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The Geothermal Anomaly of Landau/Pfalz: An Attempt of Interpretation

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Abstract. The geothermal anomaly in the oil-field Landau (Rhinegraben, Germany) is modeled postulating the rise of deep groundwater along a fault in the basement. Relations are investigated between (a) the temperature in the centre of the anomaly, (b) its lateral extension, (c) the water flux, (d) the original depth of the water, and (e) the age of the anomaly. The numerical approach takes into account two processes: (a) Thermal conduction; (b) convection in a porous medium. The estimated age of the anomaly (about 100,000 y) does not compare with the age of the Rhinegraben (about 50 my). The required water flux is very small, and the source depth of the water flow is estimated to be about 6,000 m. The presented hydrothermal model possibly may be used to interpret the shallow temperature anomalies in the whole Rhinegraben.

Key words: Rhinegraben – Geothermal anomalies – Uprising deep waters – Hydrothermal processes – Heat transfer in porous media.

Introduction

The Rhinegraben between Frankfurt and Basel is one of the best studied continental rift systems. A nearly complete coverage of the results can be found in several proceedings of Rhinegraben symposia, such as edited by Rothe and Sauer (1967), Illies and Müller (1970) and Illies and Fuchs (1974). This area is noteworthy from the geothermal aspect. In the Rhinegraben we have to distinguish between the temperature distribution in the depth range of the lithosphere/astenosphere (about 200 km), corresponding to the history of the rift system, and the near surface temperature distribution within the sediments caused by hydrothermal processes. The aim of this paper is to find an explanation for the geothermal anomalies in the sedimentary cover of the Rhinegraben. A fairly well-known and striking anomaly is located in the oil-field of Landau/Pfalz (Fig. 1 a), and is described by several authors (Doebl 1970; Hänel 1974; Werner and Doebl 1974; Werner et al. 1978). Within the German as well as French zone of the Rhinegraben, which is characterized by high subsurface temperatures, there are other significant anomalies (Delattre et al. 1970; Lauer 1976).

We start from the assumption that the observed thermal anomalies in the sediments of the Rhinegraben are caused by water circulation systems down to great depth. It has been shown that other attempts of interpretation (e.g., differences in the heat conductivity, existence of very young magma bodies, or the assumption of a very high density of radiogene heat sources, (see Werner 1975) lead to unrealistic results.

Our observations are limited to the uppermost part of the earth's crust. The existence of a deep geothermal anomaly in the upper mantle under the Rhinegraben (Werner and Kahle 1980) is not the subject of this paper.

Our considerations are based on new continuous temperature logs in oil wells of the Landau field. The logged depths range from 800 to 1,300 m. Further details about these measurements are described in an earlier paper (Werner et al. 1978). The results of the measurements are summarized in Fig. 1 b. Apparently, significantly high temperatures exist in this area, with values of about 100° C at 1,000 m depth in the centre of the anomaly. This corresponds to a heat-flow maximum of about 120 mW/m^2

The Concept of the Model

The Rhinegraben is a rift zone characterized by numerous faults in its sedimentary cover (Illies 1974). Some major faults continue into the crystalline basement. In the Landau field a deep reaching fault system (the so called ω-fault and γ-fault, see Fig. 1 b) is well known (Schad 1962; Doebl et al. 1974). The average thickness of the sedimentary cover in the Landau field amounts to about 2,000 m.

The question arises wether a deep-reaching fault can be considered as origin for a thermal anomaly. We do not expect that each major fault plays a geothermally active role. Our model is based on the assumption that some deep faults are permeable, at least locally, and accordingly thermal waters are able to rise up from a depth of some thousand meters. For this model it is necessary that a continuous narrow zone with a vertical permeability exists.

