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New subsurface temperature maps for the Tertiary Lower Rhine Basin and the adjacent Variscan Basement - Germany, The Netherlands, Belgium

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Abstract

The regional subsurface temperature field at the transition between the Palaeozoic Variscan Basement and the Cenozoic Lower Rhine Basin in Dutch, German and Belgium territories was mapped up to a depth of 1000 m. Temperature data from 66 wells and 11 coal mine subcrops were available. In 46 wells, temperature logs, covering a cumulative depth interval of 6600 m, were measured for this study.

Keywords: Lower Rhine Basin, Palaeozoic Basement, geothermal anomalies, isothermal maps, new temperature logs

Introduction

Where temperature data were scarce, temperature extrapolations to greater depths were made, using existing information of thermal rock properties, heat flow and geothermal gradients in the study area.

Thermal gradients within the Tertiary depocentres of the Lower Rhine Rift and the Palaeozoic basement highs are rather alike and generally do not exceed 22 °C/km. The unconformity between the Tertiary and the underlying coal-bearing Upper Carboniferous represents a thermal discontinuity. Geothermal gradients within the Upper Carboniferous average 45-50 °C/km and are explained by the low permeabilities and the heat storage effect of dispersed organic matter and coal.

In zones of rapid downward water flux, related to karstified Devonian limestone provinces, and within the highly permeable pile of low-consolidated rocks of the Tertiary Lower Rhine Basin locally even negative thermal gradients were observed. The highest measured vertical thermal gradients of up to 67 °C/km are related to a depth interval of 300 m to 500 m here, also exhibiting the most pronounced lateral temperature differences. Positive thermal anomalies are explained by the occurrence of major faults, connecting the basement with the Cenozoic sediment fill and bounding individual Tertiary depocenters in the Lower Rhine Basin.

Isothermal maps at depths of 100 m, 300 m, 500 m and 1000 m are calculated. The average detected and extrapolated temperatures are 11 °C (100 m), 18 °C (300 m), 27 °C (500 m) and 33 °C (1000 m). Temperature mapping revealed that the subsurface thermal structure closely corresponds to main tectonic features. The most prominent ones are hot springs in Chaudfontaine/Belgium and Aachen/Germany, associated with the occurrence of major thrusts at the former Variscan orogenic front. Other positive geothermal anomalies are related to block-faulting within the Lower Rhine Rift Basin and were detected by temperature measurements at the borders of the Tertiary Basin and its sub-basins. Depocentres of the Rur- and the Erft sub-basins and Paleozoic Highs of the Variscan Basement represent geothermal cooler areas. Temperatures at deeper levels (1000 m), below the Mesozoic/Cenozoic unconformity, are assumed to be governed by thermal characteristics of different lithologies, whereas the thermal effect of circulating groundwater at that level is considered unlikely.

Geological Setting

The study area has a triangular shape and is located in Belgium, the Netherlands and Germany and covers an area of nearly 5000 km^2 (Fig.1).

The regional geology is dominated by the Lower Rhine Basin, a rift structure, which has developed upon pre-existing basins of Carboniferous and Triassic-Jurassic age, extending about 100 km in length and 50 km in width. During the Neogene basin subsidence developed due to rifting, punctuated by phases of uplift and erosion. Subsidence of individual blocks was heterogeneous and was governed by NW-SE oriented faults, which cut into the north-western margin of the Rhenish Massif (Fig. 1); e.g. the central Erft Block subsided 1300 m and the Peel Block in the Netherlands 2000 m (Spelter, 1978, Klett et al., 2002). From west to east the Feldbiss, Rur and Erft faults separate the individual eastward dipping blocks. (Figs 1 & 2).

