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Qualitative Potential Identification of Hydrothermal Systems – a case study in Bad Soden-Salmünster, Germany

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ABSTRACT

Geothermal energy plays a secondary role on the extension of renewable energies in Germany and other European countries up to now. However, geothermal energy can contribute significantly to basic load compatible and peripheral electricity and heat supply. Bär et al (2011) developed the qualitative potential identification method which allows the assessment of geothermal systems at relatively low financial cost and technological effort.

Exploiting hydrothermal systems by means of existing middle deep boreholes, e.g. from spas, hydrocarbon exploration or mining, can be a cost-efficient possibility to use geothermal energy. In this case study the qualitative potential identification method is adopted for the hydrothermal system of Bad Soden-Salmünster spa involving

- Structural and hydrogeological investigations,
- Construction of an underground model to predict underlaying rock formations, as well as
- Outcrop analogue study including the measurement and calculation of thermophysical and hydraulic rock properties.

Finally, the economic viability of the exploitation of the hydrothermal system is assessed by the use of the qualitative potential identification method.

1. INTRODUCTION

Bad Soden-Salmünster is a German spa, situated 75 km east of Frankfurt. Its mineral springs were used to provide common salt since the Middle Ages (Hanna 1986). The natural springs alongside the Salz[1] Creek fell into oblivion during the 17th century. A medieval spring tapping was rediscovered in 1837, originating Bad Soden-Salmünster's development to a modern spa location. Further springs were discovered, several wells drilled and many cure, spa and bath installations constructed during the last 175 years (Fig. 1). König-Heinrich-Sprudel (KHS) and Fritz-Hamm-Sprudel (FHS) supply the local thermal bath. The mineral water of Trinksprudel (TS) dual well is mixed and offered for drinking purposes. Pacificus-Sprudel (PS), drilled in 1906/07, is inoperative but due to its depth of 406 m and location important for this study.

The thermal bath is an important economic factor for this rural region focused on tourism, especially in the fields of wellness and recreation. Strong competition leads to the necessity of continuous cost savings. High costs emerge from the brine heating for the thermal bath. Applying the qualitative potential identification method is investigated, if by deepening existing wells or by drilling a new well hotter brine could be found to avoid its heating. Hotter brine could be used to heat the bath geothermal also.

2. METHODS

2.1 Structural geology

Several faults cross the municipal area of Bad Soden-Salmünster separating the underground in tectonic blocks (Fig. 1). Estimated position and displacement of the faults were taken from literature. Striking and dipping values for each relevant block were determined (Fig. 1). Joint direction and distribution were examined in an old quarry 1 km to the north of the thermal bath.

2.2 Hydrogeology

With exemption of PS all wells listed in table 1 were investigated. Physicochemical parameters (temperature, pH, electric conductivity, oxygen saturation, redox potential) were measured in situ. Main ion concentration (Li^+, Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, F^-, Cl^-, NO_2^-, Br^-, NO_3^-, PO_4^{3-}, SO_4^{2-}) were determined by ion chromatography. Bicarbonate (HCO_3^-) contents were quantified by in situ titration. Carbonate (CO_3^{2-}) was not considered due to the acid pH-values found. Concentrations of some transition metals were identified by atomic absorption spectrometry.

Long-term measurement series of temperature, discharge, total dissolved solids and carbon dioxide

[1] German word for "salt"

concentration were compiled from literature and survey data reaching back to 1877.

2.3 Underground model

The mineral well's strata profiles (Tab. 1) were evaluated and used to construct a stratigraphic cross section of Bad Soden. These wells are this region's deepest boreholes. To estimate layer thicknesses and facies formation beneath, supra-regional facies and thickness maps, cross sections and borehole data of neighbouring regions were compiled from literature. For geothermic-hydrogeological validation knowledge of basement characteristics are crucial, because basement rocks will be sufficiently permeable and water-bearing just under special geological conditions.

2.4 Outcrop analogue study

Outcrop analogue studies serve to assess thermophysical and hydraulic rock properties. Rocks expected in the subsurface are sampled at outcrops. Applying the thermofacies concept (Sass and Götz 2012) measured rock properties are transferred to deep rocks of comparable sedimentary facies. Rocks of the Bleichenbach-Formation (10 samples) and Alzenau-Formation (25 samples) were investigated based on the findings of the underground model. Following parameters were measured by listed devices:

- Rock density and porosity – pycnometer
- Permeability – mini-permeameter
- Thermal conductivity and thermal diffusivity – thermo-scanner