The basic principle is that rising groundwater transmits its heat content to the surroundings and builds up a thermal anomaly. Although we assume the existence of rising thermal waters, our model does not explain its hydromechanical cause. Starting with a given distribution of flow the model calculation leads to a corresponding temperature distribution. The aim of the model calculation is to find quantitative relations between:

(a) The temperature in the centre of the anomaly, e.g., at a depth of 1,000 m; this allows a comparison with the field results;

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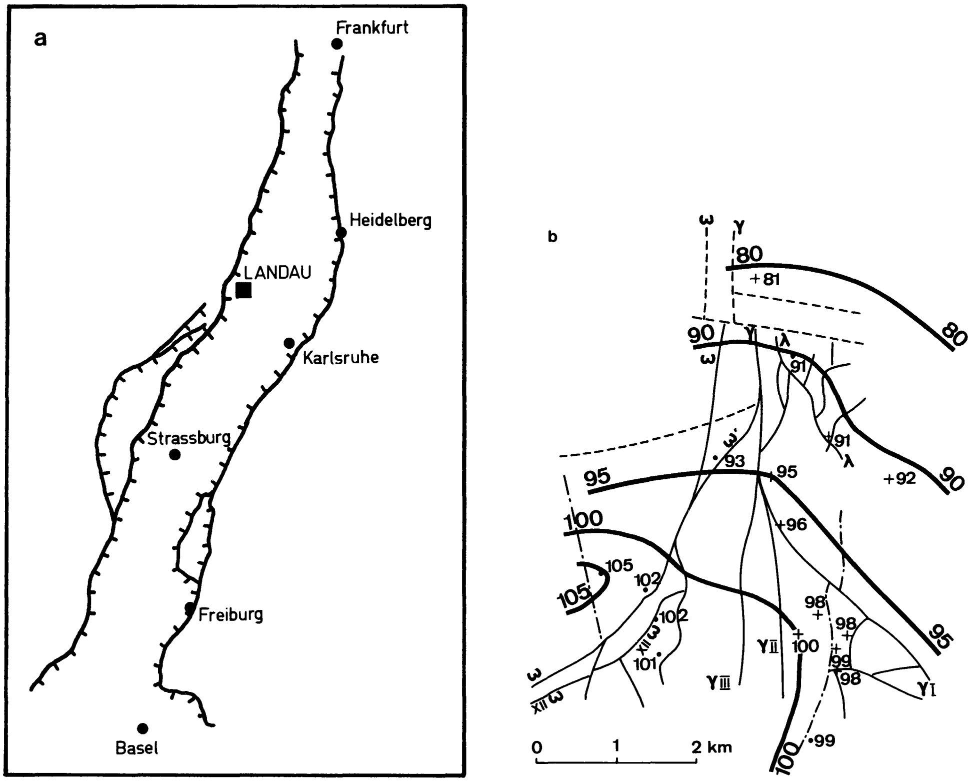

Fig. 1.
a Location of Landau.
b Isotherms and fault pattern of the Landau field at 900 m below sea level (about 1,050 m below earth surface). The *numbers* indicate temperature values in °C. The prominent fault in this region is the ω-fault

(b) the spatial extension of the anomaly, also to compare with field results;

(c) the age of the anomaly;

(d) the original depth of the thermal water;

(e) the thermal water flow, i.e., the quantity of water transported per unit time.

These quantities allow a discussion about the applicability of the model to the real situation.

The way of the rising deep groundwater consists of two paths: Path 1, from the original depth of the water up to the top of the crystalline basement; Path 2, its subsequent way through the overlying sediments. It will be shown that Path 1 is the critical one for the thermal model, i.e., the original depth of the water strongly influences the results. On the other hand, the distribution of the flow within the graben fill (Path 2) is of interest in determining the lateral extension of the thermal anomaly.

The Model Calculation

We consider a half-space in which heat transport takes place. The boundary condition at its surface is isothermal (mean annual temperature). We assume an undisturbed, 'normal' temperature field before the forming of the anomaly. Within the half-space heat is transported by:

(a) Thermal conduction;

(b) convection, caused by moving waters in a porous medium. In the heat conducting medium there are permeable zones, where movement of fluid can take place. The velocity field is given and is assumed to be constant, starting at an initial time $t=0$.

Furthermore, we distinguish two regions within the half-space: The sedimentary cover, and below this, the crystalline basement. We assume that permeable zones exist in both regions. In the permeable zones of the graben fill the flow of water is governed by the Darcy velocity, however in the faulted crystalline basement this definition is only approximately valid. No accurate description on the special mechanism of the permeability of a fault is available. We avoid this difficulty by assuming that within the fault zone the definition of a Darcy velocity is still approximately valid. Using this assumption. the two regions (sediments and crystalline) can be handled with the same mathematical formulae.

