Measurement and Simulation of Heat Transport in Rocks at a Site in the Rhenish Massif, FRG

by Burkhard Sanner and Dirk R. Brehm

Abstract

Following development of techniques for utilizing heat in the uppermost 50m of the earth's crust for space heating using ground-coupled heat pumps (GCHP), investigations were carried out to assess the heat transport process in the ground. Heat extraction and the resulting earth temperatures were monitored for nearly three years at a test site in the Rhenish Massif, FRG. Both the shape of the negative thermal anomaly and the influence of flowing ground water were measured. A computer code was developed to simulate transient heat transport by diffusion and convection. This three-dimensional finite difference model was validated against analytical solutions, results from other models, and the field data, and thus the results from the field tests may be of value in other areas.

Field Test Site

A full-scale test plant was built south of Wetzlar, in the Rhenish Massif, FRG. The rocks comprise lower carboniferous "Giessen Greywackes," with graded bedding and shale intercalations. The whole area has been intensively folded and faulted during the Variscan orogeny.

A tectonic analysis in quarries and outcrops (Dörr and Preiss 1982, Sanner et al. 1986a) showed a typical section of the eastern Rhenish Massif. The fold axes strike about 50°, and the main fissure directions are 80° and 160° (Figure 1). Drilling to 50m allowed us to establish a geological profile of the test site (Sanner et al. 1986a). An interpretive summary of the profile is shown in Figure 2.

Eleven holes were drilled, each 50m deep. Figure 3 shows the layout of the drilling field. Holes H1 and H2 serve for hydrogeological purposes, H1 has been equipped with a gauge, and H2 is a large-diameter open hole for well tests and chemical analysis of the water. In borehole Z a vertical earth heat exchanger has been installed as a heat source for a heat pump. Thus the temperature in this hole can be lowered to well below 0 C. Hole Z and all remaining holes contain temperature measurement probes, each having 24 sensors at 2m vertical distance (Sanner and Herr 1986). The first hole drilled in June 1985; the current status was achieved December 1987.

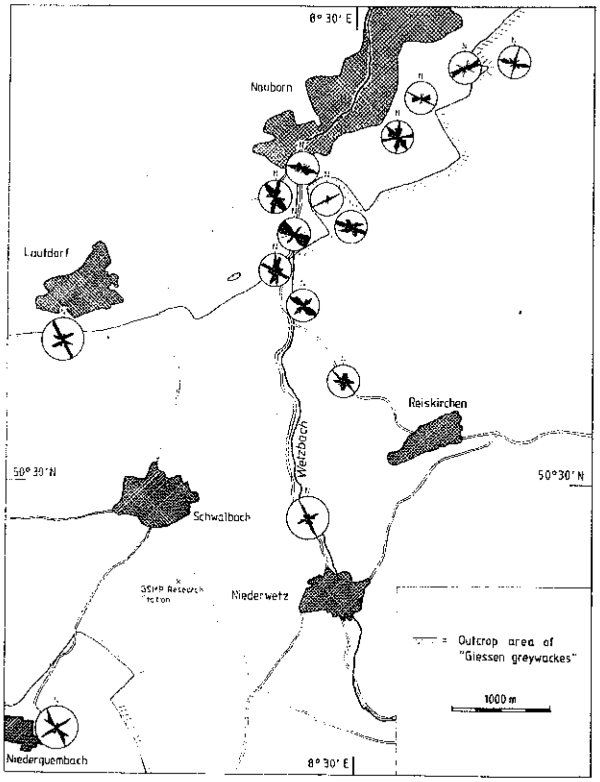


Figure 1. Fissure directions in the southeastern "Giessen Greywackes" and subjacent strata, Rhenish Massif, FRG.

