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Heat Budget and Geothermal Gradient – Study Case Bad Kissingen, Germany

Wärmehaushalt und geothermischer Gradient – Untersuchungsgebiet Bad Kissingen, Deutschland

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Inhalt

1. Introduction and objective

The main objective of the investigations is to evaluate the temperature conditions in the deep underground of the Saale river valley near Bad Kissingen on the basis of geological and hydrochemical research methods. On one hand, the geothermal heat is produced by a slow conductive flow of energy coming from the earth's interior to the earth's surface. This flow of energy causes a general basic transport of heat yielded by a radioactive decay, e. g. of thorium, uranium, zirkonium or potassium. On the other hand, increased gradient can often be observed in regions, where young volcanic or plutonic magma appears in the upper earth's crust. This appearance may additionally warm up the ground.

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In general, two ways of transporting heat may be distinguished:

- **conductive**, i. e. energy is transported, but no water, steam or gases form the transport media, or
- **convective**, i. e. energy is transported by the movement of water, steam or gases.

A thermodynamic balancing of warm and cold occurs at a conductive flow of energy. The direction of the balancing during the convective flow of heat depends on the flow direction of the moving waters, steam or gases. Cold water can penetrate from the surface into the ground and cools the ground. Alternatively, warm water rises and heats the upper parts of the aquifers. Depending on the permeability of the material, the conductive or convective transport of heat may be the main factor causing the local ground temperature. Since predominantly the permeability within a mountain range decreases with the depth, the convective share also decreases frequently in the same direction and, consequently, the conductive share begins to dominate.

2. Location and geology of the region

The Bad Kissingen spa is one of the most renowned spas of Germany. It is located in the center of Germany within the triangle of the federal states Thuringia, Hesse and Bavaria on its Bavarian side. Morphologically and geographically seen, the Bad Kissingen spa is bordered in the W by the Rhön mountains, in the N by the Thüringer Wald, in the SE by the Steigerwald and in the SW by the Spessart (see M. HOFMANN & N. GEORGOTAS, 1997, p. 130). Figure 1 shows that all Bad Kissingen medicinal wells are located along the Frankonian Saale river which flows from N to S.

With the exception of the Balthasar-Neumann well, which is situated within the community of Bad Bocklet, all medicinal springs are administered by the Bavarian federal state spa of Bad Kissingen. Because of the spatial proximity as well as its location within the Saale valley, the Balthasar-Neumann well can also be considered as affiliated to the same hydrogeologic system.

The crystalline basement presents the oldest geologic outcrop within this region, once deposited as marine sediments; they were melted during the Middle Paleozoic (Variscian folding) and metamorphically imprinted (quartzites, mica-quartzites, muscovite-plagioclase-gneisses, dolomite marble and orthogneisses). The morphology of the basin has been formed by spacially wide areas of elevations and depressions at the beginning of the Permian. The high of the Spessart-Rhön ridge in the NW, the altitudes of the Frankenhöhe and the Steigerwald in the SE define the peripheral borders. Between these altitudes the Frankonian basin has developed (F. TRUSHEIM, 1964).

At the beginning of the elevation and folding, the higher parts have been eroded and the eroded material filled the outlying districts of the basin. During the Lower Permian also effusive magma reached the surface. As a result, at the end of the Lower Permian, terrestrial and magmatic sequences (sandstones and conglomerates, porphyry, quartz-porphyry, etc.) prevailed in the Frankonian basin. Again, during the Upper Permian, marine transgressions have deposited mainly gypsum and claystones at the outer ranges of the basin and claystones – gypsum, salt rocks and sylvine in its center. The salt rocks are mainly leached today within the Bad Kissingen region.

