Leibniz Institute for Applied Geophysics

Deep Geothermal Energy

Principles and Application Possibilities in Germany

Imprint

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Contents

Preliminary Remarks

Global energy consumption increased significantly over the last decades together with an ongoing growth in world`s population.

Over the next 50 years the energy consumption is estimated to rise by a factor of three concurrent to a strong global demographic evolution from 7.4 in 2016 to 11.2 billion people in 2100 (United Nations 2015). The today's energy need is primarily fed by the combustion of fossil energy resources - mainly coal, oil and gas – with intensive negative effects on global climate through the release of greenhouse gases. Fossil energy combustion has dramatic consequences for life on Earth.

CO_2 emissions as well as emissions of methane – caused by the production and transport of natural gas – are mainly responsible for an increasing greenhouse effect, leading to a global average temperature increase. Power generation and heat production from fossil fuels contribute substantially to climate change. In comparison, the operation of modern power plants using renewable energy sources, such as photovoltaics, hydropower, or geothermal energy, is nearly emission-free. A sustainable, reliable and climate-friendly future energy supply requires therefore the substitution of fossil fuels by renewable energies as much as possible.

In Germany, the share of renewable energies has expanded particularly in the heat market in addition to supplying electrical power. The use of renewable energies and energy saving technologies are specifically supported by measures such as the amended Renewable Energies Act (EEG), the new Renewable Heat Act, by an expanded market incentive programme promoting renewable energies in the heat market, by investment incentives, and by a drilling cost subsidy for deep geothermal projects.

In addition to the use of hydropower, biomass, solar power and wind power, the use of geothermal energy plays an increasingly important role in this context. The rapid geothermal market growth leads to a coexistence of professional planning tools on the one hand and shared information demand on the other. The brochure “Deep Geothermal Energy – Principles and Application Possibilities in Germany” provides technical information and recommendations for investment decisions in favour of deep geothermal applications. The comprehensible presentation of physical as well as geothermal engineering principles and interrelationships provides a well-grounded introduction and overview of the state of the art of deep geothermal energy.

1 Introduction

The development of renewable energies is a key element of strategic energy policy in Germany. Geothermal energy can play an important role in future energy concepts as a base load capable and low-emissions form of energy. A study of the Office of Technology Assessment (Paschen et al. 2003) confirms deep geothermal energy a considerable potential, which theoretically exceeds the energy demand of the Federal Republic of Germany many times. In regions with favourable geological conditions, such as the South German Molasse Basin, the Upper Rhine Graben or the North German Basin, the use of geothermal energy is already a success story. In the North-German state Mecklenburg-Vorpommern for instance, some geothermal plants have been supplying heat since the 1980's. A recent boom in geothermal development in the Munich metropolitan area was followed by the construction of several geothermal plants, which now supply a number of municipalities with environmentally friendly heat, and in some cases with heat and power or power only.

Nevertheless, research and development in deep geothermal energy is still needed with the aim of lowering investment costs, developing new technologies, minimising the exploration risks, and developing geothermal potentials in a safe way also in less favourable regions. An important aspect in this regard is the provision of data and detailed information for project developers, decision makers and the general public. As indicated by the high interest in the German and English editions of this brochure, there is a great demand for technically sound information on the application possibilities of deep geothermal energy. The present edition will also be published in Spanish to widen the accessibility of this informative brochure to the global geothermal community. This brochure presents complex technical interrelationships in an easily understandable way, explains conventional application systems as well as geothermally relevant parameters, and elucidates the planning aspects. The first chapters introduce into the fundamental terminology and present the technologies required for deep geothermal energy utilisation, followed by a brief overview of the relevant parameters as well as operational and testing methods. The brochure is completed by an overview of the most important regions for hydrothermal applications in Germany, as well as a number of selected case studies.

The content of this brochure was compiled in the course of the initial set-up of the Geothermal Information System for Germany (GeotIS), which was funded by the German government and conducted by the Leibniz Institute for Applied Geophysics (LIAG) together with the Bavarian Environment Agency (LfU), the Freie Universität Berlin, the Geothermie Neubrandenburg GmbH (GTN), the State Authority of Mining, Energy and Geology (LBEG) of Lower Saxony, the State Agency for Environment, Nature Conservation and Geology of Mecklenburg-Vorpommern (LUNG), the District Authority Freiburg of the state of Baden-Wurttemberg (RPF), and the Karlsruhe Institute of Technology (KIT). The development and governmental funding of GeotIS is ongoing (see Chapter 6). Currently, the team that maintains and expands GeotIS also sets up a multimedia e-learning platform. This e-learning tool shall be based on, but shall not be limited to the contents of this brochure. Additional interactive media components will be developed to facilitate knowledge gain and understanding.

This brochure applies also results from the working group "Deep Geothermal Energy" initiated by the Federal/State Committee of Soil Research (BLA-GEO). This working group prepared a guideline for the use of geothermal energy in deep subsurface formations (PK Tiefe Geothermie 2007) as well as a report on parameters and investigation methods (PK Tiefe Geothermie 2008).

2 Principles of Deep Geothermal Energy

2.1 Some terminological explanations

Geothermal energy is referred to as the thermal energy generated and stored in the Earth. Synonyms include **geothermal heat**.

In principle, geothermal energy is available everywhere at any time. It is theoretically inexhaustible if exploited properly due to steady natural heat generation. On average, the temperature in the subsurface increases downwards by 3 K per 100 m when conduction dominates the heat transport. However, it could be lower in old continental shields with lower heat production in the crust. This temperature increase per depth unit is referred to as the temperature gradient or geothermal gradient, and is measured in K per km, which colloquially corresponds to °C per km. This gradient is related to the heat flow from depth to the Earth's surface. The average heat flow density in Germany is about 65 mW/m^2. The smaller part of it (~ 30 %) originates from residual heat associated with the Earth's formation. The major part (~ 70 %) is attributed to radioactive decay of uranium, thorium and potassium isotopes within the Earth's crust.

The distribution of the subsurface temperatures is heterogeneous. There are regions in Germany where the temperature gradient is much higher than the average value. Particularly, in some parts of the Upper Rhine Graben, the area around Bad Urach at the foothills of the Swabian Alb, or at the Landshut-Neuöttinger fault zone near Landshut in Bavaria, or in some parts of the North German Basin, the temperature increases by more than 5 K per 100 m depth. These areas are affected by so-called positive temperature anomalies. These anomalies are beneficial for geothermal energy utilisation because the targeted temperature can already be reached at shallower depths resulting in lower drilling and investment costs.

Geothermal systems can be classified under various aspects. In Germany, the hitherto common way is to make a distinction between shallow and deep geothermal energy or between open and closed systems (Fig. 1), taking into consideration the depth of the heat exploitation and the utilisation concept of geothermal energy. Particularly in Germany, this differentiation is still useful because the variety of required geoscientific parameters is dependent on the utilisation type.

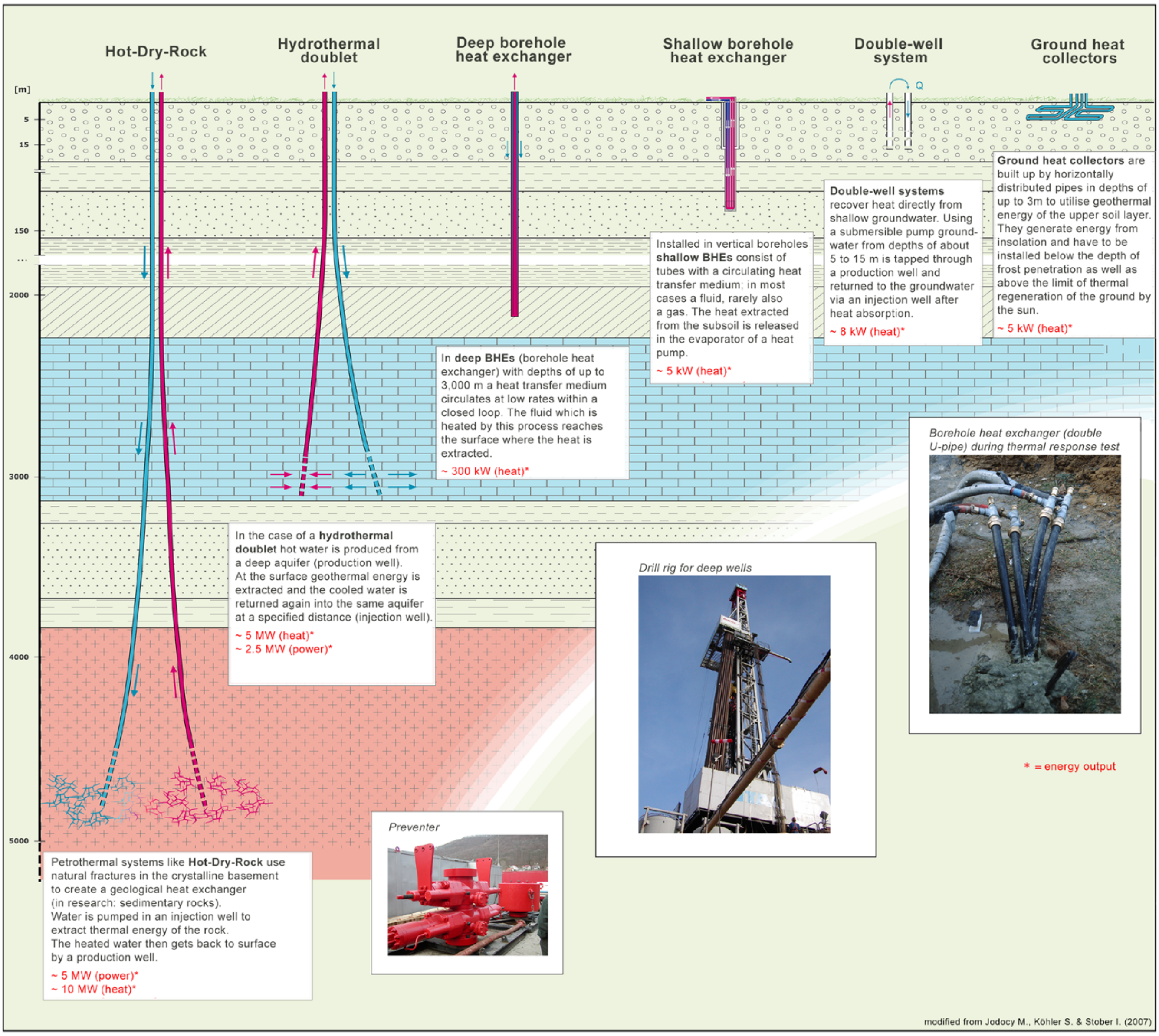

Fig. 1: Examples of different types of geothermal energy utilisation

In the case of **shallow geothermal energy utilisation**, the geothermal heat is extracted from shallow depths, e.g. by using ground heat collectors (depth of installation up to 5 m, for horizontal collectors usually 1.2 to 1.5 m), borehole heat exchangers (BHE; borehole depth commonly below 100 m due to German mining law, but also more than 200 m), groundwater wells (depth depends on ground water level) or energy piles (economically viable from about 6 m) (cf. VDI Guideline 4640 Part 2 2001). Shallow geothermal energy can only be exploited by using heat pumps, i.e. technical work is done to raise the heat from a lower to a higher temperature level. Direct heating systems (e.g. to heat railway points) via heat pipes for instance with CO_2 as the heat transfer medium are currently in the development phase.

Deep geothermal energy utilisation includes systems in which geothermal energy is extracted by deep wells. The energy can be used directly from produced hot thermal fluids (i.e. without raising the temperature level).

In Germany, deep geothermal energy commonly comprises depths of more than 1,000 m and temperatures exceeding 60 °C. Utilisation in depths between about 400 m and 1,000 m is often referred to as mid-deep geothermal applications. Areas with upwelling thermal waters (e.g. Aachen, Baden-Baden, Wiesbaden) represent a special case. Cataloguing geothermal resources by depth differs globally and might not be useful for international reporting codes. However, national reporting codes and cataloguing concepts may be justified as this German case exemplifies.

Deep geothermal energy includes the following systems, defined by the enthalpy. Enthalpy (or heat content) is a measure of the energy within a thermodynamic system.

→ **Hydrothermal systems with low enthalpy:**
The utilisation concept of hydrothermal systems refers to thermal fluids stored in reservoir rocks; in the majority of projects directly (or if necessary via a heat exchanger) used for feeding local and district heating systems, for agricultural, industrial, or for spa purposes. Temperatures above approx. 100 °C allow the generation of electricity by binary power plants (ORC or Kalina type). Examples are:
- **Aquifers** with hot (> 100 °C), warm (60–100 °C) or thermal (> 20 °C) water (Section 3.1).
- **Faults or fault zones** with elevated heat flow or fluid flow: These geothermally active fault zones are in the aforementioned temperature range in Germany. There have been ambitions to estimate the geothermal potential of regional fault systems (Jung et al. 2002) (see Section 3.2). Smaller fault zones are already drilling targets and successfully exploited in the Upper Rhine Graben as well as the Bavarian Molasse Basin (Lüschen et al. 2014).

→ **Hydrothermal systems with high enthalpy:**
Use of steam or two-phase systems for power generation; not possible in Germany due to the average too low geothermal gradient.

→ **Petrothermal systems:**
Utilisation of thermal energy stored in the rock without the need for naturally occurring thermal fluids. Examples are **Enhanced Geothermal Systems** (EGS) or **Hot Dry Rock Systems** (HDR): These systems extract thermal energy from the rock itself – they are therefore largely independent of water-bearing structures but dependent on permeability which needs to be enhanced by stimulation techniques when naturally too low. The hot rock (all types of tight rock, commonly crystalline or igneous rock but also sedimentary rock) is used as a heat exchanger (Stober & Bucher 2014). These systems are primarily used for power generation and hitherto very cost intensive (Section 3.3).

→ **Deep borehole heat exchangers (BHE):** BHEs extract thermal energy from any sequence of wet or dry rocks by circulating a heat transfer medium within a closed circuit of the heat exchanger. BHEs can only be used for supplying heat (Section 3.4).

Another possibility is the utilisation of geothermal energy from **mines, caverns and tunnels** (Section 3.5) as well as the **storage** of energy in sedimentary aquifer systems. Especially the storage of excess heat, e.g. from Combined Heat and Power Plants (CHP) or Combined Cycle Power Plants (CCPP), in deep aquifers (Aquifer Thermal Energy Storage, ATES) in summer with recovery in times of heat demand (in winter) has a large potential.

Knowledge about the properties of deep subsurface formations is important for characterising locations for the use of deep geothermal energy. The most important properties are described in the following paragraphs. Detailed information on the relevant parameters including their definitions and determinations are presented in Chapters 4 and 5.

2.2 Thermophysical properties

Apart from **temperature** T [K], the most important thermal properties include **thermal conductivity** λ [W m^{-1} K^{-1}] and **specific heat capacity** c [J kg^{-1} K^{-1}]. Thermal conductivity describes the property of a material to transport thermal energy in form of heat. Heat capacity describes its ability to store heat. The latter parameter is important for characterising transient, i.e. time-varying processes.

Another important parameter is the **heat flow density** q [W m^{-2}], the heat flow per unit area. The factor time is an integrative component of the heat flow. The heat flow density corresponds to the product of thermal conductivity λ and t**emperature gradient** grad T [K m^{-1}] and is defined by the Fourier equation which describes the conductive thermal transport:

$$q = \lambda \cdot \text{grad}\, T \qquad (1)$$

The thermal conductivity λ varies between 2 and 6 W m^{-1} K^{-1} in solid rock, whilst the thermal conductivity of water is only 0.598 W m^{-1} K^{-1} (at 20 °C). Highly permeable aquifers with high porosities therefore have a lower thermal conductivity than aquifers with lower porosities and permeabilities. Under in situ conditions the specific heat capacity c for solid rocks is in the small range of 0.8 to1.0 kJ kg^{-1} K^{-1}. In contrast, the specific heat capacity of deep groundwater is higher and ranges between 3.5 and 4.4 kJ kg^{-1} K^{-1} (depending on salinity and temperature). Effectively, water stores heat better than solid rock while the heat conductivity of water is less than of solid rock. Upwelling or downwelling groundwater, for example, can lead to temperature anomalies caused by convection. In Germany presumably differences in thermal conductivity (e.g. thick salt rock in Northern Germany) and in heat flow density at greater depth with conductive heat transport mechanism are responsible for the heterogeneous temperature distribution (Fig. 2).

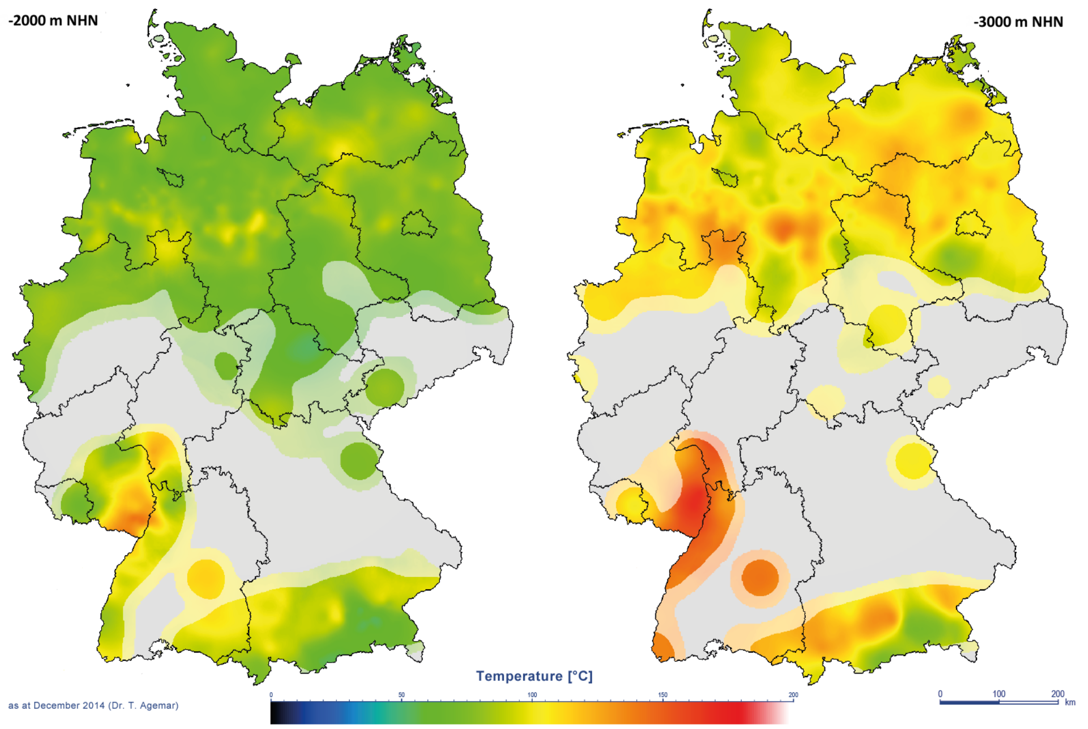

Fig. 2: Subsurface temperature distribution in depths of 2,000 m and 3,000 m below sea level. Areas without measured data are greyed out.

2.3 Hydraulic properties

Permeability and **hydraulic conductivity** describe the ability of a solid medium to channel a viscous fluid with a specific density. The permeability is limited to the properties of the rock, whilst the hydraulic conductivity also includes the properties of the – partially highly mineralised and gas-rich – water. The hydraulic conductivity k_f [m s^{-1}] indicates the flow rate Q [m^3 s^{-1}] through an area A [m^2] at a given hydraulic gradient i [–]:

$$k_f = \frac{Q}{i \cdot A} \quad (2)$$

The permeability K [m^2] is related to the hydraulic conductivity taking into account the physical properties of the water (viscosity μ, density ρ):

$$k_f = K \cdot \left(\frac{\rho \cdot g}{\mu} \right) \quad (3)$$

where g is the gravitational acceleration.

The hydraulic conductivity is of crucial importance when quantifying groundwater mass flow. It is part of **Darcy's Law** (Eq. 2). Knowing the cross-sectional area passed by groundwater flow, it is possible to calculate the amount of water per time unit Q [m^3 s^{-1}]. Darcy‘s Law is strictly speaking only valid when laminar (linear) flow occurs. Other flow laws should be used for low permeability rock and extremely low hydraulic gradients as typical for low permeable basement or crystalline rock or tight sedimentary formations, as well as for very high permeable rocks with extremely high hydraulic gradients as typical for karst in carbonate rock or fractured rock with turbulent flow.

Darcy's Law is the basis of all **hydraulic tests** in wells. Through these tests, the hydraulic conductivity of subsurface rock formations can be derived from the production or injection rate of the well and the observed gradients (rise or drop of water table, pressure build-up or reduction). However, this does not give a direct reading of the aforementioned reservoir rock permeability or hydraulic conductivity, but primarily an integral value over the test horizon (aquifer thickness H), the **transmissivity** T [m^2 s^{-1}]. Only if the aquifer is homogenous and isotropic, the hydraulic conductivity can be calculated directly from the transmissivity:

$$T = k_f \cdot H \quad (4)$$

Fig. 3: Cavernous Upper Jurassic (Malm): Example of an aquifer with very high permeability

The **total or absolute porosity** n [–] is the ratio of the pore volume of the rock to its total volume. It defines the storage capacity of an aquifer and includes the fractures and pores of the rock matrix as well as any vugs and voids in a rock mass caused by hairline cracks, through to fissures and caverns (German standard specification DIN 4049, part 3). Permeability of a rock mass and hence reservoir productivity are significantly depending on the fracture network and cavern systems. The **effective porosity** n_f [–] describes the part of the total porosity n that could contribute to fluid flow (for example no adhesive water and dead-end pores) and refers to the effectively usable pore space. The effective porosity is the total porosity less the fraction of pore space occupied by adhesive water and by dead-end pores. It provides an estimation of – but cannot be converted directly into – hydraulic conductivity because the size, shape and connections between voids are important as well. It can be determined by tracer tests or pumping tests (DVGW Regulations W 109 and W 111).