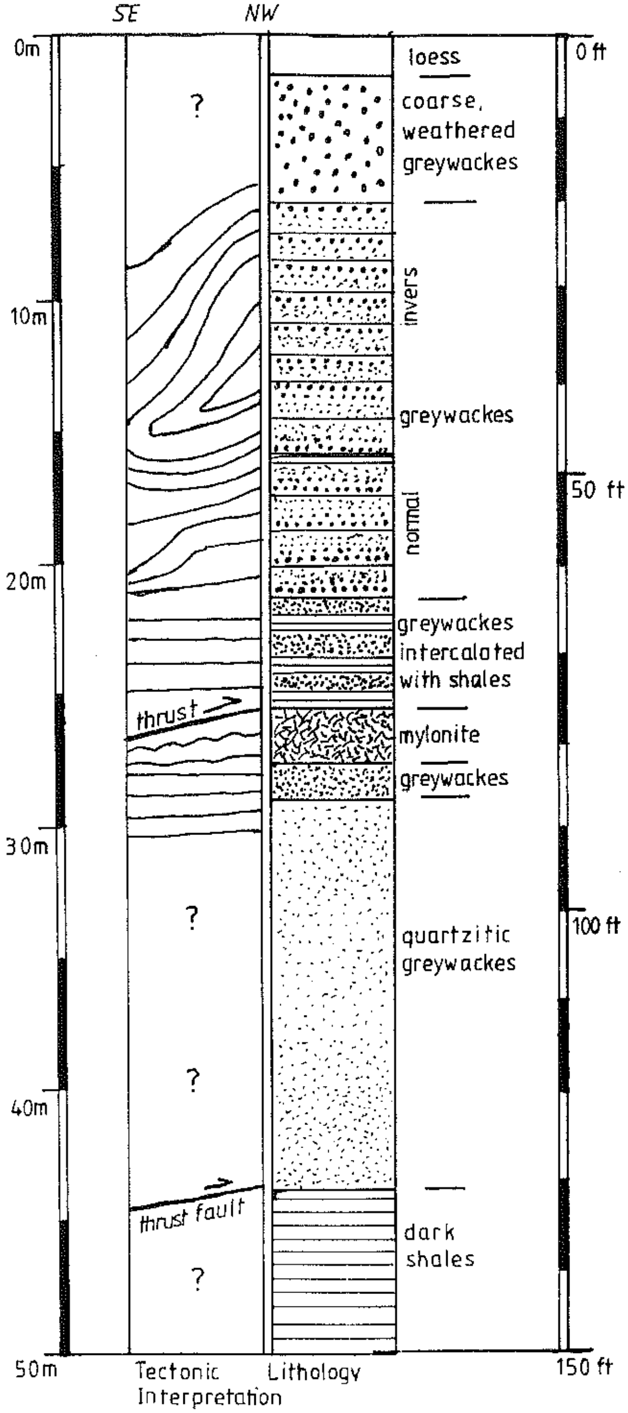


Figure 2. Summarized geological profile in borehole Z.

Hydrogeological Conditions

The test site is located on a ridge approximately 290m above sea level, close to a ground water divide. The highest point of the landscape is about 100m to the south, hence the catchment area is very small. The water table varies between 11.5 and 15.5m below ground level. Regional ground water recharge is evaluated by stream run-off measurements with 1.5 to 2.5 l/s/km^2. Average annual precipitation is 720mm, 7.5 percent of which replenishes the reservoir (Sanner et al. 1986b).

