GERMANY

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Geothermal thematic map (Plate 20)

Geothermal resources for the following aquifers in Western Germany were published in the previous atlas: Bentheimer Sandstein and Valendis-Sandstein in the North German Basin; Upper Muschelkalk, Early Triassic (Buntsandstein) and Hauptrogenstein in the Upper Rhine Graben; Aquitan-Sande, Chatt-Sande, Baustein-Schichten, Late Jurassic (Malm) and Trigonodusdolomit (Upper Muschelkalk) in the W Molasse Basin; Burdigal-Sande, Aquitan-Sande, Chatt-Sande, Baustein-Schichten, Ampfinger Schichten and Priabon-Basissandstein, Cenoman-Sandstein and Gault-Sandstein, as well as Late Jurassic in the E Molasse Basin. A reassessment of geothermal resources and update of the maps is not justified on the basis of new information.

At, present 22 geothermal installations for the direct use of geothermal heat are in operation in Germany, each with an installed capacity > 100 kW_t. Most of these plants are located in the North German sedimentary basin and in the Molasse Basin in S Germany. The remaining installations are concentrated along the Rhine Graben. Additional information and a recent review of the status of geothermal energy utilisation in Germany can be found in SCHELLSCHMIDT et al., (2000). These installations comprise district heating systems, thermal spas combined with space heating and, in some cases, greenhouses and large installations of vertical heat exchangers used for space heating or cooling.

In addition to these large-scale plants, there are 50 000 - 90 000 small units (earth-coupled heat pumps and groundwater heat pumps).

Temperatures (Plate 21)

Temperature maps are based on temperature measurements taken with various methods: equilibrium logs, non-equilibrium logs (temperatures affected by drilling disturbances), formation temperatures obtained during borehole tests (production test, drill stem tests) and Bottom Hole Temperatures (SCHULZ and SCHELLSCHMIDT, 1991). Data statistics are shown on the pie charts.

Software facilities of the Temperature Data Bank of the Joint Geoscientific Research Institute (GGA) were used to prepare the maps. The data base received the addition of a large compilation of data from the eastern part of the North German Basin. For the disturbed logs in this area no corrections were applied because an appropriate correction methodology still has to be devised for this unique type of data. The characteristics of this compilation are discussed in detail in FÖRSTER (1997). The temperature corrections are automatically chosen and applied according to data type (SCHULZ et al., 1992). Linear interpolation was applied to determine the temperatures at the specific depth of the map. No extrapolation to depth greater than measurement depth was permitted. The data are gridded using a minimum curvature algorithm (WESSEL and SMITH, 1991), including a tension parameter.

In the North German Basin, the isotherm pattern seems to be related to the shape of the subsurface salt bodies. Salt pillows in the E part are rounded almost equidimensional features in map view, while in the W part, salt structures are made up of very long roughly NS trending salt domes in the N that change to more circular forms in the S.

The Molasse Basin in S Germany shows generally EW striking isotherms, in agreement with the direction of the basin axis. There seems to be an increase in temperature from S to N. The depth to the basement of this asymmetric basin increases in the opposite direction, i.e. from N to S.

The order of magnitude of the temperature is similar in both basins, although isoline structure is quite different, with shorter wavelength in the North German Basin.

The Upper Rhine Graben shows clearly elevated temperatures compared to the Molasse and North German Basins. This pronounced temperature and heat flow density anomaly is associated with a regional redistribution of heat driven by groundwater circulation (PRIBNOW and SCHELLSCHMIDT, 2000).

Potential geothermal reservoirs

Areas for which geothermal resources where determined in the previous atlas are shown along with the new assessments of this atlas. At this large scale, practically all areas of interest in the country have been surveyed.

A large potential exists in the North German Basin. However, detailed local studies are needed, because this basin has been subjected to intense tectonic overprint with large scale salt migration, as is shown on the cross-section (HAUPT, 1996). As a consequence, geometry and properties of geothermal aquifers may vary significantly over small distances.