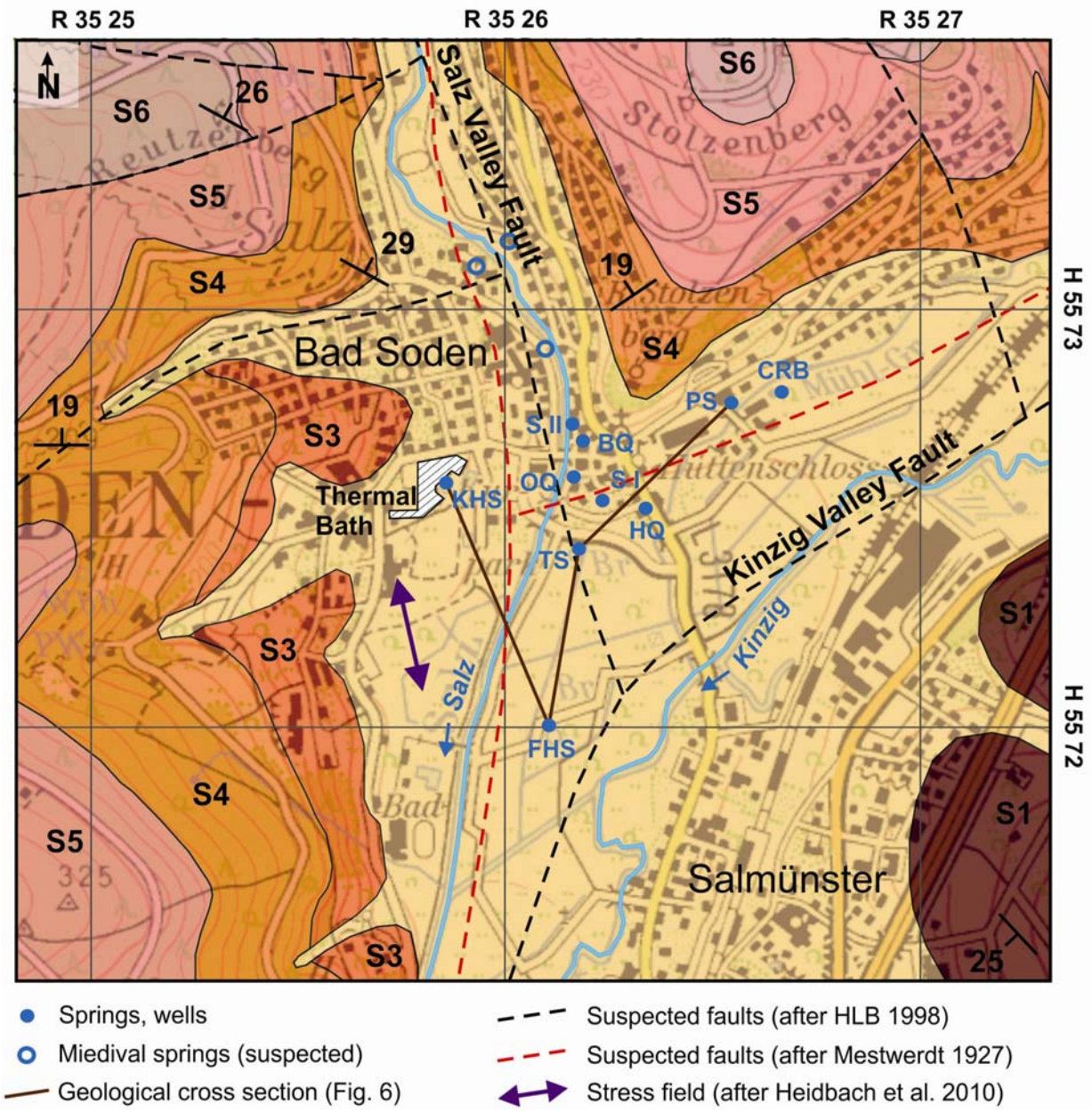

Figure 1: Geological map of Bad Soden-Salmünster based on HLB (1998). Lithological units are displayed in table 2. BQ = Barbarossaquelle, CRB = Carl-Roth-Brunnen, FHS = Fritz-Hamm-Sprudel, HQ = Huttenquelle, KHS = König-Heinrich-Sprudel, OQ = Ottoquelle, PS = Pacificus-Sprudel, S I = Sprudel I, S II = Sprudel II, TS = Trinksprudel.

Formation	Depth [m]				Thickness [m]			
	KHS	FHS	TS I	PS	KHS	FHS	TS I	PS
Unconsolidated Sediments	0-16	0-12	0-15	0-13	16	12	15	13
Detfurth-Formation (S4)	-	-	-	13-30	-	-	-	17
Volpriehausen-Formation (S3)	16-59	12-44	15-75	30-97	43	32	60	67
Salmünster-Formation (S2)	59-135(?)	44-106	75-122	97-163	85	62	>47	66
Gelnhausen-Formation (S1)	135(?)-317	106-268	-	163-340	182	162	-	177
(Z5)	317-373	268-296	-	340-379	56	28	-	39
Bröckelschiefer-Formation (Z6)		296-302	-	379-387		6	-	9
(Z7)		302-328	-	387-400		26	-	13
Aller-Formation (Z4) Leine-Formation (Z3)	373-407	328-387	-	400-407	34	59	-	≥7
Staßfurt-Formation (Z2)	407-501	387-420	-	-	94	33	-	-
Werra-Formation (Z1)	501-538	420-490	-	-	37	70	-	-
Rodenbach-Formation Bleichenbach-Formation	538-539	490-503	-	-	≥1	≥13	-	-

Table 1: Drilled thicknesses in the mineral wells of Bad Soden-Salmünster.