We use a basic equation, whose applicability to shallow aquifers has already been successfully tested (Werner and Kley 1977). In the permeable zones, the equation is

$$\gamma \mathbf{u} \operatorname{grad} T+\frac{\partial T}{\partial t}=D \nabla^2 T. \tag{1}$$

In zones with pure heat conduction Eq. (1) reduces to:

$$\frac{\partial T}{\partial t}=\kappa \nabla^2 T \tag{2}$$

where

T = temperature
t = time
$\mathbf{u}$ = vector of the Darcy velocity (approach velocity, specific discharge)
$\gamma = c_w \rho_w / c \rho$ = ratio of the heat capacities of water and rock
ρ = density of rock
$\kappa = K/c \rho$ = thermal diffusivity of rock in the zones of pure heat conduction
K = thermal conductivity
D = 'effective thermal diffusivity' in water permeable zones, which includes the effect of thermal dispersion.

The Darcy velocity **u** can be calculated from the mean flow velocity **v** (advance velocity) by

$$\mathbf{u} = p\mathbf{v}$$

where p indicates the effective porosity.

For the heat transport the Darcy velocity has to be used, because this quantity (specific discharge) describes the liquid flow as mass per unit time (in the strict sense **u** should not be called a velocity).

The parameter D, which we call 'effective thermal diffusivity', is exactly a tensor quantity influenced by diffusion and dispersion. We assume here that D can be considered as a scalar constant (see e.g., Werner and Kley 1977).

As it is evident from (1) and (2) radiogenic heat sources are not taken into account. They are omitted because their effect on our hydrothermal model is negligible.

We consider a two-dimensional problem. With x as horizontal and z as the positive downward direction coordinates (1) and (2) can be written as follows:

$$\frac{\partial T}{\partial t} = D\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}\right) - f_x \frac{\partial T}{\partial x} - f_z \frac{\partial T}{\partial z} \tag{3}$$

for the permeable zones, where $\mathbf{f} = (f_x, f_z) = \gamma\mathbf{u} = \gamma(u_x, u_z)$, and

$$\frac{\partial T}{\partial t} = \kappa\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}\right) \tag{4}$$

for zones with pure conduction.

The field **f** is a given quantity, i.e., it is an 'input parameter' of the calculation. In our model it is assumed that **f** is constant with time.

The equation of mass conservation is div $\mathbf{f} = \text{div } \mathbf{u} = 0$. This means that thermally induced density changes are not considered.

The problem is solved with a finite difference method, i.e., the differential Eqs. (3) and (4) are converted into equivalent difference equations. The temperature at every point of a grid with point distance $\Delta x = \Delta z = 200$ m is calculated after every time step Δt. It is advantageous to work with two different time steps, according to the different heat transport rates by either pure conduction or by convection. We select $\Delta t' = 60$ years for the permeable zones and $\Delta t = 300$ years for the zones with pure conduction. The choice of the ratio between Δx, Δz and Δt, $\Delta t'$ is limited by the stability condition of the numerical method.

The fault in the crystalline basement (more precisely, the narrow zone in which the thermal water can rise) is assumed as perpendicular to the earth's surface and is chosen to be 200 m wide, corresponding to one distance step Δx. Our two-dimensional calculation is limited to a symmetrical case where the axis of symmetry at $x = 0$ coincides with the z-axis.

Models for the Landau Anomaly

Figures 2, 4, and 5 show different model versions of the geothermal anomaly of Landau, which are distinguished by different assumptions on the path of the thermal water in the graben fill. In the first model (Fig. 2) it is assumed for simplicity that the water flows in a narrow, horizontal aquifer. In this case no water movement takes place within the sediments apart from the aquifer.

In our calculation the sediment cover has a laterally constant thickness of 2,000 m. The thickness of the aquifer is assumed to be 200 m, corresponding to the distance step Δz. The width of the vertical permeable zone in the basement is also assumed to be 200 m.