An intensive and systematic program of geothermal resource evaluation in the German Democratic Republic produced maps at a scale of 1 : 200 000 covering that whole country. The present assessment for the aquifers of the E North German Basin have strongly drawn from the work of DIENER and WORMBS (1988-1990) as well as DIENER and WORMBS (1990-1992).

Aachen Area (Plate 21)

H. Karg and C. Bücker

This area lies at the boundary between the tectonic blocks of Erft and Rur. The potential reservoir comprises the Grafenberg sand at the base of the Tertiary sequence (KARG et al., 1998), deposited in a shallow marine and estuarine environment. The depth and thickness of the Grafenberg sands echoes the palaeogeography and tectonic pattern of the Lower Rhine Embayment during the Oligocene.

The highest temperatures are observed in the vicinity of Liège and Maastrich in Belgium, and along the Rur boundary fault. Regions with elevated temperatures are associated with ascending groundwater from deeper levels of the Lower Rhine Basin. The centres of the tectonic blocks in the Lower Rhine Embayment appear as low temperature regions due to descending cold meteoric waters. These large areas show relatively uniform subsurface temperature distribution unrelated to tectonic structure. Temperature increases steadily towards the NE, with increasing depth. The elevated temperatures in the depocentre are overprinted by the effects of forced convection of heated groundwaters associated with the Erft boundary fault system. In this region, maximum temperatures above 44 °C are expected at the top of the aquifer. This is much higher than the mean temperature of about 28 °C resulting from averaging all thermal data for the Grafenberg aquifer. Additionally, gravity-driven groundwater flow directed towards the NE, i.e. towards the centre of the basin, affects the temperature field. Thus the shape of the 28 °C and the 32 °C isotherms E of Jülich indicate the direction of flow resulting from a slope in the regional groundwater table.

An estimated mean porosity of 25 % was used to calculate the geothermal resources within the Grafenberg reservoir.

The resources map shows a similar pattern to the temperature map. Geothermal resources increase towards the NE, where the greatest depth and temperatures are reached.

Eastern North German Basin

The North German Basin is the central part of the Central European Basin. The present-day sediment thickness in the North German Basin ranges from 2 - 10 km. Halokinetic movements of the Zechstein layers are responsible for the intense and complex deformation of Mesozoic and Cenozoic formations (DEKORP-BASIN Research Group, 1998; FRANKE et. al, 1996). This tectonic disturbance strongly affects the local conditions of the geothermal reservoirs. Because of the salt tectonics, great variations of depth (locally > 1000 m) and thickness occur along short distances. Therefore, the temperature and resource maps are strongly influenced by the depth range of the respective aquifer.

The Mesozoic deposits of the North German Basin are made up of sandstones, claystones and carbonates, with evaporite intercalations. Four Jurassic and Triassic sandstone aquifers are of interest for direct use of geothermal energy: (1) Aalen, (2) Lias and Rhät, (3) Schilfsandstein, and (4) Buntsandstein.

Generally, salinity of the formation water increases with depth: as a rule, for each depth interval of 100 m, salinity augments by 10 g/l. The fresh/salt water interface (1 g/l) is at 50 - 300 m depth, after which, salinity increases strongly. Highly concentrated Na-Cl-brines of 150 - 280 g/l and greater can be found in the sandstone aquifers of this basin. Many salt water outlets at the surface have been detected and, in some regions, the infiltration of meteoric waters dilutes the formation waters. Corrosion is potentially more important than precipitation, as these waters are rich in chloride therefore re-injection is compulsory for any geothermal application.

Porosity data from measurements on cores and from geophysical logs were used for the calculation of resources. Porosities obtained from geophysical logs were averaged and weighted according to the depth interval of measurement. Porosities from borehole cores were averaged. Mean porosities from geophysical logs and laboratory measurements were combined to a mean aquifer value for each borehole.