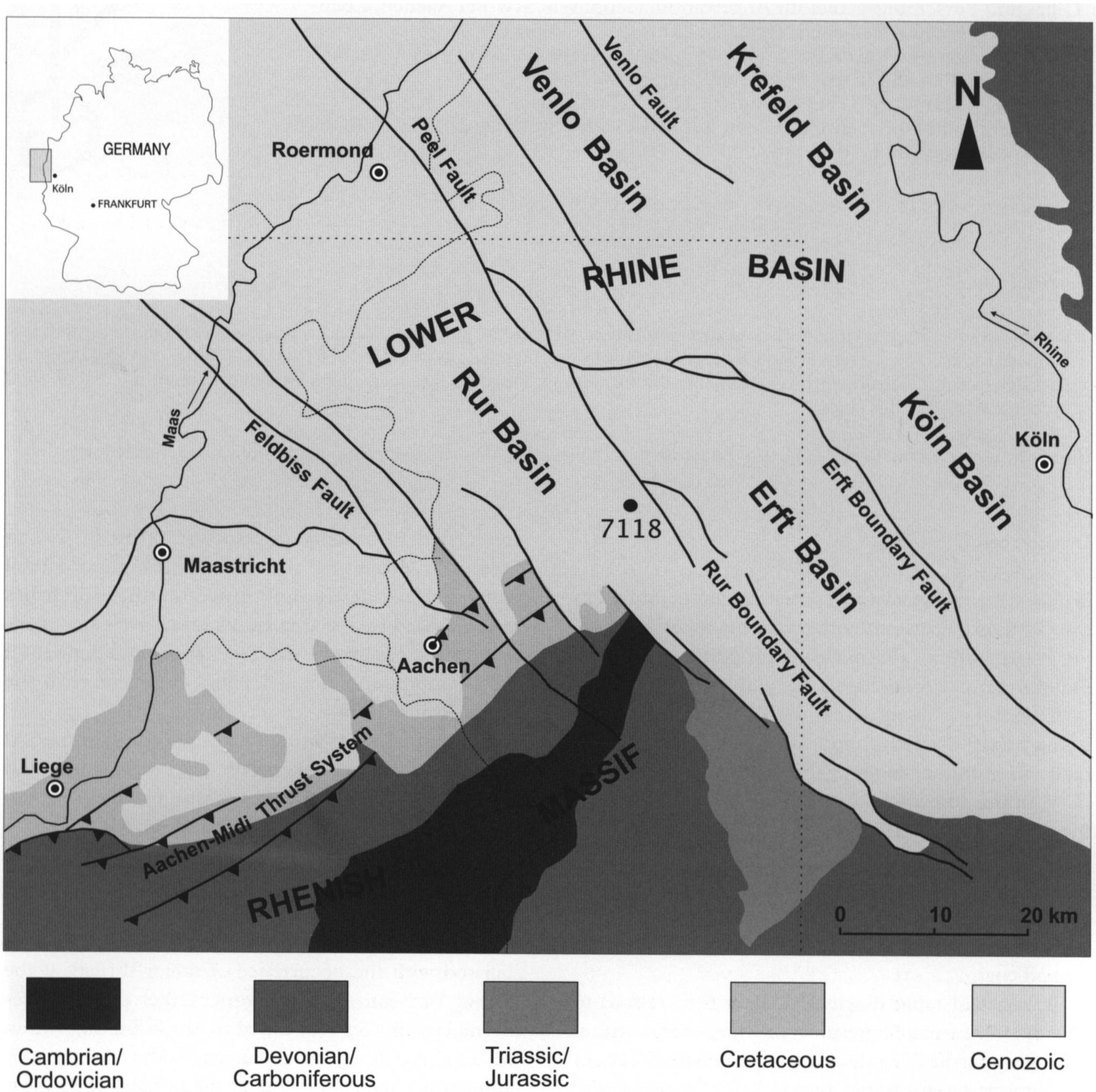

Fig. 1. Geologic map of the Lower Rhine Basin and adjacent areas. For the Lower Rhine Basin the most important structural elements and sub-basins are shown.

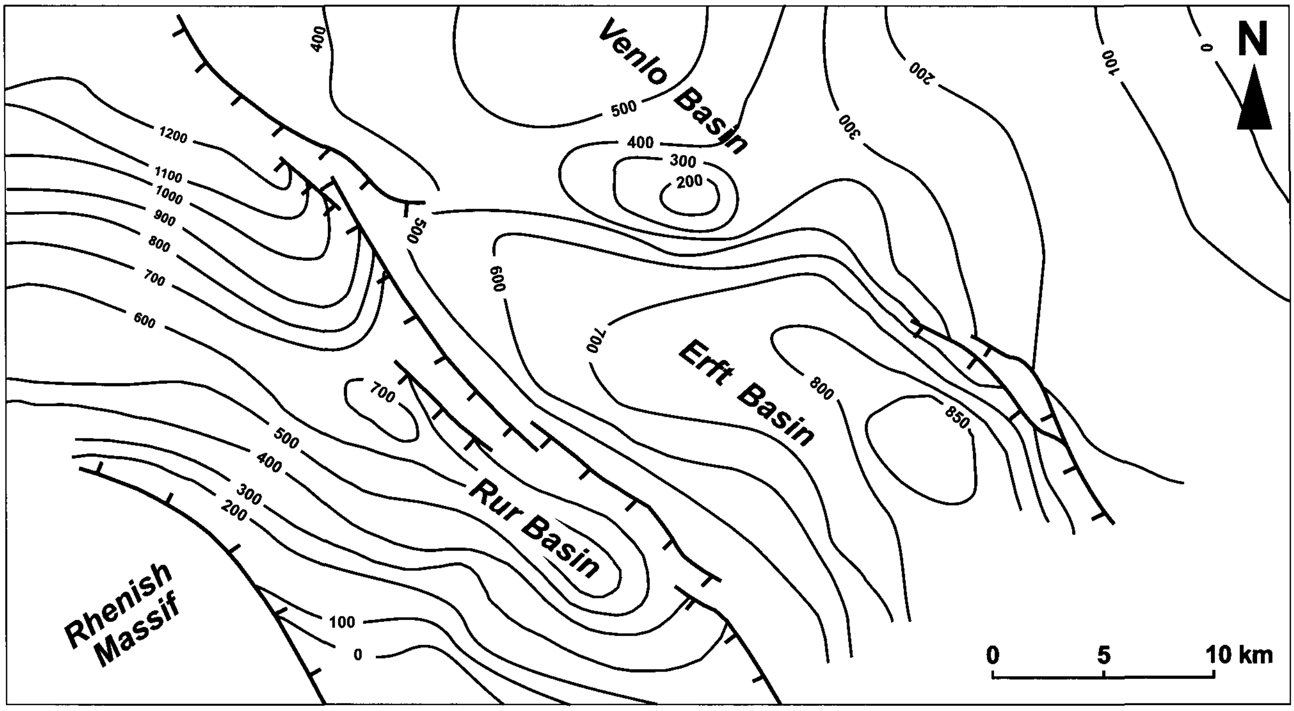

Fig. 2. Base Tertiary depth map for the Lower Rhine Basin, as derived from well results and gravimetry (modified after Dürbaum & Wolf, 1958).

The entire rift structure of the Lower Rhine Basin is bordered by Devonian and Carboniferous rocks, forming the Variscan Basement (Rhenish Massif) in the southwest and the northeast. Variscan deformation shows a trend perpendicular to the overlying Cenozoic structures. Permian and Triassic rocks are also locally preserved beneath the Tertiary graben systems.

For the understanding of the subsurface thermal field, geologic and tectonic features at the transition from Variscan basement to the Cenozoic rift basin and the internal rift geometry play an important role.

Previous thermal data – A review

The earliest subsurface temperature measurements recorded in the study area were conducted as isolated rock temperature determinations in hard coal mining districts of the South Limburg and the Peel region in the Netherlands (De Braaf & Maas, 1952, Sadée, 1975). De Braaf & Maas (1952) found that thermal gradients within Upper Carboniferous strata average 40 °C/km, whereas within the Cenozoic sedimentary cover lower gradients of 21 °C/km occur. Similar observations were made by Stuffken & Arts (1965, in Visser, 1978) from 56 subsurface temperature determinations within Upper Carboniferous rock units. They found thermal gradients of 20 °C/km and 38 °C/km within the Cenozoic cover and the Upper Carboniferous respectively. More recent thermal data from the German coal district revealed similar temperature gradients between 44 and 50°C/km (Mücke, 1986; unpublished) within the coal bearing Upper Carboniferous section, being very similar to the Dutch data. The difference in the thermal regimes between the Cenozoic cover and the underlying Palaeozoic is usually explained by a thermal blanketing effect caused by lower thermal conductivities of coal bearing strata. Lower thermal conductivities are usually observed in more recently deposited, high porous Tertiary sediments. As a result of low conductivity the surface heat flow is reduced, causing a warming effect in underlying sediments. The same observation is made by Van Balen et al. (2002) in wells of the Roer Valley Graben in the Netherlands.

The first comprehensive analysis of the subsurface temperature field in the southern Netherlands was published by Van Dalfsen (1981). Based on temperature logs from the *Echt, Sittard, Vlodrop, Susteren* and *Mheer* geothermal wells he constructed isothermal maps to a depth of 250 m. The maps show a laterally homogenous thermal field with temperatures between 14 and 16 °C at a depth of 250 m.