Fluvial and terrestrial sediments as well as warm climate conditions determined the time of the Lower Triassic. At the beginning of the Lower Triassic, the morphology

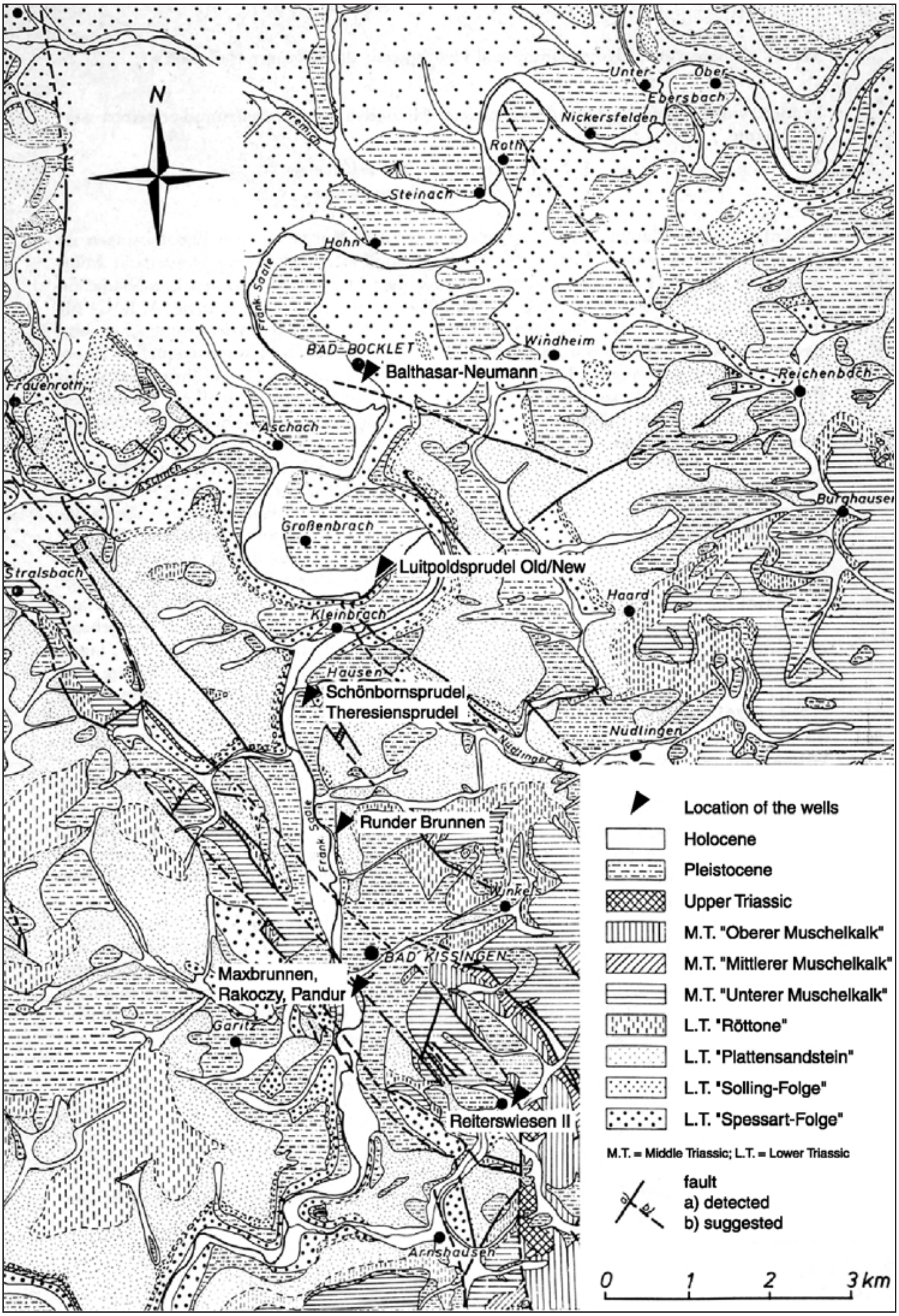

Fig. 1: Geological map of the Bad Kissingen region (after: N. GEORGOTAS, 1972).
Geologische Karte der Bad Kissinger Region (nach: N. GEORGOTAS, 1972).

between the outer ridges and the basin was equalized, and no big difference in thickness – as it could be observed during the Upper Permian and particularly in the Lower Permian – arose. The Frankonian basin formed the southern fringe of the Germanic basin, a flat basin approximately at sea level. A further subsidence of the area during the Middle Triassic led to marine, predominantly carbonatic, in parts clayey-silty deposits. Marine brackish conditions (sandstones, clay beds) dominated during the Upper Triassic, which indicate the slow process of alluviation of the area including some individual smaller transgressions. Figure 1 presents the simplified geological structure of the area.