Hydraulic tests can be used to determine the transmissivity as well as the **storage coefficient** S [–]. The storage coefficient is a measure of the volumetric change of the stored water ΔV in response to a change in the pressure head of the water column Δh per surface A:

$$S = \frac{\Delta V}{\Delta h \cdot A} \quad (5)$$

The **specific storage coefficient** S_s [m^{-1}] refers to a volume rather than a surface. The relationship between the storage coefficient and the specific storage coefficient is analogous to the relationship between transmissivity and hydraulic conductivity. The following is valid for homogenous isotropic aquifers:

$$S = S_S \cdot H \quad (6)$$

2.4 Investigation methods to determine geothermal reservoir parameters

Hydraulic tests (pumping tests) are carried out in wells to determine the permeability and storage properties of subsurface rock formations (DVGW Regulation W 111). Execution and evaluation of hydraulic tests in wells for geothermal purposes are also based on the test methods used by the oil and gas industry (e.g. drill stem test, slug and bail test, pumping or injection test). Section 5.1 contains a detailed description of the tests.

The evaluation of hydraulic tests for geothermal wells is usually limited to water level measurements or pressure measurements in one borehole. **Well-specific influences** such as wellbore storage or skin effects must be taken into consideration. The longer a hydraulic test lasts, the greater the volume of the subsurface rock formation covered by the pressure signal; wellbore storage is then no longer effective. The hydraulic parameters characterise the rock mass unaffected by the zone close to the well. The test data also allow conclusions to be drawn about additional disruptive effects at larger distances, such as fault zones (hydraulically effective boundaries). The producing horizon is often tested separately by installing packers. A large number of evaluation methods and programs are available to analyse the various hydraulic tests. These methods and programs take into consideration the different starting and boundary conditions, and allow the different aquifer models to be identified and assessed (Stober 1986).

Geophysical well logging methods can provide additional information for determining the hydraulic properties of an exploitable horizon. Please refer to DVGW Regulation W 110 and Fricke & Schön (1999).

The following geophysical well logging methods are the minimum required to answer geothermal questions:

→ **Temperature log**, measures the temperature of the well fluid. Due to the disturbance of the formation temperature by the drilling process, measurements should be repeated or carried out after a longer standstill period in order to determine the undisturbed formation temperature. Changes in the gradient can indicate inflows or outflows of water.

→ **Gamma ray log**, measures the natural gamma radiation generated by potassium with the radioactive ^{40}K isotope – particularly common in clay minerals – as well as by isotopes of the uranium and thorium series.

→ **Caliper log**, uses extendable arms to record the cross-section of a well. It reveals zones where the rock has collapsed to form cavities due to drilling the well and the natural stress field.

→ **Density log**, uses an active gamma radiation source. Secondary gamma rays caused as a result are a measure of the rock density.

→ **Acoustic or sonic log**, measures the propagation velocity of seismic waves within the rock which is dependent on the material, the degree of fissuring and the porosity. These tools can be used to determine continuous porosity logs (log of the total porosity).

In addition, there are other logging methods, e.g. to determine any water inflows into the well (**flowmeter**), the quality of the casing cementation as well as techniques which are described in the DVGW Regulation W 110.

The magnitude of the hydraulic conductivity is significantly influenced by the density and viscosity of the mineralised water. The physical properties of water itself are dependent on the total dissolved solids, the gas content, the pressure, and the temperature (Section 4.3.7). Also the fluid-independent parameters permeability and porosity are often used instead of hydraulic conductivity or transmissivity.

In the oil and gas industry the permeability and porosity are often determined only from **core samples in the laboratory** – they are called **"poro-perm data"** (Section 4.2). A relationship between porosity and permeability can be empirically determined for specific lithologies. The parameters measured in the laboratory are related to the rock matrix. Permeability and productivity of the rock mass are in contrast determined by the fracture network and the cavern system, and can therefore be several orders of magnitude higher than the laboratory results.

The economic success of a geothermal well is determined by the productivity of the well. The parameter often selected for this purpose is the **productivity index** *PI* [$m^3\ s^{-1}\ MPa^{-1}$], a simplified parameter compared to transmissivity *T* or transmissibility *T**. The productivity index describes the production rate *Q* [$m^3\ s^{-1}$] as a function of the pressure drawdown Δp [Pa] and strictly speaking, can only be determined under stationary flow conditions (Section 4.2.6).

The different permeability parameters (K, k_f, T, T^*, PI), storage parameters (n, n_f, S, S_S, …) or transport properties of the subsurface rock formations can be determined by hydraulic tests. These tests provide parameters of different accuracy. For proper validation, the test results should therefore be considered together with the specific test conditions and the evaluation methods applied (Section 5.1).

3 Deep Geothermal Energy Utilisation Systems

3.1 Hydrothermal systems with low enthalpy: aquifers

3.1.1 Doublets

In the case of hydrothermal utilisation, water is produced from deep aquifers and the heat is then extracted via a heat exchanger. If the thermal water has a low level of mineralisation it could in principle be discharged after cooling into sewage systems or receiving waters. However, the cooled water usually has to be returned (injected) into the same aquifer system at a certain distance from the production well to stabilise the hydraulic head of the aquifer or to accomplish an environmental safe disposal. Such a utilisation system (Fig. 4) consists of at least one production and one injection well (**doublet**). A combination of several production and injection wells is possible.

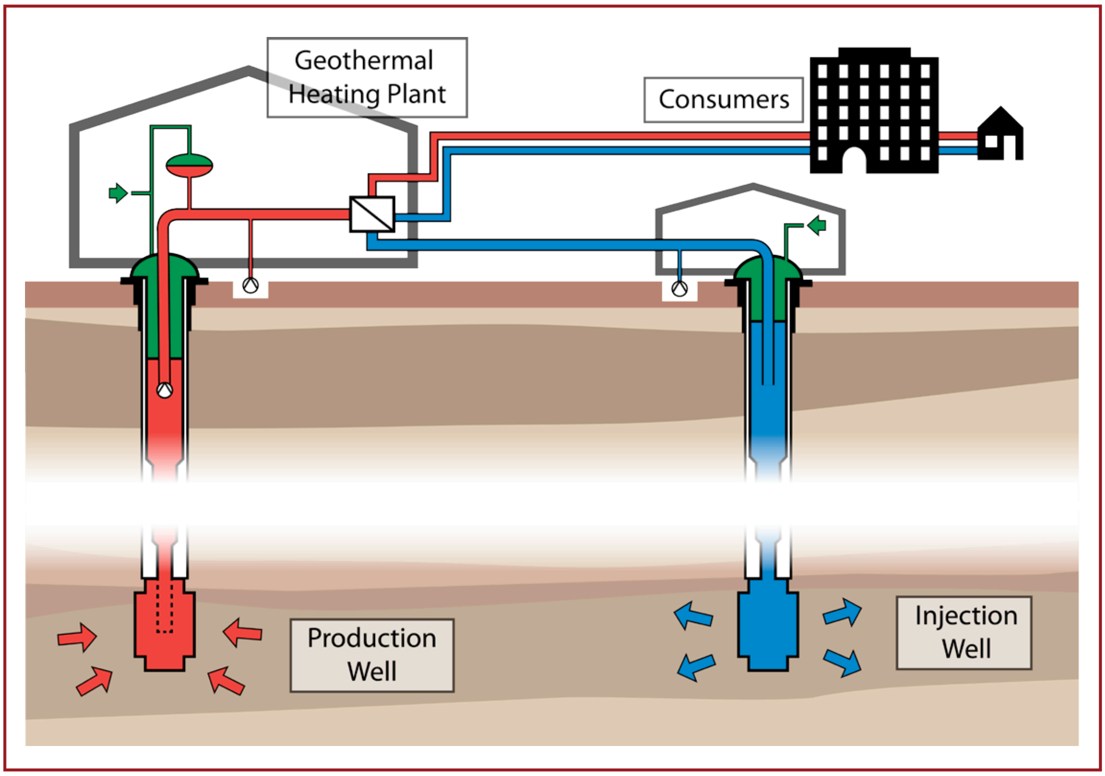

Fig. 4: Diagram of a doublet for hydrothermal utilisation

Hydrothermal well doublets are suitable for aquifers with high hydraulic conductivity. The critical parameter in addition to the temperature of the aquifer is the productivity, i.e. the production rate which can be achieved for an economically and technically acceptable drawdown of the water level. The productivity index of the well (cf. Section 4.2.6) can be derived on the basis of flow rate, draw down and well diameter. The productivity index is usually determined directly from well production tests (rarely from injection tests) but can also be estimated before drilling from regional reservoir parameters as described in Section 4.2 or from neighbouring wells.

High salt loads and large amounts of dissolved gas frequently found in deep formation fluids require reinjection due to regulatory standards. From a hydrogeological point of view, it is problematic if injection does not take place in the same aquifer from which the water was originally produced (lack of recharge, potential precipitation).

The system of a well doublet consists of two vertical wells (Fig. 4). The production and the injection well are frequently drilled from the same drill pad because the target horizon can be tapped by directional drilling. This increases the length of the well section connected to reservoir rock resulting in a larger reservoir access area than with vertical wells. In addition, the surface facilities, e.g. drilling site, connecting pipelines, will require less space when the well heads are close to each other. All technical installations can be built at one location and long connecting pipes on the surface can be avoided.

Hydrothermal utilisation using well doublets is a known technology. Hydrothermal plants exist already for many years and in some cases for several decades, in France in particular, but also in Italy, Poland, Austria, Russia and Germany (for example Neustadt-Glewe, Waren, Neubrandenburg, Unterhaching, Bruchsal). However, the technology is not mature yet because each hydrothermal project is site-specific, and individual plants with technical specifications need to be constructed for each site. In contrast to site-specific individual technological solutions, the general utilisation concept is adoptable: the produced and re-injected cooled water circulates at the surface within a closed circuit which frequently has to be maintained at pressure (e.g. by means of nitrogen admission) to prevent the precipitation of minerals from the highly saline water. The thermal water transported to the surface with the help of a submersible pump passes through a heat exchanger where the extracted **heat** is fed into a secondary circuit, such as a district heating network.

Power production with steam turbines and a conventional Rankine steam cycle at water temperatures below 180 °C has very low efficiencies (< 10 %). No geothermal well has ever exceeded this temperature in Germany. At temperatures between 100 and 180 °C, **electricity** production benefits from more efficient energy conversion in so-called binary power plants. These use additional technologies, such as Organic Rankine Cycle (ORC) or Kalina Cycle systems to transfer heat from the brine to a working fluid via a heat exchanger. ORC units (Fig. 5) use organic fluids like for instance isopentane, whereas the working fluid in Kalina units is commonly a water-ammonia mixture. Already at moderate temperatures, these working fluids have the advantage that large amounts of vapour can be produced to drive the turbine. An additional heat exchanger, called condenser, which discharges the residual heat is required for condensation or absorption of the ammonia having passed through the turbine. It is important to note that storage and handling of ammonia or organic fluids must comply with security standards. Due to the chemical aggressiveness of the water-ammonia mixture, appropriate materials and seals must be selected for Kalina units. The more complex engineering of Kalina plants leads to higher investment and maintenance costs. However, compared to ORC units Kalina plants have a higher efficiency at water temperatures below 150 °C. In Germany, there are more plants using the ORC than the Kalina cycle which is limited to the sites Unterhaching, Taufkirchen and Bruchsal.

Another form of geothermal utilisation is the **balneological use** of hydrothermal resources in thermal baths. Only a single (production) well is required for this purpose because the injection of spent bathing water does not comply with hygiene regulations.

Fig. 5: ORC plant (section)

3.1.2 Exploration risk

The exploration risk is the risk of drilling one (or more) well(s) into a geothermal reservoir with lacking sufficient quantity or quality.

The quantity is defined by the thermal capacity which can be achieved by using the well. This capacity P is proportional to the production rate Q and the temperature T:

$$P \sim Q \cdot T \quad (7)$$

The term quality basically in this context stands for the composition (chemistry) of the water (Section 4.3), whereas reservoir parameters like permeability and porosity control the production rate. The water could contain constituents such as gases or high mineral contents, which prevent or hinder geothermal utilisation. However, the waters encountered so far in geothermal wells in Germany have usually been considered manageable with respect to geothermal utilisation, although with a varying level of technical effort.

Fig. 6: Fractured Bunter Sandstone: example of a fracture aquifer

Fig. 7: Karstified, fractured Muschelkalk: example of a karst aquifer

A geothermal well is therefore considered to be successful if

→ the flow rate of the thermal water reaches a minimum production rate Q at a maximum drawdown Δs and if

→ a minimum temperature T is reached.

The minimum production rate and temperature for economic use must be determined by the operator or license owner.

In solid rock aquifers, the transmissivity, and therefore the productivity of the aquifer depends on the presence of open fractures or caverns, sufficient effective porosity, as well as other macroscopic pore spaces such as may be encountered i.a. in fault zones. Depending on the main share of its pore space aquifers can be divided into three basic types: porous, fractured and karstic (cf. also Figs. 3, 6, 7).

If the minimum flow rate is not achieved during development, **enhancement** or **stimulation** measures can be applied. Examples of these measures include acid treatment of carbonaceous rocks or fractured rocks with carbonate fillings and hydraulic stimulation (hydraulic fracturing), also in combination with acid stimulation where necessary. Productivity can also be increased by drilling deviated wells or side tracks into the target horizon, because – as described above – the well section connected to the reservoir is increased.

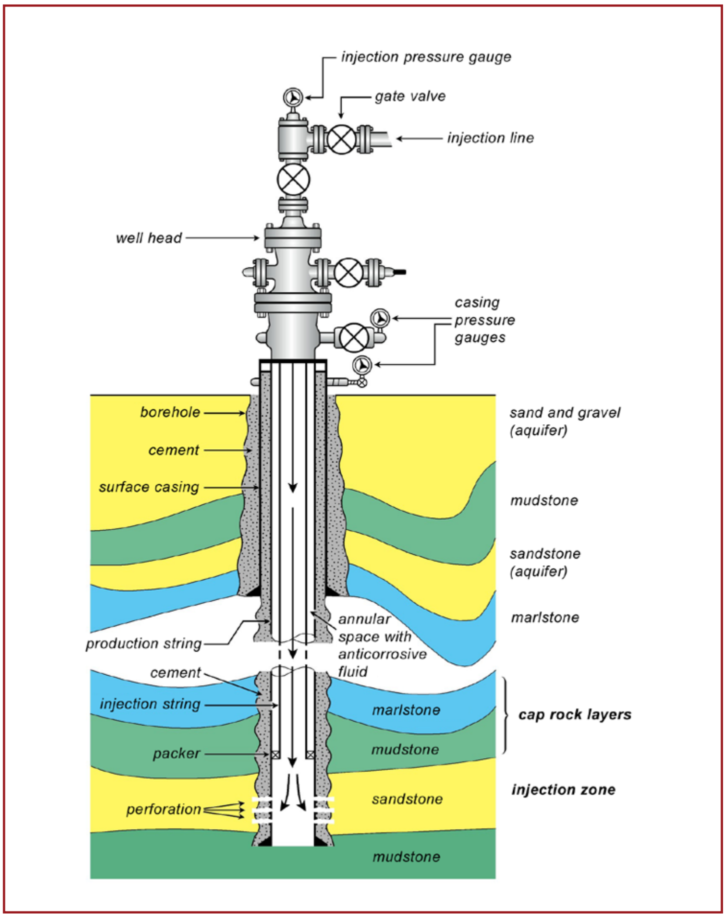

Fig. 8: Diagram of an injection well (modified after Owens 1975)

3.1.3 Distance between wells

There must be no **hydraulic** or **thermal "short circuit"** between the production and the injection well in hydrothermal applications, i.e. a fast connection between both wells has to be avoided. Hydraulic connections to other groundwater reservoirs must be prevented by installing appropriate seals. Fig. 8 shows the relevant diagram for an injection well.

The distance between the injection and production well must be large enough to ensure that no negative temperature reductions occur in the production well as a result of the injection of cool water into the exploited hydrothermal reservoir for the whole of the planned operating period (usually 30 years). Certain minimum distances between two wells in the aquifer have therefore to be kept. However, the distance has to be short enough to ensure a hydraulic connection between the two wells and to guarantee the long term productivity of the production well.

Numerical models are used to optimise the distance between production and injection well. However, because of the limited amount of data available, and the assumptions incorporated in the numerical models, it is only possible to describe subsurface conditions in a very simplified way.

3.1.4 Economic efficiency

Fig. 9: Work being carried out on a well head

Statements on efficiency, durability and profitability of a plant are crucially dependent on the hydraulic and thermal properties of the exploited horizon and the composition of the water. These properties must be optimally determined by conducting investigations in advance. All information with respect to the selected investigation and evaluation methods have to be documented in detail. The final decision on the profitability of geothermal plants is finally in the hands of the operator/investor on the basis of economic considerations. The customer structure has a very high priority in this context.

Sites with raised temperature gradients (temperature anomalies) can be associated with cost savings because shallower drilling depths may be sufficient. However, the achievable production rate must always be taken into consideration. Because of the relatively normal subsurface temperature conditions in Germany, geothermal energy is primarily used in form of heat, e.g. for heating plants, district heating systems or drying plants. An advantage of geothermal energy is the year-round availability of heat. From an economic and ecological point of view, it is also desirable to use the heat successively at a range of temperature levels (cascade systems) such as a combination of district heating (90 - 60 °C), greenhouses (60 - 30 °C) and aquaculture (below 30 °C). Also of great interest are hybrid systems, such as the combination of a cogeneration plant with a geothermal doublet, in order to store the plant's excess heat during summer months in a deep aquifer. If needed, the thermal energy stored in this way can be used for heating via the geothermal doublet.

Power generation is usually only possible at temperatures above 100 °C with ORC or Kalina processes which are practical applications of the theoretical Carnot cycle. Therefore, the efficiency of power production depends on the temperature difference of the medium in the working circuit: the higher the inlet temperature level and the lower the outlet temperature level in the process, the greater its efficiency. In addition, cogeneration allows to utilise and market residual heat, which from an ecological and economical point of view often makes sense. Analogous considerations apply to the use of petrothermal systems (Section 3.3).

3.1.5 Project planning of a hydrothermal plant

The following check list contains the most important steps which need to be gone through when planning the utilisation of a hydrothermal resource.

Phase I: Pre-study

1. Objective/public participation
2. Geoscientific principles
   → Availability of data (data review; in particular seismic profiles and wells, hydraulic tests, temperature details)
   → Geological structure (geological cross sections through the study area, interpretation of seismic profiles)
   → Depth and thickness of water-bearing horizons
   → Initial estimation of the temperature of potential productive horizons
   → Permeability, possible production rates
   → Hydrochemistry
   → Review of mining law, mining law permits
   → Environmental or cultural/religious protection areas, local protection regulations
3. Energetic use
   → Planned/existing heat supply (details from the municipality or the local energy utility: how much must/can geothermal energy contribute to the heat supply)
   → Power generation (optional, if wanted)
4. Draft technical concept for the geothermal plant
   → Existing and planned heat supply
   → Exploitation options (e.g. doublet, distance between wells, deviated wells)
   → Planned depth and well completion (as basis for a cost estimate)
   → Surface facilities
5. Cost estimate
   → Economic situation, financing options

Phase II: Feasibility study

1. Public relations
2. Items 1-5 of the pre-study as detailed concept; defining the options to be planned, including the determination of missing geoscientific investigations or technical surveys as well as the development of an integrated heat concept
3. Investment costs
   → Exploration
   → Subsurface facilities
   → Surface facilities
4. Economic efficiency
   → Operating costs
   → Expenses and revenues
   → Profitability calculation
5. Risk analysis, exploration risk, etc.
6. Life cycle assessment
7. Project schedule, assessment of approvability

Phase III: Exploration

1. Hiring a planning office/project management
2. Involvement of the public
3. Applying for a licence area from the mining authorities
4. Geophysical exploration where necessary
5. Drilling concept (considering the specifications of the mining authority)
6. Invitation to tender for the first well, preparation of an operating plan
7. Set-up of monitoring networks (seismic monitoring, groundwater monitoring wells)
8. Planning plant construction/surface facilities, approval process
9. Drilling site (permission, environmental impact assessment where necessary, site preparation)
10. Business plan

Phase IV: First development stage

1. Planning work for well drilling, requirements of licensing authorities (mining law, water law, environment protection)
2. Planning of investigations during drilling, obtaining of necessary permissions
3. Planning of improvement measures and the required approvals (if necessary)
4. Environmental impact assessment for drilling phase and tests
5. Public participation, public relations
6. Consideration of alternative uses or backfilling where required
7. Drilling the well performing the planned investigations and tests including legal approval requirements; analysis of the investigations, verification of suitability, alternatives
8. Improvement measures if necessary, permissions, verification of suitability
9. Adjustment of the hydrogeological subsurface model, hydrochemical calculations (scaling, corrosion), verification of avoidance strategies for scaling and corrosion (material usage), seismological monitoring with modelling
10. Assessment of discovery, further actions

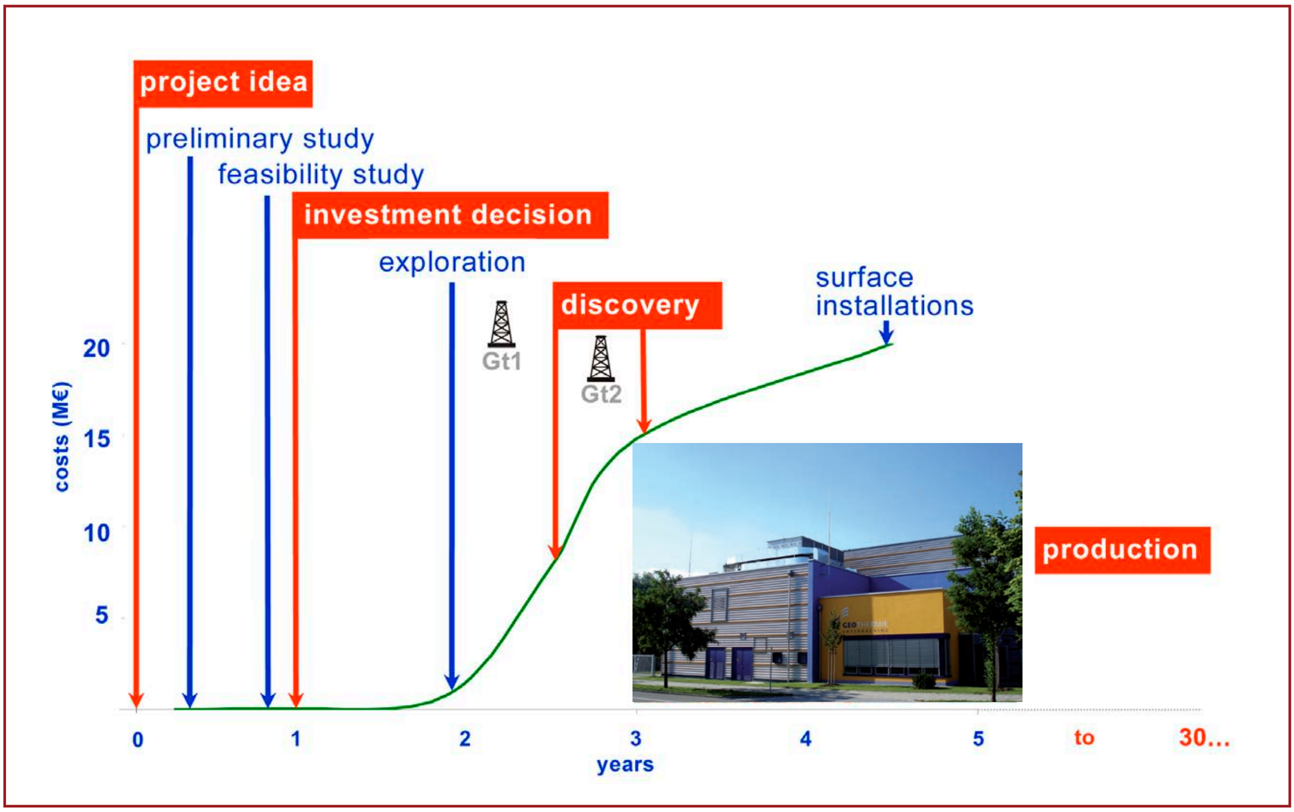

Fig. 10: Different stages of a geothermal energy project: time line in comparison to necessary investments (green line); the size of the investments can fluctuate strongly depending on the nature of the project.