For the Belgium territory, Legrand (1975) published temperature data from the geothermal wells *Soumagne, Chaudfontaine* and *Val Benoit,* located at the northern flank of the London-Brabant Massif. They constructed isothermal maps, partly based on temperature extrapolations, to a depth of 3000 m. A geothermal anomaly occurs at the *Chaudfontaine* location, a geothermal spring with surface water temperatures between 30 °C and 36 °C. The elevated temperatures are explained by a rapidly circulating groundwater recharge and discharge system within Lower Carboniferous limestones (Graulich, 1983). Pommerening (1992) estimates circulation depths of 700 m in this area.

Temperature maps from Vandenberghe & Fock (1989) show elevated geothermal gradients for the north-eastern part of Belgium. Temperatures in depths of 1000 m and 2000 m average 60° and 90° respectively. The interpretation of the geothermal anomaly, however, has to be done with a certain degree of caution as the maps rely on only few, and partly extrapolated data. Towards the central parts of Belgium subsurface temperatures appear to decrease. At a depth of 2000 m temperatures around 50 °C are implied and are attributed to a rise of the Caledonian basement at shallow subsurface depths (Vandenberghe & Fock, 1989).

A detailed geothermal study on a smaller regional scale was carried out by Pommerening (1992) in the city of Aachen, where Europes hottest geothermal springs with surface temperatures of more than 70 °C occur. An analogue to the above mentioned *Chaudfontaine* well, Pommerening (1992) relates the presence of hot springs in Aachen to groundwater recharge and discharge processes along major thrust faults at the northern rim of the Rhenish Massif (Aachen-Midi thrust system). Temperature measurements in a shallow well in the vicinity of this thrust system proved temperatures of 40 °C at a depth of only 50 m. Such temperature data, related to a highly disturbed thermal regime, were not used for isothermal mapping, as this study aims to portray the regional subsurface temperature field.

For the Northern Rhenish Massif, where the Palaeozoic basement crops out, only scarce subsurface temperature data exist due to a lack of exploratory and industrial wells. However, detailed geothermal data (temperature logs, heat conductivity determinations on rock samples, heat flow measurements) from the research borehole Konzen 1 at the southern flank of the Stavelot-Venn anticline (Fig. 1) were published by Schürmeyer et al. (1984). The well reached a depth of 400 m. An average geothermal gradient of 22 °C/km and a heat flow density of 72.2 ± 0.3 mW/m^2 was determined (Dornstaetter & Sattel, 1985). The latter value is in good agreement with a regional heat flow density map, published by Haenel (1983) for the Rhenish Massif and is also in line with the mean heat flow of 76 mW/m^2 in the Netherlands (Ramaekers, 1991).

The majority of the thermal data used in this study was obtained from the southwestern Lower Rhine Basin, characterised by its thick infill of Cenozoic sediments. This area has undergone intensive lignite exploration during the last few decades and therefore contains a large number of exploration and groundwater observation wells drilled by RWE-Rheinbraun. Balke (1973) was the first to systematically investigate the subsurface temperature field of this province and to publish subsurface temperature data and isothermal maps. His interpretation, however, is only related to the Cenozoic Graben systems and does not extend to the older Palaeozoic highs bounding the Tertiary Basin.

A recent contribution to the geothermal data base in the Lower Rhine Embayment was made by the Institute of Joint Geoscientific Research in Hannover. In the early 1990's they carried out detailed temperature logging in a large number of groundwater observation wells, most of them reaching depths of 550 m.

The assessment of data quality for the previous thermal data is difficult as mostly no information of the applied measurement technique and in only a few cases relative errors were given. In some cases relative errors of ±0.1 to 0.01 °C were noted, which was regarded as reliable data quality. The least reliable data were considered the subsurface rock temperatures in German and Dutch coal mines, as usually no absolute or relative errors were given.

Continuous temperature logs from wells are in general considered most reliable. In all cases the temperature measurements were carried out several months or years after drilling so that effects of mud circulation could be ignored. Where thermal profiles exhibit marked effects of circulating groundwater, the data were not used for contouring isothermal maps.

For the wells *Kastanjelaan, Heugem* and *Straeten-1* only bottom-hole-temperature data were available, without information on mud circulation times and data correction procedures were available. A deep well in the Roer Valley Graben is the Straeten-1 hydrocarbon exploration well, penetrating more than 1200 m of Tertiary sediments.

Results

New temperature measurements and data statistics

In order to enhance the present thermal data base for the study area systematic temperature logging in 46 wells, of which 24 wells are located within the Cenozoic fill of the Roer- and the Erft sub-basins, has been carried out (Fig. 1). The other 22 wells are located at the northern rim of the outcropping Variscan Basement and eight of them reach depths greater than

100 m. The temperature measurements carried out in the individual wells cover a depth range from 50 m to more than 500 m. For statistical analysis of the data and for contouring isothermal maps, it was decided to disregard wells shallower than 100 m.

Altogether temperature logs with a cumulative depth of 6600 m were measured during various logging campaigns. The sampling interval during temperature logging was 0.2 m and the temperature probe was calibrated before each logging campaign. The absolute and relative measurement error was determined as ± 0.1 °C and ± 0.02 °C for a temperature interval between –20 °C and +80 °C respectively. The data were registered down-hole to guarantee a widely undisturbed water column in the borehole.

Including our new temperature measurements, a total of 66 wells (63 continuous temperature logs and 3 BHT data) and 95 individual temperature determinations in mining subcrops (covering a depth interval between 380 m and 875 m) constitute the database of the presented study. The well data temperature and thermal gradient curves are plotted as a function of depth in Fig. 3a and b. Horizontal bars are indicative of lateral variations in the data at the respective depth interval. It is clear that the amount of data (number to the right of the variation bars) decreases steadily with depth and the number of wells deeper than 500 m becomes significantly scarce. Only 5 temperature data measurements are available at 1000 m.

The maximum lateral temperature variations of 27 °C are observed at a depth of 400 m. Thermal gradients average between 20 and 30°C/km in the study area. Beneath 500 m thermal gradients steadily decline to values of 1.5 to 3.0 °C/100 m over the area. These values typically represent the thermal situation of the Variscan consolidated crust bordering and underlying the Lower Rhine Rift Basin.

Analysis of the temperature logs has revealed that lithology and circulating groundwater in the subsurface of the Lower Rhine Rift Basin is the reason for the distinct thermal heterogeneity observed in the area. The Tertiary sedimentary infill is typically composed of thin consolidated intercalated shales, sands and coal measures, each of them differing in their characteristic thermal and petrophysical properties, such as heat conductivity, heat capacity, porosity and permeability, governing temperature distribution and hydrodynamic properties.