Here, the Tertiary and Quarternary conditions are of additional importance. Since the magmatic sequences of older geological times are mainly cooled down, the basaltic lava found stems from the Tertiary period. These eruptive rocks however show their main dissemination in the Rhön mountains and less in the center of the basin. Hence, the carbon dioxide ingresses towards the medicinal and mineral wells of Bad Kissingen, as well as the solved salt flows from larger distances into this area.

3. Climate conditions within the Bad Kissingen region

The climate conditions within the Bad Kissingen region are determined by annual precipitations of approximately 720 mm and an evaporation of 550 mm. Apparently precipitation is lower than the average of Germany (Old-Länder, former West-Germany), whereas evaporation is comparable with the long term average value. Table 1 gives the mean annual air temperatures, measured at the weather station of Bad Kissingen.

From tab. 1 a mean annual air temperature of 9.033 °C is calculated for the period of 1987 to 1997. Since short term variations of air temperature are only be observed down to a few meters below ground surface, it can be assumed that shallow groundwater temperature is constant of about 9 °C and equal as the mean annual air temperature (Tab. 1).

Tab. 1: Mean annual air temperatures in Bad Kissingen from 1987 to 1997 calculated by daily measurements.
Mittlere jährliche Lufttemperatur in Bad Kissingen von 1987 bis 1997berechnet aus Tagesmesswerten.

Year	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
Temperature [°C]	7.75	9.49	9.59	9.64	8.71	9.50	9.01	10.31	9.12	7.38	8.86

4. Flow conditions of the groundwater

Works, particularly by N. Georgotas (1972), P. Udluft (1979), M. Hofmann (1990) and M. Hofmann & N. Georgotas (1997), contain detailed observations of flow conditions within the Bad Kissingen area. According to these comprehensive studies, the medicinal waters can be characterized in a simplified way by two different flow systems: deep groundwater flow system and shallow local groundwater flow system. The deep groundwater flow type is highly mineralized, whereby sodium and chloride (partially also sulfate) dominate and immigrate proportionally from the N (Thüringer Wald) and

W (Rhön, Spessart) into the Frankonian basin by deep fractures and fault systems. In depths of about 300–1000 m below surface it mixes with the locally infiltrating, superficial groundwater.

On the other hand, groundwater flow from local catchment area shows spatially short paths and slightly mineralized groundwater. They circulate near ground surface predominantly in the Lower or Middle Triassic aquifers.

In the Saale valley of Bad Kissingen, a stratification between the deep and more superficial groundwater types might have adjusted because of density differences. Hereby, a highly mineralized groundwater is situated below the slightly mineralized groundwater and circulates mainly in faults and tectonically weak zones above the basement and Lower Permian sediments. At few places the deep groundwater rises within the deep faults and fracture planes and mixes with the more superficial groundwater type. However, only the Bad Kissingen mineral and medicinal springs share these particular characteristics.

5. Heat budget of the Bad Kissingen medicinal wells

An increased temperature higher than the "normal" geothermal gradient is not expected within the Bad Kissingen region because of its geological conditions. Here, two different areas can be distinguished corresponding to their local geothermal gradients:

– the Saale valley, a tectonic graben structure showing different hydrogeologic characteristics and
– the area outside the Saale valley.

A somewhat higher geothermal gradient has to be estimated within the Bad Kissingen Saale valley, because deep groundwater rises by the so-called CO_2-gas-lifting effect, which transports convective heat up to more superficial zones. The temperatures of all Bad Kissingen medicinal waters within the Saale valley display these characteristics. Outside this graben structure, the groundwater as well as the convective heat flow is directed downwards, at least in large parts of the area. The superficial waters penetrating into the depth cool the ground, thereby establishing a slightly lower geothermal gradient than within the Saale valley. This is indicated, e. g. by the temperature logs in the Klauswald on the SW side of Bad Kissingen (P. UDLUFT & W. BAUER, 1996).