Phase V: Second development stage

1. Second (and possibly further) well(s), following the approach of Phase IV
2. Assessment of the discovery of the wells
3. Verification of project goals and integration possibilities in the local heat and energy concept
4. Environmental impact assessment, public agencies
5. Surface facilities
6. Calculation of hydraulic and geothermal reach, licence application for prospection
7. Test operation incl. monitoring, main operating plan
8. Continuous operation incl. monitoring, final operating plan

3.2 Hydrothermal systems with low enthalpy: faults

Very little experience is currently available on the exploitation of large fault zones (Fig. 11) as geothermal reservoirs, although faults may contribute hydraulically to well productivity (Bense et al. 2013). They are considered to have significant potential (Agemar et al. 2017, in prep.). Fault zones can act as natural migration paths for water which reach down to great depths (Faulds & Hinz 2015). Fault zones can also connect aquifers located at different depths. Depending on the fault type, i.e. how the fault was formed and/or reactivated, the recent stress conditions, as well as on geochemical and diagenetic processes, these structures can be highly permeable to impermeable.

The likelihood that fractures channel fluids is higher in the case of tectonically active faults. Inactive faults may be healed or sealed by mineralisation while faults with large throw may contain fault gouge, depending on lithology and the presence of clays or alteration products.

Faults may contribute as pathway for upwelling thermal water expelling at or close to the surface as warm or hot springs. These thermal springs can be tapped and utilised for balneological purposes. The technical realisation, however, may be complicated under these structurally controlled conditions.

Fig. 11: Example of a basement fault zone

3.3 Petrothermal systems: EGS technology

3.3.1 Basic principle

In the case of petrothermal systems, the geothermal energy of the deep underground is utilised independent of water-bearing horizons. Essentially, this involves utilisation of energy stored in hot, low-permeable or tight rocks (Hot Dry Rock – HDR), by carrying out stimulation measures to create or enhance fracture planes serving as heat exchanger at depth. At the beginning of the development different terms have been introduced for this type of geothermal energy systems. In addition to the classic term Hot Dry Rock, other terms which are used include Deep Heat Mining, Hot Wet Rock, Hot Fractured Rock and Stimulated Geothermal System. However, at present **Enhanced Geothermal Systems** (EGS) is the most common term. The following describes the EGS technology which is aimed at the high temperature utilisation of geothermal energy with temperatures of more than 150 - 200 °C, and depths of more than 3,000 m (Fig. 12). The target horizon is usually the crystalline basement, tight sedimentary rocks are less common. Economic aspects and the prospects of technical success are crucial for the use of stimulation measures. Currently, EGS technology and utilisation is still a subject of research, but has already been developed in first pilot projects.

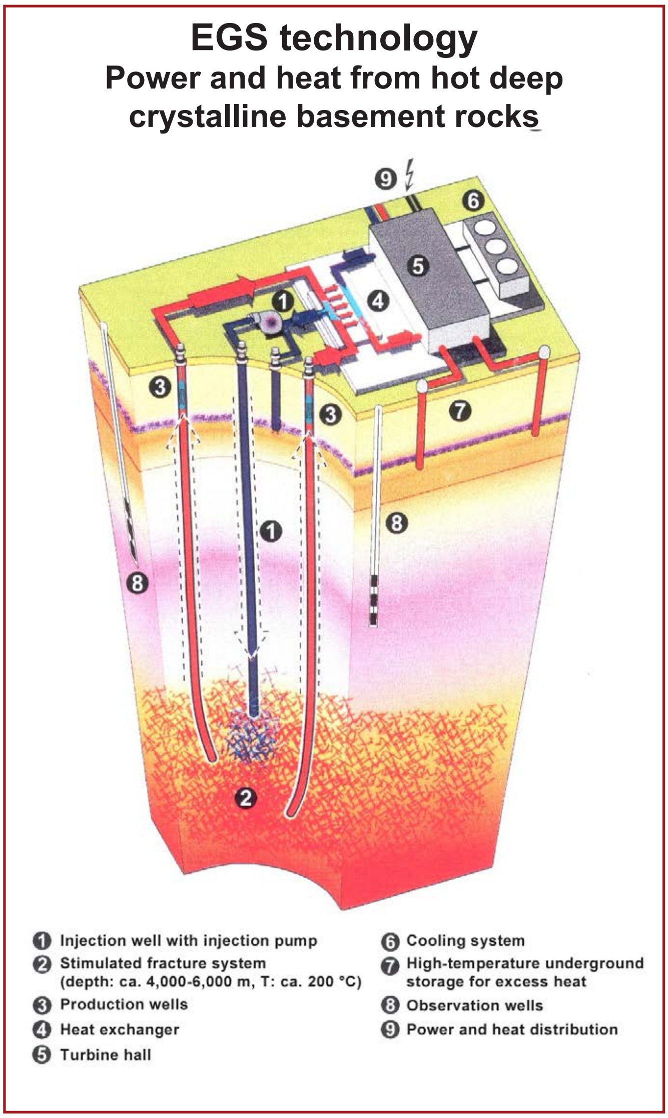

Fig. 12: Diagram showing an enhanced geothermal system (EGS) (www.geothermie.de)

The crystalline basement of the upper part of the Earth's crust is brittle and therefore fractured. Some of these fractures are open and thus filled with highly mineralised water and interconnected by a fracture network so that water circulation is possible. The crystalline basement therefore may behave like an aquifer with (very) low hydraulic conductivity. After drilling the well, water is injected into the natural fracture systems to expand existing or create new fractures; the rock is referred to as being "stimulated". The **stimulation** increases the natural permeability, enhances the migration paths for the water and allows higher production rates.

To permanently achieve the necessary flow rates and temperatures, the fracture system must have a minimum surface size acting as heat exchanger. A second well must be drilled through the stimulated zone. Surface water is pumped the injection well and produced from the production well so that it flows through this "heat exchanger" or "continuous-flow heater" to absorb the heat stored in the rock. In this system, not pure formation water but a mixture of formation water and external water is therefore the heat transfer medium, and the rock the thermal source.

The formation water at the necessary depths has a relatively high content of **total dissolved solids** with several 10 g/l (Fig. 13). When reaching the surface of the earth, the deep waters are usually oversaturated with respect to specific minerals and therefore cause precipitations. This is avoided by maintaining the water circulation at a high pressure within a closed circuit system. In some cases site specific inhibitors have to be added to prevent scaling. Specific mineralisation of deep crystalline basement rocks may lead to precipitations containing radioactive substances in individual cases; this problem affects especially heat exchangers and submersible pumps. Therefore, the produced water and precipitations have to be analysed continuously.

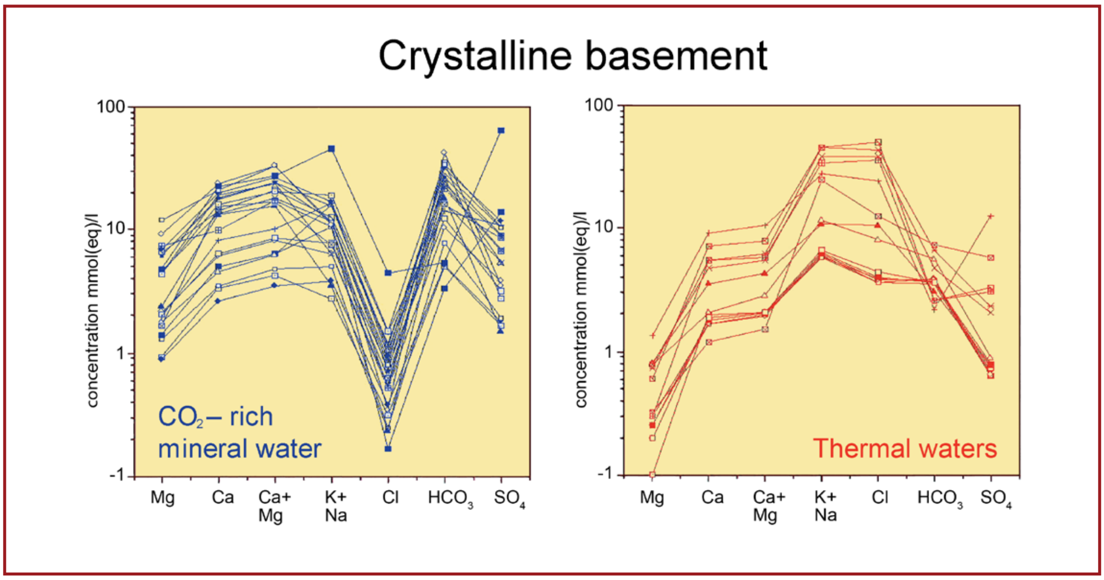

Fig. 13: Hydrochemical properties of deep water in crystalline basement (Schoeller diagram): the figure shows the concentrations of various constituents (after: Bucher & Stober 2010).

3.3.2 Requirements

The **temperature** and therefore the drilling depth is the first crucial aspect for EGS projects: the target temperatures are in the range of 200 °C. For financial reasons localities with anomalously high temperature gradients are of particular interest in this context. Another selection criterion is the **integrity** of the rock mass with respect to the present day stress field. Very strongly faulted zones should be avoided in the region of the planned stimulation when faults are close to reactivation, i.e. when they are critically stressed. Induced seismicity with not tolerable magnitudes could occur during stimulation, especially in tectonically active areas.

Fig. 14: Seismic exploration

Fig. 15: Pump installation for a frac test

Otherwise, fault zones are preferable drilling targets for EGS technology because a natural heat exchanger is already existing which could be utilised after stimulation. In addition, **water losses** should be kept to a minimum and be controllable, and not exceed 10 %.

Provided exploitation is largely restricted to the existing fracture network, the natural **fracture density** of the rock mass should be medium to high. Completely mylonitised zones, i.e. where the rock has been crushed into its smallest grain fractions, are not favourable. The natural fracture system should have a relatively uniform distribution to achieve a **heat exchange surface** of optimal size after stimulation under the existing stress field. Rybach (2004) for instance stipulates a minimum size for the heat exchange surface of more than 2 km^2. Because **granitic rock mass** reacts more rigidly to tectonic stresses than **metamorphic rocks**, granites are often more intensely fractured and therefore more permeable (Stober 1995).

The stimulated area or the reservoir should develop in the direction of the maximum horizontal principal stress within the **natural stress field**. Experience already gained from EGS projects has revealed that a steep ellipsoidal reservoir is usually formed by stimulation in accordance with the dominant stress field. According to Rybach (2004), the **volume of the reservoir** should be at least 0.2 km^3. A well doublet system would then require a subsurface distance of about 1,000 m when the length of the uncased part of the borehole (open hole) is about 300 m.

The stimulation measures should be aimed at achieving sufficiently high **connectivity to the reservoir**. If the distance between production and injection well connected by single hydraulic fractures is too short, there is a risk of **hydraulic short circuiting**, and therefore inadequate heat transfer. To avoid this risk, and to also avoid the extreme stimulation of singular fractures, it is recommended that the necessary injection tests are carried out in sections (by using packers) if technically feasible. According to simulation and monitoring results, the range of stimulation measures in a naturally fractured system can be up to several hundreds of meters.

3.3.3 Reconnaissance phase

The exploration measures start with the geological interpretation of **exploration seismic surveys** conducted by the oil and gas industry (and reprocessing which may be necessary). The objective here is to describe the geological conditions including the thickness of individual horizons and to identify faults as precisely as possible. The results of this work are used as the basis for deciding whether additional seismic or other geophysical surveys are required. It is usually much more difficult to determine the positions of faults in crystalline basement than in sedimentary rocks, however possible as shown by Lüschen et al. (2015). The interpretation of seismic profiles is also facilitated by the possibility to extrapolate faults running through the sediments down to the crystalline basement.

Geophysical seismicity monitoring as well as near-surface groundwater monitoring (quality, water level) shall be provided already prior to the first drilling. Both should be carried out throughout the entire exploration phase and into the continuous operation.

Drilling an **exploration well** into the crystalline basement (or into the rock to be stimulated) is desirable as part of the preliminary exploration work. Later on, this well could be used among other things for recording seismic signals during the stimulation tests in the deep EGS wells. The investigation programme to be carried out in the exploration well should include hydraulic tests within the crystalline basement, which gather information on the hydraulic conductivity and the storage capacity of the basement prior to the stimulation, as well as to derive data on the hydrochemical properties of the water, including its gas content. This enables measures to be implemented in a timely manner to control any problems associated with precipitation or corrosion. However, because of the high drilling costs, the first well is later usually used as the **production well** in which the stimulation measures are carried out. As a general rule, the drilling process and the stimulation work are accompanied by geophysical well logging techniques.

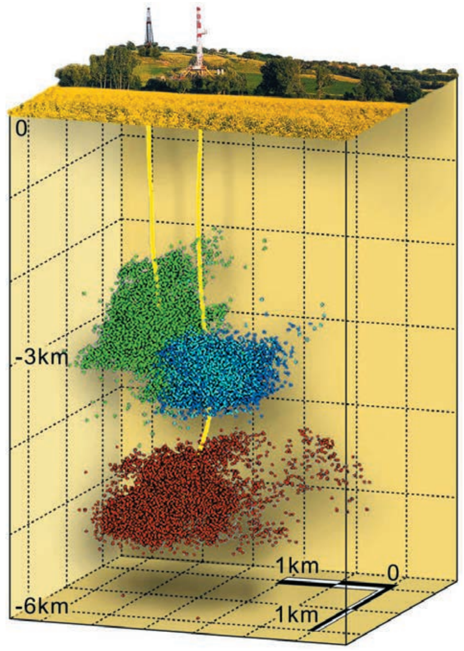

Fig. 16: Hydraulic stimulation in deep wells at the EGS project Soultz-sous-Forêts (France) (Weidler et al. 2002): Every dot corresponds to a microseismic event caused by the injection of water; the cloud of dots highlights the artificially created heat exchanger surface.

In the case of EGS projects, drilling the first well is followed by the injection of water to expand the natural fracture system which is accompanied with an increase of the rock stress. Usually, these stimulations give rise to microseismic events, the so-called induced seismicity, which may be perceptible at the surface of the earth. The number and extent of these events (Fig. 16) depend on the properties of the subsurface geology, the tectonic stresses, injection pressures or injection volumes, and also on the size of the stimulated fracture system. Therefore, the existing system of rock stress should be explored and the responsible seismological service is supposed to be involved in the planning.

3.3.4 Long-term behaviour

The first power production plant in the world operating in accordance with the EGS principle began test operations in Soultz-sous-Forêts (Alsace, France) in mid-2008. The technical installations above ground have been newly built for continuous operation in 2015.

Due to the relatively short period of operation there is hardly any practical experience in the long-term behaviour of the fracs and the rock matrix. It is possible that the stimulated or newly created fracture surfaces get sealed with respect to the rock matrix over the long injection and circulation periods. Alteration reactions (water-rock interactions) or the formation of secondary minerals have to be expected. These can reduce the porosity by precipitation or increase the permeability by dissolution and removal. In order to better understand the mechanisms of EGS further projects of this kind are necessary worldwide.

Fig. 17: Soultz-sous-Forêts EGS plant (source: Groupement Européen d'Intérêt Économique (GEIE) "Exploitation minière de la Chaleur")

3.3.5 Project planning for EGS plants

Knowledge of the following parameters is important for the project planning of EGS plants:

Distribution and depth of the basement (or of low permeable formations)
Information on the distribution of the crystalline basement and its depth is required to assess localities. Data from deep wells and seismic profiles are necessary for mapping the depth of the crystalline basement, although its surface is often not identifiable as a reflection horizon. In addition, there are only a few deep boreholes which reach into the basement, so that only little information on the **rock type** and on the hydrogeological as well as petrophysical properties are available. Knowledge of the petrographic characteristics of the rocks (like mineralogical composition and fabric) are important for the drilling technology to be used and the later stimulation measures. Granitic rock masses usually react more rigidly to tectonic stress than metamorphic rocks. Information on the integrity of the rock mass as well as the position and nature of faults is also important because the planned stimulation sections of the injection wells and the circulation areas need to be located at an adequate distance to larger faults.

Temperature and its prediction
Temperature is an important parameter. Only a small amount of temperature data is available from deep horizons so that one is usually dependent on extrapolating temperatures measured in the surrounding area and at shallower depths. If the rocks are assumed to be dense and not influenced by water movement, then temperature can be extrapolated downwards assuming a constant, vertical heat flow, only taking the thermal conductivity of the rock into consideration. At greater depths, the heat production of the rock also needs to be taken into account (cf. Section 4.1).

Thermophysical rock properties
Knowledge of thermal conductivity, density, specific thermal capacity and heat production rate are particularly important for estimating the distance between the injection and the production wells, to determine the thermal range and to forecast the lifetime of the plant.

Hydraulic properties, fracture flow system
The decisive factor for the economic success of an EGS plant is the flow rate which largely depends on the hydraulic properties of the naturally existing fracture system, as well as on the hydraulic properties of the artificially expanded or created fracture systems. The success of the stimulation measures is mainly influenced by the injection volume and rate, injection pressure or pressure gradient, as well as the hydrochemical properties of the injection fluid. An already existing natural hydraulic conductivity of the rock mass is of advantage to achieve the flow rates required for energy extraction. In order to operate a heat exchange system of sufficient extent, a minimum size of the rock mass is necessary. More accurate statements can be usually made only after drilling a well.

Formation pressure
It is crucial to have information on the hydrostatic and lithostatic pressures in the subsurface rock formations prior to drilling the well and for the hydraulic stimulation measures planned later in the geothermal reservoir.

Tectonic stresses
The in situ stress in the rock (borehole elongations, borehole caving zones) and the natural existing pore pressure of the rock formation (initial formation pore pressure) should be measured before starting the ongoing hydraulic stimulations because this is important for assessing the completed stimulation, as well as for evaluating the seismicity.

Amount of space required on the surface, size of the heat exchanger
The target zones of the wells must be oriented to the natural stress field because the stimulation zone, the reservoir, will most likely form in the direction of the stress field. If only vertical wells are planned to be used in the EGS project, a distance between the individual wells of several 100 metres on the surface needs to be taken into consideration. Problems associated with the expansion of the casing in geothermal wells can be handled much easier in vertical wells. However, in most cases deviated or even horizontal drillings are planned at present.

Properties of the formation fluid
The water in crystalline basement rocks is highly saline. The total dissolved solids range from a few tens to hundreds g/l. The main constituents are sodium, calcium and chloride (Fig. 13). Often the content of trace elements is higher, i.e. increased contents of heavy metals are possible; in addition, raised gas concentrations can be expected (Bucher & Stober 2010). In order to be able to technically control precipitation and dissolution processes during circulation operation, it is essential to know the hydrochemical properties of the formation fluid before constructing the surface facilities (Section 4.3).

Seismological monitoring
Already prior to drilling the first well seismic activity should be measured continuously. The monitoring has to be continued during drilling, stimulation and the operating phase and supplemented by ground motion measurements. The requirements for such a monitoring can be found in related recommendations (Baisch et al. 2012). In seismically active regions the size and direction of the principal stress regime should be measured in advance. Under certain circumstances, seismic events may be noticeable at the earth's surface. A risk for buildings only exists if the threshold of noticeability is exceeded by around 10 times, i.e. if the ground velocity exceeds 5 mm/s (DIN 4150). Among experts the occurrence of induced seismicity is in principle considered assessable, predictable, and also partially capable of being influenced.

In a study (Plenefisch et al. 2015) commissioned by the Umweltbundesamt (German Environment Agency), the risk to cause damage to the environment, to buildings or to infrastructure by hydraulic and chemical stimulation measures for deep geothermal energy was classified as extremely low against the background of regulations and guidelines that are applicable in Germany.

