the thermal properties of the borehole and the surrounding bedrock (see also Javed et al. 2011). In a study recently presented (Liebel et al. 2011), the temperature recovery in a 138 m deep borehole was registered also after the TRT was finished. The temperature dropped within the first four hours by 2.6°C. Within the next hour the temperature decrease was 0.1°C only (heat input during the TRT: 3 kW for 94 hours). The temperature recovery is very fast in the first few hours before it slows down significantly. Therefore, four to five hours after a TRT seem to be a good timing for the temperature measurement after the TRT.

Fiber optic cables have recently been applied to observe temperature variations along the entire borehole (Fujii et al. 2009, Acuña and Palm 2010). They give very good control over temperature variations and temperature developments. However, their applicability is to date restricted to research due to the high costs of the analytical equipment. Therefore, economically attractive, ordinary temperature dataloggers are used in this study.

Results and discussion

Observations at the different sites

From a dataset of about 20 TRTs performed in Norway, four illustrative cases were chosen to be discussed in this study (see Figure 3).

All cases show phenomena that can be found frequently in temperature measurements related to TRTs and they have different implications on the evaluation of the TRT results. Some general data of the TRTs are presented in Table 1.

Fredrikstad

Outcrops close to the borehole in Fredrikstad show a rather homogeneous light reddish, biotite-bearing, medium-grained Iddefjord granite, which crystallised from magma in the Precambrian around 920–930 Ma ago (Pedersen and Maaloe 1990). The granite contains quartz, biotite, orthoclase, plagioclase, some muscovite and small amounts of apatite, titanite, magnetite and zircon (Holtedahl 1953) and it is interpreted as the continuation of the Bohus granite in Sweden. Outcrops around the borehole and information from the driller's well report indicate granite along the entire borehole length.

Regional fracture zones are present but show low hydraulic conductivity because of the appearance of swelling-clay minerals due to hydrothermal alterations and/or deep weathering in

Table 1. General data of the four TRTs presented in this study.

Location	Coordinates	Altitude m a.s.l.	Borehole depth (m)	Date of TRT	λ_{eff} (W m^{-1}K^{-1})	Duration of TRT (hr)
Fredrikstad	611848 E 6565630 N	17	200	26.07.–29.07.2009	3.15	72
Nordstrand	600555 E 6637162 N	130	200	06.07.–09.07.2009	3.23	65
Lade	572043 E 7037069 N	25	150	20.09.–04.10.2009	4.11	333
Bjørnegård	583691 E 6639799 N	6	200	26.08.–30.08.2010	4.81	95

Coordinates refer to UTM zone 32, WGS84.

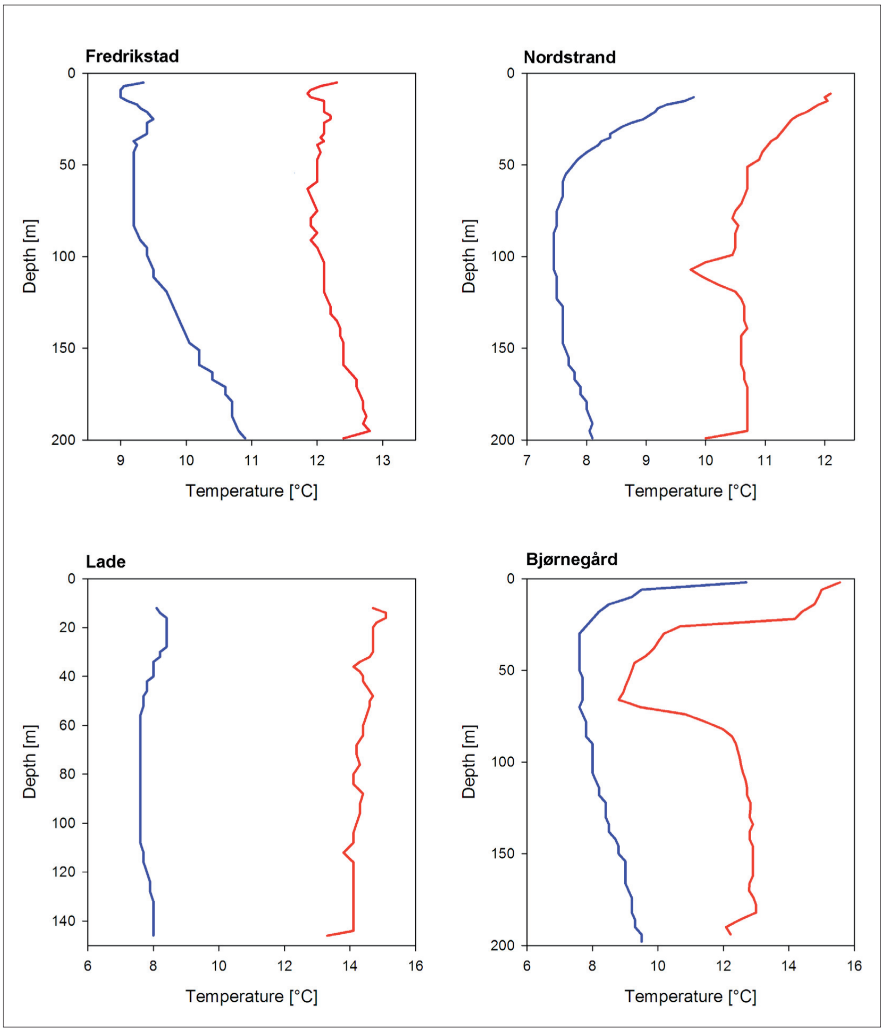


Figure 3. Temperature profiles before (blue) and after (red) a TRT at the four different study sites: Fredrikstad, Nordstrand, Lade and Bjørnegård.

the Triassic and Jurassic period (Banks et al. 1992a, b, 1994, Olesen et al. 2006).

Slagstad et al. (2009) measured a rock core thermal conductivity of 3.1 W $m^{-1}K^{-1}$ in the Iddefjord granite which is consistent with the TRT result: 3.15 W $m^{-1}K^{-1}$. The almost identical result indicates that the borehole is surrounded by granite only with negligible alteration of effective thermal conductivities due to groundwater flow. Also the temperature profile taken after the TRT supports this hypothesis (Figure 3). The uppermost ten metres of the borehole are influenced by seasonal variation while the following 60 m are influenced by (palaeo-) climatic effects as described by Slagstad et al. (2009), before a normal geothermal gradient is followed down to the base of the borehole.

The latter effects are most pronounced in the temperature profile before the TRT, but they are still detectable in the temperature profile after the TRT. The temperature profile shows no major variations along the borehole with the exception of a sudden temperature drop at the base. This effect can be explained with a stronger vertical heat flow at the bottom of the borehole due to heat flow from the sides and from below. As a consequence the cool-down is faster than in other parts of the borehole.