If a "normal" geothermal gradient is considered, as it is to be expected in Bad Kissingen, conductive water paths deep under the ground surface are necessary to extract warm water in corresponding depths. Assuming a "normal" gradient of approximately 3 °C/100 m depth, water of about 25 °C will be encountered in a depth of at least 540 m. However, drillings, e. g. the new drilling at the Luitpoldsprudel or the Schönbornsprudel, show that the actual temperature in this depth does not reach the theoretical value.

6. SiO_2-geothermometry

The hydrochemical geothermometry is a method for calculating the deep groundwater temperatures (M. HOFMANN et al., 1991). The most common and reliable geothermometers represent the SiO_2-geothermometers (quartz and/or chalcedony). The most important requirements for applying these geothermometers are: one of the SiO_2 mineral phases (quartz or chalcedony) forms the source of the SiO_2-concentrations in the waters, and a thermodynamic equilibrium between one of these mineral phases and the groundwater has been reached. The advantage of this method is that even the water temperature decreases while ascending from larger depths, silicic acid however does not precipitate or only slightly.

By means of hydrogeochemical model calculations, the equlibrium temperature between the deep water and the SiO_2 mineral phase can therefore be calculated, i. e. it can adjust to each particular water type. The circulation depth can also be calculated taking into account the geothermal gradient of the region.

However, for mixed waters that dominate in the Bad Kissingen region, a proportional mean SiO_2-concentration in the water at the point of outflow is measured. This concentration does not correspond to the deep groundwater. Nevertheless, a supersaturation with respect to chalcedony and/or quartz is often calculated, also in the Bad Kissingen medicinal wells. Thereby, according to the ratio of superficial waters from the Lower Triassic aquifers and deep groundwaters of the Upper Permian stratas, a proportional mean circulation depth for the Bad Kissingen medicinal waters is determined.

The highly mineralized medicinal waters of the Upper Permian are the most appropriate (strong influence of the Upper Permian facies) to calculate the depth temperature. Hence, the waters of the Schönbornsprudel and Runder Brunnen are used to calculate the equilibrium temperature by using their measured SiO_2-concentrations.

Figure 2 shows the shape of the maximum soluble SiO_2-concentrations with respect to the mineral phases chalcedony and quartz at temperatures between 10 and 60 °C for the named medicinal waters. The shape of the curves reflects the exponential rise of the SiO_2-solubilities from low to high temperatures. Whereas, the solute mineral content of the water influences the solubility of the SiO_2 in the waters only slightly (differences between Schönbornsprudel and Runder Brunnen), the solubilities of quartz and chalcedony differ clearly and the solubilities with respect to chalcedony are reached at lower temperatures than those of quartz.

For the Schönbornsprudel and Runder Brunnen (wells with a high and relatively warm share of deep groundwater) and using their measured SiO_2-concentrations of 21.6 mg/l and 18.5 mg/l, respectively (as H_2SiO_3; horizontal arrows), the corresponding equilibrium temperatures of about 26 and 24 °C (vertical arrows) have been calculated. The estimations of the temperatures have to be increased if the influx of cold water from the upper layers is considered.

For the remaining medicinal wells in Bad Kissingen the results given in tab. 2 are achieved in the same way using a geothermal gradient of 3 °C/100 m. The results show that the calculated quartz temperatures are much higher than the chalcedony temperatures. The circulation depths calculated by using the quartz temperatures appear to be too great and for hydraulical-hydrogeologic reasons to be out of the question. However, the chalcedony temperatures indicate a temperature range and circulation depths that seem to be hydraulically plausible for the investigated area.

For the interpretation of the chalcedony temperatures and circulation depths all medicinal waters present mixing waters from different groundwater horizons. Best results are obtained from waters predominanted by high deep groundwater flow components, as in case of the wells Schönbornsprudel and Runder Brunnen. There, a circulation depth between 585 and 520 m appears to be plausible. In these depths the