3.4 Deep borehole heat exchangers

Deep borehole heat exchangers (DBHE) have vertical closed circuits installed in wells with depths of some 100 m. They use a technology similar to shallow borehole heat exchangers. In a deep borehole heat exchanger, a heat transfer medium circulates within a closed system usually down to depths between 800 and 3,000 m (Fig 18).

By conduction from the rock, through the casing and the back-fill material heat is transferred to the fluid circulating in the borehole heat exchanger. If a coaxial pipe system is used, the cold fluid is pumped downward in a volume-controlled manner through the annular space. As it moves slowly down the pipe (5 – 65 m/min) it is heated up and then rises up to the surface through the insulated inner pipe (Fig. 18). At the head of the borehole heat exchanger the warm fluid enters the surface installations where it is cooled down to approximately 15 °C and pumped back into the annular space by a rotary pump. Ammonia is frequently used as the fluid. The surrounding rocks cool down because of the extraction of heat. This gives rise to a horizontal temperature gradient which causes heat to flow in from the surrounding area.

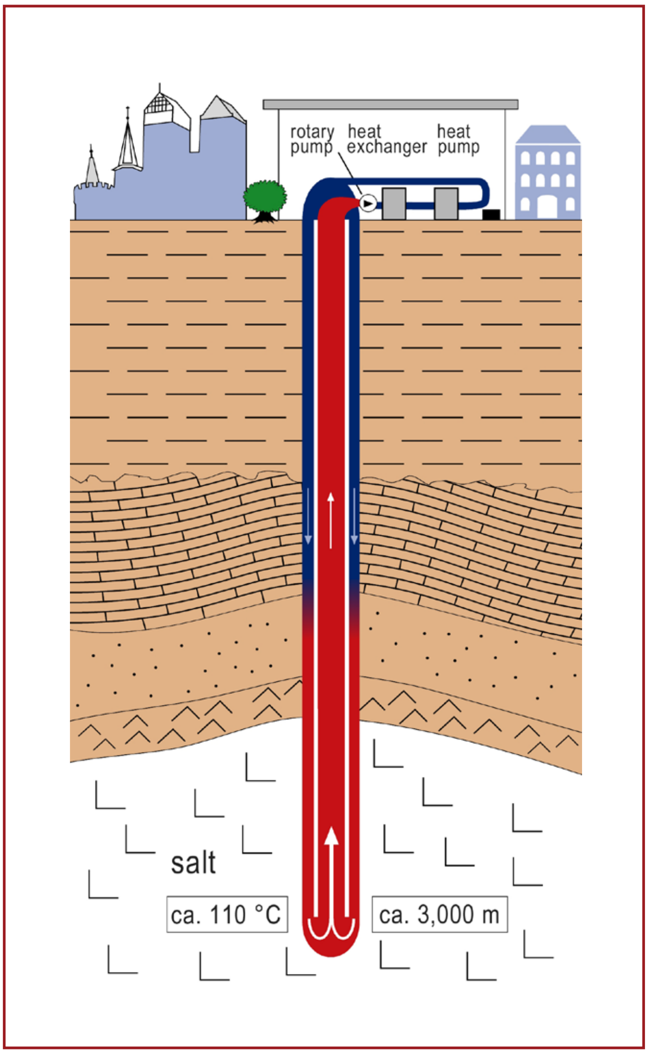

Fig. 18: Geothermal plant operated by the municipal utility in Prenzlau: Example of a deep borehole heat exchanger (source: Stadtwerke Prenzlau)

Deep borehole heat exchangers are not dependent on highly permeable aquifers, and can therefore be installed almost anywhere in theory. Because deep borehole heat exchangers have a closed circuit, they have no impact on the natural chemical equilibrium of the rock mass. Dissolution or precipitation reactions which can occur in the case of hydrothermal systems or EGS systems are therefore completely excluded.

The effective amount of energy delivered by a borehole heat exchanger primarily depends on the subsurface temperature; areas with positive temperature anomalies are therefore particularly suitable. Other important parameters are the thermal conductivity and the temperature gradient. The effective amount of energy which can be extracted also depends on the operating time, as well as on the design of the borehole heat exchanger and the riser, and therefore also on the thermal properties of the materials used for construction. Long heat exchangers with large diameters have a larger heat exchange surface.

Deep borehole heat exchangers are used in projects intended at providing a location-independent supply of heat at average temperatures (up to approximately 60 °C feed-in temperature).

Borehole heat exchangers generally only have capacities of a few hundred kW_{th} and therefore much less than open systems. This is due to the small size of the heat transfer surface in contact to the rock mass because it only corresponds to the outer casing surface of the well. In contrast to open systems there is no exploration risk in the case of closed deep borehole heat exchangers.

The main cost factors are the drilling costs because of the large well depths usually required. Even though the efficiency of deep borehole heat exchangers is not as dependent on the subsurface geological conditions as in the case of hydrothermal systems for instance, the planning and risk minimisation demand the most accurate prediction possible of the geological conditions. Due to the high investment costs deep borehole heat exchangers are particularly suitable at a location with an already existing unused deep well, e.g. making use of old oil and gas wells or dry geothermal wells.

Information on the following parameters is required when planning a deep borehole heat exchanger:

- → Target depth
- → Depth-dependent subsurface temperature
- → Lithological composition, thickness of the geological units
- → Water-bearing formations
- → Structural geology, in particular faults
- → Thermal conductivity of the rocks
- → Thermal capacity of the rocks

3.5 Tunnels, caverns, mines

If there is a high discharge of warm tunnel or mine water (up to a few 100 l/s) it can be used as an energy source. Useable tunnel waters have average temperatures of 12 - 24 °C. The temperature of this water can be raised to a utilisable level using a heat pump. Waters with much higher temperature can be used directly if applicable. Where necessary, costs for local or district heating pipelines should be incorporated in the economic calculations of the overall energetic assessment. Similar considerations also apply to waters from abandoned mines, e.g. in the German Ruhr Area where dewatering is necessary.

The total heat capacity of tunnel water currently used in Switzerland is about 4 MW_{th}. Two tunnel water facilities are also operated in summer to provide geothermal cooling. The utilisation of tunnel water is also planned for the new Gotthard Base Tunnel. Investment costs for the distribution of the heat increase with the distance between the source and the consumers.

4 Relevant Parameters for Geothermal Utilisation

Different parameters are important for the individual systems utilising deep geothermal energy. For instance, hydrothermal utilisation systems are more strongly dependent on the natural hydraulic properties of the subsurface than deep borehole heat exchangers or petrothermal systems like EGS systems. On the other hand, the thermophysical rock properties are highly significant for deep borehole heat exchangers even though they are only of secondary interest for hydrothermal systems. In the latter case, information on the fluid properties, particularly with respect to corrosion, precipitation and the like, is indispensable, whereas they can be completely ignored in the case of deep borehole heat exchangers. The following table provides an overview of the natural parameters relevant to each of the different systems.

Properties	Hydrothermal (aquifers)	Petrothermal (EGS)	Borehole heat exchanger	cf. section
Thermophysical rock properties				
thermal conductivity	3	2	1	4.1.3
rock density	3	2	1	4.1.4
heat capacity	3	2	1	4.1.5
temperature	1	1	1	4.1.1
heat flow density	2	2	2	4.1.2
Hydraulic properties				
permeability / hydr. conductivity	1	2	3	4.2.2
transmissivity / transmissibility	1	3	3	4.2.3
porosity	1	3	3	4.2.4
storage coefficient	2	3	–	4.2.5
productivity index	1	3	–	4.2.6
hydraulic tests	1	1	–	5.1
Fluid properties				
density, viscosity, compressibility	1	2	–	4.3.1/2/3
pH, E_H, temperature	1	1	3	4.3.4/5
total dissolved solids (TDS)	1	1	3	4.3.7
anions - cations	1	1	3	4.3.7
undissociated substances	1	1	–	4.3.7
gases	1	1	2	4.3.8
Geological properties				
faults, stress field	2	1	3	3.3.5
petrography / rock type	1	1	2	3.3.5
aquifer geometry / heat exchange surface	1	1	–	3.1.3/3.3.5

1 = very important 3 = less important
2 = relevant – = not important

Table 1: Overview of the relevant physical parameters for each of the different geothermal utilisation systems

4.1 Thermophysical parameters

Thermal conduction is described by the Fourier equation (Section 2.2):

$$q = \lambda \cdot \mathrm{grad}\, T \qquad (8a)$$

where q [W m^{-2}] is the heat flow density (cf. Section 4.1.2), λ [W m^{-1} K^{-1}] is the thermal conductivity (cf. Section 4.1.3) and grad T [K m^{-1}] is the temperature gradient (cf. Section 4.1.1). Because heat flow in the earth's crust is usually oriented vertically upwards, the Fourier equation can be used in a 1D approach:

$$q = \lambda \cdot \frac{\mathrm{d}T}{\mathrm{d}z} \qquad (8b)$$

Equation (8b) can be rewritten assuming that no heat sources exist between the measuring point at the earth's surface and at depth z:

$$T(z) = T_0 + q \cdot \frac{z}{\lambda} \qquad (8c)$$

where T_0 is the average temperature at the earth's surface. The following is valid in the case of existing heat sources:

$$T(z) = T_0 + q \cdot \frac{z}{\lambda} - \frac{1}{2} \cdot H \cdot \frac{z^2}{\lambda} \qquad (8d)$$

where H [W m^{-3}] is the specific volumetric heat production.

4.1.1 Temperature T, temperature gradient grad T

Measurement unit: °C for T; K for temperature difference; K m^{-1} for grad T

Definition: The temperature gradient is the increase in temperature per depth unit.

Determination: In situ measurements in wells

Methods: Correction methods to determine undisturbed formation temperatures
(e.g. from BHT values; BHT - Bottom Hole Temperature)

Secondary parameters for correction methods:
→ Well diameter [m]
→ Standstill period [h]
→ Thermal diffusivity α of the rock [m^2 s^{-1}], a parameter directly proportional to thermal conductivity λ [W m^{-1} K^{-1}]: $\alpha = \lambda / (\rho \cdot c_p)$

Value range: The average temperature gradient in Germany is 30 K km^{-1}. The average temperature T_0 at the earth's surface in Germany is 8.2 °C (lowest value at the summit of the Zugspitze = - 4.8 °C). The highest temperature T_z ever measured in a German borehole is 253 °C at a depth of 9,063 m (KTB Upper Palatinate).

The Geophysics Information System (FIS GP, http://www.fis-geophysik.de) of the Leibniz Institute for Applied Geophysics provides a database which can be used to calculate subsurface temperatures. It contains temperature information from approximately 11,500 deep wells drilled in Germany including:
→ **Undisturbed temperature logs:** continuous temperature measurements with depth.
→ **Disturbed temperature logs:** continuous measurement of temperature with depth, disturbed by the drilling process, cementation or hydraulic circulation.
→ **Reservoir temperatures:** available as a comprehensive series of measurements with up to 100 individual values thanks to the regular control of production wells over many years. These temperature measurements mainly fluctuate by less than 1 K so that they can usually be summarised within one measured temperature value.
→ **Test temperatures:** temperature measurements during production tests, drill stem tests, etc.; corrected discharge temperatures (cf. Section 5.1).
→ **Bottom Hole Temperatures (BHT):** BHT measurements are carried out in almost all industrial wells at the bottom of the borehole immediately after terminating the drilling work, and are thermally disturbed by the drilling process (mud circulation); a correction (extrapolation) of these BHT values to get undisturbed temperatures is possible due to the fact that the disturbing influence of the drilling fluid circulation on the temperature field is at its minimum at the bottom of the borehole: different correction methods are used depending on the standstill period after drilling, the duration of drilling fluid circulation and the number of temperature readings available from each depth.
→ **Single point measurements** in mines and tunnels.

4.1.2 Heat flow density *q*

Measurement unit: $W\ m^{-2}$

Definition: The heat flow density is the heat flow from the earth per unit area.

Determination: In situ temperature measurements in wells and the temperature gradient derived from these results; thermal conductivity measurements in the laboratory on cores (alternatively literature values for the same lithology, cf. Section 4.1.3).

Methods: Temperature extrapolation to depth z (cf. Section 4.1). The extrapolation requires pure conductive heat transfer.

Secondary parameters for the calculation:
→ Average temperature at the earth's surface T_0
→ Thermal conductivity λ

Value range: 30 – 120 $mW\ m^{-2}$. The average heat flow density in Germany is about 65 $mW\ m^{-2}$.

4.1.3 Thermal conductivity λ

Measurement unit: $W\ m^{-1}\ K^{-1}$

Definition: The thermal conductivity is the quotient of heat flow density and the temperature gradient (cf. Section 4.1.1). The thermal conductivity is temperature and pressure dependent.

Determination: Laboratory measurements on cores
Values at room temperature are usually given when specifying the thermal conductivity of a medium. Knowing the reservoir temperature and comparison with references allows giving estimations for deep aquifers. Another critical aspect for the value of the thermal conductivity is whether measurements were carried out on dry or wet cores.

Value range: 1.2 – 6.5 $W\ m^{-1}\ K^{-1}$

4.1.4 Rock density ρ

Measurement unit: $kg\ m^{-3}$

Definition: Mass per volume

Determination: Laboratory measurements on cores; geophysical well logging

Value range: 2,000 – 3,200 $kg\ m^{-3}$; sometimes higher values possible (e.g. in eclogites which are created under high pressure conditions).

4.1.5 Heat capacity *c*

Measurement unit: J kg^{-1} K^{-1} for specific heat capacity *c*, J m^{-3} K^{-1} for volumetric heat capacity $c{\cdot}\rho$

Definition: The specific heat capacity is the ratio of the heat transfer to a body to the associated temperature change and its weight. It describes the ability of a material to store heat and is temperature-dependent. The isobaric specific heat capacity c_p is the specific heat capacity under constant pressure. The volumetric heat capacity is the product of specific heat capacity and density and is used to calculate the thermal capacity of geothermal projects.

Determination: Laboratory measurements on cores

Value range: 700 – 1,100 J kg^{-1} K^{-1} (average value: 840 J kg^{-1} K^{-1} – with low ranges of variation) for specific heat capacity *c*; 1.9 – $2.5{\cdot}10^6$ J m^{-3} K^{-1} (average value: $2.1{\cdot}10^6$ J m^{-3} K^{-1} – with a low range of fluctuation) for volumetric heat capacity $c{\cdot}\rho$

Fig. 19: Geothermal well Unterhaching Gt1

4.2 Hydraulic parameters

The mass flow within a porous medium is described by *Darcy's Law*:

$$q = k_f \cdot \nabla h \tag{9a}$$

where q [m s^{-1}] is the volumetric flow rate per unit area, k_f [m s^{-1}] is the hydraulic permeability (hydraulic conductivity) (cf. Section 4.2.2) and ∇h is the hydraulic potential gradient. The following is valid for the 1D approach:

$$q = k_f \cdot \frac{\delta h}{\delta x} = k_f \cdot i \tag{9b}$$

where δh is the potential difference along the travel distance δx in the flow direction and $\delta h/\delta x$ is described as the hydraulic gradient i. If the cross section A – passed by the groundwater – is known, it can be used to determine the flow rate per time unit Q [m^3 s^{-1}] as follows:

$$Q = k_f \cdot A \cdot \frac{\delta h}{\delta x} = k_f \cdot A \cdot i \tag{9c}$$

Darcy's Law is used for almost all flow processes in porous, fractured and karst aquifers, as well as for the evaluation of hydraulic tests in one or more wells. Strictly speaking though, it is only valid for laminar (linear) flow.

4.2.1 Hydrostatic pressure p_g

Measurement unit: bar (1 bar = 10^5 Pa = 0.1 MPa; 1 Pa = 1 N m^{-2})

Definition: Pressure is the ratio of force F to effective area A, on which the force acts vertically.

$$p = \frac{F}{A} \tag{10a}$$

The hydrostatic pressure is the pressure exerted by a static fluid (usually water) under the influence of the earth's gravity g. It is a static parameter which is dependent on the height h of the liquid column and the density ρ_F above the measurement point.

$$p_g = h \cdot \rho_F \cdot g \tag{10b}$$

The absolute hydrostatic pressure (or the „pressure") at a point within a groundwater volume, is the sum of atmospheric pressure p_{atm} and the relevant hydrostatic pressure p_g:

$$p = p_{atm} + p_g \tag{10c}$$

Determination: Measured in wells using a pressure sensor;1 m water column (m WC) = 0.9807 kPa ≈ 0.1 bar

4.2.2 Permeability K, hydraulic conductivity k_f

Measurement unit: m^2 (1 Darcy = $0.98697 \cdot 10^{-12}$ m^2) for permeability K; $m\ s^{-1}$ for hydraulic conductivity k_f

Definition: The permeability and the hydraulic conductivity describe the ability of a porous medium to channel a fluid (e.g. water). The permeability is solely related to the formation properties, the hydraulic conductivity also incorporates the properties of the fluid. The hydraulic conductivity defines the volume flow Q which flows per area A affected by a hydraulic gradient i and a specific fluid temperature. Permeability is related to the hydraulic conductivity by taking into consideration the dynamic viscosity μ and the density ρ_F of the fluid and the earth's gravity g given by the equation:

$$k_f = \frac{K \cdot \rho_F \cdot g}{\mu} \tag{11}$$

The following is equivalent for pure water at 10 °C: a hydraulic conductivity of 10^{-5} $m\ s^{-1}$ corresponds to a permeability of 1 D and 1 $m\ s^{-1}$ corresponds to 10^{-7} m^2, respectively. K and k_f can both be direction-dependent and must then be described as tensors.

Determination: Laboratory measurements on cores (property of the rock matrix); extrapolation from well measurements (permeability); evaluation of pumping and injection tests as well as of tracer tests (property of the rock mass)

Secondary parameters (cf. Sections 4.3.1/2)**:**

→ Dynamic viscosity of the fluid μ [$kg\ m^{-1}\ s^{-1}$]

→ Kinematic viscosity of the fluid $\nu = \frac{\mu}{\rho_F}$ [$m^2\ s^{-1}$]

→ Density of the fluid ρ_F [$kg\ m^{-3}$]

The hydraulic conductivity is significantly influenced by the density and viscosity of the water. The parameters are dependent on the nature and amount of the dissolved solids, the pressure, the gas content and the temperature.

Value range: $10^{-8} – 10^{-20}$ m^2 (good values > 10^{-13} m^2) for K, $10^{-1} – 10^{-13}$ $m\ s^{-1}$ (good values > 10^{-6} $m\ s^{-1}$) for k_f. The minimum permeability/hydraulic conductivity for hydrothermal utilisation should be above 10^{-13} m^2 or above 10^{-6} $m\ s^{-1}$.

4.2.3 Transmissivity *T*, transmissibility *T**

Measurement unit: T in $m^2\ s^{-1}$, T^* in m^3

Definition: The transmissivity is the integral value of hydraulic conductivity over aquifer thickness:

$$T = \int_0^H k_f \, \mathrm{d}z \qquad (12a)$$

If the aquifer is homogenous and isotropic, the following applies:

$$T = k_f \cdot H \qquad (12b)$$

The following applies if an aquifer is composed of several layers (stockworks):

$$T = \sum k_{f,i} \cdot H_i \qquad (12c)$$

If one integrates the permeability K instead of the hydraulic conductivity k_f, this corresponds to transmissibility [m^3].

Determination: Evaluation of pumping and injection tests (cf. Section 5.1)

Value range: $10^0 – 10^{-11}\ m^2\ s^{-1}$ for transmissivity; $10^{-7} – 10^{-18}\ m^3$ for transmissibility. The minimum values for transmissivity and transmissibility with respect to hydrothermal utilisation should be above $5 \cdot 10^{-5}\ m^2\ s^{-1}$ and above $5 \cdot 10^{-12}\ m^3$, respectively.

4.2.4 Porosity Φ

Measurement unit: per cent [–]

Definition: The **total porosity** is the proportion of void space n [–] with respect to the total volume of the rock. The **effective porosity** n_f is the proportion of pore space containing freely movable water, and thus for example no connate water. Although the effective porosity is a precondition for permeability, it cannot directly be correlated because the size, shape and connections between the pore spaces have also a crucial influence.

Determination: Laboratory measurements on cores (property of the rock matrix); evaluation of geophysical borehole logs; the effective porosity can be determined from tracer tests and possibly from pumping tests (property of the rock mass).

Further processing: There is an empirical relationship between porosity and permeability which applies specifically to a lithology, and cannot be transferred to other geological units.
The relationship between porosity and permeability can be described using capillary models, sphere models and approaches based on fractal theory. The relationship for a specific lithology can be expressed by a function of the type $K = x_1\Phi + x_2\Phi^2 + x_3\Phi^{10}$. Minor changes in porosity therefore have a strong influence on the value of the derived permeability K.

Value range: 0 – 30 % (total porosity); 0 – 15 % (effective porosity)

4.2.5 Storage coefficient S, specific storage coefficient S_s

Measurement unit: [–] for storage coefficient S; m^{-1} for specific storage coefficient S_s

Definition: The specific storage coefficient S_s is defined as the change in the stored water volume per volume unit of the aquifer when changing the pressure head or the level of the water column by one meter. In confined aquifers, it is largely determined by compressibility. The storage coefficient is, analogous to transmissivity and the k_f value, the integral of the specific storage coefficient over the groundwater thickness (equations 13a–c). The storage coefficient S is therefore a measure of the change in stored water volume ΔV per surface unit A for a drawdown Δh of one metre:

$S = \Delta V / (A \cdot \Delta h)$.

Only the storage coefficient can be determined directly from pumping tests.

$$S = \int_0^H S_s \, \mathrm{d}z \qquad (13a)$$

The following applies if the aquifer (with a thickness of *H*) is homogenous and isotropic:

$$S = S_s \cdot H \tag{13b}$$

The following applies if the aquifer consists of several layers (stockworks):

$$S = \sum S_{s,i} \cdot H_i \tag{13c}$$

Determination: Evaluation of pumping tests (cf. Section 5.1)

Value range: The specific storage coefficient in confined aquifers is $10^{-6} – 10^{-7}$ m^{-1}. The storage coefficient can be up to around two orders of magnitude higher. In free aquifers, the storage coefficient roughly corresponds to the effective porosity.