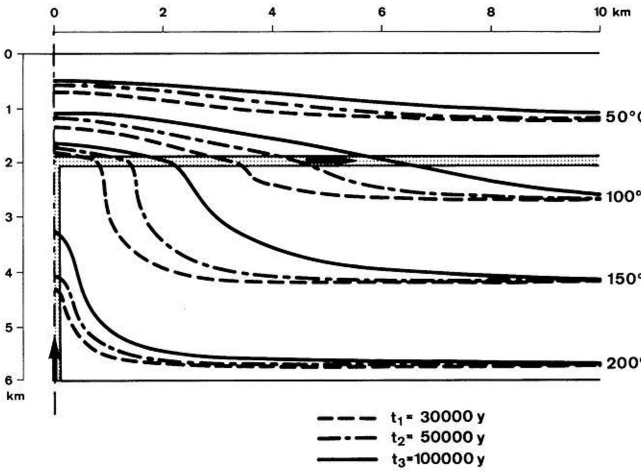

Fig. 2. Hydrothermal model 1 (two-dimensional, symmetrical) Deep groundwater rises along a fault zone and builds up a thermal anomaly. The dotted zones are assumed to be permeable, the arrows indicate the direction of the water flow. The isotherms show the evolution of the anomaly in space and time. $dT/dz =$ 33 deg/km is the temperature gradient of the undisturbed field. The total amount of the deep groundwater flow is $S = 100$ m^2/year ($= 100$ m^3/year for 1 m length perpendicular to the figure plane). In the centre of the anomaly at a depth $z = 1{,}000$ m a temperature of about 100° C is obtained after 100,000 years, corresponding to the observations in the Landau field

The quantity S (flux of deep groundwater) is assumed to be 100 m^2/y (i.e., 100 m^3/y along 1 m perpendicular to the plane of the figure).

A decisive parameter in our calculation is the original depth z_o of the thermal water. To build up a thermal anomaly as it is observed near Landau, we must assume an original water depth of about 6,000 m, if the initial temperature distribution is assumed as normal (33 deg/km).

The result of the calculation is shown in Fig. 2 in form of isotherms. The shape of the anomaly and its evolution with time can now be recognized. After 100,000 years a state is reached which is very similar to the observed temperature field in Landau. For a comparison of the model results with the observations, we can consider on the one hand the temperature at $z = 1{,}000$ m in the centre of the anomaly, on the other hand the decrease of the temperature with increasing distance from the centre of the anomaly. Figure 3 shows such a comparison: It can be seen that the observed temperature decrease (dots) agrees with the model results. There are, however, two reasons which allow only a qualitative comparison between model and observation:

(1) The model is two-dimensional and therefore not comparable in detail with three-dimensional data (see Fig. 1b);

(2) in our model the conductivity (resp. the diffusivity) of the sediment body is assumed as constant, whereas newest research work (Sattel 1979; see also Werner and Fuchs 1977) shows an increase of the thermal conductivity with depth. In order to demonstrate that the distribution of water flow within the sedimentary cover does not influence strongly the calculated temperature field we constructed two further models. In each model the quan-

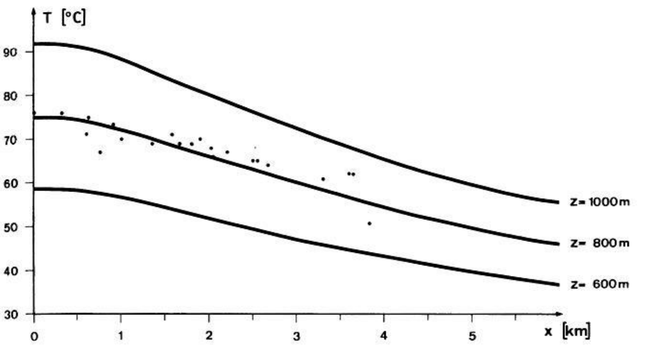

Fig. 3. The lateral temperature distribution at different depths z after 100,000 years according to model 1. For comparison measured values are shown plotted as function of the distance from the centre of the anomaly

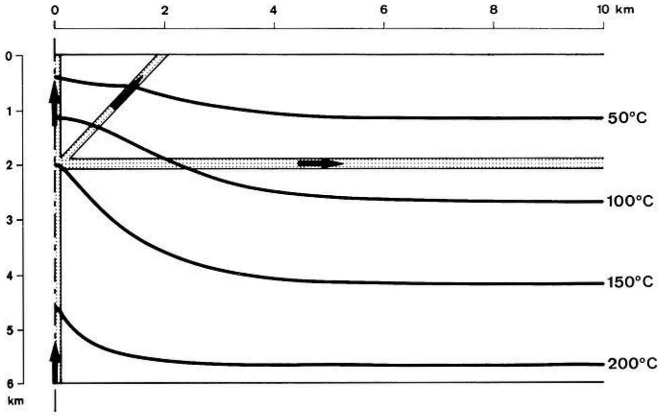

Fig. 4. Hydrothermal model 2. As distinguished from model 1 water-bearing faults within the sediment body are assumed. With this flow pattern a quantity $S=40\ \mathrm{m}^2/\mathrm{y}$ is sufficient to build up a similar temperature anomaly after 100,000 years