System	Group	Formation	Lithology
Quaternary		Unconsolidated Sediments	Sand, silt, clay, fluvial gravels, loess, haugh
Triassic	Middle Buntsandstein	Solling-Formation (S6)	Sandstone
		Hardegsen-Formation (S5)	Sandstone, sporadic siltstone and claystone
		Detfurth-Formation (S4)	Sandstone, sporadic siltstone and claystone
		Volpriehausen-Formation (S3)	Sandstone, sporadic siltstone and claystone
	Lower Buntsandstein	Salmünster-Formation (S2)	Sandstone, sporadic siltstone and claystone
		Gelnhausen-Formation (S1)	Sandstone
Permian	Zechstein	Bröckelschiefer-Formation (Z5-Z7)	Siltstone, claystone, sporadic sandstone
		Aller-Formation (Z4) Leine-Formation (Z3)	Claystone Dolomite
		Staßfurt-Formation (Z2)	Claystone, dolomite, marl, anhydrite
		Werra-Formation (Z1)	Limestone, dolomite, claystone, anhydrite
	Rotliegend	Rodenbach-Formation Bleichenbach-Formation	Conglomerate, breccia, sandstone Siltstone
Cambrian	Basement	Alzenau-Formation	Homogeneous or banded amphibolites, hornblende plagioclase gneiss

Table 2: Stratigraphic sequence in the surroundings of Bad Soden-Salmünster.

3. LOCAL GEOLOGY

3.1 Morphology

Bad Soden-Salmünster is situated on the confluence of NE-SW flowing Kinzig River and N-S flowing Salz Creek. The valley floor is located at round about 150 m a.s.l.; surrounding hills reach altitudes of up to 430 m a.s.l..

3.2 Tectonics

Both Kinzig and Salz valley are marked by regional faults. All mineral springs are situated on or next to these faults (Fig. 1). After Reul (1989) the Kinzig Valley Fault has a vertical displacement between 130 and 250 m. The north western block is the elevated one. The Salz Valley Fault is an eastward dipping normal fault with a vertical displacement of about 50 m (Reul 1989). The exact position of these two faults is not clarified conclusively so far. Amounts of horizontal movements are unknown, but certainly existing in significant scale due to the regional stress field. A lot of other local faults divide the subsurface into some rotated tectonic blocks.

3.3 Stratigraphy and Lithology

An overview of the local stratigraphic sequence and lithology is given in table 2. Buntsandstein builds the slopes and hills on both sides of Kinzig and Salz valleys (Fig. 1). Gelnhausen-Formation outcrops on the south-easterly slope bottom. The opposite slope bottom consists of Volpriehausen- and Detfurth-Formation. Unconsolidated quaternary sediments fill the valley plains and cover the lowest hillside parts. These quaternary deposits and the Buntsandstein can be identified with exemption of few horizons as aquifer. Zechstein layers are the subjacent beds of the Buntsandstein. Merely Bröckelschiefer-Formation crops out at Bad Orb, 7 km southward Bad Soden-Salmünster. The Bröckelschiefer-Formation acts as aquiclude. Underlying formations are known from wellbores, only.

4. RESULTS

4.1 Hydrogeology

Physicochemial and hydrochemical measurements led to the results presented in table 4. The waters undoubtedly arise from the same reservoir due to the hydrochemical signature. Thermal brine with concentrations higher than 100 g/l obtained from KHS and FHS circulates within the lower Zechstein layers. Bröckelschiefer-Formation acts as aquiclude and seals the Zechstein beneath. Driven by CO_2-gaslift brine can infiltrate the Bröckelschiefer-Formation wherever faults or other division surfaces provide an ascending path. Reaching the Buntsandstein the brine intermixes with vadose (phreatic) groundwater lowering dissolved solids and water temperature. Brine temperature and dissolved solids load are depth depending (Fig. 2 and 3). The geothermal gradient was determined with 2.6°C/100 m. Total dissolved solids increases with 0.2 g/l per 100 m. The average productivity of KHS is 1.57 l/s. FHS and TS have to be pumped (0.55 l/s from FHS and 0.03 l/s from TS in 2011).

Well water temperature fluctuates up to ±3 °C within one year. The investigated wells show different temperature fluctuation patterns. The patterns seem to be not correlated. A satisfying explanation could not be found yet.

4.2 Underground model

The soil profile interpretation of Bad Soden-Salmünster's wells led to the supposed layer thicknesses shown in table 1. It should be emphasised, that the evaluation of KHS and PS profiles are problematically. Definition of several stratigraphic divisions and classifications changed since that time complicating a correlation to the formations as they are defined today. However, it becomes evident that KHS and FHS boreholes penetrate the whole Zechstein ending in the Rotliegend. Rotliegend consists in KHS of a conglomerate and in FHS of a white to grey sandstone rich in lithic components.

Palaeoenvironmental reconstructions clarified, that a SW-NE striking sedimentary basin existed in central Hesse during the Permian (Lietz 1967, Kowalczyk and Prüfert 1974, Kowalczyk 1983). In the south this basin was delimited by a mountain range, which was located roughly at the today's place of Odenwald, Spessart and Rhön range. The basin margin was located few kilometres south of Bad Soden-Salmünster. Close to the basin margin are expected coarse conglomerates and breccia (Rodenbach-Formation), whereas the facies becomes more and more fine-grained in direction of the basin centre (Bleichenbach-Formation). The border between both formations follows nearly the Kinzig River (Fig. 4). Thus KHS and FHS are situated directly on the facies border. Estimated Rotliegend formation thicknesses are taken from the 3D structural model of Hesse (Sass et al 2011, Arndt et al 2011).