4.2.6 Productivity index *PI*, injectivity index *II*

Measurement unit: m^3 s^{-1} MPa^{-1}

Definition: The productivity index *PI* describes the ratio of the production rate to the pressure drop. In the case of injection wells, the injectivity index *II* is the analogue to the productivity index. It describes the injection rate dependent on the pressure rise. The following conversion table is derived when taking into consideration the different units:

Unit	m^3 s^{-1} MPa^{-1}	m^3 h^{-1} MPa^{-1}	l s^{-1} (m WC)$^{-1}$	l s^{-1} bar^{-1}
m^3 s^{-1} MPa^{-1}	1	3,600	9.806650	100
m^3 h^{-1} MPa^{-1}	$0.278 \cdot 10^{-3}$	1	$2.724 \cdot 10^{-3}$	$27.8 \cdot 10^{-3}$
l s^{-1} (m WC)$^{-1}$	0.101971	367.098	1	10.1971
l s^{-1} bar^{-1}	0.01	36	$98.067 \cdot 10^{-3}$	1

Table 2: Conversion table with respect to the various measurement units used for the productivity index *PI*

Determination: The index is usually determined from hydraulic tests although it has to be considered that in the case of short test periods the drawdown has not reached its maximum due to the existence of an unsteady state. However, the productivity index is not solely dependent on the properties of the subsurface geology, but also on the properties of the well (wellbore storage, skin effect).
The productivity index can be estimated mathematically with the help of the well equation from Thiem (1906) for the preset drawdown *s* (where $p = \rho \cdot g \cdot s$) and well radii *r*, if the k_f value, the aquifer thickness *H* and the radius of the cone of depression *R* are known:

$$PI = \frac{Q}{s} = 2\pi \cdot k_f \cdot H \frac{1}{\ln \frac{R}{r}} \qquad (14)$$

The productivity index determined in this way must be converted to the usual dimension by using the density ρ_F and the earth's gravity *g*.

If the fracturing pressure of the rock mass is not exceeded (elastic or pressure mechanical deformation), the injectivity index is identical to the productivity index in the case of an ideal aquifer with the same fluid properties. However, because the pressure differences to be applied in this case are dependent on the viscosity and density of the fluid, and because the viscosity in particular is very strongly temperature-dependent, the injectivity index in a geothermal well (injection of cooled water) is often several times smaller than the productivity index (production of hot or warm water). This means that a higher pressure difference must be applied to inject the cooled water than is required to produce warm water at the same rate.

4.2.7 Other parameters

In addition to the most important hydraulic parameters discussed above, **dispersion** *D* [m^2 s^{-1}] and the **dispersivity** α [m] are also of significance. They are a measure of the mixing and distribution of fluids and therefore play a special role in particular for doublet operations with respect to heat propagation in the subsurface rock formations. Dispersion is dependent on the magnitude of the flow velocity. The range of values is therefore very large and generally between 10^{-9} m^2 s^{-1} and over 10 m^2 s^{-1}. In the case of dispersivity, most values lie between 10^{-1} m and 10^3 m.

The drawdown and recovery process or the pressure history in a production well are not only determined from the aforementioned parameters, but also significantly by the **wellbore storage** *C* [m^3 Pa^{-1}] and the **skin factor** s_F [–].

Wellbore storage is the intrinsic capacity of a well, i.e. the specific change in volume per pressure difference. The duration of wellbore storage is dependent on the diameter of the well, the transmissivity of the aquifer, as well as the skin factor (permeability in the immediate vicinity of the well). The skin factor is a measure of the change in hydraulic conductivity in the area immediately surrounding the well which can be caused by the drilling process, the casing of the well, or the operation of the well. The skin factor can vary between - ∞ and + ∞.

4.3 Physical-chemical fluid properties

The following presents the most important physical and chemical parameters for deep water relevant for geothermal wells. These parameters are essential for carrying out thermodynamic calculations as well as for determining dissolution and precipitation processes.

4.3.1 Fluid density ρ_F

Measurement unit: kg m^{-3}

Definition: Mass per volume
The density is influenced by pressure and temperature. Under normal pressure, pure water reaches its greatest density at 4 °C. It decreases with rising temperatures and increases with rising pressure. Under normal geothermal gradients, the temperature effect dominates slightly so that a decrease in density can be expected with increasing depth. However, the upwelling of hot water is usually counteracted by the decreasing permeability of the rock with depth and the increasing mineralisation of the water. Deep water can have a total dissolved solids (TDS) content of over 100 g/kg, which also causes an increase in density.

Value range: $0.8 – 1.5 \cdot 10^3$ kg m^{-3}

4.3.2 Dynamic viscosity μ, kinematic viscosity ν

Measurement unit: Pa s, or m^2 s^{-1}

Definition: The dynamic viscosity of a fluid is a measure of its resistance to shear flow. It is almost completely temperature-dependent. The variation of the dynamic viscosity of water at temperatures between 0 °C and 150 °C exceeds the variation of the density many times over. It is therefore crucially important for the flow behaviour of thermal groundwater.

Value range: $0.2 – 1.75 \cdot 10^{-3}$ Pa s

Kinematic viscosity is the ratio of dynamic viscosity to the density of the fluid:

$$\nu = \frac{\mu}{\rho_F} \quad (15)$$

4.3.3 Compressibility *c*

Measurement unit: Pa^{-1}

Definition: Volume change per pressure change with respect to the initial volume.
Compressibility is inversely proportional to pressure. It increases with temperature at temperatures above 50 °C, but decreases at temperatures below 50 °C.

Value range: $4.0 – 5.5 \cdot 10^{-10}$ Pa^{-1}

4.3.4 *pH*

Measurement unit: [–]

Definition: pH is the negative common logarithm of the hydrogen ion concentration: $pH = -\log H^+$.

In neutral solutions, there are equal concentrations of $[H^+]$ and $[OH^-]$ ions, and at room temperature they have a *pH* of 7.0. *pH* influences the solubility of many substances and their ion concentrations in water. Vice versa, substances dissolved in water frequently change the *pH*. *pH* is therefore also very important for calculations to determine whether water is saturated or oversaturated with respect to certain minerals. *pH* usually decreases with increasing temperature because the neutral point (*pH* = 7.0 at room temperature) drops to smaller values.

Value range: 5.5 – 8.0

4.3.5 E_H (redox potential), p_ε

Measurement unit: V

Definition: The reduction-oxidation (redox) potential E_H is a measure of the relative activity of oxidised and reduced substances in a system.
The solubility of various elements not only depends on *pH*, but also on their given oxidation levels in the relevant fluid or rock. In the presence of electrochemical potentials, reduction-oxidation (redox) reactions take place involving the transfer of electrons. Oxidation is generally defined as the loss of electrons, and reduction as the gain of electrons.
In a fluid which contains various oxidation levels of a substance, the redox potential is measured as an electrical potential (voltage) between an inert metal electrode and a standard reference electrode dipped into the solution. E_H applies to those redox potentials which are measured using a hydrogen electrode as the reference electrode (hydrogen is assigned a redox potential of 0 volt in this case). Most redox reactions are dependent on *pH*. E_H is temperature-dependent.

Instead of the redox potential E_H, frequent use is made of the parameter p_ε [–] as a measure of the concentration of redox-active species. p_ε is related to E_H via the following relationship:

$$p_\varepsilon = \frac{E_H}{2{,}303 \cdot R \cdot \frac{T}{F}} \quad (16)$$

where R is the universal gas constant, T the absolute temperature, and F the Faraday constant.

4.3.6 Electrical conductivity, salinity

Measurement unit: S m^{-1}
Real and potential electrolytes disassociate in aqueous solutions. This generates ions which make the solution electrically conductive. The ions have different conductivities depending on the degree of dissociation and their mobility. Electrical conductivity comprises the conductivity contributions from the individual cations and anions. The electrical conductivity therefore provides an initial indication of the total content of dissolved substances and the evaporation residues, and is therefore an easily ascertainable control parameter. The electrical conductivity is often measured in wells using a geophysical logging technique to identify the location of inflowing water with different mineralisation, where it is frequently referred to as salinity. Electrical conductivity is a temperature-dependent parameter.

4.3.7 Dissolved substances in a fluid

Measurement unit: mg/kg, or mg/l

Definition: Concentration of dissolved substances or mass per volume unit

Cations – anions
The scope of the analysis undertaken on a water sample largely depends on the aim of the investigation, the state of the scientific and practical understanding of the importance of specific parameters, and on the analytical methods which are available. Important cations are: sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn) and ammonium (NH_4). Important anions are: chloride (Cl), hydrogen carbonate and/or carbonate (HCO_3 and/or CO_3 depending on pH), sulphate (SO_4), fluoride (F), bromide (Br), iodide (I), nitrite (NO_2), nitrate (NO_3) and phosphate (PO_4). Especially for thermodynamic calculations, it is usually inadequate to restrict the information to the main cations and anions, so that trace elements such as aluminium (Al), arsenic (As), lead (Pb), mercury (Hg), barium (Ba) and strontium (Sr) also need to be analysed. DVWK Regulation 128 (1992) contains a great deal of information on sampling and the scope of the analysis.

Undissociated substances
The undissociated substances include silica (SiO_2) and boric acid/boron (B). Silicic acid can be used as a geochemical "geo-thermometer" and therefore provides important information on the temperature and depth of the "reservoir", particularly when thermal waters are involved. Boron is very rare in natural, shallow waters. The element is often used as a tracer to gather information on the origin of the water. An important source of boron is, for example, volcanic gas.

Total dissolved solids – TDS
The total dissolved solids is the sum of all dissolved cations and anions. The TDS of low mineralised water is frequently also given in mass per unit volume.

The deep waters in the Upper Rhine Graben, for instance, are highly concentrated Na-Cl fluids (around 80 – 200 g/kg), independent of the stratigraphy, and are usually also rich in CO_2. The waters in the Malm aquifer of the South German Molasse Basin usually have a very much lower degree of mineralisation although the concentration and the Na-Cl content increase towards the deepest parts of the basin. Formation fluids of Na-Cl or Ca-Na-Cl type dominate in the North German Basin and can have total dissolved solids of over 300 g/kg in some areas (Stober et al. 2014).

4.3.8 Gases, gas content of a fluid

The solubility of gases in water is gas-specific and depends on the water temperature, the pressure (or partial pressure in the case of gas mixtures) and on the total dissolved solids (TDS). The solubility of a gas λ in l/l [–] can be described by the Henry-Dalton equation:

$$\lambda = K' \cdot p \qquad (17)$$

where p is the pressure or partial pressure, and K' a temperature-dependent proportionality factor.

There are various water-gas mixtures which contain dissolved and undissolved components. Mixtures with CO_2 occur preferentially in nature, but also mixtures containing nitrogen, methane, hydrogen sulphide and other gases can be observed. The water-gas mixtures have different hydraulic properties to normal groundwater.

The solubility of gases in water changes in the presence of dissolved solids.

If a fluid comes into contact with atmospheric air, these go into equilibrium in accordance with the partial pressures of the constituents of the air in the gaseous space, and the dissolved gases. Water which is saturated under high pressure with a gas, e.g. CO_2, releases this gas continuously until equilibrium is reached with the atmosphere. This applies particularly to gases such as H_2S, H_2 and CO_2, whose partial pressures in the atmosphere are virtually zero or very low.

Considerable amounts of aragonite and/or calcite ($CaCO_3$) can be precipitated as a consequence of the reduction of free dissolved CO_2, such as after making contact with the atmospheric air, or as a result of the reduction of the fluid pressure, e.g. when thermal water is transported upwards from a great depth. To avoid contact with atmospheric air, the thermal water in geothermal wells is transported within a closed system. This closed system is also kept under pressures of approximately 20 bar. Oversaturation of the water with quartz or barite can be far more problematic. Calculating the pressure required in each case can be done theoretically using thermodynamic programs or practically with laboratory tests. Both of these methods require very precise knowledge of the hydrochemical composition of the fluid. Analysing the gases and gas concentrations in the reservoir fluid has a very high priority. A very important aspect of this is specifying the reference of the measurement units and the measuring conditions.

Fig. 20: Fluid sampling to determine the water and gas composition at the Horstberg well

5 Test Procedures and Reservoir Modelling

5.1 Hydraulic tests

5.1.1 Single well tests

Hydraulic tests are investigation methods or technologies which are carried out within a well and used to determine hydraulic parameters. The main parameters of interest are the transmissivity (Section 4.2.3) and the storage coefficient (Section 4.2.5). The transmissivity can be used to calculate the hydraulic conductivity k_f in a homogenous, isotropic aquifer, with a known aquifer thickness H (Section 4.2.2). The following describes the most important test methods for deep wells (e.g. Kruseman & de Ridder 1991, Stober 1986, Niedersächsisches Landesamt für Ökologie & Niedersächsisches Landesamt für Bodenforschung 1997, PK Tiefe Geothermie 2008).

Using deep wells for hydrothermal purposes takes place almost exclusively by exploiting solid rock aquifers. The groundwater conditions in these deep aquifers are generally confined. Only one well is usually available to carry out the test; there is no grid of monitoring wells. This is therefore a so-called single well test. Various test configurations in the well exist for this purpose (cf. Fig. 21):

→ Tests in open wells with or without packers (single or double packer)
→ Tests in cased monitoring wells

Hydraulic tests are generally not very informative if different geological horizons or aquifers are tested at the same time and no differentiation is possible. It is possible, however, to test individual horizons or beds separately by using packers, special casing programmes in the well, or by carrying out suitable geophysical well logs. This allows assigning hydraulic parameters to specific geological sections.

Hydraulic tests carried out in **open holes without a packer** (Fig. 21, left) provide information on the entire tested well section.
The hydraulic parameters determined in this way, such as hydraulic conductivity, permeability, or specific storage coefficient, are only representative of the rock mass when uniform conditions exist in the subsurface or when separate sections can be weighted on the basis of additional information such as flow meter, conductivity or temperature logs.

A test assembly is required when carrying out hydraulic tests in **open wells with packers**. This test assembly consists of a test string with a test valve and one or two packers. A packer is a 0.5-1 m long reinforced rubber sleeve whose shape can be changed by applying mechanical or hydraulic-pneumatic pressure. The purpose of the packer is to hydraulically seal off the interval to be tested by expanding the packer when set at its defined position in the well.

Single packer tests are often carried out while drilling a well if for instance inflows of formation water or mud losses indicate migration paths for water. The test rod with a single packer is then set at the desired depth to seal off the test interval between the packer and the bottom of the borehole against the annular space above the packer (Fig. 21, centre).

A **double packer test** is normally carried out after drilling a longer section of the well. The test rod is equipped with two packers which can isolate and test a specific interval within the well with a height of approximately 1.5-5 m. This test involves measuring the temperature and pressure in the test interval, as well as above and below the interval depending on the specific type of test assembly (Fig. 21, right).

The use of packers for **tests in cased monitoring wells** only makes sense if the packers are installed in an interval with seals built-in behind the casing. By this hydraulic isolation selected test intervals can be examined separately.

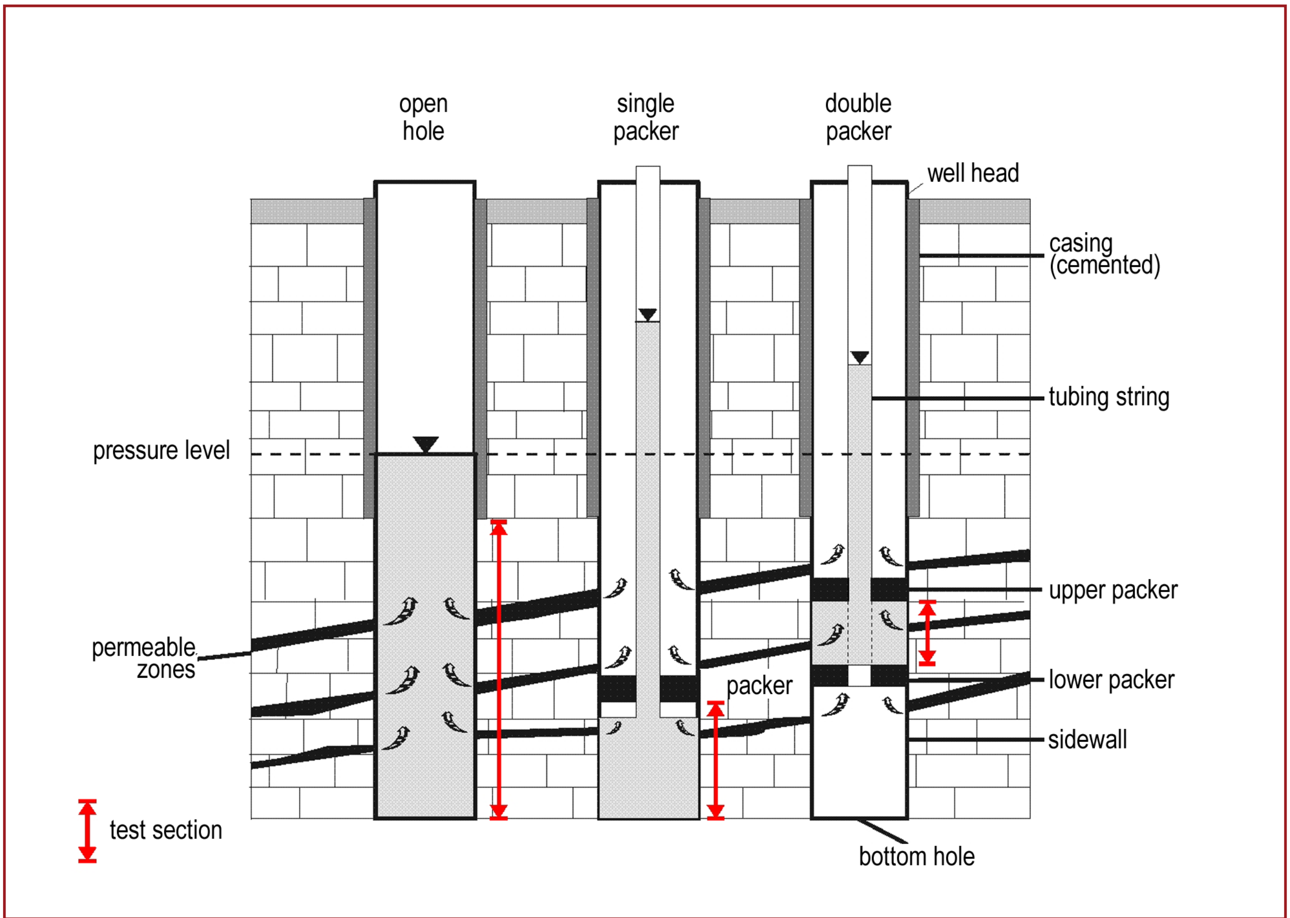

Fig. 21: Different methods for carrying out hydraulic tests in boreholes (after: Niedersächsisches Landesamt für Ökologie & Niedersächsisches Landesamt für Bodenforschung 1997)

5.1.2 Test principle

The test principle is the same for all hydraulic tests in wells: the initial pressure measured in the test interval (or aquifer) serves as the reference pressure or static water level. When carrying out tests with packers, this initial pressure is measured after setting the packer. This is followed by a so-called compliance period during which external disturbances in deep wells return to normal (exception: tidal effects).

In the first test step, the initial pressure in the test interval is artificially changed by producing or injecting water (in dense rocks: gas). Withdrawal of water causes the pressure to drop while injection increases the pressure. The withdrawal or injection is stopped in the second test step, and the pressure recovery to the formation pressure (the undisturbed rock pressure) is monitored. The initial and the formation pressure should be identical.

The test analysis is based on the temporal change of the flow rates and pressure (non-steady state). The longer the hydraulic test period, the larger the amount of three-dimensional space measured by the pressure signal, and the larger the chance of gaining undisturbed measurements beyond the immediate vicinity of the disturbed zone around the well (skin), because zones very close to the wellbore can be affected by the drilling process or the casing of the well. Tests in large diameter boreholes or in aquitards are additionally strongly influenced during the initial phase by the intrinsic capacity of the wellbore (wellbore storage). Nevertheless, tests in deep wells are often carried out for the shortest possible period for financial reasons. If the individual test periods or test steps are too short, it will not be possible to draw any conclusions on zones further away from the wellbore, e.g. conclusions on the aquifer parameters or boundaries.

The classic pump and injection tests preferentially carried out in thermal water wells are characterised by very long withdrawal or injection periods and therefore have a very high test quality.

If measuring the water level (or a pressure considerably above the test horizon) instead of the initial pressure, then the measured water level must be corrected for thermal influences in deep wells. Because the density of water is temperature-dependent, water columns of the same weight have different lengths at different temperatures. Although the density variation is very minor, the effect can lead to a difference in length of some meters for water columns with an extent of several hundred meters. In case of a non-operating state, the water temperature in a well will go into equilibrium with the formation temperature. When water is withdrawn from a well, the warm water from the deeper parts flows quickly upwards which results in warming up the whole water column. As a result, the water level at the beginning of a pumping test can initially rise instead of fall because of these temperature-related changes in density. When carrying out the analysis, it is therefore necessary to convert the drawdown or the length of the water column for a defined temperature, which means that a density correction of the water column has to be carried out for every measured value (Stober 1986).

5.1.3 Test procedures

There are a large number of hydraulic test procedures. The aim of the tests and particularly the expected hydraulic conductivity play important roles in selecting the most suitable method. Figure 22 schematically shows the areas of application of the different tests depending on the hydraulic conductivity.

Pumping test, injection test

According to DVGW Regulation W 111 (1997), a **pumping test** is a relatively complex controllable field experiment in which groundwater is produced from one or more wells. The objective of pumping tests is to determine the capacity of the well(s) or the potential production capacity of a test interval in the well, to determine the hydraulic properties of the aquifer and the neighbouring rocks in situ, as well as to measure the properties of the groundwater. The influence of defined boundary conditions can be taken into consideration when evaluating pumping tests.

An **injection test** is in principle the reverse of a pumping test because water in this case is injected into the rock instead of being withdrawn from the rock.