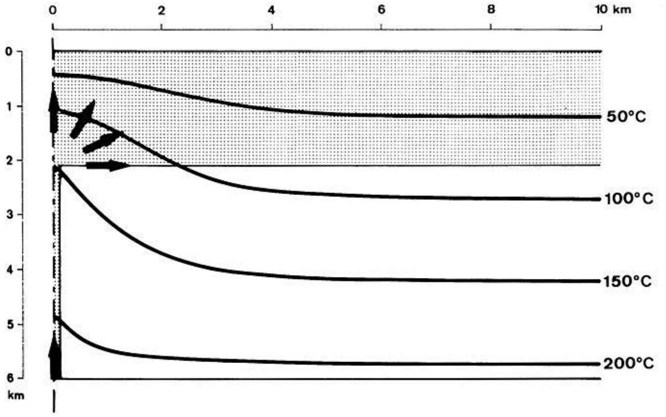

Fig. 5. Hydrothermal model 3. In this case the whole sediment body is assumed to be permeable with a radial flow distribution (*arrows*). The temperature field is shown for a flow $S=33\ \mathrm{m}^2/\mathrm{y}$ after 100,000 years. As in the models 1 and 2 the original depth z_0 of the thermal water must be chosen to be 6,000 m. With a smaller depth z_0 the Landau anomaly could not be explained without changing the basic conditions of the model

tity S was chosen so that the maximum temperature is nearly the same in the three models. The second model (Fig. 4) is an attempt to divide the groundwater flow into different paths. For this model the existence of permeable zones in the graben fill is required. In this case a flux of water $S=40\ \mathrm{m}^2/\mathrm{y}$ was assumed and the temperature distribution after 100,000 years is shown. The original depth z_0 is still 6,000 m. A comparison with the model in Fig. 2 shows that the flow pattern within the sediments is a secondary question.

This can be seen in the third model too (Fig. 5). Here we assume that the whole graben fill is permeable and that the flow of water is radially distributed. The situation in the basement is the same as in the other models (Figs. 2 and 4), and for this example $S=33\ \mathrm{m}^2/\mathrm{y}$. Figure 5 shows the isotherms for an age of the anomaly of 100,000 years.

The sequence of these model examples could be continued, changing the flow pattern in the sediments. The original depth z_0 of 6,000 m must be considered as a minimum value. Calculations with $z_0 < 6{,}000$ m cannot fit the observed anomaly if the same order of magnitude of the flux S is supposed. This means that our model is particularly suited for obtaining indications about the quantities z_0 and S.

The Origin of the Deep Groundwater

In our model the quantity of the water is prescribed, i.e., the hydromechanical causes are not explained. We assume that these deep waters are part of a wider circulation pattern. They accumulated in the basement by percolation from the earth's surface and are therefore not interpreted as juvenile waters.

For the geothermal anomaly of Landau large parts of the Pfälzer Wald come into question as source drainage area. If we assume a drainage area 100 km wide, the deep groundwater flux S amounts to some 0.1% of the annual rainfall. This value is sufficiently small to be considered as realistic. The original depth of the water at 6,000 m leads to the hypothesis of a 'crystalline aquifer' in a similar depth. Seismic investigations indicated a zone of about 10 km thickness with low seismic velocity (Müller et al. 1973). Possibly there is a relation between this zone and the postulated aquifer.

A support to our model is the salinity distribution in the Landau field. According to Schad (1962), a strong increase in the salt content of pore water is observed in the field from west to east; within a few kilometers it increases from 0 to 130 g/l. It is remarkable that the zone of fresh water almost coincides with the centre of the anomaly. This fact can be well explained with the flow distribution of the model in Fig. 5. Assuming a deep water flow of fresh water, which displaces the saline pore water, an explanation of the salt distribution in the field is obtained.