The basement is underlying the Rotliegend deposits discordantly. Bad Soden-Salmünster is situated within the Mid German Crystallin Rise, the SW-NE striking core zone of the Variscan Orogeny. Next basement outcrops can be found at the Spessart Range, circa 20 km southwest of Bad Soden-Salmünster. The metamorphic and plutonic rocks of the Spessart can by interpolated in NW direction by findings of several drilling at the Hessian Bavarian state border and in the region around Bad Brückenau. Figure 5 shows a simplified geological map (Schäffer 2012). Drilling sites and its lithologic findings were taken from Weinelt et al (1985). The approximated basement surface altitude was taken from Trusheim (1964). Actual state of knowledge indicates that the highest basement consists probably of Alzenau-Formation in Bad Soden-Salmünster (Fig. 5). Bordered by the Michelbach Thrust Fault Alzenau-Formation is interpreted as nappe (Okrusch and Weber 1996). The thickness is supposed to be higher than 1000 m due to its outcropping on surface and bedding conditions (Hirschmann 2007). In this case no other basement rocks are relevant for this study. Paragenesis indicates metamorphic conditions of at most 630 °C and 0.5 GPa (Okrusch et al 1985).

These findings were used to construct a cross section shown in figure 6. Own outcrop observation led to the conclusion, that Alzenau-Formation has low porosity and marginal divisional surfaces and is hence to be attributed to aquicludes. The radioactive heat production is calculated using the approach in Landolt-Börnstein (1992) [1]:

$$A = 10^{-5} \cdot \rho \cdot (9.52 \cdot C_U + 2.56 \cdot C_{Th} + 3.48 \cdot C_K) \quad [1]$$

Rock composition data were taken from Marx (2008). Alzenau-Formation's estimated radioactive heat production between $1 \cdot 10^{-4}$ and $1.4 \cdot 10^{-3}$ $\mu J\ s^{-1}\ m^{-3}$ is relatively low and can be neglected.

Table 3: Physicochemical and hydrochemical properties of mineral wells in Bad Soden-Salmünster, measured on 13/03/2012. Iron and manganese values are systematically underestimated on account of precipitation inside the sampling bottles before measuring.

Well	König-Heinrich-Sprudel (KHS)	Fritz-Hamm-Sprudel (FHS)	Trinksprudel I (TS)	Trinksprudel II (TS)
Year of Drilling	1927/28	1971/72	1970/71	1970/71
Depth [m]	538.8	503	122	30
Temperature range 1970-2012 [°C]	18.4 – 23.7	11.2 – 23.5	11.7 – 15.0	10.4 – 12.8
Temperature [°C]	21.7	15.5	12.6	12.2
pH [-]	6.16	6.10	5.82	5.98
Electric conductivity at 25 °C [mS/cm]	126.1	125.4	37.9	7.84
Oxigen saturation [mg/l]	2.61	5.02	0.77	6.34
Oxigen saturation [%]	29.2	48.7	7.2	58.6
Redox potential E_H [mV]	193	201	257	300
Mineralisation [mg/l]				
Lithium (Li^+)	49.4	28.2	6.2	1.4
Sodium (Na^+)	33,464	34,066	7,413	1,533
Ammonium (NH_4^+)	61.7	10.3	0.66	0.33
Potassium (K^+)	1,843	2,131	408.1	94.8
Magnesium (Mg^{2+})	630.16	481.82	347.78	40.01
Calcium (Ca^{2+})	3,317	3,377	1,132	123.6
Iron ($Fe^{2+/3+}$)	15.28	17.56	15.83	5.15
Manganese (Mn^{2+})	2.24	2.40	1.82	0.12
Cobalt (Co^{2+})	< 0.01	< 0.01	< 0.01	< 0.01
Nickel (Ni^{2+})	< 0.50	< 0.50	< 0.10	< 0.10
Cupper (Cu^{2+})	< 0.50	< 0.50	< 0.01	< 0.01
Zink (Zn^{2+})	2.62	3.68	0.07	< 0.01
Lead (Pb^{2+})	< 0.50	< 0.50	< 0.01	< 0.01
Cadmium (Cd^{2+})	< 0.01	< 0.01	< 0.01	< 0.01
Fluoride (F^-)	59.2	32.9	3.87	3.55
Chloride (Cl^-)	59,153	53,926	13,576	2,387
Nitrite (NO_2^-)	< 0.01	< 0.01	< 0.01	< 0.01
Bromide (Br^-)	46.8	26.4	6.07	6.95
Nitrate (NO_3^-)	123.5	38.0	5.13	6.78
Phosphate (PO_4^{3-})	39.72	< 0.01	7.73	< 0.01
Sulphate (SO_4^{2-})	3,848	3,050	1,034	232.4
Bicarbonate (HCO_3^-)	4,048	3,597	1,268	370.7
Total dissolved solids [mg/L]	**106,703**	**100,788**	**25,227**	**4,806**
Total equivalent concentration [mmol/l]	**3,553**	**3,396**	**845**	**158**
Balance error [%]	**-2.55**	**3.05**	**-0.74**	**0.22**
Water type (defined by DH and DT 2005)	Iron, fluoride and carbonic acid bearing thermal brine	Iron, fluoride and carbonic acid bearing brine	Iron, fluoride and carbonic acid bearing brine	Fluoride bearing mineral water