The local discontinuities due to faults are not considered explicitly for isoline tracing. Therefore, the isolines on the maps are a smoothed expression of regional geologic struture based on borehole data. Consequently, local studies are necessary in order to better constrain the geometry and dimensions of the aquifers and its engineering characteristics.

Aalen (Plate 22)

The Aalen sandstone is the basal unit of the Dogger formation. It is intruded frequently by salt structures, over which it has been eroded (N and W Brandenburg and parts of Mecklenburg). The sand proportion of the Aalen sediments decreases from N to S and from E to W.

These deposits comprise medium to fine sandstones with clayey portions. The lower part of the aquifer consists of alternating grey to dark grey sandstones and siltstones of variable clay content. Locally, the clay intercalations contain pyrite concretions. The upper part of the aquifer comprises fairly clean sandstones and silty interlayers. Sometimes the low cohesiveness of these rocks prevents cores being recovered (in this case porosities measured in the laboratory are biased towards lower values). The aquifer is confined by a claystone layer. Although the sandstones are poorly cemented, local variations in reservoir properties due to cementation occur.

The mean porosity determined on core samples is 25 %. Mean permeability is 1000 mD, although values up to 3000 mD have been measured.

Lias and Rhät (Plate 22)

This aquifer complex extends over the whole North German Basin with exception of regions above salt domes where these deposits were eroded off. Depth to the bottom of this aquifer varies laterally from 500 m to > 2000 m. As a function of the salt structures, the thickness of the aquifer is also highly variable.

The lithology and thickness of the Lias-Rhät sequence is affected by synsedimentary tectonic activity (including salt kinetics). The Rhät sandstone is heterogeneous, 50 - 100 m thick. At the base, two alluvial fans make up the sandy facies. The remaining region is covered by sandy-clayey deposits overlain by 20 - 30 m thick sandstones, with locally significant shaly intercalations. The Lias is separated from the Rhät aquifer by a predominantly shaly layer (Triletes). Sometimes this separation is missing. Therefore, the Lias is treated together with the Rhät as one single hydrologic unit. The Lias aquifer units comprise principally the Hettang and Lower Sinemur sandstones, but may, in some places, include sandstone horizons from the Domer.

Porosity ranges from 10 - 35 %, with a mean of 25 %. The permeability ranges from 250 - 2000 mD.

Schilfsandstein (Plate 23)

The Schilfsandstein consists of fluvial delta deposits, that are observed extending from Scandinavia to southern Germany. In some places, these sediments have been eroded above salt domes. Rapid vertical and lateral lithologic variations are a result of the depositional environment. Lateral depth variations of the bottom of the aquifer of up to 1800 m occur, depth being shallower above salt bodies. Fine to medium grained grey to grey-green sandstones make up these deposits. They are sometimes coarser toward the bottom and exhibite distinctive cross-bedding. Alternating layers of silt and clay containing carbonaceous material may occur at the bottom and at the top of the sandstones. In some places, the pores are filled with gypsum and anhydrite cement.

Porosity data are mostly from geophysical logs with few measurements on cores. Values range 10 - 35 % with a mean of 22 %. Permeability is about 10 mD, from limited data. Salinity increases with depth and ranges from 86 - 215 g/l.

Buntsandstein (Plate 23)

The Middle Buntsandstein was deposited during the main subsidence episode of the basin. The deposits exhibit uniform lithologies and thickness over large distances. The uplifted regions to the N and to the S are the source areas of the clastic material. Coarser sandstones were deposited along the margins and finer grained sediments in the central part of the basin. Posterior salt kinetics has significantly affected the depth to these formations, causing lateral variations of the order of a few thousand metres.

The deepest aquifer complex is the Middle Buntsandstein comprising 4 units, representing each a cycle of fining upward: (1) Solling, (2) Hardegsen, (3) Detfurth, and (4) Volpriehausen. Each unit begins with a coarse sandstone at the base overlain by alternating sandy-silty strata.