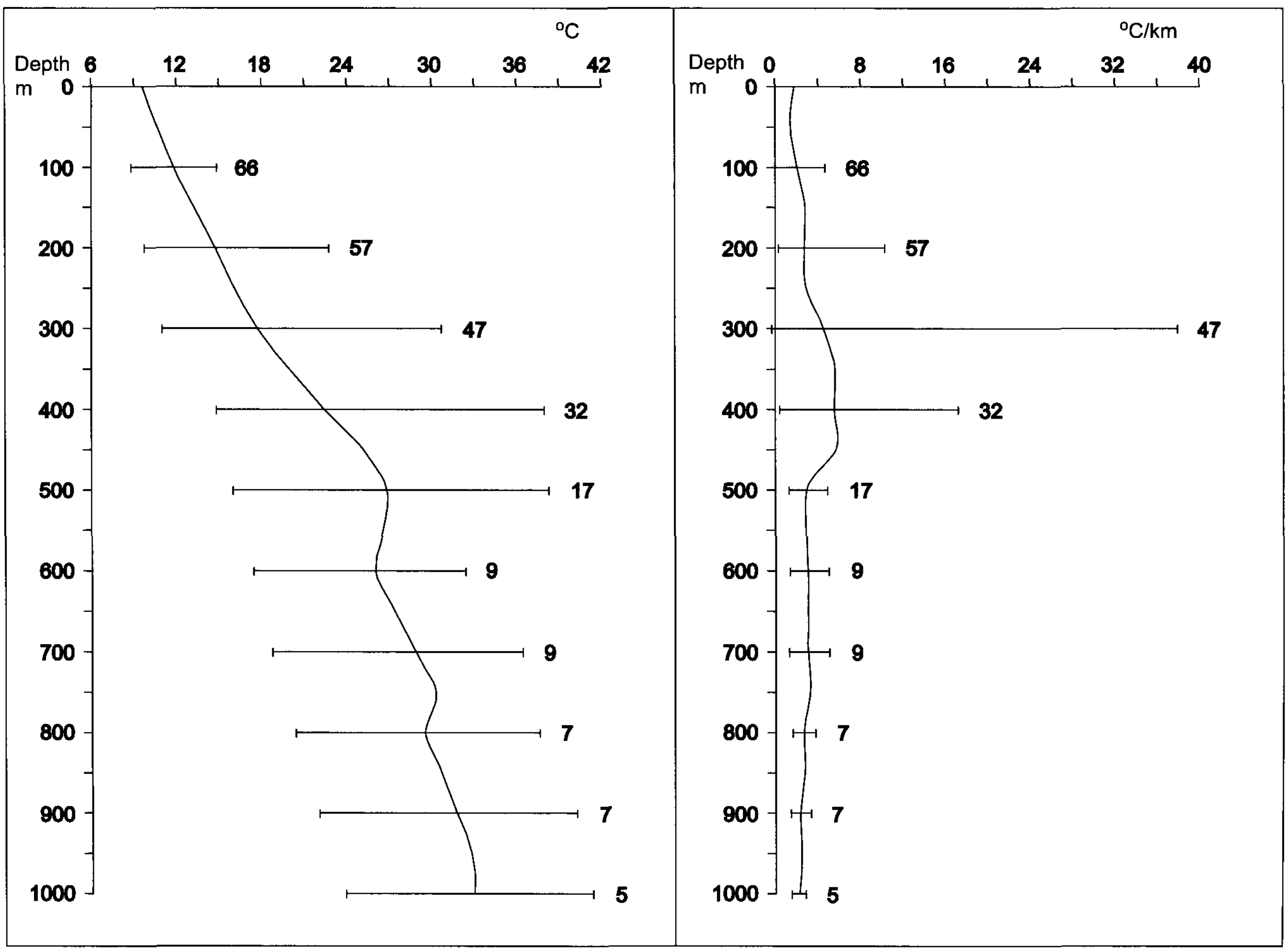

Fig. 3. Geothermal database of the study area. Curves show the average temperatures (left) and the average geothermal gradients (right) as function of depth. Horizontal bars are indicative of the data variability in the respective depth level. Numbers indicate amount of available data.

Deep seated sub-vertical faults divide the basin into several sub-basins and are considered as pathways for groundwater, that is heated at the basin floor at depths around 1200 m to 1300 m and migrated upward until reaching an aquifer in a shallower level. An example for this mass-bounded heat transfer process is the well 7118, situated close to the Rur boundary fault, separating the Roer- from the Erft sub-basin (Fig. 4). At a depth between 260 m and 290 m a strong positive heat anomaly was measured with a geothermal gradient up to 38 °C/100 m (Fig. 4). The interval with the anomalous high temperatures coincides with the occurrence of a sandy aquifer, which is sealed at the top and at the base by impermeable lignite measures. Secondary anomalies were observed in

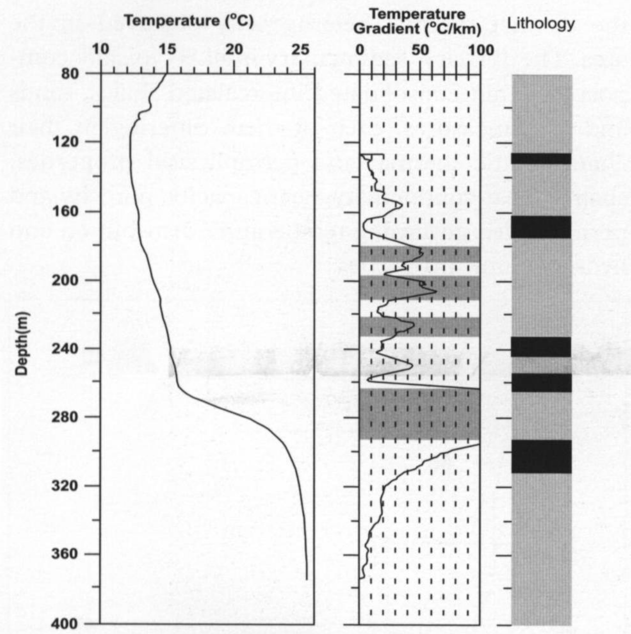

Fig. 4. Temperature log of the well 7118 (for location see Fig. 1). Note the influence of circulating groundwater in different sandy aquifer intervals (shaded in gray). Highest thermal gradients are observed at a depth between 270 m and 290 m. Tertiary coal seams (black signature in lithology column to the right) act as aquicludes for the sandy aquifers (gray signature).

another aquifer at a higher stratigraphic position.
In other wells, the vertical mobility of groundwater even causes negative geothermal gradients, when cold water from shallow levels is rapidly recharged into the sedimentary sequence. Examples are found in the Lower Rhine Rift Basin in variable depths, as well as in karstified limestones from the Variscan Basement at depths up to 100 m.