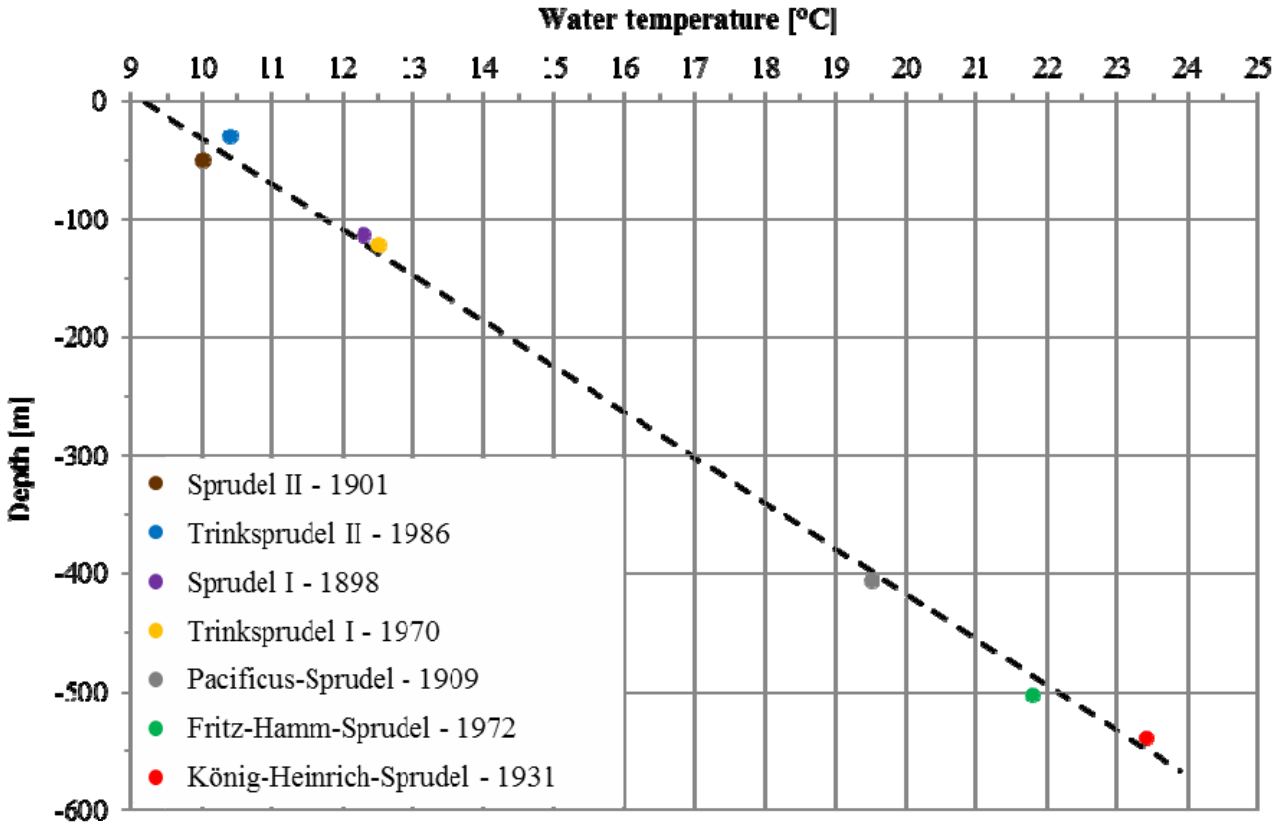

Figure 2: Water temperature according to well depth.

