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GEOHERMIC MODEL FOR THE RISE OF DEEPER GROUNDWATER

ALONG FAULTS IN UNCONSOLIDATED ROCKS *)

by

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Abstract

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A simple model is presented to explain measured temperature anomalies in areas of unconsolidated rocks disturbed by faults. In this model it is assumed that deeper groundwater is rising along the faults. Temperature measurements in the Niederrhein-Bucht were used in the calculations. A quantitative relationship between the temperature anomaly and the vertical flow of deeper groundwater is found. As a main result it is shown that the amount of water flow necessary to produce the observed temperature distribution is very small. Thus it can be concluded that no hydrological contradictions are associated with the presented model.

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MODÈLE GEOTHERMIQUE POUR LA MONTÉE DES EAUX SOUTERRAINES
DE GRANDE PROFONDEUR LE LONG DES FAILLES DANS DES SÉDIMENTS
NON CONSOLIDÉS

Résumé

Un simple modèle est présenté, lequel permet d'expliquer les anomalies de la température trouvées dans des sédiments non consolidés, perturbés par des failles.

Dans ce modèle, il est assumé que des eaux souterraines montent le long des failles.

Pour la calculation on se servait des mesures de la température effectuées dans la Niederrhein-Bucht. Une relation quantitative a été trouvée entre l'anomalie thermique et le flux de l'eau montante. Comme résultat principal, il est démontré que la quantité de l'eau nécessaire pour expliquer ces anomalies est relativement très petite. Ce modèle ne mène pas à des contradictions hydrologiques.

Introduction and generalities

Pronounced geothermic anomalies are most commonly observed in tectonically disturbed zones, where hydrological anomalies generally occur in conjunction with the latter. It is thus appropriate to investigate models which may describe the relationship between geothermics and hydrogeology. The Niederrhein-Bucht is presented here as an elementary set-up for such models. To date there are but few areas in the Federal Republic of Germany which have received sufficient geothermic investigation as to be suitable for consideration. Among these few there exist the Erft region, which is dealt with here, (BALKE, 1973), the northern Oberrhein-Graben (WERNER & DOEBL, 1974) and the Schwäbische Alb (CARLÉ, 1974).

The Niederrhein-Bucht is a young area of depression which received its tectonic character during Tertiary and Quaternary times. The area is composed of several component blocks (fig. 1), the result of tectonic dilation (AHORNER, 1962, TEICHMUELLER, 1974). The greatest crustal stretching occurred in a S.W. - N.E. direction, in other words normal to the Erft fault and the fault system of the Rurrand.

The pre-tertiary basal complex consists of Devonian slates and graywackes, covered from place to place in angular unconformity by Mesozoic sediments. The Tertiary is represented by a succession of gravels, sands and clays with numerous lignitic seams (fig. 2). These beds are overlain by Pleistocene terrace gravels.

Since 1955 open-cast mining of the lignite from the Ville Block has been carried on, which necessitated lowering of the water table to

below mining level. It was noted that in several drainage shafts - especially in the case of the open-cast mine Fortuna-Garsdorf - water rose from a depth of 300 m with a temperature of about 40⁰C.

The situation has been presented and analysed by BALKE (1973). Numerous temperature measurements in groundwater depth gauges have revealed normal geothermic conditions within the Erft Block. In the neighbourhood of the Erft fault system and, to a lesser extent, at the Rurand fault too considerable temperature increases were observed (fig. 1 and 3).

Fig. 1 represents temperature distribution in the form of isotherms at a depth of 100 m below sea level. The anomaly is especially pronounced in the Ville Block near Bedburg.

The thermic profile (fig. 3) and the isothermic map (fig. 1) indicate clearly that the positive temperature anomalies are connected with tectonic disturbances. The cause of such temperature increases may be related to rising warm deeper groundwaters.

Little is known concerning the paths taken by rising water in disturbed unconsolidated rocks. But it is quite certain that open joints cannot play a role. It seems reasonable to attribute a certain vertical permeability to the zones of disturbance. This is the consequence of the dislocation of aquifers and impermeable beds. The case may be illustrated in a simplified and idealized form in fig. 4. One can say, that the disturbances are "smeared" zones.

There are observations about the materials within the fault zones. In an exposure of the Erft fault (at the western edge of the former open-cast mine between Törnich and Mödrath) clayey as well as sandy sediments

were encountered which had been dragged into the fault zone

(AHORNER, 1962).

More detailed investigations of flow conditions of deeper groundwaters in the Erft area do not exist. This paper relies solely on temperature data (BALKE, 1973). Using our model a quantitative relationship between temperature anomaly and flow of deeper groundwater can be established.