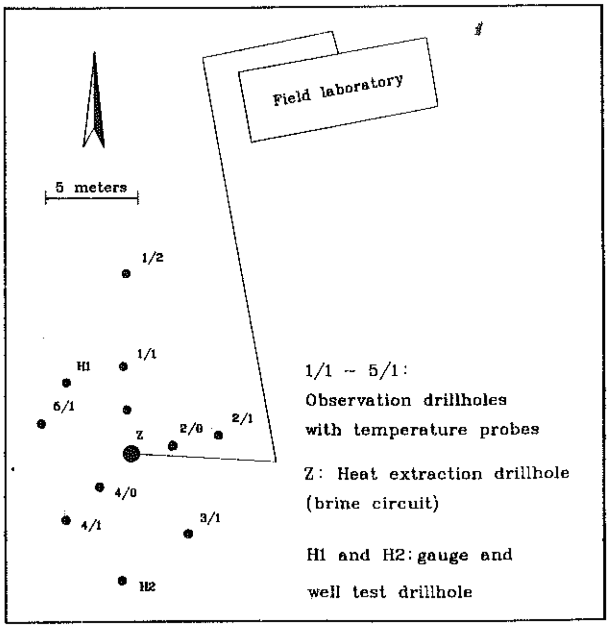


Figure 3. Well layout of the GCHP-Research Station Schwalbach, at December 1987.

To assess the velocity and direction of groundwater flow, a tracer test with a NaCl brine was carried out. The resulting flow velocity is 2×10^{-5} m/s. Pumping tests were made until steady state conditions were reached.

Well-skin effects were detected by the application of the type curve technique (Gringarten et al. 1979, Bourdet and Gringarten 1980). If it is assumed that the aquifer was penetrated in its total thickness by the drilled wells, then only few open fissures are to be found in the Rhenish Massif below a depth of 50m (Krapp 1979). A transmissivity of $T = 6.4 \cdot 10^{-4}$ m^2/s and a hydraulic conductivity of $k_f = 1.8 \cdot 10^{-5}$ m/s were found.

Heat Extraction

Heat extraction in borehole Z can be accomplished in three different ways: (1) Heating mode, controlled by ambient air temperature; the temperature in the earth heat exchanger varies; (2) Constant temperature in the earth heat exchanger; excess heat is dumped into the air by large blowers; and (3) Manual control to test the limits of the system.

The heating mode was tested during three heating periods (1985/86, 1986/87, 1987/88) each from the end of October to the end of April. After each heating period the heat pump was switched off and the natural recovery of ground temperature was monitored. Figure 4 shows the development of earth temperatures at the outer wall of the earth heat exchanger over 2.5 years.

Test runs with quasi-constant earth temperatures were undertaken to make validation of the computer codes easier. A run with about -3 C is shown in Figure 5. The nearby (2.5m distance) probes 2/0 and 4/0 are affected by this heat extraction; there is a slight decrease in temperature in the 5-m distant holes

(1/1 - 5/1) at the end of the period, and probe 1/2 (10m distance) remains undisturbed.

Numerical Model

Because of the complex nature of the physical phenomenon, it is nearly impossible to cover all aspects of heat transfer in aquifers with a numerical model. Thus, the following simplifying assumptions were made in this preliminary version of the program called TRADIKON-3D: Darcy's law is applicable; the rock matrix and convective fluid are in local thermal equilibrium; heat transport is by radiation and the effect of thermal dispersion is negligible (Cheng 1985); moisture migration in the unsaturated zone forced by the thermal gradients is also negligible; the aquifer is fractured and is treated as a pseudo-porous aquifer; and the directions of anisotropies for both thermal conductivity and hydraulic permeability extend parallel to the axes of the cartesian system of coordinates.

The three-dimensional flow of ground water with constant density through a porous medium can be described (Bear 1979) by:

$$\nabla\cdot(\bar{\bar{k}}\ \nabla\ h) - W = S_s \frac{\delta h}{\delta t}$$

where:

$\bar{\bar{k}}$ hydraulic conductivity tensor $[Lt^{-1}]$
h hydraulic head $[L]$
W fluid source/sink $[L^3t^{-1}]$
S_s storage coefficient [-]
t time [t]

The transient heat transport through a saturated porous medium is given by:

$$\nabla\cdot(\bar{\bar{K}}\ \nabla\ T) - \rho_w C_w \bar{q}\cdot\nabla\ T + S = [\rho_w \Phi C_w + \rho_r(1-\Phi)C_r]\ \frac{\delta T}{\delta t}$$

where:

$\bar{\bar{K}}$ effective thermal conductivity tensor $[MLt^{-3}T^{-1}]$
T temperature [T]
t time [t]
ρ_w density of fluid $[ML^{-3}]$
ρ_r density of rock $[ML^{-3}]$
C_w, C_r specific heat capacities $[L^2t^{-2}T^{-1}]$
$\bar{q}$ fluid flow vector $[L^3t^{-1}]$
Φ total porosity [-]
S heat source/sink $[MLt^{-3}]$

TRADIKON-3D has also been designed to solve only parts of various problems such as ground water motion through a known temperature field, and conductive and convective heat transfer through an aquifer with a given flow field. During a fully coupled simulation the programme solves, alternatively, the fluid flow equation and the heat transport equation with respect to both the changes in fluid properties and to the convective part of the heat transport. In cases of high heat extraction the effect of latent heat of water is numerically treated as a part of the source/sink term. Because the convection term has an inseparable connection with the diffusion term, both need to be handled as one unit.

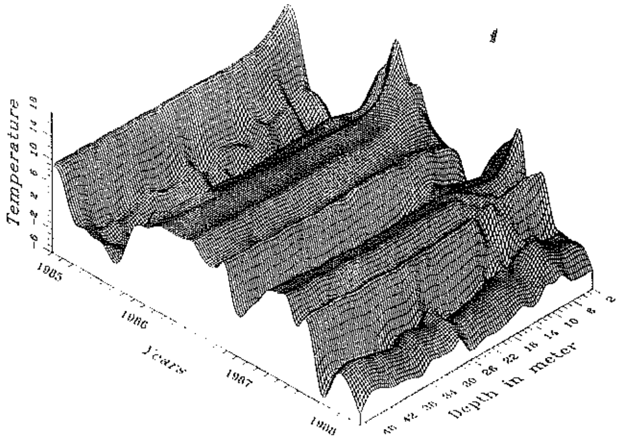


Figure 4. Temperature history in the extraction hole Z; October 1985 - April 1988.

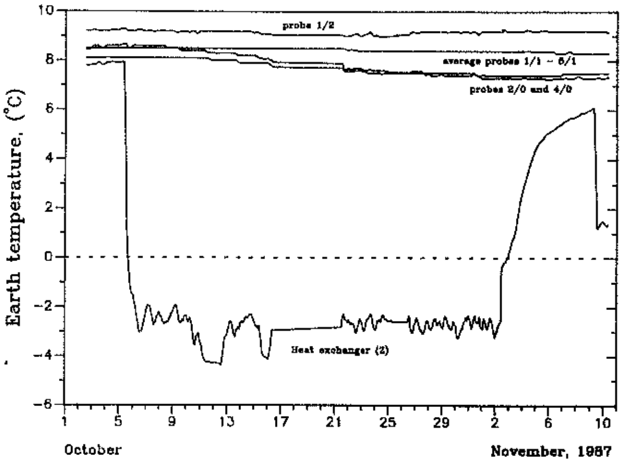
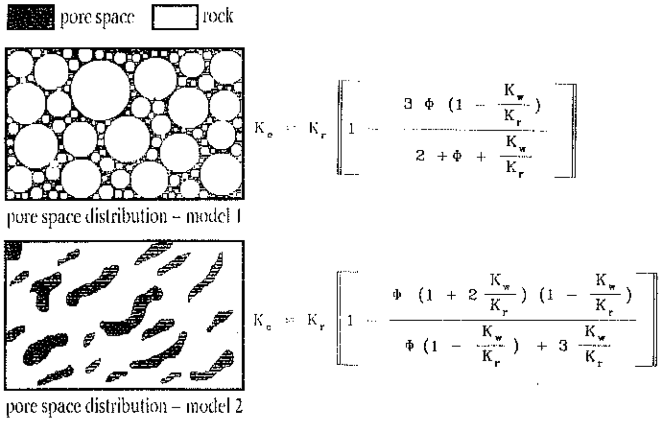


Figure 5. Test run with quasi-constant brine temperature in the extraction hole.