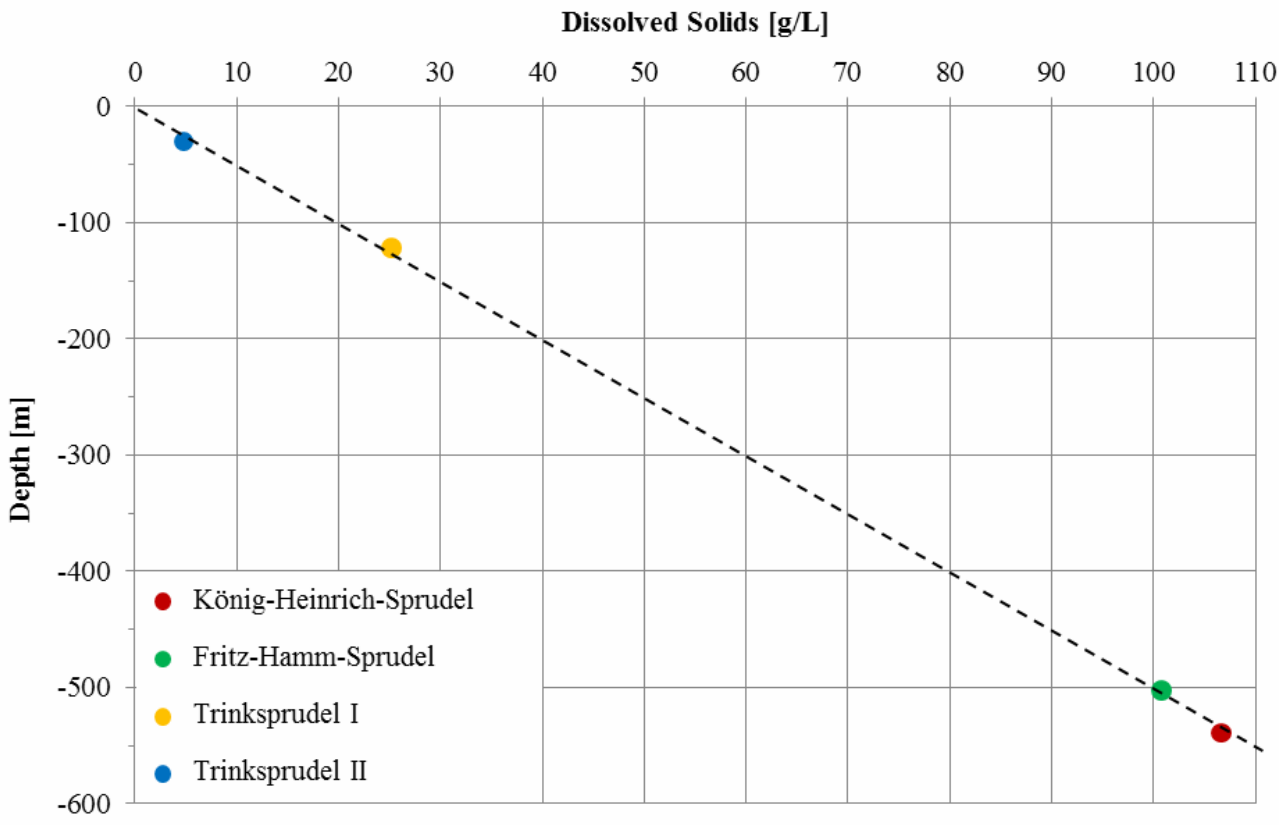

Figure 3: Dissolved solids load according to well depth.

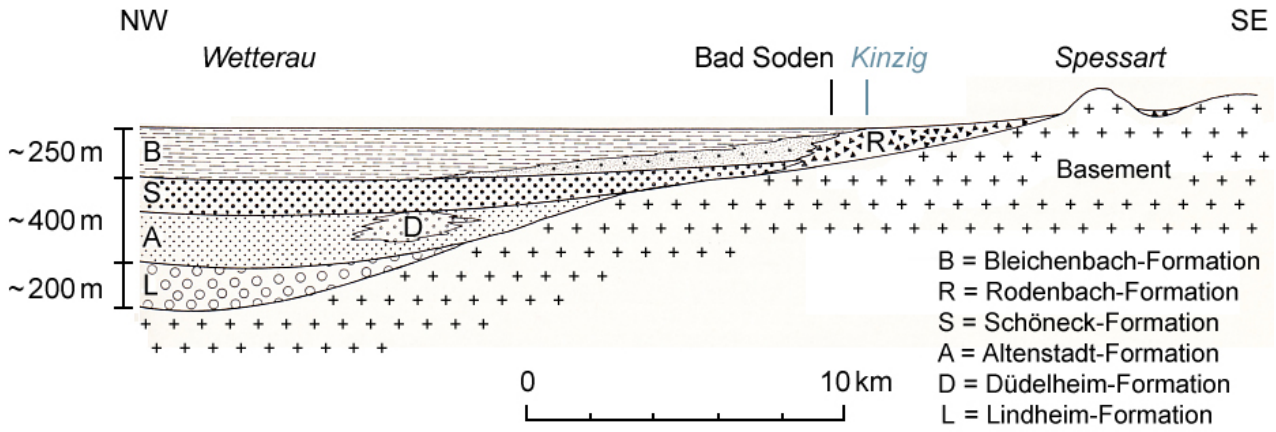

Figure 4: Depositional environment during Permian, Rotliegend formations and facies division between Wetterau and Spessart, modified after Kowalczyk (1983).