The question is: what extent of rising warm water is required in order to explain, within the context of the model, the measured temperature increases.

Model of calculation

In order to attain a practical mathematical formulation it is necessary to idealize the geological situation. A half space with uniform surface temperature (mean annual temperature T_0) and constant thermic material parameters (K = thermal conductivity, κ = thermal diffusivity) are given. Within this undisturbed system the existence of an area of width B is presumed (fig. 4), which is typified by two characteristics:

1. an increased temperature, 2. parallel vertical zones of faulting of width d . Between these fault zones d there exist thermoconductive (but without groundwater flow) blocks of width b . The blocks b are about 1 km across, whereas the width of the fault zones d lies between 3 and 10 m (AHORNER, 1962). Thus it follows $d \ll b$. In the model the fault zones d are treated as surfaces on which isothermal boundary conditions obtain.

This raises two problems: 1. The calculation of the warming of blocks b

under isothermal boundary conditions, 2. The temperatures obtaining in the faults (zones d) must be quantitatively related to the rising groundwater flow.

Problem 1 serves to prove that the warming of the block b is a fairly quick process compared to the age of the fault. A component part b of the half space is considered which is surrounded by three isothermal surfaces; the surface and two fault planes. The calculation is two-dimensional and is based on a difference procedure corresponding to the equation of thermoconductivity:

$$\frac{\partial \theta}{\partial t} = \kappa \left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial z^2} \right) = 0 \quad (1)$$

We distinguish a stationary undisturbed temperature field $\Theta(z)$ from a non-stationary anomaly component $\theta(x, z, t)$. These two make up the total field:

$$T(x, z, t) = \Theta(z) + \theta(x, z, t)$$

For the depth here considered $\Theta(z)$ is linear:

$$\Theta(z) = T_0 + \alpha z$$

We have $\theta(x, z, t) = 0$ at the starting point $t = 0$.

The boundary conditions are as follows:

$$\theta(x, 0, t) = 0 \quad (\text{surface})$$

$$\theta(0, z, t) = \theta(b, z, t) = \theta_0(z) \quad (\text{fault planes}).$$

The solution of problem 2 of our model is of greater importance. The isothermic boundary conditions proposed for the fault planes require continual energy input. The energy is assumed to be supplied from water flow I. The following relationship (WERNER, 1975) between water flow I (cm^2/s), temperature gradient dT_v/dz in the fault plane, and the horizontal temperature gradient $d\theta/dx$ in the immediate neighbourhood of the fault plane can be drawn up:

$$I c_w \rho_w \frac{dT_v}{dz} = 2 K \left(\frac{\partial \theta}{\partial x} \right)_0 \quad (2)$$

with c_w , ρ_w - specific heat, density of water,
 K - thermal conductivity.

Assuming an effective porosity p for the filling material of the fault zones, one can write:

$$I = p v d, \quad (3)$$

where v represents the mean vertical flow velocity.

Our model is founded on the idealized assumption that within the thermal conductive blocks b there is no water movement. Only vertical water flows in the fault zones are considered.

Results

The solution of problem 1 with $\kappa = 7 \times 10^{-3} \text{ cm}^2/\text{s}$ results in a temperature field as given in fig. 5. On the right the model temperatures $T_v(z) = \theta(z) + \theta_0(z)$ are shown. Isotherms (continuous lines) represent the stationary temperature distribution which,

assuming a block width $b = 1$ km, is attained after approx. 20,000 years. The marked sagging of the isotherms is conspicuous. This results from surface conditions which exert a cooling influence. Such behaviour cannot be demonstrated with existing temperature measurements. There are two separate reasons for this state of affairs. Firstly the observation positions were not close enough. Secondly the model is too simplified and too idealizing for such details.

In the context of the model, horizontal water movements between the fault planes are not allowed for. The model error thus caused can be estimated by supplementing equation (1) with a convective term:

$$\frac{\partial \theta}{\partial t} - \kappa \left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial z^2} \right) + p v_x \frac{\partial \theta}{\partial x} = 0 .$$

For this relationship one can also insert a corresponding difference procedure. Let us consider, by way of example, an aquifer at a depth of between 50 - 250 m with a horizontal flow velocity $v_x = 10$ cm/day and with $p_n = 20\%$. This results in the dashed isotherm diagram in fig. 5. This secondary aspect serves to throw light on the problems involved in drawing up a realistic model for local hydrothermic phenomena.

The result of problem 1 which we anticipate is as follows. The minimum age for the thermal anomaly of about 20,000 years contrasts with that of the block faulting which began in the Oligocene, i.e. about 30 m.y. ago. Thus one can state that the time necessary for the warming up of the entire anomaly area B is small with respect to the age of the faulting.