Temperature extrapolations

As data become scarce at depths greater than 500 m temperature data were mathematically extrapolated to assess the deeper thermal field. A high degree of uncertainty therefore has to be considered when interpreting the 1000 m-isothermal map.

If parameters like thermal conductivity, heat production rate of the subsurface rocks and heat flow are known, it is possible to extrapolate temperature data to a given depth using a method proposed by Schulz & Schellschmidt (1991). Instead of employing heat flow data for temperature extrapolations geothermal gradients for specific intervals can be used, provided appropriate information is available.

For the study area an average surface heat flow of 72 mW/m^2 was assumed, according to the work of Schürmeyer (1984). A number of heat flow values for the Tertiary Lower Rhine Rift Basin was published by Balke (1970) but these data exhibit strong variations due to arbitrary thermal conductivities of the water-filled and highly porous Tertiary sediments. Thermal properties of poorly consolidated Tertiary rocks (gravel, sand, shale, lignite) were taken from Balke (1973), who determined an average value of 2.9 W/mK for Tertiary water-saturated sands and gravels, the predominant lithology in the Lower Rhine Rift Basin. Thermal conductivity measurements for the Lower Palaeozoic basement were performed by Schürmeyer (1984) and revealed very similar values of 2.8-3.1 W/mK. The heat storage effect of organic matter and coal is important for the Upper Carboniferous. Low thermal conductivities of 1.8-2.2 W/mK, as determined by Mücke (1964), clearly explain the observed high thermal gradients, as published by Visser (1978).

For temperature extrapolations in wells within the Lower Rhine Rift Basin the Base Tertiary unconformity was considered as a thermal discontinuity. In general, lower geothermal gradients are observed within the Tertiary sediments than in the coal bearing, low-conductivity rocks of the Upper Carboniferous. The base Tertiary surface for each well location was determined using the map in Fig. 2 and for each corresponding well, temperatures below the Tertiary were calculated using an average geothermal gradient of 45 °C/km, representative of the Carboniferous section.

It should be noted that the above described assumptions for temperature calculations do not take into account that the subsurface temperature field within the Tertiary basin fill is strongly influenced by heat convection and variable thermal conductivities in porous media and thus involves a major simplification.

Temperature maps

Continuous temperature logs, bottom-hole temperatures, and extrapolated temperature data were compiled from 66 wells and from about 90 individual subsurface temperature determinations in German and

Dutch coal mines to construct isothermal maps for the study area.

Contouring of the isotherms was performed by using a software from the BGR/GGA in Hanover. As no topographic correction was applied to the data, all maps are referred to topographic surface level.

In this paper the temperature distribution in depths of 100 m, 300 m, 500 m and 1000 m are shown (Figs. 5-8). Isothermal lines were contoured at variable intervals, according to the density of available data. For the isothermal maps up to 300 m of depth, each isothermal line was contoured ($\Delta T=1$ °C). For the 500 m isothermal map each 2 °C and for the 1000 m level each 4 °C-line is plotted.

The major structural elements, as far as considered relevant for the temperature distribution, and important geologic features, like the limit between the Variscan basement and the Tertiary Lower Rhine Rift Basin, are shown as overlay on each isothermal map.

As the rationale of this study was the compilation of a regional subsurface temperature field it should be noted that the isothermal maps have been biased in that the temperature anomalies caused by the Aachen hot springs were omitted. The latter are known to cause locally very pronounced thermal effects with surface temperatures of more than 70 °C.

The 100 m isothermal map (Fig.5)
Measured temperatures at the 100 m level oscillate between 8 °C and 15 °C. Although this level exhibits