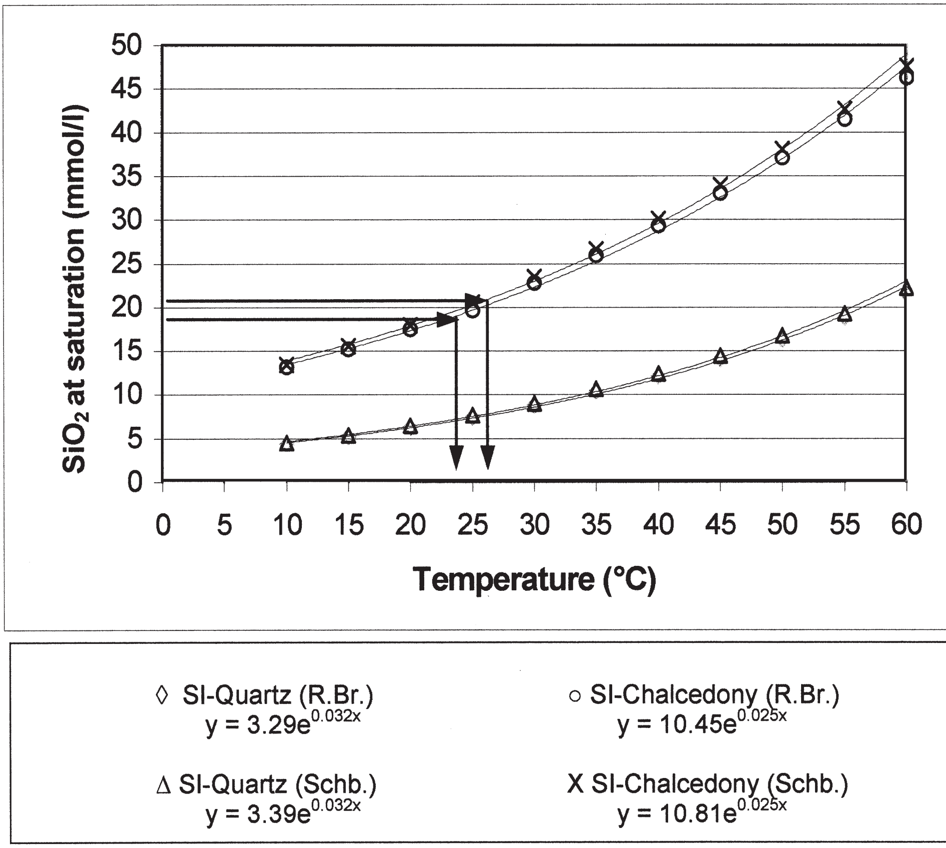

Fig. 2: SiO_2-solubilities in the Schönbornsprudel and Runder Brunnen at different temperatures.
SiO_2-Löslichkeiten im Schönbornsprudel und Runder Brunnen bei verschiedenen Temperaturen.

Upper Permian strata are found – at least in the area of the Bad Kissingen Saale valley which indicates that deep groundwaters rise in parts of the Bad Kissingen valley from depths of about 600 m below ground surface.

In the remaining cases the chalcedony temperatures are lower (exception: Luitpoldsprudel New). Therefore it has to be concluded that the amount of waters from the Lower Triassic zone is higher and the SiO_2-concentrations have decreased by mixing processes. This is also confirmed by the lower total mineralization of these waters as well as by their lower temperatures at the outflow. In extreme case, the amount of water from the upper aquifers is as high that undersaturation with respect to chalcedony may result (Maxbrunnen and Theresiensprudel) or no influence of deep groundwater can be observed as in the Reiterswiesen drillings.

The highest supersaturation with respect to chalcedony was calculated for the Luitpoldsprudel New. However, the cause for the high SiO_2-concentration and ultimately the high supersaturation and the high circulation depth is not clear. Of course, the water of the Luitpoldsprudel New has an increased temperature at outflow (16.22 °C) as well as a high CO_2-concentration, which allows the ascent from large depths. Never-

Tab. 2: Outflow, chalcedony and quartz temperatures (in °C) and calculated circulation depths for the Bad Kissingen wells. T_{mes} – measured temperature at outflow; m b.g.s. – meters below ground surface; SiO_2-content in the Luitpoldsprudel Old is unknown.
Entnahme-, Chalcedon- und Quarztemperaturen (in °C) sowie berechnete Zirkulationstiefen für die Bad Kissinger Brunnen. T_{mes} – am Austritt gemessene Temperatur; m b.g.s. – Meter unter Geländeoberkante; der SiO_2-Gehalt im Luitpoldsprudel Alt ist unbekannt.