Problem 2, the determination of water flow I from (2), presume knowledge of the factor $(\frac{\partial \theta}{\partial x})_0$. A mean value is known from the solution of problem 1. The gradient dT_v/dz is already stipulated by $\Theta(z)$ and $\theta_0(z)$, (fig. 5), which were selected according to data observed in the field.

The flow of deeper groundwater can be estimated by use of the numerical values $(\frac{\partial \theta}{\partial x})_0 \approx 2 \times 10^{-4}$ deg/cm, $c_{wpw} = 1$ cal/cm³ deg and $K = 4 \times 10^{-3}$ cal/cm s deg :

$$I = 2 \frac{K (\frac{\partial \theta}{\partial x})_0}{c_w \rho_w \frac{dT_v}{dz}} \approx 4 \times 10^{-3} \text{ cm}^2/\text{s} \approx 12 \text{ m}^2/\text{annum}.$$

This means: for a length of 1 m (normal to the plane of the drawing) of the fault plane an annual discharge of 12 m³ occurs. This is a very slight flow. The discharge of this water near to the surface leads to no further hydrological problems.

Table 1 gives a clue as to the order of magnitude of flow velocity corresponding to flow I. It is founded on equation (3) where $p = 10\%$.

Table 1

d	=	1	5	10 m
v	=	35	7	3.5 cm / day

One can see that the factors p and v acquire values which can also be found approximately in normal horizontal aquifers. This result agrees with the idea outlined at the beginning of this paper in which the faults were looked upon as "smeared" zones.

The whole problem under consideration here may also be looked upon from a simpler, generalized point of view. One limits oneself to a stationary heat flow balance. Once again we consider water flow I, which is necessary to maintain constantly the amount of heat contained in the anomaly. The sole supposition is that the entire block B is pervaded by watercourses so that the heat can be distributed. For this we consider both the mean heat flows on the surface q_A in the disturbed area B and q_N in the neighbouring undisturbed area. The difference $\Delta q = q_A - q_N$ must be made up by heat input from the deeper groundwater flow I. The thermal energy lost by the water to its surroundings in rising through the disturbed zone may be calculated from the temperature reduction ΔT of the water; however, this depends on the depth under consideration. Thus it follows:

$$I = \frac{\Delta q \cdot b}{c_w \rho_w \Delta T}$$

b represents (as in the case of our model outlined above) a characteristic width of about 1 km.

The heat flow situation in the Erft area (BALKE, 1973) is known to an approximation. Taking $q_A \approx 3.5$ HFU (10^{-6} cal/cm² s), $q_N \approx 1.4$ HFU and $\Delta T \approx 40$ deg one arrives at $I \approx 5 \times 10^{-3}$ cm²/s. This forms another confirmation - we are dealing here only with approximate values - of the results already attained.

Summarizing one can say: the rising of deeper groundwater along faults in unconsolidated rocks proves to be a sufficiently realistic

model to explain temperature anomaly. The simple model considerations presented in this paper lead neither to geothermic nor to hydrological contradictions. Unresolved, however, remain the hydrodynamic causes for the rise of deeper groundwater. This problem applies not only to the Niederrhein-Bucht, but also to the Ober-rhein-Graben and the Schwäbische Alb as well as to structures which are geothermically and tectonically striking.

It would be exceedingly interesting and advantageous if hydrodynamic models, too, were to be drawn up. This would oblige geothermic research to orientate itself to rival models.

Figure Captions

Fig. 1: Isothermal map of the Erft region (Niederrhein-Bucht).
Temperatures relate to a depth of 100 m below sea level.
The temperature anomaly of the Erft fault is striking.

Fig. 2: Schematic geological sequence of the Niederrhein-Bucht.

Fig. 3: Temperature profile A - B (cf. fig. 1).

The thermal anomaly along the Erft fault is explained as
a hydrological consequence of the fault.

Fig. 4: Idealized model of the fault system. In the narrow
faulting zones ($d \approx 3-10$ m) warm groundwater rises and
warms the intervening blocks ($b \approx 1$ km).

Fig. 5: Isothermal diagram of a model block $b \approx 1$ km (continuous
lines). The temperature distribution is a result of iso-
thermal boundary conditions, in our case: virtually
stationary conditions after 20,000 years.

$\theta(z)$ represents the undisturbed field, $\theta_0(z)$ the effect
of increased water temperature within the fault.

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Designation of
geological units
resp. hydrogeol. stores
after SCHNEIDER

Fig. 2

Fig. 3

Fig. 4

Fig. 5