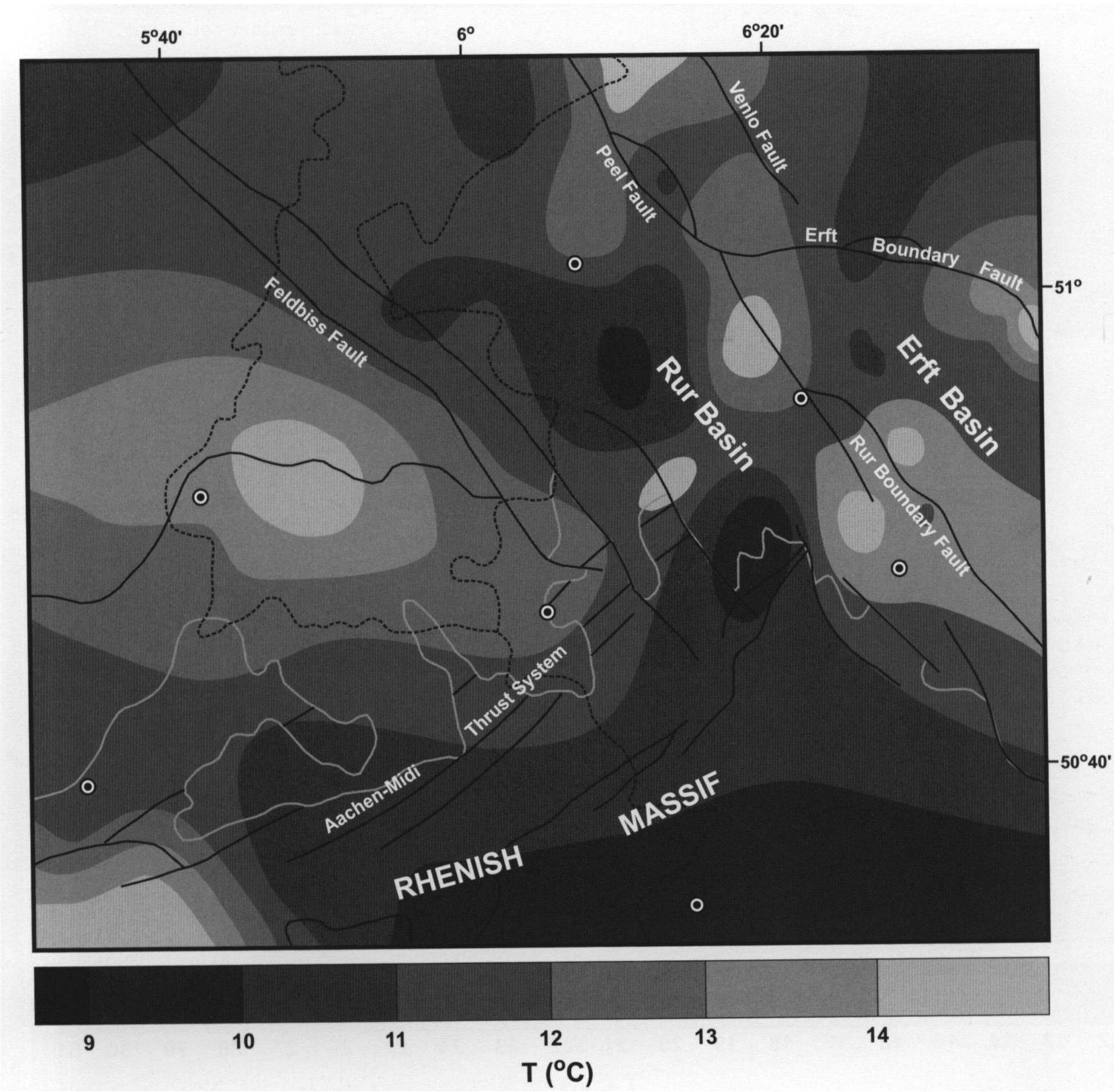

Fig. 5. Temperature distribution at 100 m depth. The dashed line indicates country borders. The limit between the Tertiary basin fill to the Paleozoic is marked by a continuous line. Major faults are labeled. Isothermal contours: 1°C.

only small lateral variations in temperature, a discrimination between warmer and colder domains can be made, which corresponds to important geologic features. Maximum temperatures are detected along the Roer- and the Peel Fault and in the vicinity of Maastricht. In contrast, in the southern part of the map, the lowest temperatures appear, where Palaeozoic rocks crop out.

The 300 m isothermal map (Fig.6)
At the 300 m-level substantial lateral temperature variations of about 20 °C are observed. The highest temperatures of up to 31°C appear in the southwest (close to Luettich, Belgium) and again at the tectonic boundary between the Roer and the Erft blocks. The depocentres of the Tertiary sub-basins continue to appear as low-temperature regions. This is presumably due to the effect of descending cold surface waters. Clear evidence for this mechanism of cooling is given in some wells, where a negative thermal gradient in certain depth intervals of some tens of metres was observed, evidencing locally strong groundwater fluxes. The Variscan Basement also show up as a geothermal cold area, best represented by the Konzen-1 well, where temperatures of 14 °C were measured at 300 m.

A comparison of the map image with the statistical variations of geothermal gradients and temperatures (Fig. 3), implies that fault-related heat transport

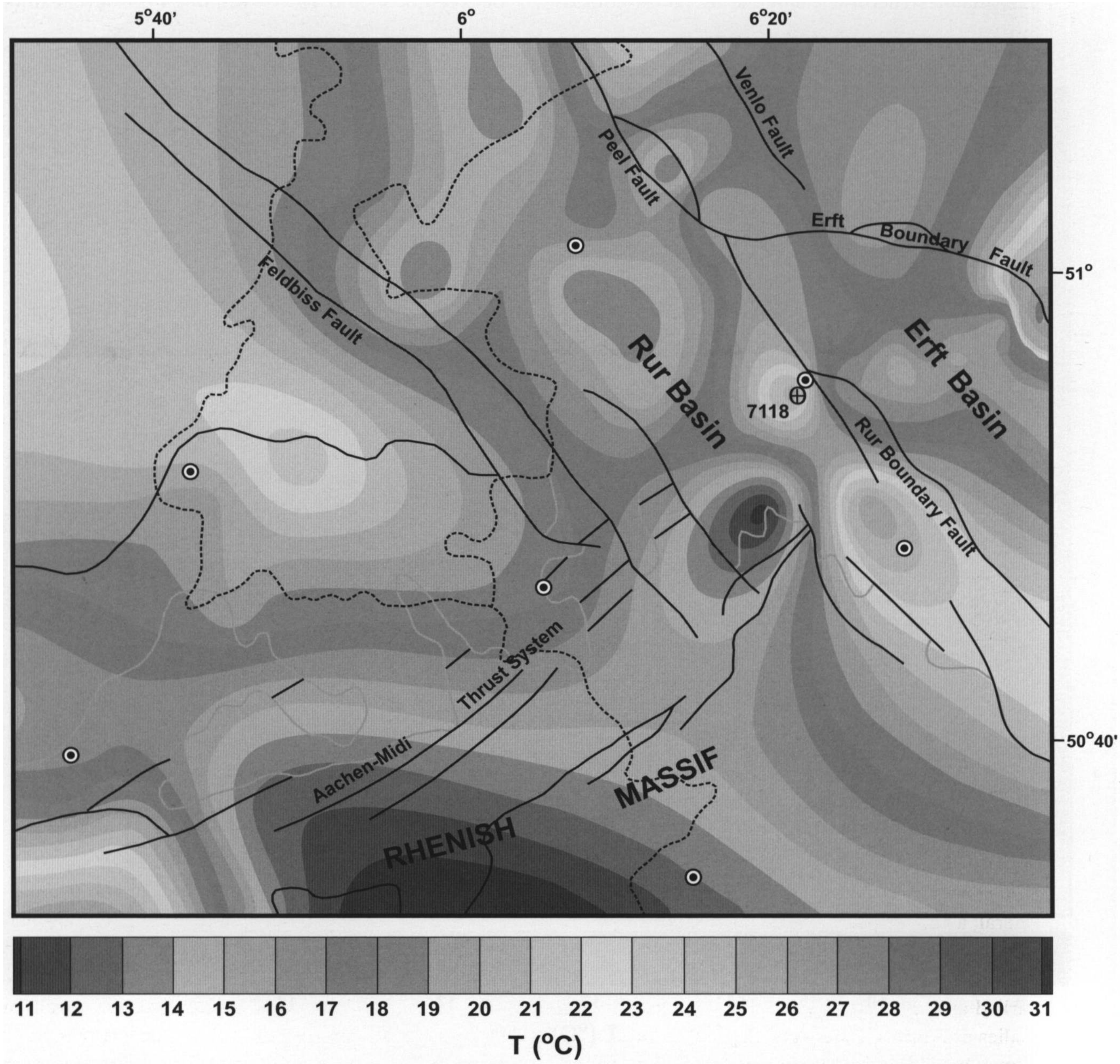

Fig. 6. Temperature distribution at 300 m depth. The location of well 7118 is indicated (for explanations see text). The dashed line indicates country borders. The limit between the Tertiary basin fill to the Paleozoic is marked by a continuous line. Major faults are labeled. Isothermal contours: 1°C.