Bad Kissingen wells	T_{mes} [°C]	Chalcedony temperature [°C]	Circulation depths [m b.g.s.]	Quartz temperature [°C]	Circulation depths [m b.g.s.]
Schönbornsprudel	20.4	26	585	59	1,687
Runder Brunnen	19.5	24	520	55	1,553
Rakoczy	12.9	16.5	270	50	1,387
Pandur	12.9	22	453	54	1,520
Maxbrunnen	11.6	< 5	–	34.5	870
Theresiensprudel	10.9	< 5	–	22	453
Luitpoldsprudel New	16.22	38	987	70	2,053
Luitpoldsprudel Old	12.8	–	–	–	–
Reiterswiesen II	10.35	< 5	–	25	553
Balthasar-Neumann	15.0	20.5	403	53	1,497

theless, a circulation depth of barely 1000 m cannot be hydraulically and hydrogeologically explained.

For the medicinal wells of Bad Kissingen (exception: Luitpoldsprudel New), the circulation depths between ground surface and 585 m are calculated by using a uniform geothermal gradient of 3 °C/100 m . If the geological conditions within this area are considered, the depths from where the waters are proportionally originating can be used as first indicators for each well. Thereby, the warm spring Schönbornsprudel shows with 585 m the deepest circulation depth, whereas the most shallow circulation was found for the relatively cool Maxbrunnen. Taking into account all results, best and most important indications for further investigations concerning the geothermal gradient are expected for the Schönbornsprudel and Runder Brunnen.

7. Hydrochemical calculation of the depth temperature

Similar to the process for calculating by means of the SiO_2-geothermometers, the depth temperature might also be determined using the chemical equilibrium with respect to other mineral phases. Nevertheless, their solubilities depend not as strong on the temperature as the SiO_2 mineral phases.

In the given case study a correlation analysis was made between the temperatures at outflow and the different components of the investigated waters. The strongest dependence is observed between the sulfate concentration and the temperature ($R^2 = 0.815$). It is known from the reports of the deep drillings Schönbornsprudel, Luitpoldsprudel and the work of N. Georgotas (1972) that gypsum from the Upper Permian zone has to be considered as the sulfate supplier for the medicinal waters. Furthermore, a chemical equilibrium can be assumed between gypsum and the waters within the Upper Permian aquifer. In fig. 3 this dependence is presented graphically by a trend line (steep incline) enabling the calculation of the temperature in the Upper Permian aquifer.

Furthermore the sulfate concentration was calculated for all waters, which would be detected at a chemical equilibrium with respect to the gypsum mineral phase (solution of gypsum up to their saturation at temperature at outflow). These results are also represented by a trend line (flat incline) in fig. 3. At saturation with respect to gypsum about 2,150–2,450 mg/l of sulfate is theoretically soluble in the Bad Kissingen waters at their outflow temperature. The changes proceed more or less linearly within this temperature range and the solubility increases slightly at higher temperatures.

Projecting both trend lines up to their intersection, both lines meet at a temperature of about 26.5 °C. This temperature can be interpreted as the temperature of gypsum saturation prevailing in the Upper Permian aquifer.

Comparing the calculated temperatures of the Schönbornsprudel obtained using the method of the SiO_2-geothermometry with respect to chalcedony (26 °C; tab. 2) and the Runder Brunnen (24 °C; tab. 2) with the calculated temperature of equilibrium for gypsum (26.5 °C) within the Upper Permian aquifer, a quite good agreement between the results can be observed. It is not very surprising that the chalcedony temperatures are a little bit lower than the temperature calculated for Upper Permian aquifer, as the Schönbornsprudel and Runder Brunnen are mixed waters of different groundwater layers.