Nordstrand

The borehole used for the TRT at Nordstrand (borehole 3, see Figure 4) was drilled only two metres away from a large school building which dates back to the year 1926. Through the last 85 years, heat has been transferred from the building to the ground due to poor insulation.

The area around the investigated well field is dominated by garnet-rich tonalitic gneisses, a few kilometres west of the Mysen syncline (1660–1500 Ma; Graversen 1984, Lutro and Nordgulen 2008).

Sheet silicates like biotite are a main component of the gneisses at Nordstrand. They are responsible for a strong anisotropy effect in their thermal conductivity. Clauser and Huenges (1995) investigated the thermal conductivity of biotite and measured 3.1 W $m^{-1}K^{-1}$ parallel to the sheets and 0.5 W $m^{-1}K^{-1}$ perpendicular to the sheets. The strike and dip direction is expected to vary along the borehole as outcrops showed folding in the gneisses.

At an outcrop approximately 50 m west of the well field, another local rock type was discovered: a felsic pegmatite dyke (about 2 m thick). It is expected that the dyke cuts the borehole so that both gneiss and pegmatite are present in the well.

The thermal conductivity of the gneiss is expected to be somewhat lower than that of the pegmatite. Values recommended to be used in Earth Energy Designer for gneiss and pegmatite are 2.9 and 3.4 W $m^{-1}K^{-1}$, respectively (Eskilson et al. 2000). In the GEOS (GEOlogy of the OSlo region) database of the Geological Survey of Norway a median value of 3.04 W $m^{-1}K^{-1}$ for the gneiss present at Nordstrand was calculated based on 91 surface rock core samples. The effective thermal conductivity measured with the TRT in this study is 3.23 W $m^{-1}K^{-1}$ and is within the expected range. The driller's well report indicates a water-bearing fracture zone at 110–112 m depth.

Two different phenomena can be discovered while studying the two different temperature profiles related to the TRT: 1) the thermal influence of buildings on the temperature field in the ground, and 2) the presence of groundwater flow at 34 m depth.

The temperature increase in the temperature profile taken before the TRT is remarkably high in the uppermost 60 m of the borehole (see Figure 3). Therefore, three additional temperature profiles were taken in surrounding boreholes 1, 2 and 4 (see Figure 5).

The thermal disturbance in the ground decreases proportionally to the increasing distance to the main building of Nordstrand school. The same phenomenon was described for a building in Cambridge (Massachusetts, USA) where the influence was modelled to be down to almost 150 m, 50 years after the construction of the building (Roy et al. 1972). Roy et al. modelled the underground heat plume defining a Dirichlet temperature boundary condition for the building which was set to 15°C. This strategy was taken in a simple two-dimensional finite-element model for the thermal plume at Nordstrand school. The model was built up in FEFLOW 5.4 (DHI–WASY GmbH, Berlin, Germany). Using a transient model with a thermal conductivity of 3.23 W $m^{-1}K^{-1}$, a matrix porosity of 5% (used as pseudoparameter), a geothermal gradient of 0.7 K per 100 m and a simulation time of 82 years (time since the building was built), the temperatures measured in the uppermost 100 m can be simulated successfully (see Figure 6 and compare also with Figure 5).

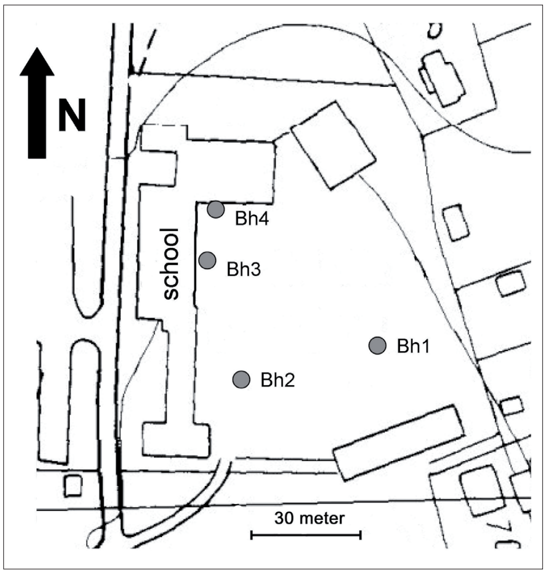


Figure 4. Map over Nordstrand school and position of boreholes (Bh) where temperature profiles were taken (map taken from www.norgeskart.no, 08.12.2009, mod.).

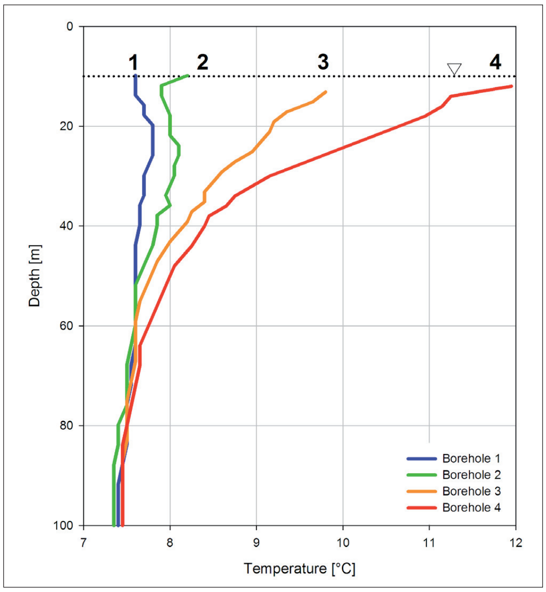


Figure 5. Temperature profiles in four boreholes at Nordstrand. The dotted line and the triangle show the groundwater level.

The heat loss through the foundations of the building over many years is significant and underlines the importance of good insulation.

Groundwater has an influence on the temperature recovery after the TRT. The driller's well report indicates a water-

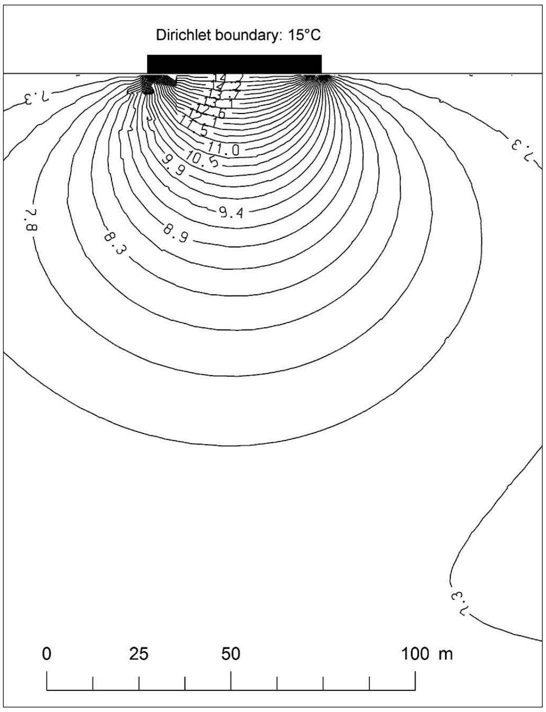


Figure 6. Simulated heat plume below Nordstrand school 82 years after the construction.

bearing fracture zone at 110 to 112 m depth and exactly there, the temperature decrease is fastest after the TRT. The effect of groundwater on the temperature profile was further investigated in a research borehole of the Geological Survey of Norway at Lade (see discussion below).