$$K_e = K_r \left[1 - \frac{3\ \Phi\ (1 - \frac{K_w}{K_r})}{2 + \Phi + \frac{K_w}{K_r}} \right]$$

$$K_e = K_r \left[1 - \frac{\Phi\ (1 + 2\frac{K_w}{K_r})\ (1 - \frac{K_w}{K_r})}{\Phi\ (1 - \frac{K_w}{K_r}) + 3\ \frac{K_w}{K_r}} \right]$$

Figure 6. The two models show the maximum (model 1) and minimum (model 2) influence of the pore space filling on the effective thermal conductivity K_E; K_r = thermal conductivity of the rock, K_w = thermal conductivity of the pore space filling.

Patankar (1980) pointed out that there exists five

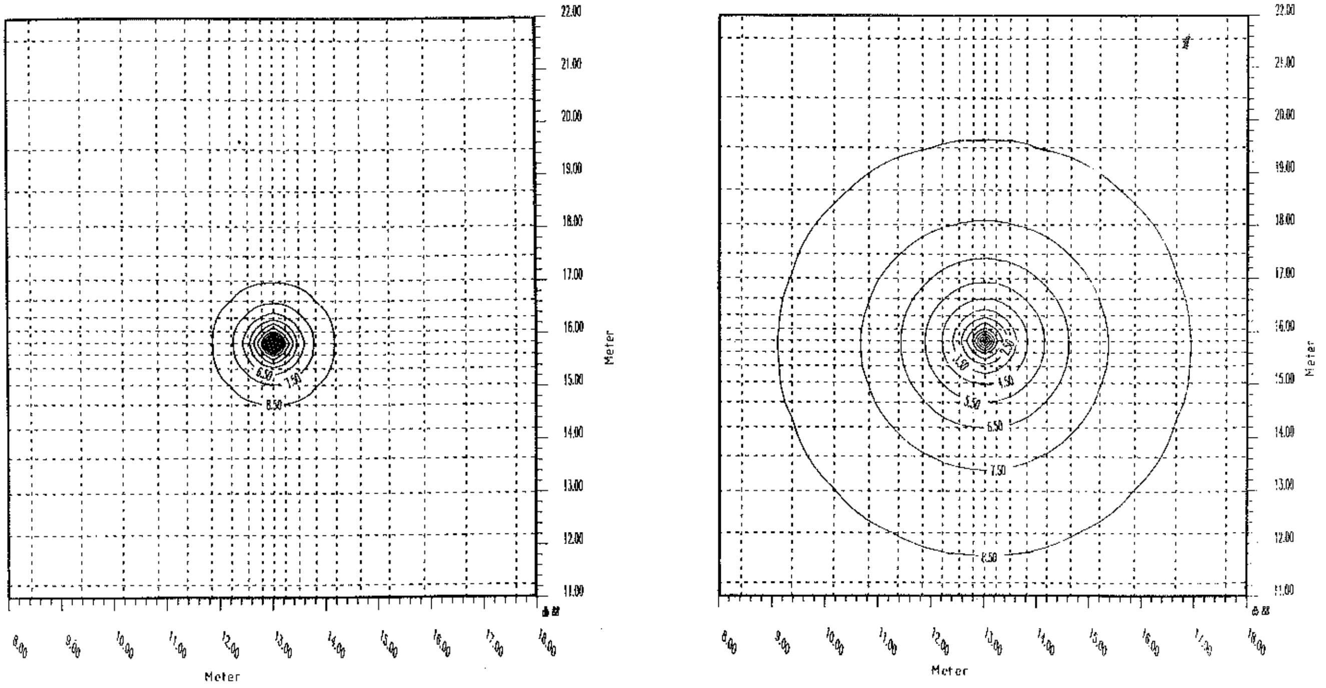


Figure 7. Development of the calculated thermal anomaly after two and 26 d heat extraction; direction of ground water flow from N to S.

different schemes to weight diffusion and convection independent of the local Peclet-number. For small Peclet-numbers $|P|<2$ all schemes leads to physically realistic results. However, fluid velocities are unknown in fully coupled runs at the start of a simulation and it is often not feasible to discretize extremely fine grids for economical reasons. Therefore, one of two exponential weighting functions known as "Exponential-Scheme" and "Power-Law-Scheme" should be preferred. TRADIKON-3D caters for each of the five mentioned schemes.