Considering the inherent uncertainties of both methods, the gypsum temperature of equilibrium is more reliable, since the procedure of determination eliminates the effect of mixing between the water of the Lower Triassic and of the Upper Permian by projecting the trend lines as shown in fig. 3. Furthermore, assuming a depth of 530–550 m

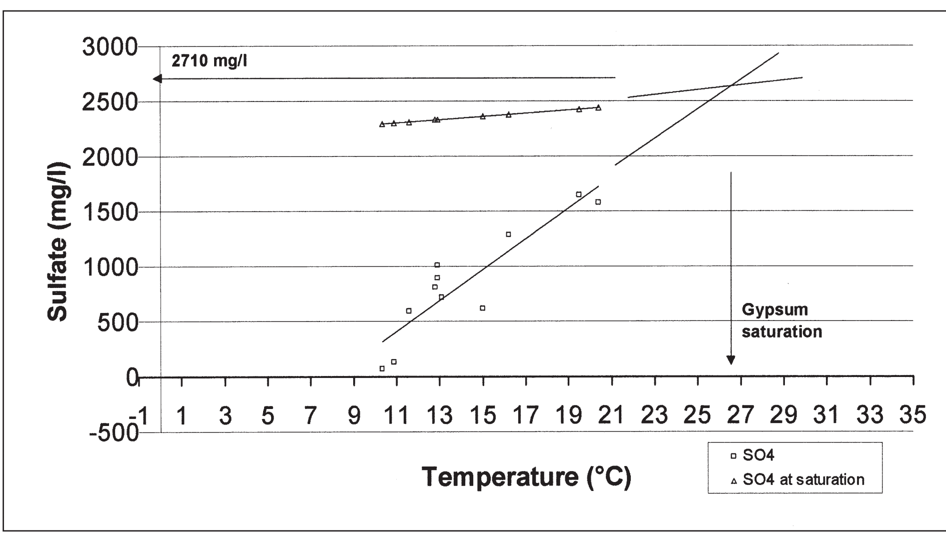

Fig. 3: Correlation between the sulfate contents and their corresponding outflow temperature of the Bad Kissingen medicinal wells.
Korrelation zwischen den Sulfatgehalten und den entsprechenden Austrittstemperaturen der Bad Kissinger Heilwässer.

for the gypsum bearing Upper Permian strata, the method determines a quite exact geothermal gradient of 3.2–3.3 °C/100 m.

8. Mixing ratios of the Lower Triassic and Upper Permian waters

If a gypsum saturation within the Upper Permian aquifer is considered and no additional sulfate is coming from the Lower Triassic aquifer then the mixing ratio of these two groundwater zones can be determined for the Bad Kissingen medicinal wells.

Firstly, the sulfate concentration at gypsum saturation and a temperature of 26.5 °C has been calculated for the Schönbornsprudel with the help of the hydrogeochemical model PHREEQC (D. L. PARKHURST, 1995). In this way, a value of 2,710 mg/l SO_4^{2-} is obtained (Fig. 3). Next, the relationship between the values of the measured and calculated sulfate concentrations has been determined. This determines – considering all uncertainties and simplifications – the ratio between both groundwater zones. Table 3 presents the results.

Despite all uncertainties, the results given in tab. 3 show clearly that there exists – in contrast to numerous other assumptions – no relation between the depth of the drillings and the share of deep water from the Upper Permian. Of course, the deepest drilling (Schönbornsprudel, 469 m b.g.s) holds a high share of water of the Upper Permian zone, but already the groundwater from Runder Brunnen – despite its clearly shallow depth of drilling (94 m b.g.s.) – is higher mineralized than that from Schönbornsprudel.

Furthermore, no clear relation exists between the CO_2-concentration in the waters and the high share of the Upper Permian water, although, certainly, the degassing of solved carbon dioxide favours the ascend of deep groundwater. All knowledge about the hydrogeology of the Bad Kissingen Saale valley system indicates that available water-conductive faults and fracture planes, which allow the groundwater to ascend from large depth, affect the temperature and the chemical composition of the waters. Furthermore, all investigations point out that water of the Upper Permian has pene-

Tab. 3: Ratios between Upper Permian and Lower Triassic waters in the Bad Kissingen medicinal wells.
Verhältnis zwischen den Anteilen an Wässern aus dem Zechstein und Unteren Buntsandstein in den Bad Kissinger Heilwässern.