Lade

The upper 93 m of the borehole at Lade consist of Lower Ordovician greenstones while the lower part is characterised by trondhjemite based on driller's observations and an investigation with an optical televiewer. The borehole was tested for hydraulically active fractures with the help of a groundwater pump installed at 20 m depth. During pumping of water with a volumetric flow rate of 780 l hr^{-1}, a propeller was lowered in the borehole. The number of rounds per time interval can be used to detect and calculate groundwater flow through open fractures. In the depth around 34 m a pronounced fracture appears, which is visible in the flow measurement (reduction of number of rotations below 34 m) as well as in an optical televiewer image (see Figure 7). The televiewer image and the test data were made available by Harald Elvebakk who performed the measurements in 2003.

The effective thermal conductivity measured with the TRT is 4.11 W $m^{-1}K^{-1}$. This value is higher than the median rock core thermal conductivity measured in Norwegian greenstones (2.7 W $m^{-1}K^{-1}$, n=37, unpublished data, NGU) and trondhjemites (2.7 W $m^{-1}K^{-1}$, n=11, unpublished data, NGU).

The temperature profile at Lade is characterised by a negligible geothermal gradient and little variation along the borehole. However, the effective thermal conductivity measured at the borehole was higher than the laboratory measured thermal conductivities would suggest for greenstones and trondhjemites. A closer look at the temperature profile taken after the TRT reveals a faster recovery around 34 m than at the rest of the borehole (Figure 3).

As described above, the flow measurement showed a water-bearing fracture at this depth. A natural, regional groundwater flow can therefore be expected, similar as in the study of Liebel et al. (2011), which is responsible for an increased effective thermal conductivity. Even if the effect of the open fracture is rather small at Lade, it was chosen as an example because of the complete dataset comprising hydrogeological data for the borehole. A more pronounced effect of groundwater on the temperature profile than in this case can frequently be found (see e.g., Liebel et al. 2009).

Bjørnegård

The borehole at Bjørnegård (Bærum municipality, Oslo region) is drilled primarily in Ordovician limestones and shales according to the geological map and to outcrops from the area. The sedimentary cover is 28 m thick and consists of clays. The median thermal conductivity from rock core samples from the Ordovician limestones and shales is 2.7 W $m^{-1}K^{-1}$ (GEOS database, NGU 2011 unpubl.). The TRT result shows a pronounced higher effective thermal conductivity of 4.81 W $m^{-1}K^{-1}$. The driller's report indicates a water-bearing fracture at 60 to 62 m depth with a water yield of more than 1000 l hr^{-1}. The driller's estimate of the water yield for the entire borehole is 15000 l hr^{-1}. During drilling the borehole was artesian. After the drilling was finished, a tight plug was installed to stop the outflow from the borehole.

The temperature profiles at Bjørnegård show an anomalous temperature increase towards the surface (uppermost 10 m) which can be explained with two neighbouring injection wells where surface water is infiltrated into the aquifer with a total rate of ca. 38 litres per minute. Infiltration is done to avoid surface subsidence damages related to a lowered groundwater level as a consequence of the relatively new railway tunnel nearby. Figure 8 visually shows the hydrogeological situation at Bjørnegård.

The temperature profiles were taken in August 2010. The shallowest temperature field is altered due to solar irradiation on the parking lot and heat flow from the surface towards the ground (Figure 3). Elsewhere, the temperature profile before the TRT shows no unexpected variations. Very different, however, is the temperature profile after the TRT. The borehole cuts an open fracture at 60 m depth belonging to a presumably confined aquifer (artesian). Water intrudes the borehole and flows upwards to the next possibility where it can flow into the sur-

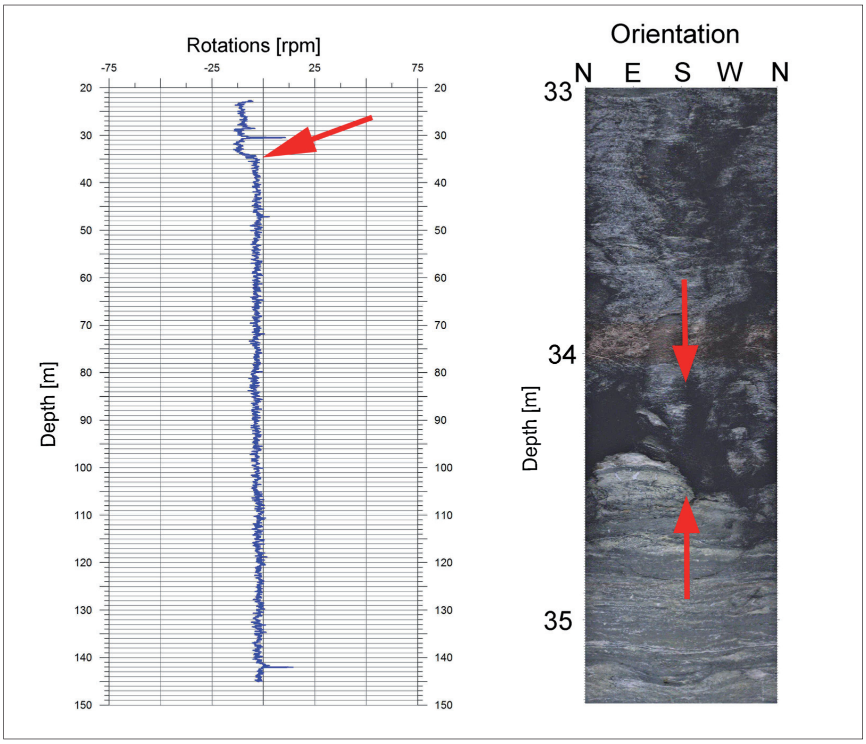


Figure 7. Results from the flow measurement (left) and optical televiewer image of the main fracture in the investigation borehole (right, H. Elvebakk, unpubl.); red arrows indicate the main fracture.

rounding formation, which is in this case at the contact between the bedrock and the sedimentary cover at about 28 m depth. Therefore, the temperatures recover fastest in the profile taken after the TRT in the interval between 60 and 28 m, while the heat takes longer to be dissipated in the other parts of the borehole. Similar temperature profiles were reported from Sweden (G. Hellström, pers. comm. 2011) and Germany (M. Sauer, pers. comm. 2011).

Conceptual models

Conceptual models of the four discussed cases are shown in Figure 9 and discussed in the following.