Tests with constant flow rates or with constant pressures are both special types of pumping tests or injection tests. Tests carried out with constant rates (aquifer tests) provide by far the widest range of information (Stober 1986), because in this case, a large number of different evaluation methods exist depending on the defined flow model (type curve methods, analytical and numerical evaluation methods, approximate solutions).

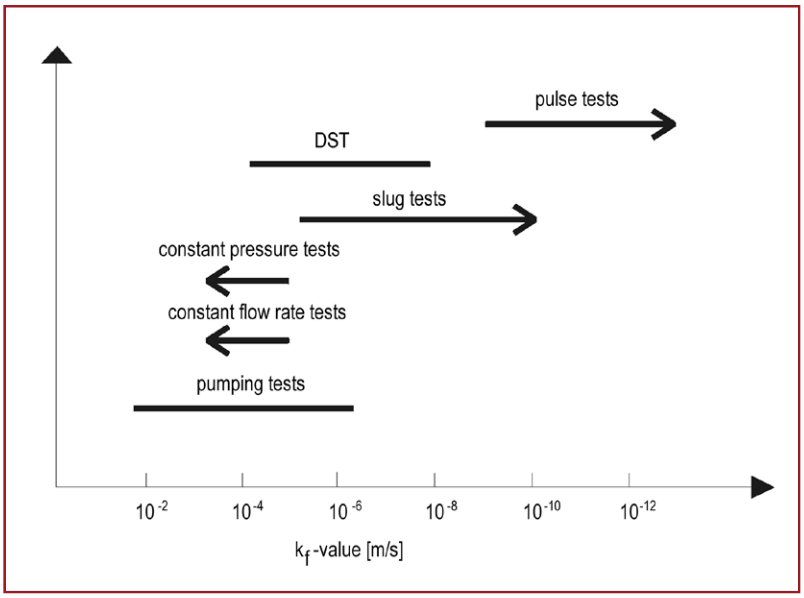

Fig. 22: Application ranges of various hydraulic test methods depending on the hydraulic conductivity (after: Niedersächsisches Landesamt für Ökologie & Niedersächsisches Landesamt für Bodenforschung 1997)

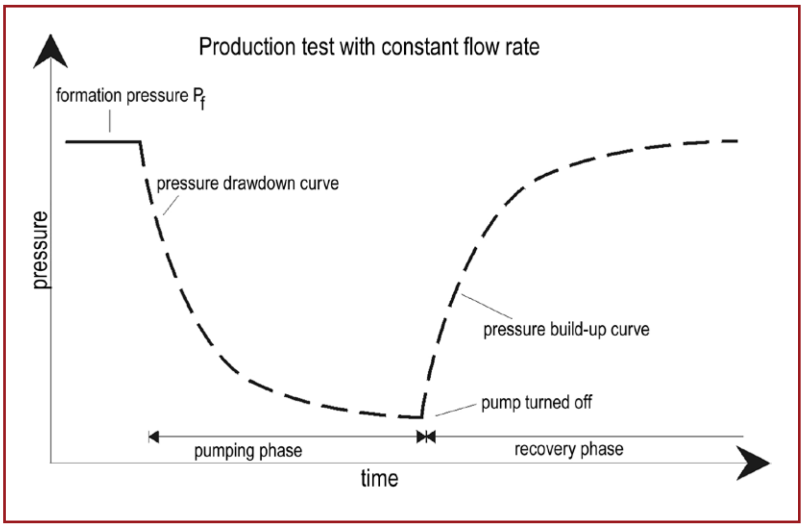

Fig. 23: Typical pressure response from a production test (after: Niedersächsisches Landesamt für Ökologie & Niedersächsisches Landesamt für Bodenforschung 1997)

Slug test
The slug test is used in the case of low to medium rock permeability. It helps to measure the transmissivity from which the permeability and the hydraulic conductivity can be derived, as well as to determine the storage coefficient and the skin factor (e.g. Cooper et al. 1967, Ramey et al. 1975).

In this hydraulic test, the pressure in the wellbore or test interval is changed abruptly followed by a measurement of the subsequent pressure built-up or pressure decrease. When the test valve is opened, the pressure change is transferred very rapidly to the test interval. During the subsequent flow phase, pressure compensation takes place during which water either flows into the well (slug withdrawal test) or into the rock (slug injection test; Fig. 24) depending on the pressure gradient involved.

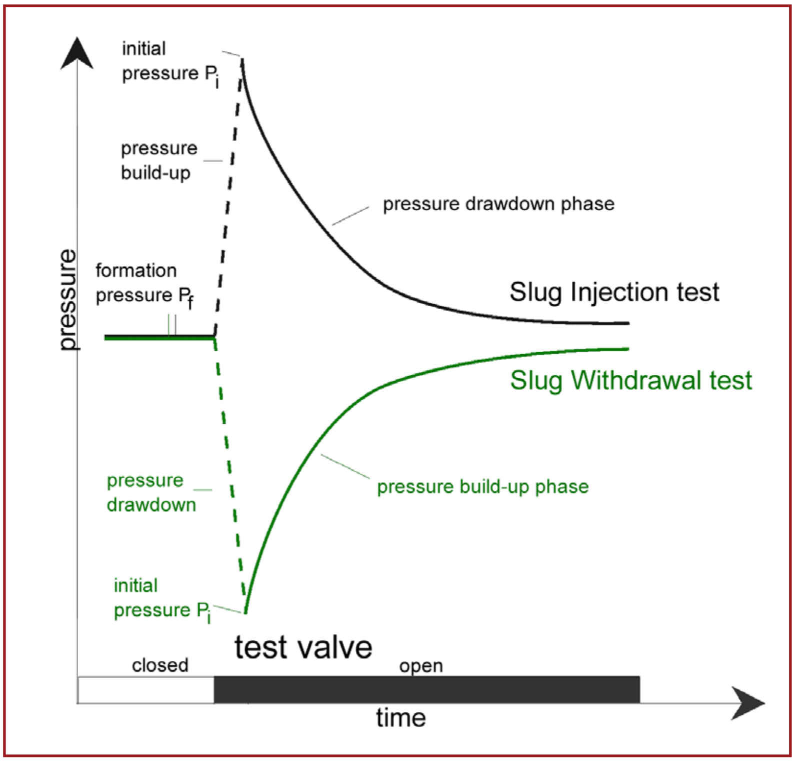

Fig. 24: Typical pressure response during a slug test (after: Niedersächsisches Landesamt für Ökologie & Niedersächsisches Landesamt für Bodenforschung 1997)

Slug/bail test
In a similar way to the slug test, the principle of the slug/bail test is a sudden change in pressure. Unlike the slug test, the change in pressure is not generated by injecting or withdrawing water, but by submerging and retrieving a displacement body. Evaluations of this test can be carried out using e.g. the type curve methods from Hvorslev (1951), Papadopulos et al. (1973) or Cooper et al. (1967). There are also numerical evaluation methods.

Pulse test
The pulse test is performed to determine the transmissivity, storage coefficient and skin factor, and is used in rocks with very low to low permeabilities. If an appropriate packer system is used, this method can also be applied to investigate the hydraulic conductivity of specific zones within the rock mass. During the pulse test, a pressure change is created in the test interval in the same way as during the slug test (with the same test equipment). In the pulse test, the test valve is only opened for a very short period of time and then closed again immediately. This is followed by monitoring the pressure compensation in the test interval until reaching the formation pressure.

Drill stem test (DST)

The drill stem test (DST) can be used to determine the permeability, wellbore storage and the skin factor. The name drill stem test is derived from the synonym for the drilling string, namely a drill stem.

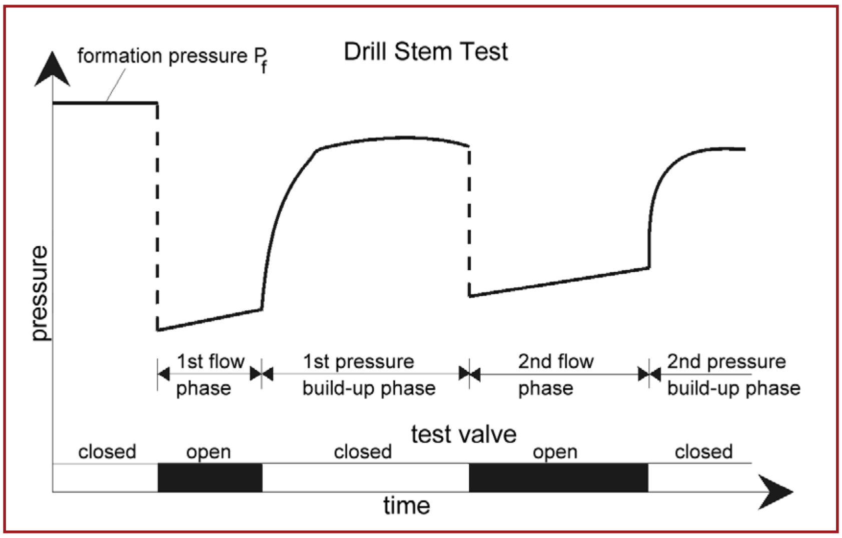

Fig. 25: Typical pressure response during a drill stem test (after: Niedersächsisches Landesamt für Ökologie & Niedersächsisches Landesamt für Bodenforschung 1997)

As shown in figure 25, the DST is divided into an initial short flow period, an initial shut-in phase, a second long flow period and a second long shut-in phase. Opening the valve creates a negative pressure within the test zone causing the fluid to flow out of the rock formation into the wellbore. During the shut-in phase (valve closed) the pressure builds up again reaching the formation pressure if possible. The valve is opened again for a longer flow period and the procedure is repeated. Pressure measurement devices are used to measure the relevant flow and shut-in pressures over a longer period of time. Because any temperature fluctuations that occur during the test can have a strong impact on the change in pressure, it is also necessary to record the temperature in addition to the pressure to enable corrections to be undertaken during evaluation. The time required to carry out the DST depends on the transmissivity and integrity of the rock mass.

If a stationary flow state is achieved, the evaluation can also make use of the method from Horner (1951) for example; the type curve method for instance from Gringarten et al. (1979) can be used for the evaluation of pressure curves at a transient state. There are also type curves for a number of possible subsurface models. In addition, numerical methods are used for the evaluation.

Interference test

Several monitoring wells are required to carry out an interference test because this enables the hydraulic contact between different wells to be determined, as well as the size and shape of the cone of depression, and the transmissivity distribution within the vicinity of the well.

5.2 Reservoir modelling

The spatial extent of a geothermal reservoir plays an important role in geothermal utilisation. The volume and therefore the energy content of the reservoir can be calculated from the geometrical shape of the reservoir, i.e. from the horizontal dimension and its thickness. A reservoir with the same hydraulic conductivity but a greater thickness has a higher transmissivity and therefore also a higher potential production rate.

A subsurface geometrical model is built up on the basis of data from geophysical exploration activities – mostly in the form of seismic surveys, and more rarely in the form of geoelectric surveys – as well as the results from wells. If available, data from hydrocarbon exploration can be used, supplemented by specific investigations for geothermal projects. Wells provide information on the subsurface geology along one trajectory, whereas 2D seismic sections provide information in the form of (vertical) cross sections of the underground. Only 3D seismic can provide a spatial model of the subsurface geology.

The raw seismic data has to be processed using complex mathematical techniques in order to obtain depth information from time information („processing“; a detailed description can be found in Hartmann et al. 2015). Based on this evaluation the geological interpretation has to be carried out in consideration of geothermal issues. The aim is then to create a three-dimensional geological structural model based on the usually irregularly distributed 1D well information, and the 2D seismic information. The three-dimensional geological model produced in this way shows the bedding of the different geological horizons and their thickness.

The structural model and the hydrostratigraphic data are then used as the basis for developing a thermo-hydraulic model concept which forms the initial basis for the hydrogeological model. This involves in particular converting the lithostratigraphic units in the 3D structural model into hydrostratigraphic units and assigning hydraulic parameters to these hydrostratigraphic units. In addition, the appropriate thermophysical parameters have to be assigned to the individual horizons.

The (simplified) hydrogeological model then forms the basis for the numerical modelling of the heat and mass transport. A stationary groundwater flow model is then developed making assumptions about the geohydraulic boundary conditions and any groundwater recharge and deep water upwelling which may be involved. In the course of stationary calibration, the geohydraulic aquifer parameters and boundary conditions must be adjusted within the numerical groundwater flow model to achieve the best possible match between the measured and the calculated potential values and potential distributions, as well as to achieve a plausible groundwater balance. Parameter variations should only be made within a plausible range of values. However, this calibration is usually associated with considerable uncertainties because of the small number of data points.

The stationary calibrated groundwater flow model is then used to model the natural temperature field, although the natural convection is usually not taken into consideration in this strongly simplified model due to the usually small database. Then it is possible to start with numerical simulations of geothermal operations with one or more doublets.

It is obvious that the simulation results are strongly dependent on the density and quality of the measured hydraulic and thermal parameters. The modelling scale also plays an important role in the accuracy of the model.

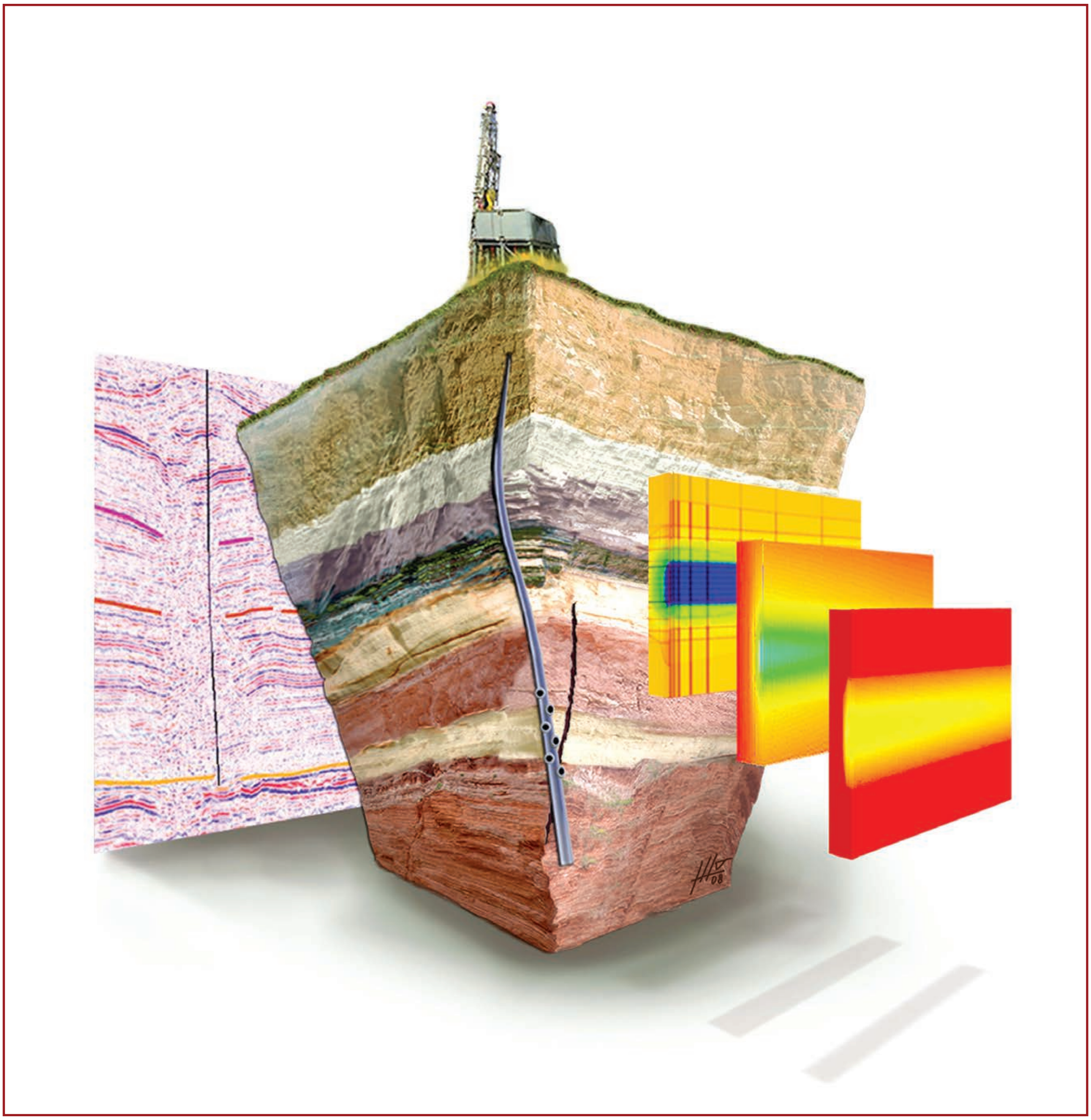

Fig. 26: Subsurface model

6 Geothermal Information System

Access to geological and geophysical data is one of the most important prerequisites for planning geothermal projects. The research and compilation of relevant data and maps can be very time-consuming and cost-intensive. However, it is a necessary step in the assessment of the geologic setting, subsurface temperature and chemical fluid composition as well as in estimating production and injection rates. The more data are accumulated over time, the lower is the exploration risk.

Experiences from adjacent geothermal facilities, data from deep wells and seismic surveys close by the planned location are most valuable for the planning of geothermal projects. In Germany, the bulk of relevant data is related to oil and natural gas exploration and owned by the licence holder. Taking advantage of these data for geothermal activities requires an official agreement with the owners of the data. According to the Federal Mining Act and the Exploration Law licence holders are obliged to deliver particular exploration results – formatted in an appropriate way – to the competent authority (geological survey or mining agency), which are however bound to secrecy. It is a German peculiarity that the protection of these proprietary rights is not limited in time and does not expire after a period of 3 to 10 years like in most other European countries. Project planners must contact data owners on any account to use the desired data.

Today, the bulk of data required for a preliminary study of a geothermal project can be obtained from free public sources. The main source of free geoscientific data related to deep geothermal energy is the geothermal information system GeotIS (Agemar et al. 2014). It provides plentiful geological and geophysical data of German regions with geothermal potentials at great depths. GeotIS is equipped with a graphical user interface and can be accessed online at http://www.geotis.de (Fig. 27). Users can create interactively cross sections and maps with faults, depth contours, distribution range, and temperature field of target formations. It is possible to point on maps and cross sections to obtain temperature predictions including the expected uncertainty range.

The subsurface temperature estimates are based on a 3D geostatistical model which extends from the surface to a depth of 5 km below sea level and has been calculated for a grid resolution of 2 km lateral and 0.1 km vertical (Agemar et al. 2012). Besides the display of geological structures and subsurface temperatures, many other parameters can be retrieved like for instance hydraulic conductivity and facies of target formations. The hydraulic conductivity has been mapped as transmissivity divided by aquifer thickness (T/H).

Maps of the karstified Malm aquifer in the South German Molasse Basin were derived from hydraulic tests in wellbores and facies distribution (Birner et al. 2014, Stober et al. 2013). The maps for North-East Germany are based on core analysis and hydraulic tests as well. Hydraulic conductivity data were also determined for individual geothermal target horizons of the Upper Rhine Graben (Stober & Bucher 2014). The generalised maps of hydrothermal and petrothermal potential presented in the "Atlas to visualise potential conflicts of interest between CO_2 storage (CCS) and deep geothermal energy" (Suchi et al. 2014) are also part of GeotIS.

Statistical information on geothermal power generation and direct use as well as operating data of individual installations supplement the offer of information on the website. It is possible to select sites according to the location or technical specifications such as type of use or output parameters. Geothermal production data are updated annually and users can plot them for all or a number of sites for any period of time. First records date back to 2003 for geothermal power production and to 1999 for direct use. Examples for geothermal installations are described in chapter 8.

There are also map layers available showing the location of 2D/3D seismics and deep wells. The dissemination of further information, like for instance well logs or core analysis, is prohibited by the Federal Mining Act.

Additional offers of information and research tools are provided by the state geological surveys. Planning guidelines, geothermal maps, well locations and other information relevant for project developers can be found on the websites of these state authorities. Many federal states of Germany formed the Hydrocarbon Geology Alliance coordinated by the State Authority of Mining, Energy and Geology of Lower Saxony (LBEG) in Hanover. The LBEG is responsible for the collection, processing and documentation of industrial exploration, production and storage data as well as for archiving these data in data bases and for the maintenance of the Hydrocarbons Information System (KW-FIS). The map server of the LBEG offers metadata on deep wells, reflection seismic, and gravity measurements. Seismic profiles, for instance, can be inspected at the corresponding geological survey or at the LBEG. However, data owners will not grant project developers the right to use the data until charges are paid.

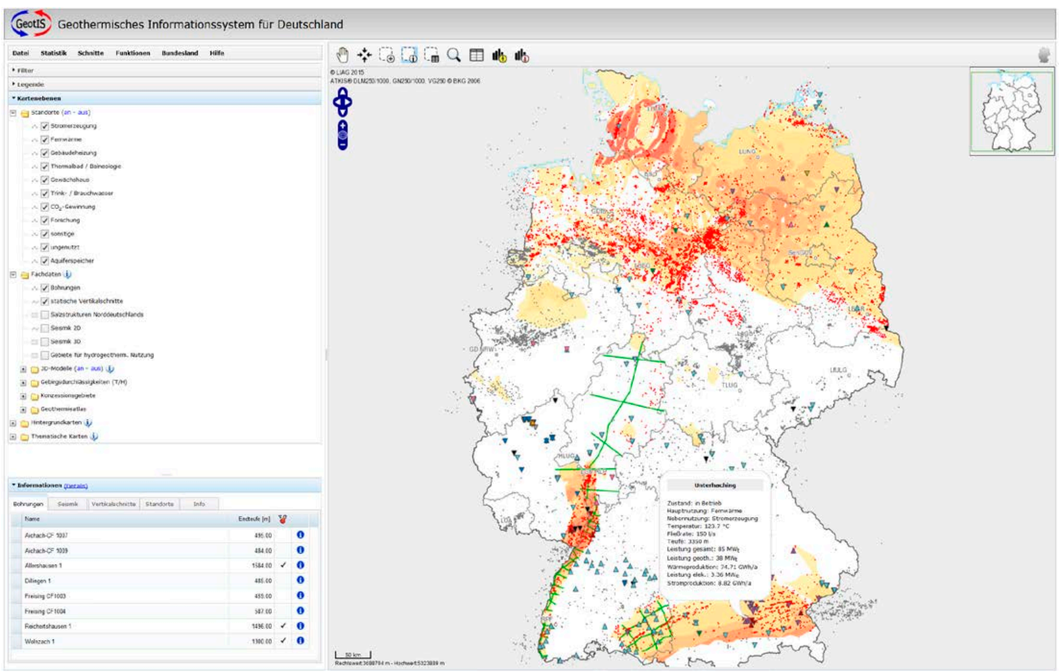

Fig. 27: Screenshot of GeotIS. The geothermal information system offers information on geothermal installations in Germany and comprehensive data for estimating regional potentials of deep geothermal energy.