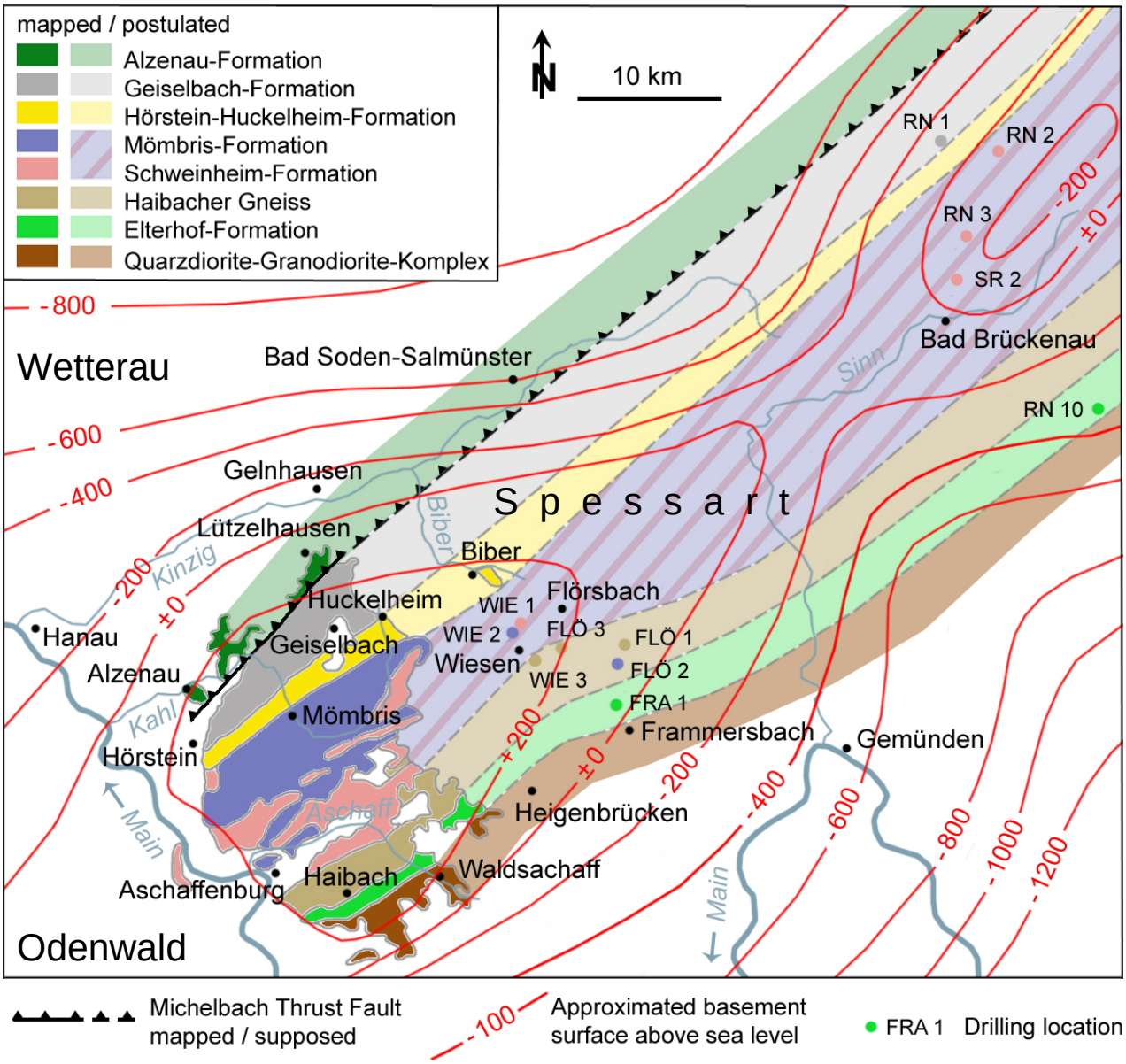

Figure 5: Simplified geological map of basement outcropping at western Spessart (based on Matthes 1978, Hirschmann and Okrusch 1988), and its interpolated subsurface expansion in northeastern direction.

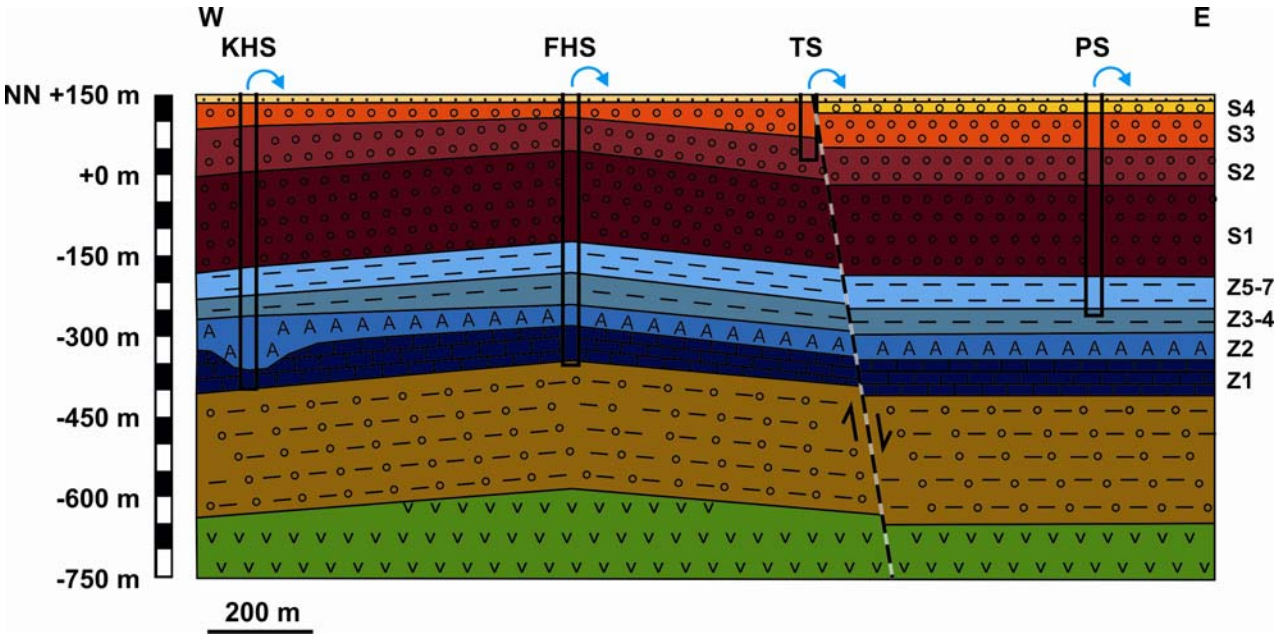

Figure 6: Geological cross section through König-Heinrich-Sprudel (KHS), Fritz-Hamm-Sprudel (FHS), Trinksprudel (TS) and Pacificus-Sprudel (PS).