Case 1:

If the rocks in a borehole are homogeneous concerning mineral content and if no permeable fractures occur, a temperature profile may be measured after a TRT as shown in Figure 9. The temperature recovery after the TRT is fastest in the upper part of the borehole as the temperatures of the surrounding rocks are colder. Here the temperature gradient is largest resulting in a high heat flux according to Fourier's law. Further down in the borehole the undisturbed rock temperature increases according to a geothermal gradient. The temperature difference decreases between the heated borehole and the surrounding rock. Therefore, the temperature recovery is slow in the low part of the borehole (low heat flux). A temperature drop at the base of the borehole can be observed due to heat dissemination also in vertical direction.

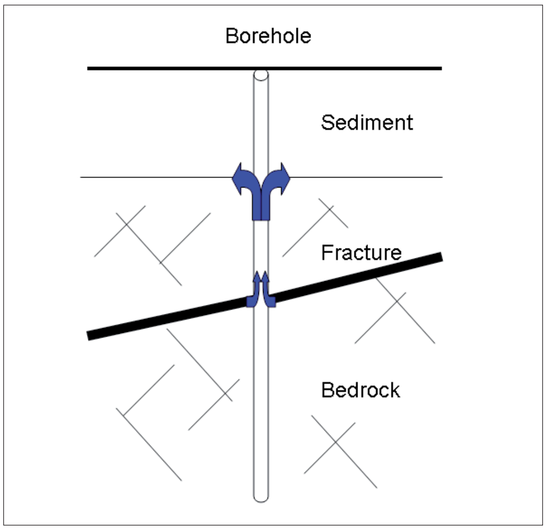


Figure 8. Schematic diagram showing the groundwater flow through the open fracture at Bjørnegård and the upward flow through the borehole with the final inflow into the sediments.

A temperature profile of this kind is the optimum for the TRT evaluation. The assumptions for the TRT analysis for example with the infinite line-source theory are met.

Case 2:
In case 2 the geological conditions are similar as in case 1 but the temperature in the upper part of the well is higher due to an increase in heat flow from the surface. Possible alterations may be due to the construction of a building with poor insulation towards the ground, a parking lot (pronounced effect with dark asphalt) or a forest clearing which increases the irradiation and the heat transfer towards the ground.

A temperature profile of this type does not implicate a special TRT evaluation. However, it gives valuable information on the expected operation of a ground-coupled heat pump installation. An increased heat transfer from the surface is positive for the heat extraction from the ground as the removed heat is restored fast from the surface.

Case 3:
If the borehole passes through a water-bearing fracture, a fast temperature recovery can be expected in the vicinity of the fracture (Figure 9).

If a temperature profile taken some hours after a TRT indicates a water-bearing fracture, the TRT results need a cautious interpretation. Groundwater flow through the borehole during the TRT can be discovered from the TRT results in certain circumstances. One possibility is that the effective thermal conductivity does not converge with time but does increase continuously (Witte 2002, 2007). If the groundwater flow volume through the open fracture is relatively small or if the total time of the TRT is chosen too short, this effect cannot be discovered

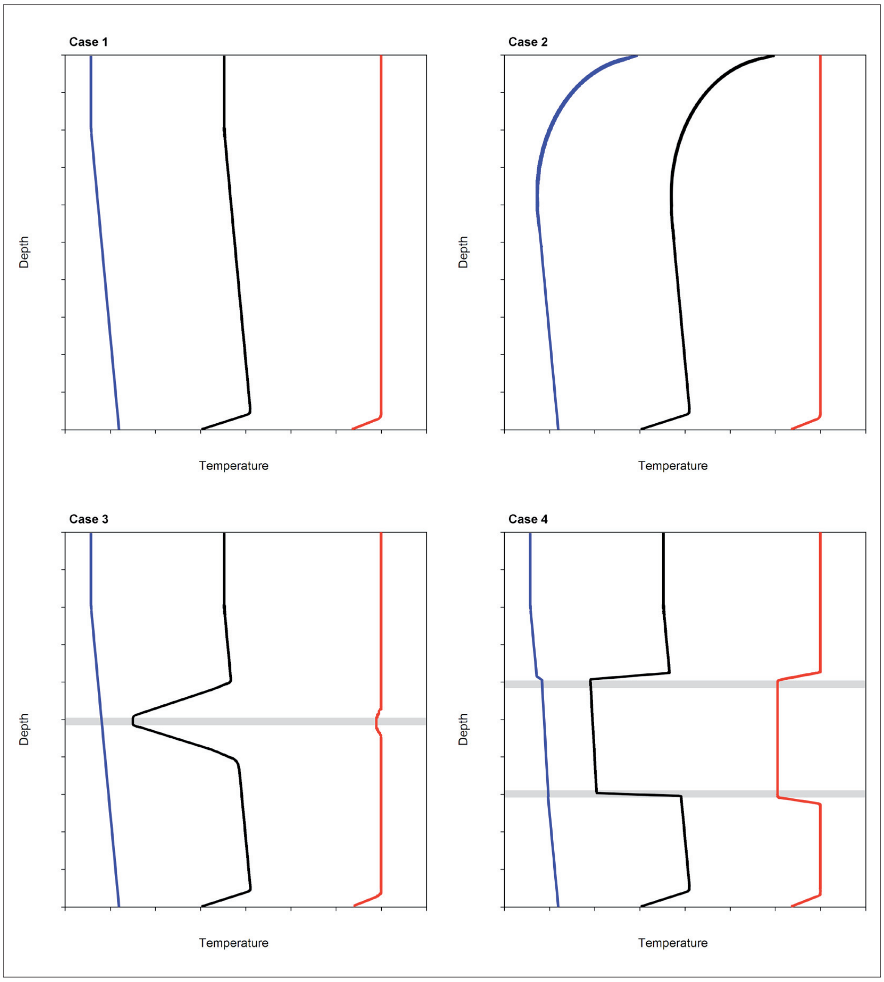


Figure 9. Fictitious temperature profiles before (blue), right after (red) and five hours after (black) a TRT in homogeneous rock for the four cases. Case 1: no water-bearing fractures; case 2: temperature anomaly towards the surface due to poorly insulated buildings or solar collectors (e.g., parking lot, pitch); case 3: one water-bearing fracture; case 4: two open fractures short-circuiting a confined lower aquifer with an unconfined upper aquifer.

in the TRT results. Results from a study in Bryn (Oslo region) show, however, that the effective thermal conductivity increased by 0.4 W $m^{-1}K^{-1}$ due to an increased groundwater flow through one fracture. In this case two TRTs were compared to each other, one without artificial groundwater flow and one with pumping of groundwater from a close-by well (for more details see Liebel et al. 2009).

Even if the groundwater flow is not detectable directly in the TRT results, it will transport heat away from the well during operation in cooling mode and it will transport heat towards the well in heating mode, which has to be taken into account for the dimensioning of a ground-coupled heat pump system.

The temperature profile after the TRT may indicate groundwater flow, even if the TRT results seem normal. In this case a more detailed hydrogeological investigation and a groundwater flow simulation should be performed to estimate the influence of groundwater on the borehole heat exchanger during operation. Parameter estimation techniques are a possibility to estimate the thermal conductivity based on the TRT results (e.g., Hellström 1997, Spitler et al. 1999).