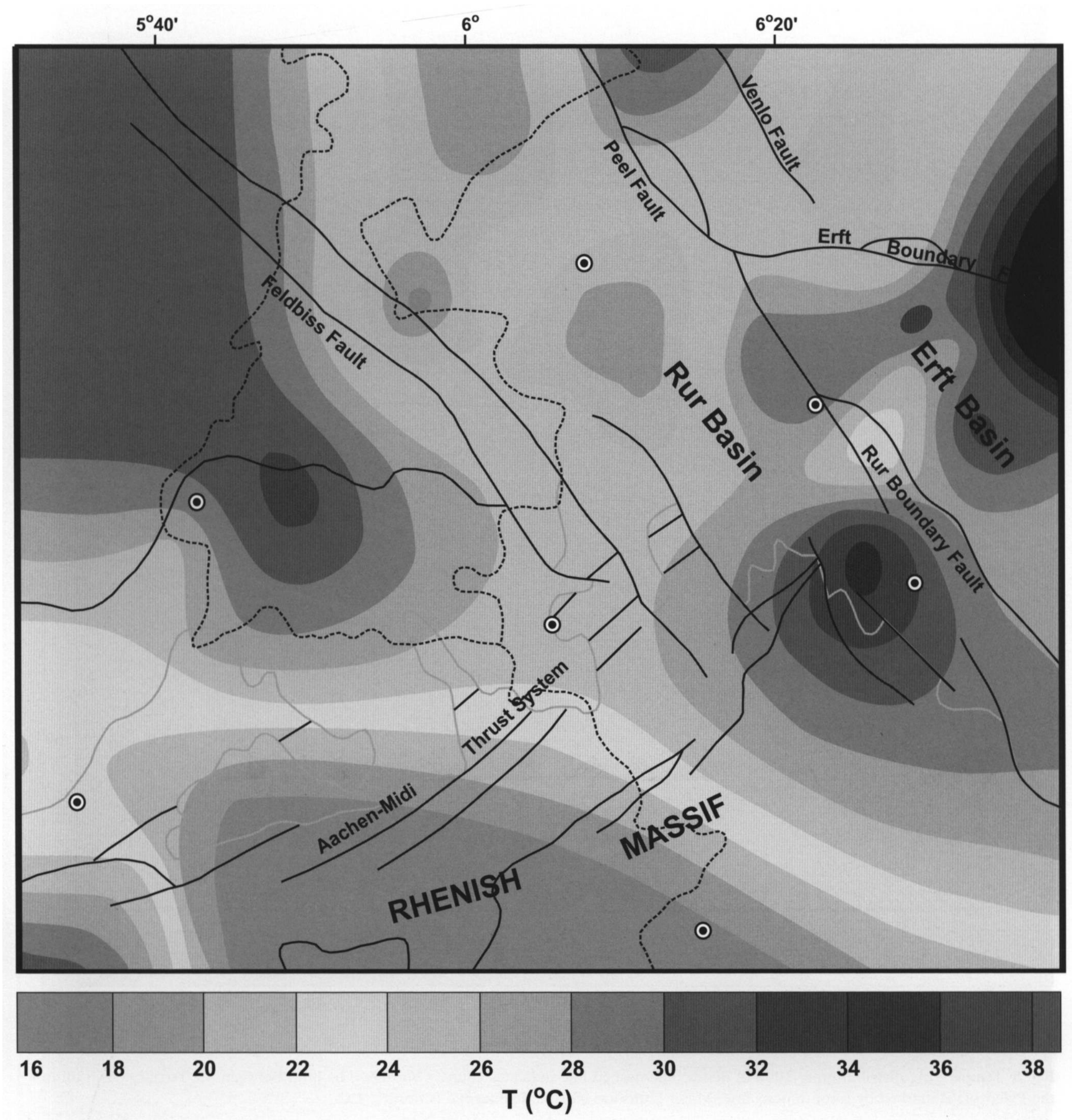

Fig. 7. Temperature distribution at 500 m depth. The dashed line indicates country borders. The limit between the Tertiary basin fill to the Paleozoic is marked by a continuous line. Major faults are labeled. Isothermal contours: 2°C.

processes are very important at this depth level.

The 500 m isothermal map (Fig.7)

In general, a similar picture as described for shallower levels is represented by the 500 m isothermal map. The lateral temperature gradients at this level are not so marked and the boundaries of positive geothermal anomalies are not as sharp as at the 300 m-level. This effect may be caused by the increasing thermal equilibration in deeper parts of the basin, due to less pronounced temperature gradients between descending and ascending groundwater. The most pronounced positive temperature anomalies are detected at the easternmost part of the study area and are related to the Erft boundary fault, where maximum temperatures up to 38°C were measured; and at the transition between pre-Tertiary rocks and the Tertiary Basin fill. The latter is related to the southwestern boundary faults of the Tertiary rift basin. The centres of the Roer and the Erft sub-basins are characterised by temperatures between 18 °C and 26 °C, which convert to average geothermal gradients of 18 to 34 °C/