7 Areas for Hydrothermal Utilisation in Germany

The most important regions in Germany with respect to hydrothermal utilisation are the North German Basin, the Upper Rhine Graben and the South German Molasse Basin (Fig. 28). The hot water of deep subsurface reservoirs in these regions can be used directly for heating purposes at temperatures above 60 °C. In addition, temperatures exceeding 100 °C allow the generation of power suitable for base load supply. The seasonal subsurface storage of excess heat and subsequent extraction can be realised in further regions.

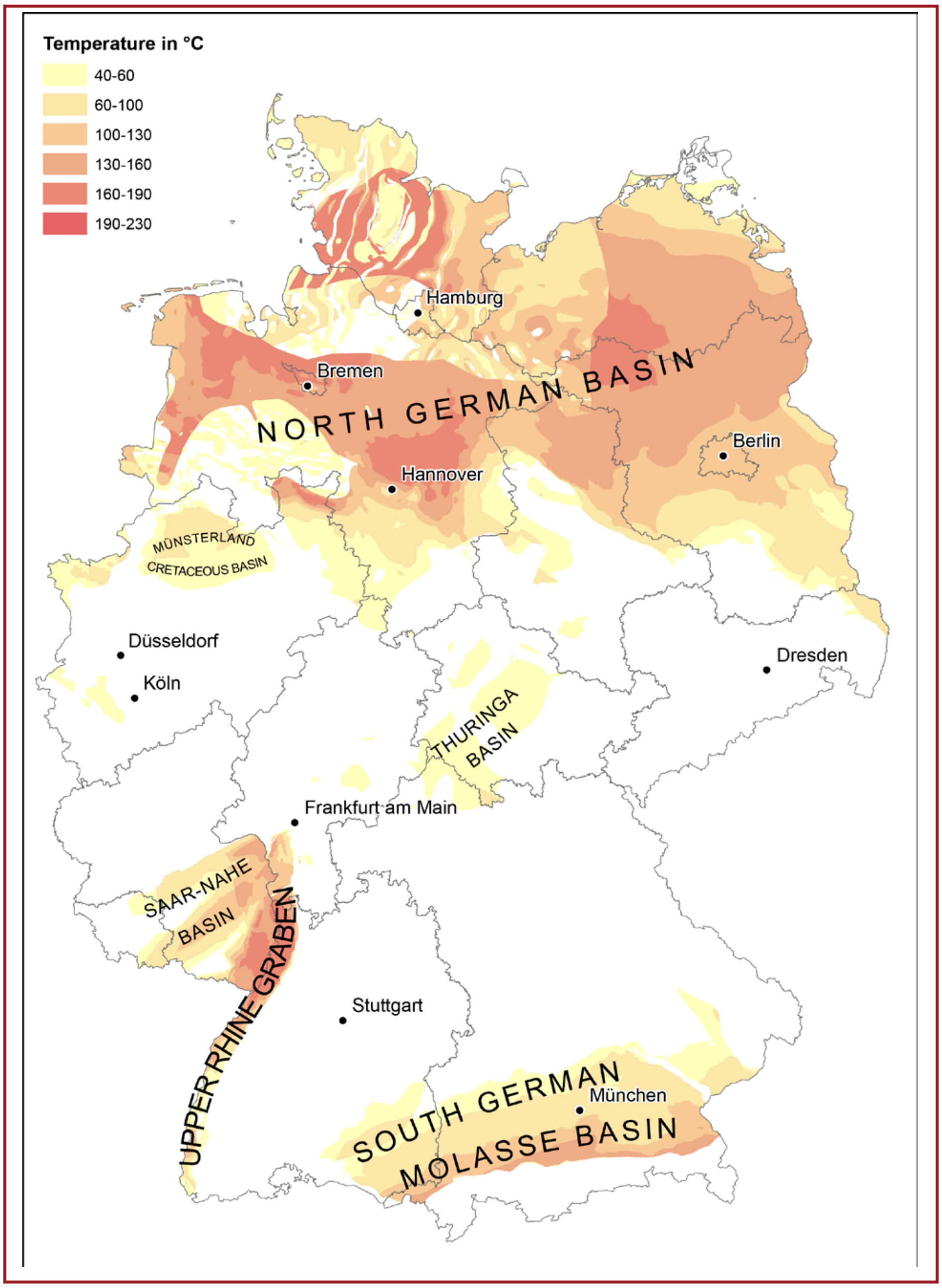

Fig. 28: Overview of regions in Germany considered suitable for hydrothermal utilisation and associated temperature ranges (map adapted from Suchi et al. 2014). The most important regions are the North German Basin, the Upper Rhine Graben and the South German Molasse Basin.

7.1 North German Basin (eastern part)

In the eastern part of the North German Basin, best reservoirs for geothermal utilisation include the sandstones of the Rhaetian/Lias, Middle Jurassic, Lower Cretaceous and Middle Bunter. The sandstones of the Rotliegend and the Schilfsandstein formation of the Middle Keuper may be considered as geothermal aquifers as well due to their distribution, porosity and temperature, but to a minor degree (Katzung 1984, Feldrappe et al. 2008, Obst et al. 2009; Fig. 29).

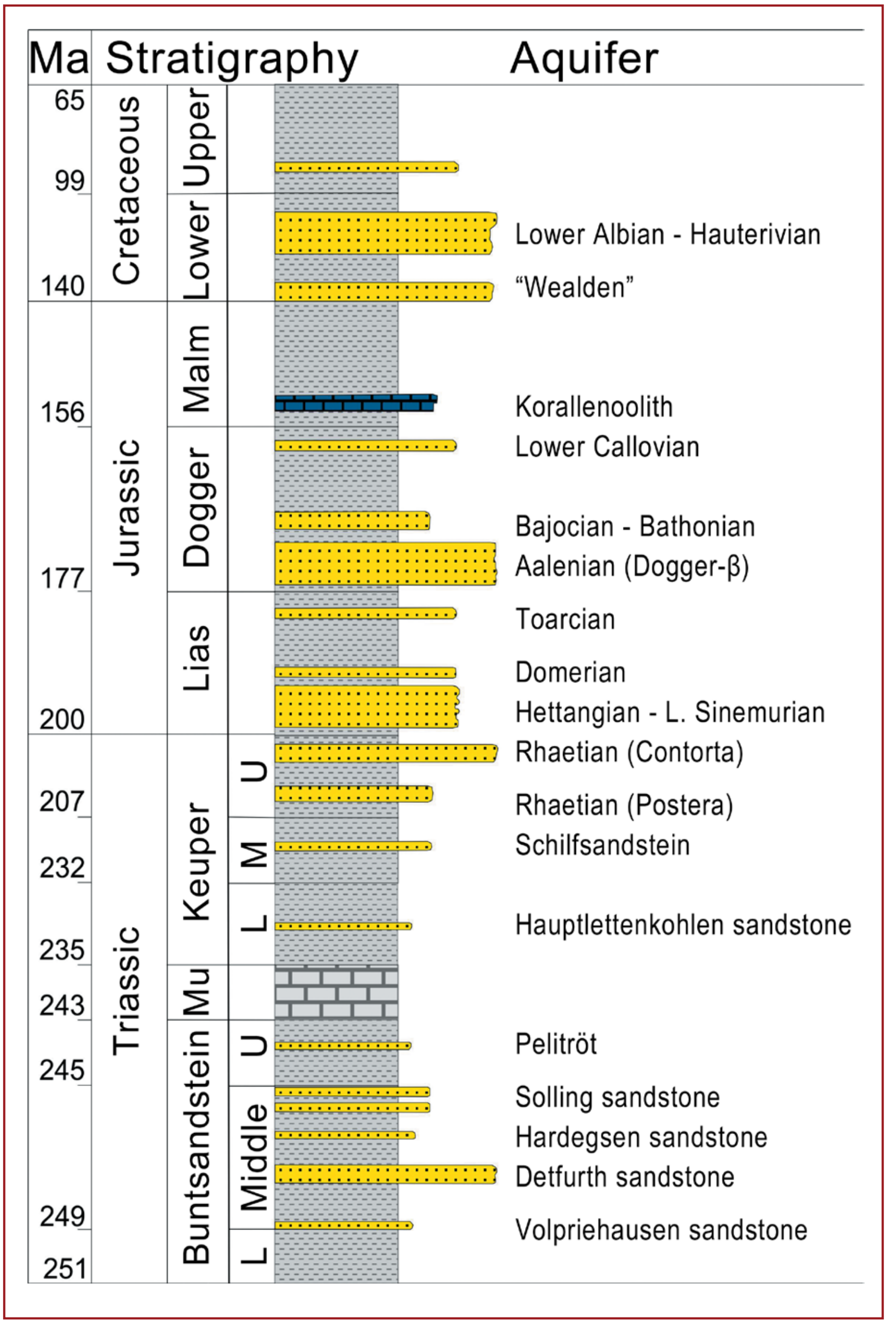

Fig. 29: Mesozoic sandstone aquifers (yellow) in the North German Basin (Wolfgramm et al. 2004, Feldrappe et al. 2008)

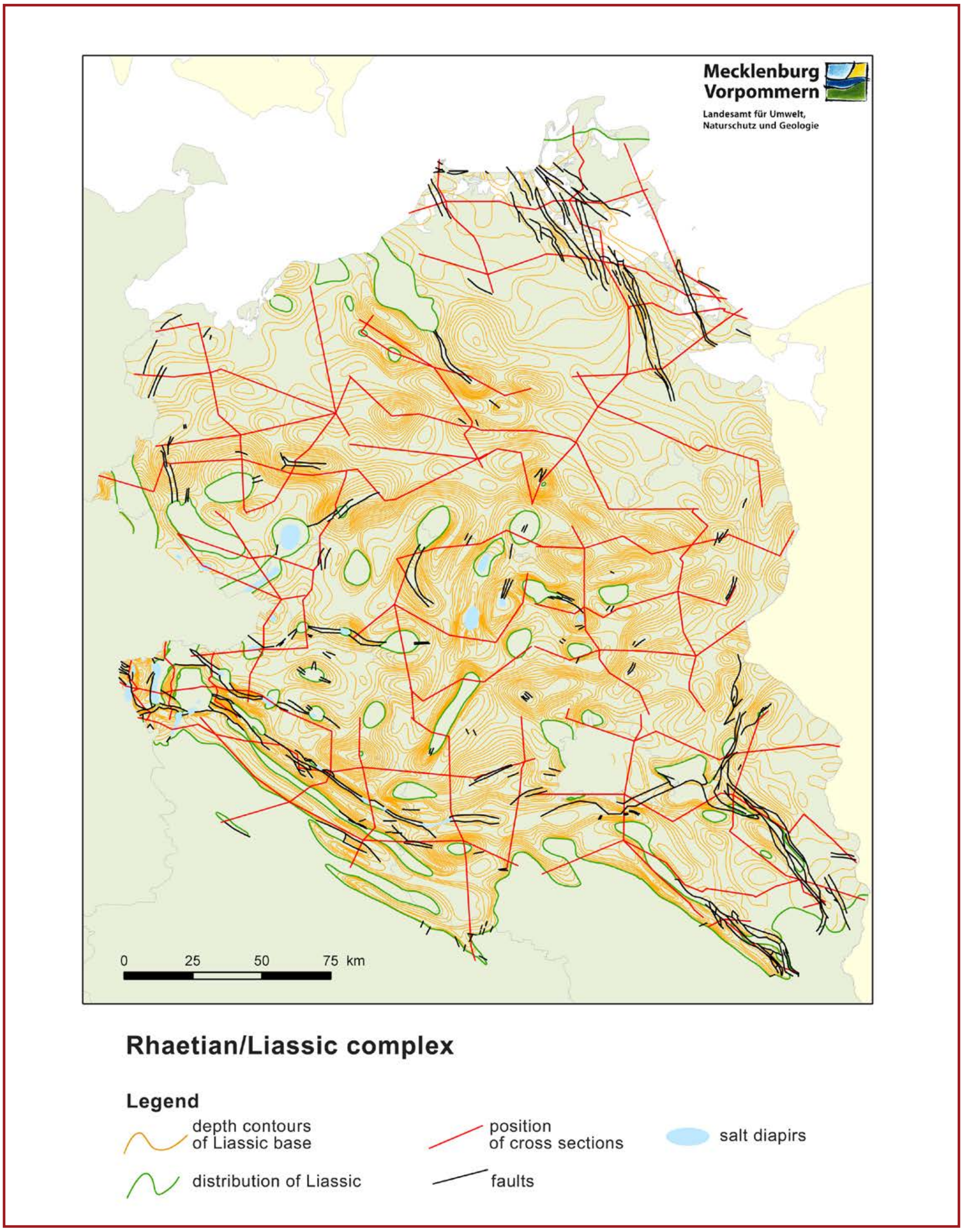

Fig. 30: Distribution and depth of aquifers in the Rhaetian/Lias complex in northeast Germany. The figure also shows the most important faults and salt structures, as well as the position of cross sections (red) (Obst et al. 2009).

With only a few local exceptions, the Rhaetian/Lias aquifer complex is distributed across the whole of the eastern part of the North German Basin (Fig. 30). Sandstone aquifers in the Rhaetian are found in the Postera, Contorta and Triletes beds. Usually they reach a thickness of more than 10 m. Horizons used for geothermal heat production in Mecklenburg-Vorpommern are the sandstones of the Upper Postera beds and the Contorta beds. The poorly cemented sandstones have porosities of 25 - 30 %, permeabilities of 500 - 1,000 mD, and productivities of 50 - 150 m^3 h^{-1} MPa^{-1}. The properties of the Lias sandstones (Hettangian, Sinemurian, Pliensbachian) are comparable to those of the Rhaetian. The Middle Jurassic sediments in the North German Basin show a complex setting. Sandstones can be found in the Aalenian as well as in the younger strata of the Bajocian/Bathonian and the Lower Callovian.

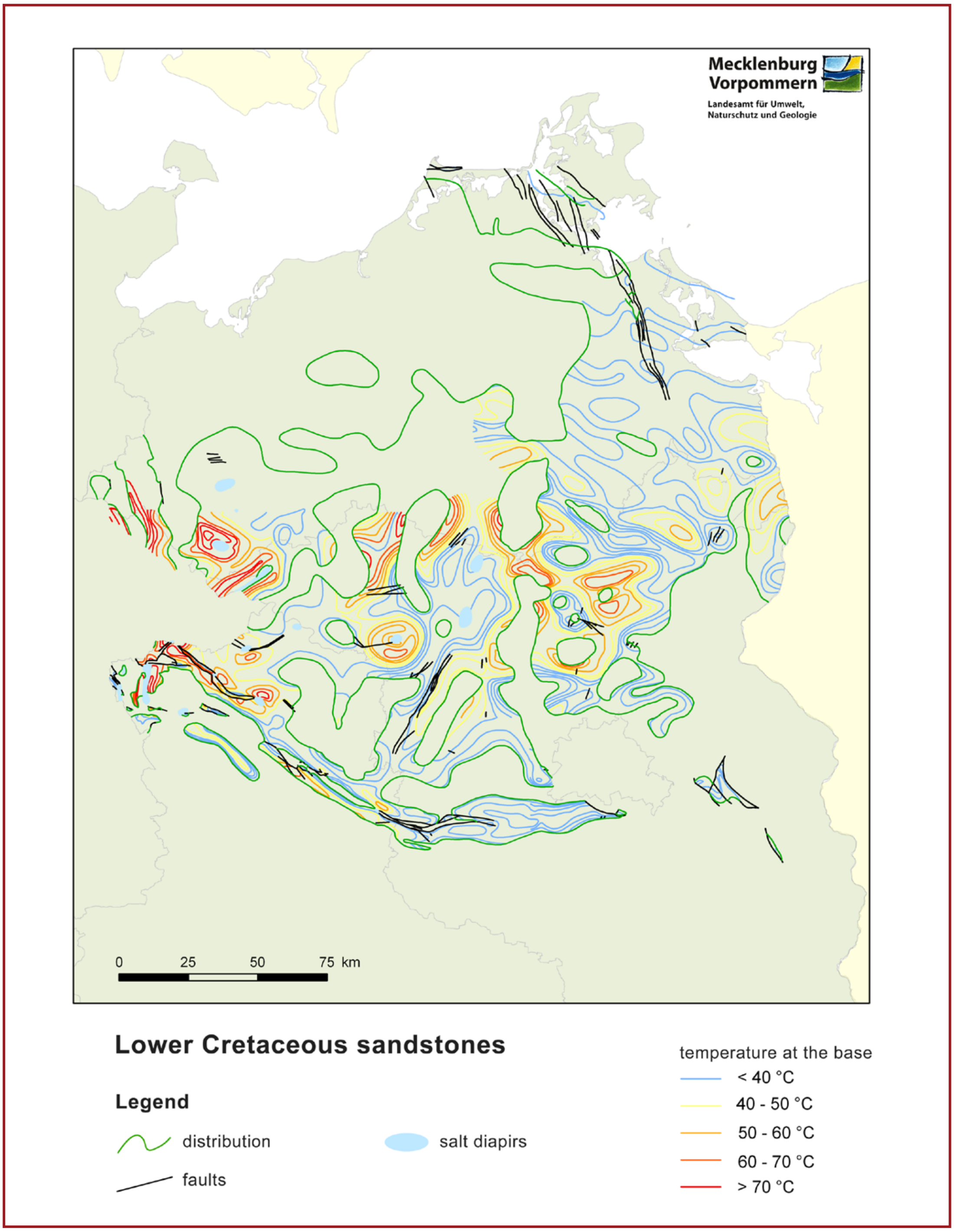

Fig. 31: Regional temperature distribution in the sandstones of the North German Basin (in this case, the Lower Cretaceous) (Obst & Brandes 2011).

The Aalenian sandstones form aquifers with outstanding storage properties with estimated productivities of 150 to 300 $m^3\ h^{-1}\ MPa^{-1}$. The Lower Cretaceous sandstones are widely distributed as well (Fig. 31) and show porosities of around 30 % (25 - 37 %) and permeabilities averaging 250 mD, allowing productivities of more than 100 $m^3\ h^{-1}\ MPa^{-1}$. The aquifers of the Middle Bunter show good reservoir properties near the Baltic Sea coast – in other words, at the northern edge of the basin – where they have porosities of generally more than 20 %. Analogies with the productivities of the geothermal wells in Stralsund and Karlshagen indicate that the Detfurth sandstone for example could have productivities of about 100 $m^3\ h^{-1}\ MPa^{-1}$. The Schilfsandstein (in particular the channel facies) of the Middle Keuper, as well as the Rotliegend sandstones, could only be utilised locally as geothermal aquifers.

The following stratigraphic horizons in the North German Basin were prepared for GeotIS (Section 6):

→ Lower Cretaceous
→ Middle Jurassic (Aalenian sandstone)
→ Lias
→ Rhaetian
→ Middle Keuper
→ Middle Bunter

Information about other, only locally or regionally developed aquifers (e.g., Lower Keuper, Toarcian, Bajocian/Bathonian, and Callovian) are not yet included.

An additional database, set up for north-eastern Germany, provides point-related information from over 1,640 wells that can be used for detailed investigations. Beside the header data of the wells, the stratigraphic data of the horizons relevant for geothermal applications are of particular interest for potential investors. Therefore, additional tables with information about the depth of the bases of the stratigraphic units, as well as the number and total thickness of the corresponding sandstone horizons (more than 8,000 data sets) were generated by data queries. Details on porosity and permeability were also incorporated. However, they are only available for approximately 1,300 and 600 data sets, respectively.

Deep geothermal projects realised so far in north-eastern Germany include the geothermal heating plants in Waren, Neubrandenburg and Neustadt-Glewe (Fig. 32) which exploit the sandstones of the Rhaetian/Lias aquifer complex. Their operating parameters have been documented and are updated on an annual basis (see Section 8.1).