A second explanation for a temperature profile with a fast recovery in one zone is a layer of improved thermal conductivity due to a different mineral content (for example a high quartz content). In most cases, the driller's observations of the colour of the drilling mud indicate different geological layers and mineral contents. If percussion drilling is applied, cuttings should be sampled in a regular interval (e.g., every three metres) to get more information about changing rock type and mineral content in the well. The driller's observations can be correlated to areas with fast temperature recovery in the temperature profile. In this case, the TRT results give effective thermal conductivities that converge and a standard data evaluation can be accomplished.

Case 4:

In this case the borehole penetrates two fractures where the lower one belongs to an artesian and the upper one to an unconfined aquifer. An upstream of groundwater towards the upper fracture is going to be established. Alternatively, the upper fracture can be replaced with the border between bedrock and permeable sedimentary cover.

A weaker upward flow might be established during the TRT if a thermosiphon effect appears (Gehlin et al. 2003).

The phenomenon of upwards flowing groundwater is easily discovered with the help of a temperature profile after the TRT as the temperature recovery will be fast in the area of flowing groundwater (Figure 9).

During a TRT, the temperature of the heat-carrier fluid in the borehole heat exchanger increases less if groundwater flow is present. The effect of upwards flowing groundwater on the effective thermal conductivity measurement may be stronger than of groundwater flow through fractures crossing the borehole. With up-flowing groundwater large areas of the borehole heat exchanger are affected by the contact with cold groundwater. In the case of horizontal fracture flow through the borehole, however, only limited areas of the borehole heat exchanger get in contact with cold groundwater. The measured effective thermal conductivity will be higher than the actual thermal conductivity of the bedrock in both cases, but highest in the case of upstreaming groundwater. Parameter estimation techniques are a possibility to estimate the thermal conductivity based on the TRT results (e.g., Hellström 1997, Spitler et al. 1999). For the dimensioning of a borehole field, further hydrogeological studies should be carried out, including a flow simulation for the influence area of the borehole field.

Conclusion

Temperature profiles before a TRT are taken as a standard procedure to calculate the undisturbed ground temperature and the thermal borehole resistance.

This study highlights the importance of taking temperature profiles also after the TRT is finished.

The temperature profiles yield important hydro- and thermogeological information based on a measurement that takes only about one hour. The driller's reports give an indication for areas of high probability for open fractures only. In the temperature profile after the TRT, the water-bearing fractures can be located precisely. Upcoming groundwater from confined artesian aquifers can be detected clearly. Layers of different mineral content showing varying thermal conductivities can be located and distinguished from zones of groundwater flow with the help of the driller's well reports.

Information gained from temperature profiles after a TRT, supplements the data obtained from various other sources such as: TRT, the driller's well report, rock core thermal conductivity measurements, the measurement of the undisturbed ground temperature, the geological map and so forth. The combined evaluation of all data available for a borehole can then be used to define the required capacity of a ground-coupled heat pump system and to predict the behaviour of the plant in operation. The extra information gained helps also to decide whether further site investigations or groundwater flow simulations are needed. Further work should focus on the quantification of the influence of groundwater flow on the estimate for the effective thermal conductivity.

Acknowledgements

We would like to thank the pre-submission readers and the reviewer of this manuscript (Bjarni R. Kristjànsson, NGI) for useful comments. The authors thank Båsum Boring AS for offering access to boreholes at Fredrikstad and Nordstrand and to AsplanViak for offering a borehole at Bjørnegård to be used for our scientific investigation. We are grateful to the Geological

Survey of Norway (NGU) for letting us use their TRT equipment and investigate their research borehole at Lade. Allan Krill (NTNU) corrected the English. The project was funded by the Norwegian University of Science and Technology (NTNU) and the Faculty of Engineering Science and Technology.

References

Acuña, J. and Palm, B. (2010) A novel borehole heat exchanger: Description and first distributed thermal response test measurements. Proceedings World Geothermal Congress 2010, Bali, Indonesia, 25–29 April 2010, 7 pp.

Andersson, O. (2011) Chapter 2 - Limitations. *In* McCorry, M. and Jones, G.L. (eds.) Geotrainet training manual for designers of shallow geothermal systems. Geotrainet, European Federation of Geologists, Brussels, pp. 15–20.

Austin, W.A. (1998) *Development of an in situ system for measuring ground thermal properties*. MSc thesis, Oklahoma State University, Stillwater, OK, USA, 164 pp.

Banks, D., Solbjørg, M.L. and Rohr-Torp, E. (1992a) Permeability of fracture zones in a Permian granite. *Quarterly Journal of Engineering Geology*, **25**, 377–388.

Banks, D., Rohr-Torp, E. and Skarphagen, H. (1992b) An integrated study of a Precambrian granite aquifer, Hvaler, Southeastern Norway. *Geological Survey of Norway, Bulletin*, **422**, 47–66.

Banks, D., Rohr-Torp, E. and Skarphagen, H. (1994) Groundwater resources in hard rock; experiences from the Hvaler study, southeastern Norway. *Applied Hydrogeology*, **94**, 33–42.

Clauser, C. and Huenges, E. (1995) Thermal conductivity of rocks and minerals. *In* Ahrens, T.J. (ed.) *Rock physics and phase relations–A handbook of pysical constants*. American Geophysical Union, Washington, USA, pp. 105–126.

Eskilson, P., Hellström, G., Claesson, J.,Blomberg, T. and Sanner, B. (2000) *Earth Energy Designer version 2.0*. Blocon software, Sweden.

Fujii, H., Okubo, H. and Chono, M. (2009) Application of optical fiber thermometers in thermal response tests for detailed geological descriptions. Proceedings of Effstock 2009 Conference on Thermal Energy Storage for Efficiency and Sustainability, Stockholm, Sweden, 6 pp.

Gehlin, S. (1998) Thermal response test. *In situ measurements of thermal properties in hard rock*. Licentiate thesis, Luleå University of Technology, 1998:37, 73 pp.

Gehlin, S. (2002) Thermal response test. *Method development and evaluation*. PhD thesis, Luleå University of Technology, 2002:39, 191 pp.

Gehlin, S.E.A. and Hellström, G. (2003) Influence on thermal response test by groundwater flow in vertical fractures in hard rock. *Renewable Energy*, **28**, 2221–2238.

Gehlin, S.E.A., Hellström, G. and Nordell, B. (2003) The influence of the thermosiphon effect on the thermal response test. *Renewable Energy*, **28**, 2239–2254.

Graversen, O. (1984) Geology and structural evolution of the Precambrian rocks of the Oslofjord-Øyeren area, southeast Norway. G*eological Survey of Norway Bulletin*, **398**, 1–49.