Porosity ranges from 10 – 35 %, with a mean of 22 %.

Northern Upper Rhine Graben

C. Fitzer, S. Fluhrer and B. Sanner

In the N part of the Upper Rhine Graben the vertical temperature gradient in the sediments averages 60 mK/m, twice the mean value for Germany. In this area two stratigraphic units are useful from the geothermal perspective: the Rotliegend layers (Permian) and the Hydrobien layers (Tertiary).

Hydrobien (Plate 24)

Hydrobien layers consist of clayey-marly sediments and dip towards the S down to a depth of 800 m. These layers reach thicknesses of about 800 m in the S and thin out towards NE. Minimum thickness of 100 m is observed in the NE, E of Frankfurt. A porosity of 20 % was assumed for the resources calculation. The maximum resources occur in the NE of Worms.

Rotliegend (Plate 24)

The Rotliegend crops out in the Frankfurt area and dips towards the W down to a depth of 2300 m W of Mainz. The aquifer extends over a thickness of more than 2200 m in the NW and thins out towards the E. The temperature at top of the Rotliegend is between 90 - 130 °C. The resources increase from E to W as a result of the great depth and thickness of this formation.

Present status and future perspective of the use of geothermal energy.

A conservative estimate of the total thermal power installed at present yields roughly 323 MW_t. About 12 % is provided by large installations. Currently 14 new centralised plants are planned. Additionally, > 20 potential sites have been identified for direct use of geothermal heat in Germany. By the year 2000, the increase in both types of applications, centralised and decentralised units, is estimated to boost the total installed thermal power in Germany to about 467 MW_t (CLAUSER, 1997).

Most plants are located in the North German Basin, in the Molasse Basin in S Germany, or along the Rhine Graben. The three largest geothermal plants - Waren (Müritz), Neubrandenburg, and Neustadt-Glewe - are located in the eastern North German Basin and operate since 1984, 1988, and 1995, respectively. The total installed power of these major installations is about 22 MW_t.

Resources and probable reserves of Germany

Reg.	Aquifer	A	T_t	Resources		A´	Probable reserves P		
		km²	°C	10^{18}J	GJ/m²	km²	10^{18}J	GJ/m²	MW_t
A	Valendis Sst.	143*	50	0.11	0.79	96	0.023	0.24	24
	Bentheimer Sst.	361*	54	0.28	0.78	158	0.078	0.49	82
B	Aalen	66250	43	80.83	1.22				
	Lias and Rhät	68125	38	102.87	1.51				
	Schilfsandstein	63125	48	37.88	0.60				
	Buntsandstein	67500	49	70.88	1.05				
C	Garfenberg-Schicht	597	28	0.29	0.48				
D	Hydrobien-Schicht	2117	30	5.72	2.70				
	Ob. Muschelkalk	2060	137	3.17	1.53	1880	0.210	0.11	222
	Buntsandstein	2746*	137	45.72	16.65	2574	1.830	0.71	1937
	Rotliegendes	2117	110	89.79	42.41				
E	Hauptrogenstein	332	79	0.49	1.47	236	0.019	0.08	20
	Ob. Muschelkalk	1616	75	1.11	0.69	764	0.033	0.04	35
	Buntsandstein	1688*	85	9.78	5.80	6.28	0.220	0.35	233
F	Aquitan-Sande	3776	48	6.79	1.80				
	Chatt-Sande	2564	72	9.05	3.53	944	1.050	1.11	1111
	Baustein-Schichten	880	45	0.36	0.41				
	Malm	7740*	69	11.79	1.52	6568	0.570	0.09	603
	Ob. Muschelkalk	3728	67	1.29	0.34	140	0.001	0.01	1
G	Burdigal-Sande	268	45	0.22	0.82				
	Aquitan-Sande	763	45	1.33	1.82	124	0.100	0.80	106
	Chatt-Sande	3348	53	10.48	3.13	2044	1.850	0.90	1958
	Baustein-Schichten	304	42	0.14	0.47				
	Ampf., Priabon	436	79	0.39	0.89	156	0.040	0.25	42
	Gault/Cenoman	6112	77	4.61	0.75	1040	0.230	0.27	243
	Malm	8790*	78	17.05	1.94	6444	0.630	0.10	667