The governing partial differential equations can be solved by the method of finite differences. In this case, the domain of interest has to be subdivided by a rectangular grid into a finite number of cells, sufficiently fine so that the differential equations can be replaced by discretization equations. This resulting system of linear equations can be solved by direct methods or iterative techniques.

TRADIKON-3D makes use of the Gauss-Seidel iteration, which can be combined with the 'Successive-Over-Relaxation' procedure for a more rapid convergence solving nonlinear problems. The model has been validated against analytical solutions of two-dimensional transient diffusion problems found in the literature (Carslaw and Jaeger 1959).

In field applications of the model it is necessary to have sufficiently exact information about the thermo-physical properties of the heat source rock and the pore space distribution. Walsh and Decker (1966) have shown that the maximum and minimum influence of the pore space filling on the effective thermal conductivity can be evaluated by two different models (Figure 6). Both models were implemented in TRADIKON-3D.

The modular structure of the computer code allows, if necessary, an easy integration of further improvements.

Application of the Model

A two-dimensional, horizontal-cut sample calculation with a constant brine temperature of -5.0 C was used to estimate the influence of the flowing ground water to the shape of the resulting thermal anomaly. The following physical properties of the heat source rock were given: isotropic thermal conductivity 3.0 W/mK; heat capacity 850 J/kgK; density 2700 kg/m^3, effective porosity 3 percent model 2 (ref. Figure 5). The ground water velocity was assumed to be constant at 2×10^{-5} m/s over the total simulation period of 26 d. At the beginning of the calculation the undisturbed background temperature of the rock should be 9.0 C. The model area has been discretized by 29 x 31 cell-centered nodes.

The slight elongation of the isotherms (Figure 7) indicates the small influence of the convective component of heat transfer at the Schwalbach Research Station. Figure 8 shows the earth temperature recovery after a month of heat extractions; this is similar to the run shown in Figure 5. The calculated values reproduce the measured data acceptably.

Conclusions

At this early stage of our investigations the process of heat transport at the described site could be reproduced sufficiently exactly by application of the numerical model with straightforward input parameters and boundary conditions. Due to the geological and hydrological situation in Schwalbach, diffusive heat

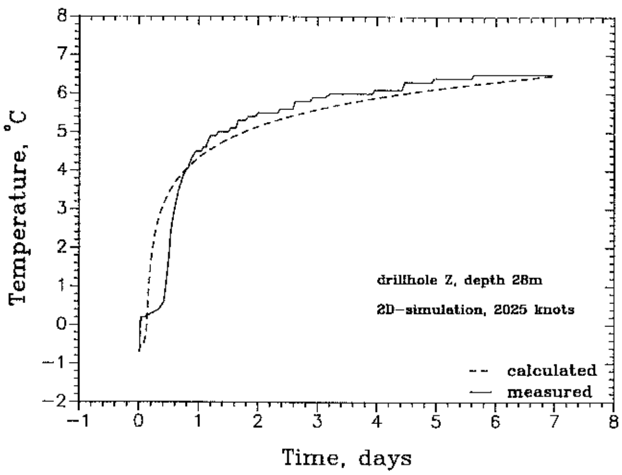


Figure 8. Measured data and calculated values of earth temperatures in recovery period.

transport strongly dominates the system. More rigorous three-dimensional calculations will have to be carved out to reflect the influence of isolated open fissures with locally increased ground water velocities.

Four additional sites with different geological and hydrological conditions have also been equipped with monitoring devices. The data from these plants will enable further improvements of the code.

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