Gustafsson, A.M. (2006) *Thermal Response Test–Numerical simulations and analyses*. Licentiate thesis, Luleå University of Technology, 2006:14, 118 pp.

Gustafsson, A.M. and Westerlund, L. (2010) Multi-injection rate thermal response test in groundwater filled borehole heat exchanger. R*enewable Energy*, **35**, 1061–1070.

Gustafsson, A.M., Westerlund, L. and Hellström, G. (2010) CFD-modelling of natural convection in a groundwater-filled borehole heat exchanger. *Applied Thermal Engineering*, **30**, 683–691.

Hellström, G. (1997) Thermal response test of a heat store in clay at Linköping, Sweden. Proceedings of Megastock '97, Sapporo, Japan, pp. 115–120.

Holtedahl, O. (1953) *Norges geologi. Bind I*. Aschehoug & Co. Oslo, Norway, 583 pp.

Hughes, P.J. (2001) Geothermal heat pumps as a cost saving and capital renewal tool. E*nergy Engineering*, **98**, 59–80.

Ingersoll, L.R. (1948) *Heat conduction–With engineering and geological application*. McGraw-Hill Book Company, New York, USA, 278 pp.

Javed, S., Claesson, J. and Beier, R.A. (2011) Recovery times after thermal response tests on vertical borehole heat exchangers. Proceedings of The 23rd IIR International Congress of Refrigeration, Prague, Czech Republic, 9 pp.

Liebel, H.T., Huber, K., Frengstad, B.S., Ramstad, R.K. and Brattli, B. (2009) Thermogeology in the Oslo region and Kristiansand–Results from thermal response tests (TRT) with and without artificially induced groundwater flow. *NGU Report 2009.069*, 57 pp.

Liebel, H.T., Stølen, M.S., Frengstad, B.S., Ramstad, R.K. and Brattli, B. (2011) Insights into the reliability of different thermal conductivity measurement techniques: a thermo-geological study in Mære (Norway). *Bulletin of Engineering Geology and the Environment*, DOI: 10.1007/s10064-011–0394-3, 9 pp.

Lund, J.W., Freeston, D.H. and Boyd, T.L. (2005) World-wide direct use of geothermal energy 2005. Proceedings of World Geothermal Congress 2005, Antalya, Turkey, 20 pp.

Lund, J.W., Freeston, D.H. and Boyd, T.L. (2010) Direct utilization of geothermal energy 2010 worldwide review. Proceedings of World Geothermal Congress 2010, Bali, Indonesia, 23 pp.

Lutro, O. and Nordgulen, Ø. (2008) Oslofeltet, Bedrock geological map, scale 1:250,000, *Geological Survey of Norway*.

Nordell, B. (2008) Bergvärme och bergkyla–princip och funktion. Presentation at Informations- och utbildningsdagar, Föreningarna Byggnads och VVS-inspektörer, 8th of May 2008, Uppsala, Sweden.

Olesen, O., Dehls, J.F., Ebbing, J., Henriksen, H., Kihle, O. and Lundin, E. (2006) Aeromagnetic mapping of deep-weathered fracture zones in the Oslo Region–a new tool for improved planning of tunnels. *Norwegian Journal of Geology*, **87**, 253–267.

Pedersen, S. and Maaloe, S. (1990) The Iddefjord granite: geology and age. *Geological Survey of Norway Bulletin*, **417**, 55–64.

Philippe, M., Bernier, M. and Marchio D. (2009) Validity ranges of three analytical solutions to heat transfer in the vicinity of single boreholes. Geothermics, **38**, 407–413.

Roy, R.F., Blackwell, D.D. and Decker, E.R. (1972) Continental heat flow. Chapter 19. *In* Robertson, E.C. (ed.) *The Nature of the Solid Earth*, McGraw Hill, New York, USA, pp. 506–544.

Shonder, J.A. and Beck J.V. (1999) Determining effective soil formation properties from field data using a parameter estimations technique. *ASHRAE Transactions*, **105**, 458–466.

Signorelli, S., Bassetti, S., Pahud, D. and Kohl, T. (2007) Numerical evaluation of thermal response tests. *Geothermics*, 36, 141–166.

Slagstad, T., Balling, N., Elvebakk, H., Midttømme, K., Olesen, O., Olsen, L. and Pascal, C. (2009) Heat-flow measurements in Late Paleoproterozoic to Permian geological provinces in south and central Norway and a new heat-flow map of Fennoscandia and the Norwegian-Greenland Sea. T*ectonophysics*, **473**, 341–361.

Spitler, J.D., Yavuzturk, P.E.C. and Jain, N.K. (1999) Refinement and validation of in-situ parameter estimation models. Short report, Oklahoma State University, 6 pp.

Wagner, R. and Clauser, C. (2005) Evaluating thermal response tests using parameter estimation for thermal conductivity and thermal capacity. *Journal of Geophysics and Engineering*, **2**, 349–356.

Witte, H. (2002) Ground thermal conductivity testing: Effects of groundwater on the estimate. Abstract. 3. Kolloquium des Arbeitskreises Geothermik der DGG, Aachen, Germany, 1 pp.

Witte, H. (2007) Advances in Geothermal Response Testing. *In* Paksoy, H.Ö. (ed.) *Thermal Energy Storage for Sustainable Energy Consumption*, Springer, Netherlands, pp. 177–192.

Zervantonakis, I.K. and Reuss, M. (2006) Quality requirements of a thermal response test. Proceedings of the 10th International Conference on Thermal Energy Storage 'Ecostock 2006', Stockton, NJ, USA, 7 pp.

Paper 7

Reference to the paper

Liebel, H.T., S. Javed, G. Vistnes (2012): MIR-TRT with forced convection in a groundwater-filled borehole in hard rock. Accepted at Renewable Energy (Elsevier).

Note on contributions

The candidate wrote this paper based on two MIR-TRTs performed together with Gunnar Vistnes. The data analyses were performed by S. Javed and the main author. Parameter estimation and numerical models were run by S. Javed in Gothenburg (Sweden).

Is not included due to copyright

Appendix A on CD (attached to the thesis):

I) Geological Survey of Norway, Report 2009.069

Reference to the report:

H.T. Liebel, K. Huber, B.S. Frengstad, R. Kalskin Ramstad and B. Brattli, 2009: Thermogeology in the Oslo region and Kristiansand – Results from thermal response tests (TRT) with and without artificially induced groundwater flow. Geological Survey of Norway, Report 2009.069, 57 p.