Medicinal wells	Ratio of waters from Upper Permian and Lower Triassic
Schönbornsprudel	1 : 1.72
Runder Brunnen	1 : 1.64
Maxbrunnen	1 : 4.60
Pandur	1 : 2.69
Rakoczy	1 : 3.04
Luitpoldsprudel New	1 : 2.12
Luitpoldsprudel Old	1 : 3.36
Balthasar-Neumann ("Bad Bocklet")	1 : 4.38

trated extensively into the Lower Triassic aquifer within the Saale valley system of Bad Kissingen.

Summary

All hydrogeologic processes are controlled or at least influenced, directly or indirectly, by the temperature of the water. For the medicinal wells of Bad Kissingen, this means not only the composition of the medicinal wells is influenced by the temperature dependence on the mineral solubilities, but also the density and CO_2-concentrations depend on the local temperature conditions. Furthermore, the flow directions and velocities are linked directly to the temperature.

Basing on the extensive hydrogeologic investigations in the Bad Kissingen region, the question on the potential of thermal water within the studied area was pursued. All results indicate that the potential exists, although the maximum temperature and available quantity to be encountered may be low. The distribution and depth of the Lower Permian as an aquifer of low permeability restricts both the maximum depth of the drilling as well as the extractable water quantities.

The geothermal gradient plays an important role in the assessment of the heat budget. It is however very difficult to determine the geothermal gradient exactly. Using hydrogeochemical and model calculations, the geothermal gradient for the Saale valley at Bad Kissingen was determined with a sufficient accuracy. In this case a geothermal gradient of 3.2–3.3 °C/100 m was calculated, which is in agreement with the method of the SiO_2-geothermometry and a new method using correlation analysis and hydrochemical-hydrogeologic interpretations.

With the knowledge of geothermal gradient, the exploitation of thermal water within the Saale valley is facilitated considerably, since the least drilling depths and the costs can be estimated.

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Zusammenfassung

Alle hydrogeologischen Prozesse werden direkt oder indirekt von der Temperatur des Wassers gesteuert oder zumindest beeinflusst. Für die Heilwässer Bad Kissingens bedeutet dies, dass nicht nur deren Zusammensetzung durch die Temperaturabhängigkeit der Minerallöslichkeiten beeinflusst wird, sondern auch die Dichte sowie der CO_2-Gehalt von den lokalen Temperaturverhältnissen abhängt.

Basierend auf früheren, umfangreichen hydrogeologischen Untersuchungen im Raum Bad Kissingen wurde nun der Frage nach den Möglichkeiten bzw. dem Potential einer Thermalwassererschließung in dieser Region nachgegangen. Alle Ergebnisse deuten daraufhin, dass diese Möglichkeit besteht, auch wenn sicher Einschränkungen in erreichbarer Quantität bzw. maximaler Temperatur hingenommen werden müssen. In diesem Sinne wirkt sich auch die Verbreitung und Tiefenlage der „Unteren Rotliegenden-Schichten“ als gering durchlässiger Grundwasserhorizont sowohl auf die Bohrtiefe als auch auf die erschließbare Wassermenge deutlich aus.

Der geothermische Gradient spielt bei der Abschätzung nutzbarer Wärmeenergie eine entscheidende Rolle. Dieser stellt einen Parameter dar, der meist nur schwer und mit begrenzter Genauigkeit gemessen werden kann. Es wird beschrieben, wie mit Hilfe von hydrogeochemischen Modellrechnungen der geothermische Gradient im Saaletal bei Bad Kissingen mit ausreichender Genauigkeit bestimmt wurde. Für dieses Gebiet ergab sich ein Gradient von 3,2–3,3 °C/100 m. Dieser Wert steht in guter Übereinstimmung mit Berechnungen mittels der SiO_2-Geothermometrie und mittels einer neuen Methode aus Korrelationsanalyse und hydrochemischer bzw. hydrogeologischer Interpretationen.

Die Kenntnis des geothermischen Gradienten erleichtert dabei in der Folge die Erschließung von Thermalwasser im Saaletal vorab entscheidend, dies nicht nur hinsichtlich der mindestens nötigen Bohrtiefe, sondern auch bei der Abschätzung der Erschließungskosten.

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Keywords: geothermometry, Lower Frankonia, temperature, geothermal gradient
Stichwörter: Geothermometrie, Unterfranken, Temperatur, geothermischer Gradient