5. POTENTIAL IDENTIFICATION

Geothermal potential is available if heat or another energy type can be obtained from the geological subsurface with technically justifiable effort. The geothermal potential was evaluated by means of an outcrop analogue study (Schäffer 2012). Its results are shown in Table 4. The results of this study are contrasted with Rotliegend and Mid German Crystalline Rise values from whole Hesse (Bär et al 2011) in table 4. Bleichenbach-Formation features lower petrophysical rock properties compared to Rotliegend, whereas Alzenau-Formation show more favourable parameters then the basement's average. The porosity of Bleichenbach-Formation is relatively high compared with other siltstones and is feasible for geothermal use. The Alzenau-Formation has a porosity mean of 2.0 %. This value is comparatively high for amphibolites.

The specific heat capacity c_p was calculated of thermal conductivity λ, rock density ρ, and thermal diffusivity α as given in equation [2].

$$c_p = \lambda \cdot \rho^{-1} \cdot \alpha^{-1} \qquad [2]$$

Calculated specific heat capacities are substandard compared with equivalent rocks. The other parameters are evaluated using the potential categories defined by Bär et al (2011) (Tab. 5).

Temperature and permeability are the outstanding parameters for a fault controlled hydrothermal system such as in Bad Soden-Salmünster. Porosity, tectonic and stress field are also important. The geothermal gradient of 26°/100 m (Fig 2) proceeds supposedly with minor changes in the Rotliegend and is thus categorised as low (Tab. 5). The basement will feature a higher gradient - maybe 30 to 32°C/km, which is classified as middle. Under these circumstances 36°C are expected at a depth of 1000 m, 52°C at 1500 m depth and not more than 70°C at 2000 m depth.

After table 5 the reservoir temperature until 1500 m depth is rated as very low. Permeability of Rotliegend has to be considered low and of basement very low. Bleichenbach-Formation's thermal conductivity is low; Alzenau-Formation's is middle.

6. CONCLUSIONS

The undisturbed Alzenau-Formation is not an exploration target due to its overall unfavourable geothermal properties. The thermophysical properties of Bad Soden's Rotliegend are not as good as in Hesse.

The Rotliegend basis is expected to stay in hydraulic contact with the basement and is recommended as further exploration target. The zones where the Salz Valley Fault and Kinzig Valley Fault penetrate the formations beneath Zechstein are of particular interest. A prospection of Rotliegend based on thermophysical matrix properties cannot be recommended. Higher water temperatures than the observed well water temperatures are expected at fault zones. Hence, more knowledge about Salz Valley fault and Kinzig Valley fault striking and dipping is necessary.

The possibility to find sufficient quantities of thermal brine is assessed as good.

Table 4: Arithmetic mean and standard deviation of petrophysical rock properties of Bleichenbach-Formation and Alzenau-Formation samples compared to values for whole Hesse.

	Rock density [g/cm³]	Porosity [%]	Matrix permeability log [m²]	Thermal conductivity [W/(m·K)]	Thermal diffusivity [mm²/s]	Specific thermal capacity [J/(kg·K)]
Bleichenbach-Formation	2.68 ± 0.03	17.7 ± 3.3	-14.2 ± 1.0	1.86 ± 0.37	1.29 ± 0.16	534 ± 70
Alzenau-Formation	2.80 ± 0.18	2.0 ± 1.3	-15.1 ± 0.9	2.64 ± 0.75	1.57 ± 0.86	623 ± 47
Rotliegend	-	-	-13.9 ± 1.4	2.26 ± 0.51	-	683 ± 90
Mid German Crystalline Rise	-	-	-16.4 ± 0.9	2.38 ± 0.40	-	954 ± 75

Table 5: Threshold values for the potential categories of geothermal relevant parameters, modified from Bär et al (2011).

Potential	Very low	Low	Middle	High	Very high	Rotliegend	Basement
Geothermal gradient [°C/km]	**≤ 20**	**> 20**	**> 30**	**> 40**	**> 50**	**26**	**31**
Reservoir temperature [°C]	**≤ 60**	**> 60**	**> 100**	**> 120**	**> 150**	**23.5 - 28.7**	**28.7 - 52.0**
Permeability [m²]	**≤ $1\cdot10^{-15}$**	**>$1\cdot10^{-15}$**	**>$1\cdot10^{-13}$**	**>$1\cdot10^{-11}$**	**>$1\cdot10^{-9}$**	**$6.3\cdot10^{-15}$**	**$7.9\cdot10^{-16}$**
Thermal conductivity [W/(m·K)]	**≤ 1.25**	**> 1.25**	**> 2.0**	**> 3.0**	**> 5.0**	**1.86**	**2.64**

Deepening FHS could be an option at Bad Soden-Salmünster. As next step a feasibility study could evaluate possibilities and considerations to include existing infrastructure and buildings. The development of an energetic-balneologic utilisation concept should follow as well.

This case study showed that primary exploration decisions can be made at relatively low costs and manageable efforts using the qualitative potential identification. Outcrop analogue studies and structural models like Hesse 3D are suitable to obtain basic data for a preliminary exploitation. These methods simplify a decision-making processes.

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