II) Three videos showing vertical groundwater movement in the borehole:

a. *Video 1 No heating.avi*
   → no significant groundwater movement

b. *Video 2 No pumping 83 Wm-1.avi*
   → convective flow, mostly upstream along the borehole heat exchanger, mostly downstream along the cold borehole wall)

c. *Video 3 Pumping 94 Wm-1.avi*
   → dominating downstream flow towards the groundwater pump installed at the bottom of the borehole

Appendix B: Combined thermal conductivity data (TRT and rock cores) from the Oslo region

Coordinate TRT site (UTM)	λ_{eff} [W m^{-1} K^{-1}]	R_b [K m W^{-1}]	Geomap number	Rock type	$\lambda_{Median, Geomap}$ [W m^{-1} K^{-1}]	$\lambda_{closest\ rock\ core}$* [W m^{-1} K^{-1}]	Distance to site [km]	Coordinate closest site (UTM)
32 570997 6628746	3.9	0.07	5	granite	3.02	3.39	1.2	32 571865 6627969
32 579456 6623808	3.2	-	5	granite	3.02	3.39	13.6	32 579499 6610070
32 570974 6618333	3.2	0.07	5	granite	3.02	2.93	0.7	32 570299 6618500
32 572327 6602799	3.3	0.065	5	granite	3.02	3.12	2.8	32 574978 6601884
32 604115 6648386	2.8	0.06	7	syenite	2.37	2.3	1.2	32 605278 6648589
32 606030 6649715	2.75	0.07	7	syenite	2.37	2.76	0.28	32 605756 6649656
32 603796 6647709	2.25	0.06	7	syenite	2.37	2.34	0.8	32 603207 6648181
32 606915 6649372	3.3	0.07	7	syenite	2.37	2.41	0.2	32 606708 6649503
32 599628 6648930	2.8	0.07	7	syenite	2.37	2.34	0.7	32 600287 6648704
32 591736 6646817	3.33	0.06	7	syenite	2.37	3	1.9	32 589933 6647658
32 604520 6648850	2.7	0.07	7	syenite	2.37	2.18	0	32 604520 6648850
32 568505 6610476	2.9	0.07	9	syenite porphyry	2.47	1.96	6.6	32 561885 6610802
32 580260 6565951	3.15	0.08	14	larvikite (syenite)	2.29	2.1	3.14	32 583077 6567607
32 579975 6568971	1.95	0.07	14	larvikite	2.29	2.03	2.9	32 577872 6571017
32 582006 6581860	3.06	-	19	rhomb porphyry	2.33	2.11	6.5	32 583143 6587704
32 569274 6624254	3.9	0.05	19	rhomb porphyry	2.33	3.3	3.5	32 566271 6622404
32 583649 6643494	3.2	0.06	24	sandstone	3.46	2.40	0.4	32 583649 6643494
32 584424 6642346	3.1	0.065	24	sandstone	3.46	3.6	0.8	32 584031 6642980
32 573185 6658747	3.7	0.07	24	sandstone	3.46	3.1	0.2	32 573036 6658840
32 579102 6633443	4.95	0.07	25	limestone	2.85	3.00	0.12	32 579000 6633371
32 580471 6633117	3.6	0.055	25	limestone	2.85	2.5	0	32 580471 6633117
32 580742 6633512	3.2	0.05	25	limestone	2.85	2.7	0.7	32 580882 6632798
32 584429 6641934	4.1	0.04	25	limestone	2.85	2.6	0.6	32 585109 6641902
32 579536 6632972	3.1	0.09	25	limestone	2.85	3	0.7	32 579000 6633371
32 588678 6727726	3.8	0.07	25	limestone	2.85	3.1	36.85	32 579641 6689240
32 579218 6633502	3.4	0.05	25	limestone	2.85	3	0.25	32 579000 6633371

Coordinate TRT site (UTM)	λ_{eff} [W m^{-1} K^{-1}]	R_b [K m W^{-1}]	Geomap number	Rock type	$\lambda_{Median, Geomap}$ [W m^{-1} K^{-1}]	$\lambda_{closest\ rock\ core}$* [W m^{-1} K^{-1}]	Distance to site [km]	Coordinate closest site (UTM)
32 591697 6644080	2.7	0.088	26	limestone	2.7	3.00	1.1	32 590657 6644424
32 591370 6735349	3.23	0.075	26	limestone	2.7	2.17	26	32 615126 6722846
32 597902 6643863	3.2	-	26	limestone	2.7	2.82	3.75	32 601651 6644181
32 599252 6647513	3.2	0.05	26	limestone	2.7	2.94	1.2	32 600424 6647714
32 598106 6644571	3.1	0.07	26	limestone	2.7	3.03	3	32 600392 6642634
32 600102 6642450	3.6	0.05	26	limestone	2.7	2.68	0.35	32 600392 6642634
32 598367 6644960	3.9	0.07	26	limestone	2.7	3.42	3.8	32 598107 6648752
32 598437 6646482	2.8	0.05	26	limestone	2.7	3.42	2.3	32 598107 6648752
32 593786 6642032	3.1	0.06	26	limestone	2.7	2.46	0.8	32 593048 6642320
32 583069 6627508	2.65	0.07	26	limestone	2.7	2.88	2.7	32 583683 6630134
32 599029 6647704	3.2	0.07	26	limestone	2.7	3.42	1.4	32 598107 6648752
32 595707 6643502	3.9	0.07	26	limestone	2.7	2.46	2.9	32 593048 6642320
32 598562 6646940	3.2	0.07	26	limestone	2.7	3.21	1.8	32 598107 6648752
32 533303 6561726	3.75	0.065	26	limestone	2.7	2.8	15	32 539272 6548099
32 597455 6645128	3.7	0.07	26	limestone	2.7	2.96	3.2	32 596831 6648311
32 598149 6644592	3.1	0.07	26	limestone	2.7	2.78	3.5	32 601651 6644181
32 597906 6643863	2.9	0.04	26	limestone	2.7	2.67	2.8	32 600392 6642634
32 583541 6637658	2.6	0.07	26	limestone	2.7	2.3	0.3	32 583341 6637452
32 596816 6646916	3.2	0.065	26	limestone	2.7	3.09	1.4	32 596831 6648311
32 592526 6738709	2.9	0.066	26	limestone	2.7	2.17	27.6	32 615126 6722846
32 611632 6741525	3.5	0.06	27	alum shale, limestone	2.64	2.64	49	32 581036 6702523
32 611848 6565630	3.15	0.065	30	granite	3.16	2.50	2.5	32 610015 6563904
32 610357 6567912	3.7	0.055	30	granite	3.16	3.37	1.8	32 609490 6566330
32 603564 6640107	2.85	0.07	41	gneiss	3	3.01	0.8	32 603595 6640888
32 599766 6640254	3.7	0.06	41	gneiss	3	3.12	1.6	32 598800 6641600
32 601222 6627613	4.3	0.07	41	gneiss	3	2.32	1.3	32 601766 6626486
32 596107 6599226	3.6	0.07	41	gneiss	3	3.54	0.7	32 595814 6598601
32 611499 6645632	3.1	0.06	42	dioritic gneiss	3.07	2.35	0.5	32 611047 6645739
32 611499 6645632	3.68	0.07	42	dioritic gneiss	3.07	2.35	0.5	32 611047 6645739
32 611499 6645632	3.14	0.07	42	dioritic gneiss	3.07	2.35	0.5	32 611047 6645739
32 609219 6645171	3.4	0.08	42	gneiss	3.07	2.78	0.8	32 610005 6645450