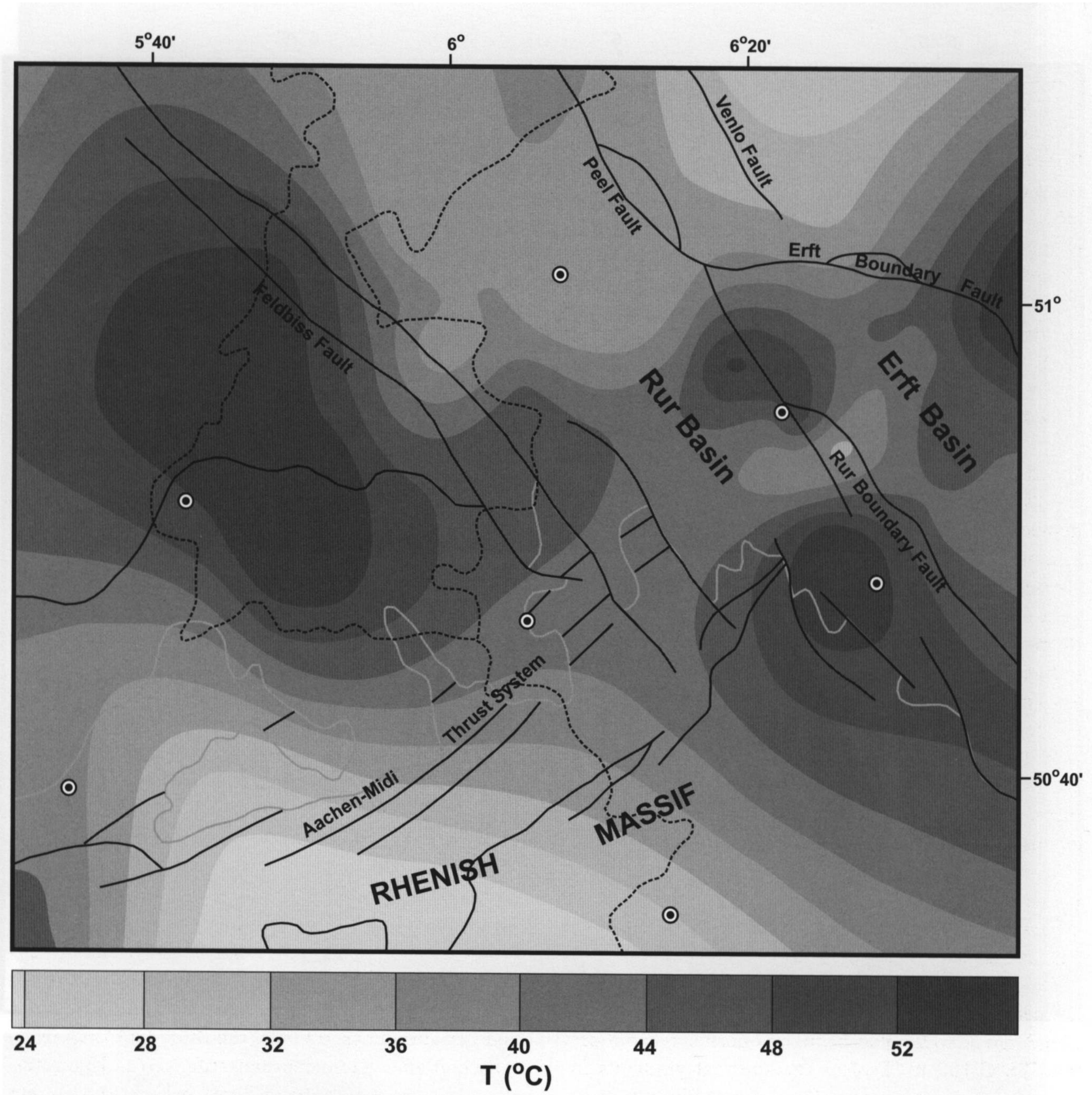

Fig. 8. Temperature distribution at 1000 m depth. The dashed line indicates country borders. The limit between the Tertiary basin fill to the Paleozoic is marked by a continuous line. Major faults are labeled. Isothermal contours: 4°C.

km. Similar thermal gradients are expected for the Paleozoic basement, however, no data for this depth are available.

The 1000 m isothermal map (Fig.8)

Five borehole data and deep temperature data from mining subcrops (up to 875 m) were available at this depth. However, most of the data used to construct the isothermal contours result from temperature extrapolations using typical thermal gradients characteristic for the Tertiary and for the Palaeozoic Basement.

Between 500 m and 1000 m the lithologic inventory changes significantly as mostly Palaeozoic rocks are encountered at depths below 1000m. For Palaeozoic lithologies a thermal effect of circulating groundwater is ruled out due to low permeabilities. It was assumed that the temperature distribution at this depth is a result of basinal heat flow and heat conduction, and reflects the differences in thermal properties of the rocks.

In the 1000 m trend map an east-west oriented, central area of elevated temperatures (40-52 °C) coincides with the distribution of low-conductive Upper Carboniferous rocks in the subsurface, as known from wells and mining activities. Lower temperatures (<40 °C) are calculated for the Lower Paleozoic basement in the south and for the northernmost parts of the study area (northern Erft Basin and southern Roer Valley Graben), where Tertiary sediments are thicker than 1000 m (Fig.2).

It should be stated again that the 1000 m isothermal map is the least data-constrained one and, apart from a few real measured temperature data points, it relies on data extrapolation. Therefore it should be referred to as a thermal trend map rather than an isothermal map. Even though for temperature calculations realistic geological assumptions have been made, the presented map was constructed only to visualise a likely state of the deep thermal field in the study area and does not claim absolute accuracy.

Discussion and Conclusions

Based on a recompilation of existing thermal data and new subsurface temperature measurements a more detailed picture of the subsurface temperature distribution in the Lower Rhine basin and the adjacent Variscan basement highs could be constructed. Temperatures and temperature gradients are typically influenced by the strongly variable thermal properties of highly compacted Paleozoic rocks and water-filled, low consolidated Tertiary sediments, by heat flow and by tectonic processes.

Regionally, the subsurface temperature field closely corresponds to the outline of typical geotectonic features, characterising the shape and architecture of the extensional Lower Rhine Basin. Within the basin, the temperature field (100-500 m) is strongly heterogeneous with clearly mappable thermal anomalies, in contrast to the Variscan Basement in the southwest. Maximum lateral temperature variations of up to 27°C were observed at a depth of 400 m. Geothermal gradients along fault zones (Rur fault, Erft fault), limiting large tectonic blocks and sub-basins, reach more than 38°C/100 m. Typical geothermal gradients in depocentres vary between 18 and 34°C/km. Surface heat flows and thermal gradients in the extensional Tertiary Basin are reduced by descending groundwater. Within highly porous strata, geothermal gradients can decrease locally to zero or even to negative values. Temperature maps provided by Van Dalfsen (1981) show average temperatures of 12-16°C in a depth between 150 and 250 m for the South Limburg area in the Netherlands and thus fit very well to our data.

It can be discussed whether groundwater pumping around the browncoal mines causes thermal effects of a magnitude that they become visible in the isothermal maps. For this study, only groundwater observation wells and no active pumping wells have been used for temperature logging. Measurement locations were chosen to have a distance of several hundred meters to several kilometres away from active pumping wells to ensure that major distortion of the thermal field can widely be eliminated.

The deeper thermal field (1000 m) is assumed to be governed by heat conduction and by the thermal properties of different lithologies rather than by convective processes. Although, interpretation for this depth level suffers from a scarcity of measured data, there is some evidence for elevated temperatures in areas where coal bearing Upper Carboniferous rocks occur in the subsurface. This is explained by low thermal conductivities, which are characteristic of this rock type. Thermal blanketing processes, where surface heat flow is reduced by groundwater flow in highly porous media and consequently temperature gradients in underlying strata increase, may also occur.

The general trends shown in our maps correspond to deep subsurface temperature data recently published by Van Balen et al. (2002) for the Roer Valley and the Peel Block. Van Balen et al. (2002) provide a regional deep subsurface temperature map of the Netherlands at a depth of 2000 m. Although these data do not allow identification of small scale thermal anomalies, it is interesting to mention that the depocentres of the Roer Valley Graben appear as low-temperature zones, which is in good agreement with the trends shown in our maps.

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