T_t = mean temperature at top of aquifer
A = areal extent of potential area
A´ = areal extent of probable reserves
P = thermal power (= reserves/30 years)

Reg.: A = W North German Basin
B = E North German Basin
C = Lower Rhine Graben
D = N Upper Rhine Graben
E = S Upper Rhine Graben
F = W Molasse Basin
G = E Molasse Basin

* These values correspond to the largest surface of an aquifer for particular regions. They are summarised in Table 2 of the previous atlas.

Current research funded by the German government involves two approaches. In the first, the behaviour of a geothermal reservoir under long term exploitation conditions is examined. In the second, the optimization of geothermal applications for the various kinds of reservoir are analized from economic and technological points of view.

The project *Hydraulic, thermal and mechanical behaviour of geothermal aquifers under exploitation,* is a joint colaboration of the GGA Institute, the Mecklenburg-Vorpommern Geological Survey, the University of Bonn, the Technical University Hamburg-Harburg, among others. Numerical modelling is conducted to predict the hydraulic and thermal long term behaviour (30 - 50 yrs) of high salinity aquifers and attempt to quantify the associated changes in reservoir properties. Numerical tools capable of dealing with coupled simulation of flow, heat and mass transport as well as the chemical interaction of fluid and rock matrix are being developed (BARTELS., 1998; KÜHN et al., 1999). Model parameters are derived from large petrophysical data sets collected from various sandstone aquifers in NE-Germany. Additionally, an experimental approach completes the research concept: high-pressure and high-temperature permeameter experiments are carried out under aquifer conditions to determine the permeability-porosity relationship for precipitation and dissolution, in particular for carbonates.

The project *Evaluation of Geologic and Economic Conditions for Utilizing Low-Enthalpy Hydrogeothermal Resources* was conducted by the GeoForschungsZentrum Potsdam (GFZ Potsdam) and involved several institutes. The complex interactions of geological, economical, technological, and ecological conditions for successful use of geothermal energy were examined, considering especially the technology developed and used in Germany over the past 20 years. An exploration strategy was conceived considering different kinds of reservoir conditions with the purpose to minimize the risk of drilling geothermal wells. The results of this project provide a basis for political decisions in the process of promoting and installing geothermal heating plants. An expert system (ERBAS et al., 1996) was created that is capable of quantifying the effect on the final energy costs of various choices in the tecnologies and components used for building a geothermal installation . It includes a comprehensive energy balance and confronts the geothermal potential with consumer demand. This analysis helps to conceive geothermal systems that are competitive when compared to other energy sources (EHRLICH et al., 1998; KAYSER, 1999). Special attention is given to the concept of geothermal water as part of a multi-user system, designed, for example, for the heating of buildings in conjunction with a balneologic utilization, which optimizes the exploitation of geothermal energy. The possibility of such combined systems has to be introduced to the public and certainly will help to convince communities to invest in geothermal heating plants.

At present no electrical power is produced from geothermal resources in Germany. The lack of appropriate high-enthalpy steam reservoirs implies that only binary or Organic Rankine Cycle (ORC) power plants can be used for electrical power generation. A successful development of the Hot Dry Rock (HDR) technology would change this situation fundamentally. An European scientific HDR pilot plant is established in the Upper Rhine Graben in France. First circulation experiments conducted in 1997, exceeded expectations. In 1998 a large circulation system was created at 5000 m depth with a temperature of 200 °C and a thermal power of 30 MW_t. The price for HDR-generated electrical power is expected to be in the range of present electricity costs by taking advantage of the local conditions of this site (JUNG et al., 1997; BAUMGÄRTNER et al., 1998).

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