Coordinate TRT site (UTM)	λ_{eff} [W m^{-1} K^{-1}]	R_b [K m W^{-1}]	Geomap number	Rock type	$\lambda_{Median, Geomap}$ [W m^{-1} K^{-1}]	$\lambda_{closest\ rock\ core}$* [W m^{-1} K^{-1}]	Distance to site [km]	Coordinate closest site (UTM)
32 616946 6642954	3.62	0.08	44	gneiss	3.04	3.33	3.7	32 615272 6644583
32 599141 6639526	3.25	0.06	44	gneiss	3.04	3.08	3.9	32 599090 6633430
32 633629 6604158	3.7	0.06	44	gneiss	3.04	3.09	2.9	32 633155 6607034
32 605035 6645481	2.06	-	44	gneiss	3.04	2.8	3.3	32 608120 6644271
32 601788 6632655	2.2	0.07	44	mica gneiss	3.04	2.46	0.2	32 601720 6632480
32 607478 6653846	3.15	0.06	44	mica gneiss	3.04	3.82	3.3	32 609410 6651214
32 611467 6648767	4.6	0.06	44	mica gneiss	3.04	2.84	1.9	32 611400 6646885
32 583649 6643494	3.23	0.09	44	gneiss	3.04	3.33	4.1	32 600603 6641316

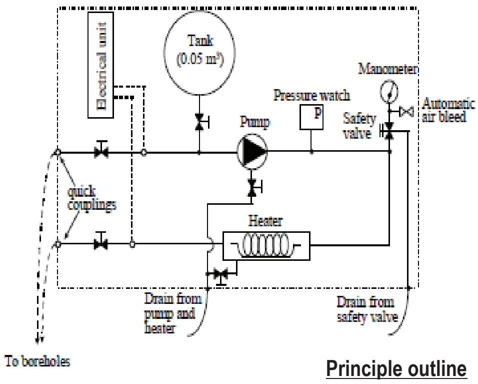
*: closest sampling site for rock cores within the same geological unit as the TRT

Appendix C: Technical data about the TRT trailer

Thermal Response Test Equipment Data	**Fill-in Date:** *10-2010*
Country: Norway	
Contact Person: Gaute Storrø, Heiko Liebel	
Organisation/Company: Norges geologiske undersøkelse	
Address: Postboks 6315 Sluppen, 7491 Trondheim, Norway	
Phone: +47 73904315	
Email: gaute.storro@ngu.no; heiko.liebel@ntnu.no	

GENERAL TRT DATA

Type: *Heat injection*	**No TRTs:** *~50*	**Size, weight:** *400 cm, 180 cm, 190 cm, 540 kg*
Aim: *Research /commercial*		**Pump:** *Duijvelaar DPV 10-80; 3kW, 2.5 l/s*
Powered by: *Electricity*		**Heater:** *Värmebaronen EK 180-12S, 8 x 3 kW*
Built on/in: *Trailer*		**HP/Cooler:** -



<u>**Principle outline**</u>

- **Temperature measurements:** *Thermocouples*
- **Flow rate measurements:** *ABB Kent Messtechnik MTH-DA-KGm-HM*
- **Voltage stabilization:** *No*
- **Supply Power Monitoring:** *Yes*
- **GPS:** *No*
- **Remote Control of Operation:** *Yes*
- **Remote Data Collection:** *Yes*
- **Logger:** *CTRX10*

TRT EXPERIENCE

Years of operation: *since 2000*

Number of performed measurements: *~35 Research/ ~15 commercial*

Typical borehole depths: *100 – 400 m*

Applications: *BHE*

Typical collector type: *1U, 2U*

Typical fluid type: HX35

Typical groundwater temperature: *4-8 °C*

Geographical area: *Norway*

Analysis Method: *Line source*

Appendix D: Contributions to conferences and workshops

Scientific results were presented at the following conferences and workshops:

a) *The 33rd International Geological Congress*, Oslo, Norway, 2008 (poster)

b) *IEA Annex 21 – TRT: Experts' Meeting*, Vienna, Austria, 2008 (oral presentation)

c) *Effstock 2009 – Thermal Energy Storage for Efficiency and Sustainability*, Stockholm, Sweden, 2009 (poster)

d) *18th National Seminar on Hydrogeology and Environmental Geochemistry*, Trondheim, Norway, 2009 (poster; award for the best student poster)

e) *1st European Geothermal PhD Day*, Potsdam, Germany, 2010 (poster and short oral presentation)

f) *Renewable Energy Research Conference*, Trondheim, Norway, 2010 (poster and short oral presentation)

g) *Water and Energy Conference*, Amsterdam, Netherlands, 2010 (oral presentation)

e) *20th National Seminar on Hydrogeology and Environmental Geochemistry*, Trondheim, Norway, 2011 (oral presentation)

f) *2nd European Geothermal PhD Day*, Reykjavik, Iceland, 2011 (poster and short oral presentation)

g) *21st National Seminar on Hydrogeology and Environmental Geochemistry*, Trondheim, Norway, 2012 (oral presentation)

h) *International Conference on Groundwater in Fractured Rocks (GwFR'2012)*, Prague, Czech Republic, 2012 (abstract accepted for oral presentation)

Appendix E: Further geoscientific contribution during the PhD

1) Liebel H.T. & Krill, A. 2011: Lille Raipas – a geological-botanical treasure chest in Alta. Blyttia 69: 74-86.

Abstract
A 3 km^2 area on the hills of Lille Raipas, 7 km southeast of the town of Alta (Finnmark) displays a wealth of geological and botanical treasures. A species list containing more than 200 taxa is presented, including some rare species such as *Epipogium aphyllum*, *Eriophorum x medium* and *Woodsia glabella*. The geology of Lille Raipas is extraordinary. Distinctive rock types, including dolomite, shale, tillite, conglomerate and slate are responsible for different soil conditions and plant communities. Stromatolites, or beds of fossil algae in the dolomites are among the oldest fossils in Europe, dating back more than 1 800 million years. Red breccias are chaotic fragmental rocks that filled cave systems below an ancient flat land surface. A younger land surface, about 650 million years old, consisted of rugged hills of quartzite. It is also well preserved here, as it was covered by glacial moraines of the spectacular Snowball Earth era. All these rocks were buried by hundreds of meters of Alta-slates that were thrust from the northwest during the Caledonian collision and mountain-building event.
The combination of different geological and botanical cites can be explored on a 3-hour walking trip using the location coordinates and descriptions presented in this article. Lille Raipas has much pedagogical value, as several different links in an intact ecosystem can be easily studied in this small area. It should be monitored and protected from damaging human impact.

Se vogliamo che tutto rimanga com'è, bisogna che tutto cambi.

If we want that all remains as it is, everything has to change.

(Novel: "Il Gattopardo" by Giuseppe Tomasi di Lampedusa)