The Age of the Anomaly

It appears from the models that the Landau anomaly is about 100,000 years old. Figure 6 shows the evolution with time of the anomaly for the model in Figure 4, described by the increase of the temperature in the centre of the anomaly for different water fluxes S.

It follows from Fig. 6 that an estimate of the age can be different depending on the choice of S. For example an age of 100,000 years can be considered as a minimum age for the case $S=50\ \mathrm{m}^2/\mathrm{y}$.

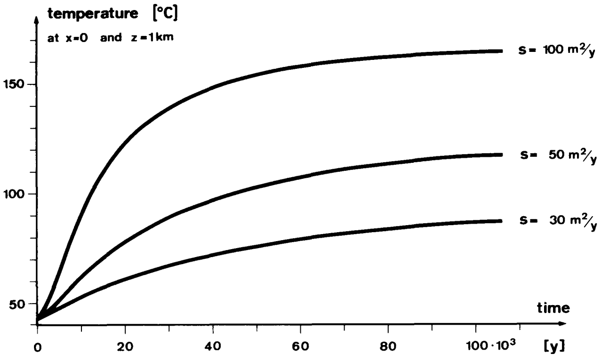

Fig. 6. The time depending temperature in the centre of the anomaly at $z = 1{,}000$ m calculated for different water flows S according to model 2. This diagram can be used for estimating the age of the anomaly

But it is also possible that the anomaly is in a phase of progressive evolution, hence in the area where the temperature curves of Fig. 6 show a marked increase. It must be noted that the quantity S can vary with time; in our model S can be considered as a mean value. With these assumptions the age of the anomaly can only be correct to within an order of magnitude.

This time period of about 100,000 years is much smaller than the age of the Rhinegraben (about 50 my). Accordingly, the presented model does not include assumptions connected with the rift building of the graben system. The process of rifting also leads to a prominent geothermal anomaly, but in a depth range which includes the lithosphere and the astenosphere (Werner and Kahle 1980). We must therefore make a distinction between two geothermal problems:

(a) the problem of shallow temperature anomalies (depth range: a few kilometers; time: about 100,000 years);

(b) the problem of the thermal anomaly of the upper mantle (depths down to 200 km; characteristic time about 50 my)

The very different orders of magnitude in space and time allow us to consider them as independent. This means that our model is not affected by the heat anomaly of the upper mantle. The age of the shallow anomaly considered here is to compare with the time period in which a permeable fault in the basement exists.

As the age of the anomaly is very small compared with the age of the graben, the existence of a water-bearing fault can be considered as a local 'episode' in the evolution of the graben. This suggests the assumption that during the graben evolution many such thermal events happened at different times and different places.

Our model is clearly valid for a temporally and spatially restricted situation within the graben tectonics. The last 100,000 years are indicated by Illies (1978) as a period of increased tectonic activity. This time span is well in accordance with the age of our model anomaly.

A further support to the young age of the Landau anomaly is the study of the degree of coalification of organic inclusions in the sedimentary rocks of the Rhinegraben (Teichmüller 1970; Doebl et al. 1974; Teichmüller and Teichmüller 1977; Buntebarth 1978). The degree of coalification of this organic material depends on the quantity temperature × time. Based on measurements of the degree of coalification the age of a thermal anomaly in the graben fill can be estimated. Investigations of Buntebarth (personal communication) support the idea that the Landau anomaly is a relatively young phenomenon, according with our model.

Outlook

The presented model is oriented to the special case of the thermal anomaly in Landau, but it could be applicated to other prominent anomalies within the whole Rhinegraben (e.g., Soultz/Pechelbronn, Stockstadt). Less pronounced local anomalies could be correspondingly interpreted with a minor source depth z_0 or smaller fluxes S. In any case a thermal anomaly would be connected with a water-bearing fault in the basement. With this we generalize the model for the case of Landau and assume that hydrothermal processes of this type are active in the whole Rhinegraben.

This supposition leads to the problem of the hydraulic system and of its causes. Such an hydraulic system includes a region which exceeds the proper graben zone. The considerations of the present paper are limited to the special part of the circulation system characterized by ascending deep groundwaters. It would be interesting to work out a hydromechanical model for the whole water circulation system in the underground of the wider surroundings of the graben, testing then the reality of our hydrothermal model.

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