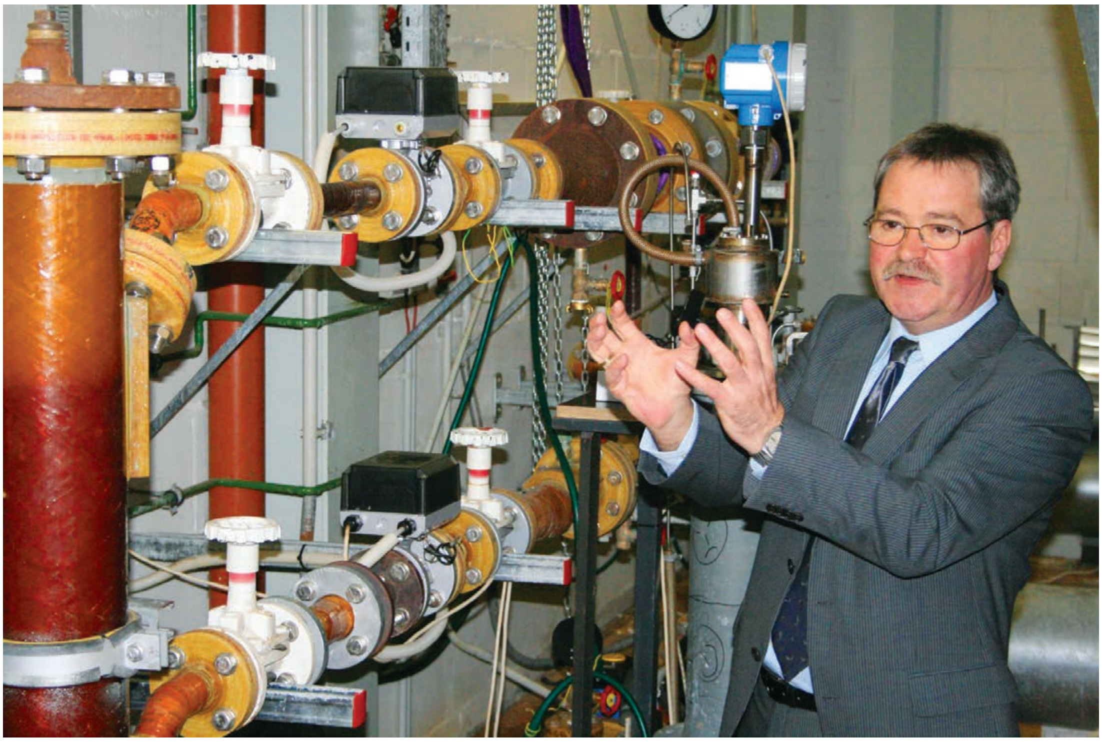

Fig. 32: Inside the Geothermal Heating Plant in Neustadt-Glewe

7.2 Upper Rhine Graben

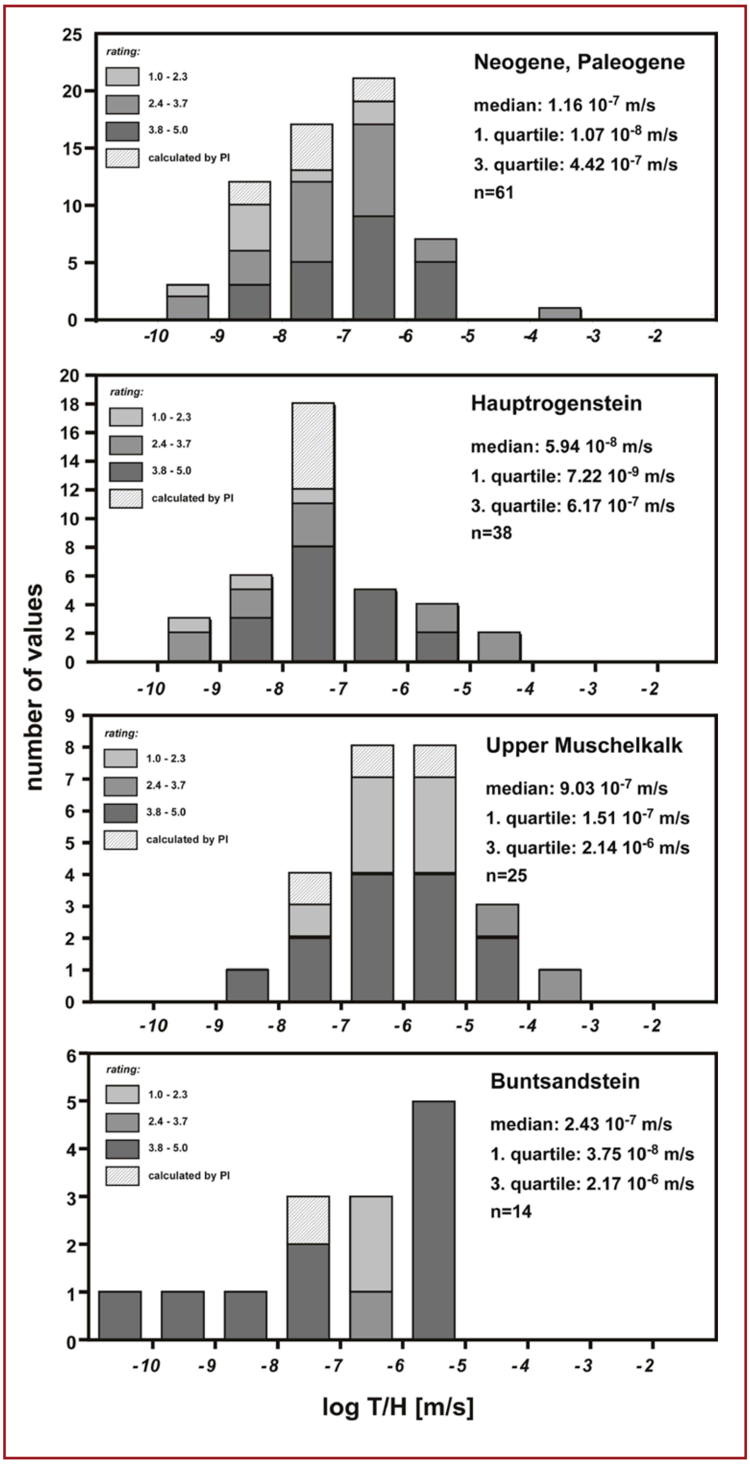

Fig. 33: Distribution of the hydraulic conductivity in the Upper Muschelkalk, Bunter, Hauptrogenstein and the deep Neogene and Paleogene sequence (Tertiary) in the Upper Rhine Graben (Stober & Bucher 2014)

Potential hydrothermal target horizons in the Upper Rhine Graben are primarily the geological formations of the Upper Muschelkalk and the Bunter. Other formations of interest are the Hauptrogenstein (Middle Jurassic; formerly Dogger) in the southern part of the graben between Kehl and Basel and the sand rich beds of the, in geological terms, relatively young Neogene-Paleogene sequence in the northern part of the graben.

The initial GeotIS project included the systematic collection, evaluation, and conductivity estimation of all hydraulic test data from deep wells drilled by the oil and gas industry, as well as from drinking water and geothermal wells on the German and French side of the Upper Rhine Graben. This data inventory has been extended by now. Figure 33 shows the distribution of the hydraulic conductivity (T/H) of potential target horizons in the Upper Rhine Graben.

The values show a log-normal distribution with a median of $T/H = 5.9 \cdot 10^{-8}$ m/s for the Hauptrogenstein and a significantly higher median of $T/H = 9.0 \cdot 10^{-7}$ m/s for the Upper Muschelkalk.

The Bunter and the Neogene-Paleogene sequence show intermediate hydraulic conductivity values with medians of $2.4 \cdot 10^{-7}$ m/s and $1.2 \cdot 10^{-7}$ m/s, respectively.

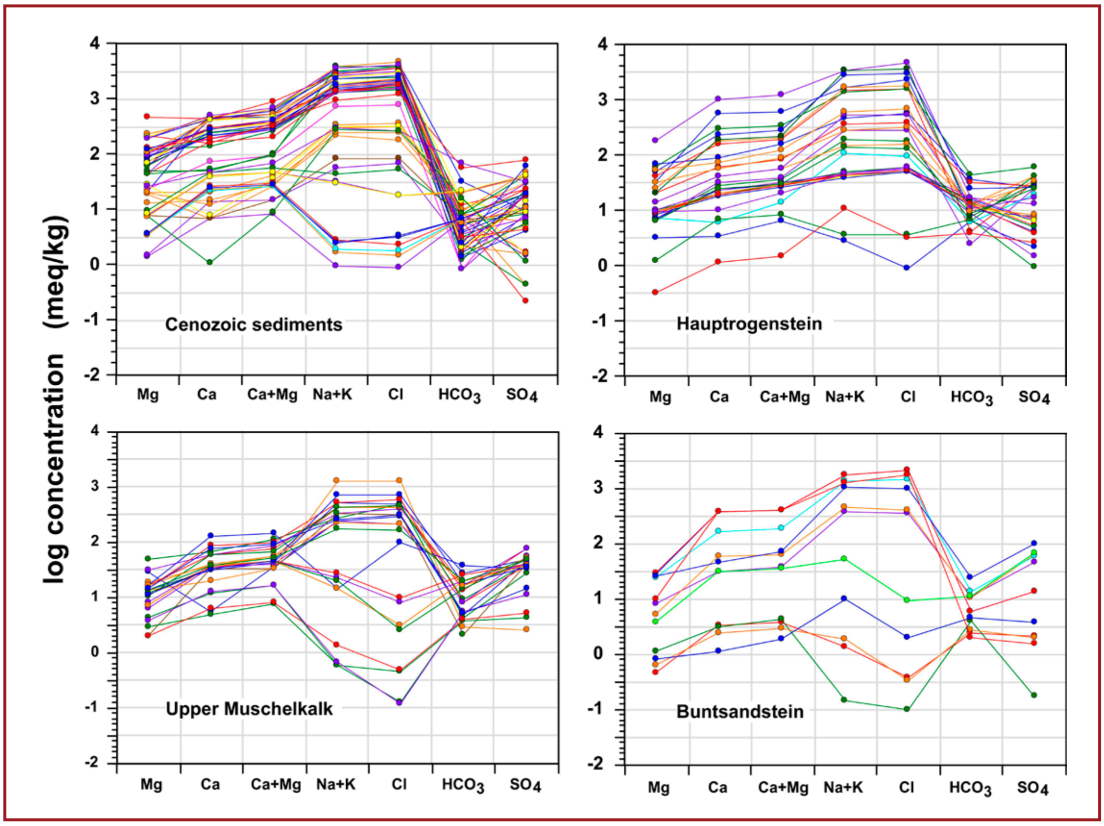

Fig. 34: Hydrochemical properties of waters from potential target horizons in the Upper Rhine Graben (Schoeller diagram) (Stober & Bucher 2014)

Deep waters in the Upper Rhine Graben have very high salt contents and are rich in sodium chloride. Figure 34 shows the main constituents as Schoeller diagrams. The total dissolved solids (TDS) as a sum parameter of all constituents dissolved in the water varies widely in the different target horizons and can be in the order of a few tens g/kg (for comparison: seawater has TDS of about 35 g/kg). TDS commonly increases with the depth of the aquifer. Waters generally have TDS above 10 g/kg at a depth of more than 1,000 m below surface. The highest concentrations were measured in waters from the Hauptrogenstein and the Cenozoic beds (Tertiary).

The Schoeller diagrams (Fig. 34) also highlight the existence of two different water types in each aquifer. Waters with a lower mineralisation are found in shallower depth and therefore near the border of the graben. These waters are characterised by intense water-rock interactions. The deep lying waters are located in the inner graben zone. They show a high level of mineralisation and contain high concentrations of sodium and chloride regardless of the host aquifer. The high Na-Cl contents are attributed to deep circulation systems extending across stratification.

Currently, two largely independently acting circulation systems are considered. Most deep waters of the Bunter are related to upwelling of sodium and chloride rich waters from the crystalline basement. Upwelling waters also control the hydrochemical properties of the deep waters of the Upper Muschelkalk, partly directly, partly indirectly via salt deposition which occurs in some areas of the underlying Middle Muschelkalk. The second circulation system encompasses the Hauptrogenstein and the Cenozoic sequence (Tertiary) where high Na- and Cl-concentrations in the Hauptrogenstein are most likely related to salt deposits of the Cenozoic sequence (Stober et al. 2014, Stober & Bucher 2014, Stober et al. 2013).

Reflection seismic sections from oil and gas exploration were interpreted geologically to develop model concepts of the structure of the deep subsurface geology. The digitised site plans and scanned seismic sections, together with the deep wells, provide the data basis for the development of geological cross sections which can be viewed in GeotIS (http://www.geotis.de). The seismic sections can provide information on the position of faults as well as the depth and thickness of hydrothermal target horizons. In recent years, new 2D and 3D seismic surveys were conducted; the results are archived at the State Authority of Mining, Energy and Geology of Lower Saxony (LBEG). Local data can be provided by the geological surveys of the responsible federal state. Information on achievable temperatures, production rates as well as the compression and extension structures can be derived from the information about the regional geological setting.

7.3 South German Molasse Basin

7.3.1 The western part of the basin

The Upper Jurassic and the Upper Muschelkalk formations are the most important potential geothermal reservoirs in the Baden-Wurttemberg part of the South German Molasse Basin. The formations of the upper part of the Upper Jurassic in the northern area are considered to be the aquifer with the greatest hydrothermal potential because of its high productivity. Divided into a northern and southern part, the Upper Jurassic contains a thick basin-parallel belt which stretches from the Constance-Singen area to the region around Pfullendorf and Aulendorf all the way to the Iller and which is of particular interest for geothermal utilisation. The Swabian facies encountered in the northern part of the basin consists of massive, partially bedded limestones and dolomites which can reach thicknesses of up to 250 m (Villinger 1988). The Lower and Upper Felsenkalke (limestones) and the underlying Bankkalke (massive bedded limestones) are characterised in particular within this belt of sponge algae reefs (Meyer & Schmidt-Kaler 1996) by cavernous rocks and corrosively expanded pore spaces generated during karstification. The natural water paths are additionally enlarged by several large-scale fault systems predominantly running longitudinally to the orientation of the basin.

The thickness of the aquifer decreases strongly in the southern basin regions due to the absence of the reef facies; only bedded limestones of much lower permeability can be found in this region.

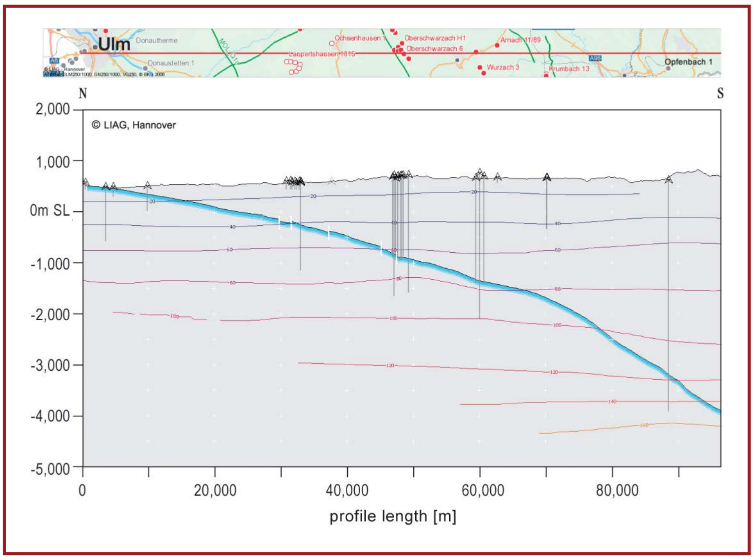

Fig. 35: Geological cross-section through the Molasse Basin (source: Geothermal Information System GeotIS): depth of top Malm (blue), position of the main faults in the Malm (short white lines) and the surrounding deep wells (dark grey). The isolines show the temperature distribution within the subsurface.

Farther in the south the bedded limestones of the Swabian facies give way to the Helvetian facies, both becoming less important as potential hydrothermal target horizons because of the absence of extensive reefs and cavernous zones (e.g. Stober 2013).

The degree of karstification of the Upper Jurassic which primarily took place during the Pliocene declines with increasing distance from the Danube and increasing depth. The Upper Jurassic is dipping down in south-eastern direction and karstification probably comes to an end south of a line from Überlingen via Aulendorf to Ochsenhausen. The overlying bedded marlstones and limestones of the Zementmergel Formation and top Bankkalke Formation are usually much less permeable according to information acquired from water extraction activities on the Swabian Alb, and in large parts, are only affected by shallow karstification (paleokarst) which in many cases does not extend down to the aquifer.

The wells drilled in the pre-Alpine Molasse Basin show a general temperature rise oriented to the south-east and therefore towards the centre of the basin in all aquifers (Fig. 35). This effect is primarily attributable to the gradual decline of the aquifers.

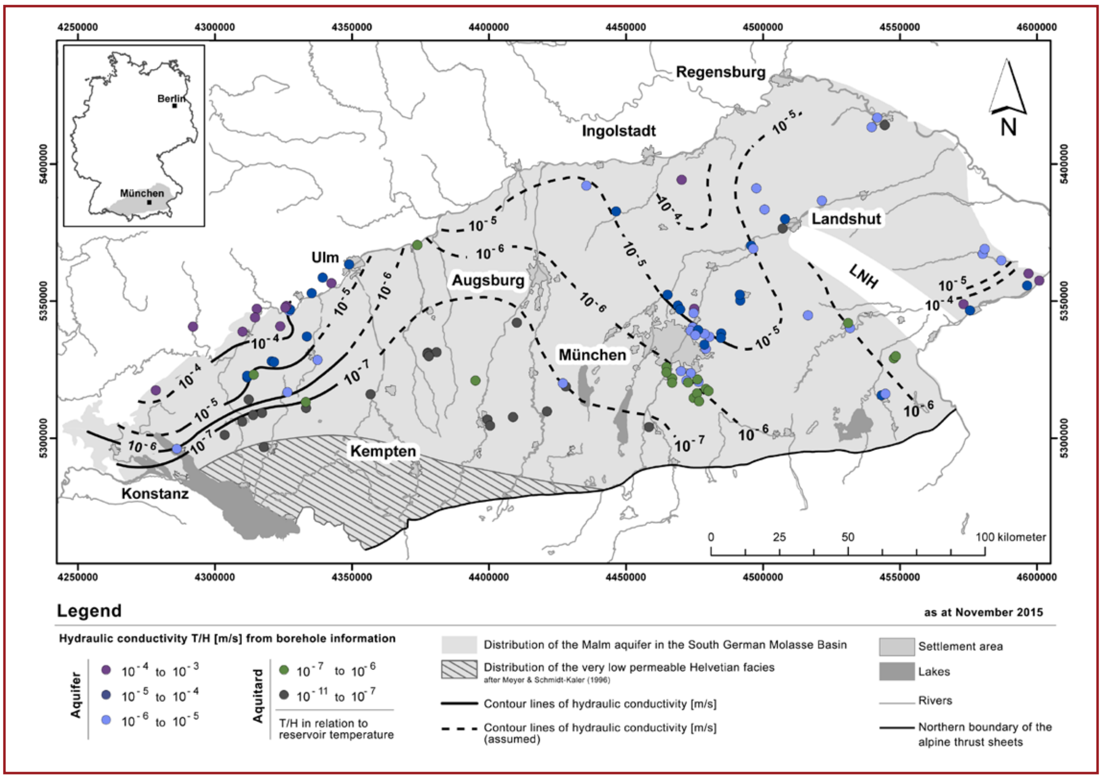

Fig. 36: Distribution of hydraulic conductivities in the Upper Jurassic (Malm) of the Molasse Basin (modified after Birner et al. 2012)

Figure 36 shows the spatial distribution of the hydraulic conductivities within the Upper Jurassic of the South German Molasse Basin (Birner et al. 2012). In the Baden-Wurttemberg part of the basin the hydraulic conductivities decrease slowly in south-eastern direction as the Upper Jurassic sequence is declining increasingly downwards. In addition to a stronger groundwater recharge and the associated CO_2 input from north-western direction in the area of the Swabian Alb, this slight reduction in hydraulic conductivity is mainly attributed to the development of a sponge-algae reef system forming a belt in the Saulgau region. Hydraulic conductivity decreases more rapidly south of the line linking Überlingen, Aulendorf and Ochsenhausen (Stober & Villinger 1997).

It is very likely that the southern boundary of the karstification (reef system) of the aquifer lies in this region. Moreover, gradual transition to the Helvetian facies also occurs in this region. This assumption is supported by the unsuccessful utilisation in the Waldsee 1 and Ravensburg boreholes and the low productivity in the Waldsee 2 well, respectively. According to this, there is no significant groundwater circulation in the upper parts of the Upper Jurassic of the southern part of the Molasse Basin in Baden-Wurttemberg.

The large majority of hydrochemical analysis of Upper Jurassic waters originate from depths above 400 m below ground level (bgl). These waters have a relatively low level of total dissolved solids (TDS) between about 0.32 g/kg and 0.75 g/kg at the maximum. The total dissolved solids only seem to increase slightly with increasing depth from 400 m bgl to 2,000 m bgl. The highest value is about 3.3 g/kg. However, most of the waters only rarely reach values above 1 g/kg. The highest measured TDS of 36.6 g/kg came from a depth of about 3,700 m. The related borehole is located at the southernmost part of the study area within the Helvetian facies. The water type within the Upper Jurassic aquifer also changes with depth. The low mineralised waters from shallow depths have high calcium and high hydrogen carbonate concentrations, as well as in part high magnesium concentrations, and are therefore classified as Ca-(Mg)-HCO_3 type. As the depth of the Upper Jurassic increases in south-eastern direction, the sodium concentration increases, coupled in some cases with a rise of sulphate and chloride concentration. It is believed that the south-easternmost part of the region within the Helvetian facies is characterised by Na-Cl type waters of high salinity (Birner 2013; Fig. 37).

7.3.2 The Upper Jurassic in the Bavarian part of the Molasse Basin

In the central and eastern part of the Molasse Basin, the Malm (Upper Jurassic), as the potentially most productive geothermal aquifer, is the main target for the energetic utilisation of geothermal energy. The Cretaceous sandstones could also be used for geothermal energy utilisation if the conditions are particularly favourable. According to the information currently available, the potential geothermal aquifers of the Lower Tertiary sequence will be primarily restricted to balneological uses (Bayerisches Staatsministerium für Wirtschaft, Infrastruktur, Verkehr und Technologie 2012).

Currently (as at November 2016) twenty hydrothermal heating plants are in operation in Bavaria from which four are combined heat and power plants. At two of these sites additional power plants are under construction or in planning. Furthermore, there are two plants which (so far) only produce electricity. Two projects for combined heat and power production are already in the drilling phase whilst other projects are ready to start drilling or are still in the planning phase. All of these plants or projects use or are aimed at the Malm as the geothermal aquifer.

The majority of these facilities are located in Greater Munich because of the favourable subsurface conditions and the existing customer structure, especially for district heating. The geothermal facilities are operated by municipalities (partially through subsidiaries) like Unterschleißheim, Garching, Unterföhring, Ismaning, an association of Aschheim, Feldkirchen and Kirchheim near Munich, Unterhaching, Grünwald, and Pullach, as well as the municipal utility of Munich and some private operating companies.

The municipal utility of Munich has set the target for Munich to be the first German city that provides district heating from 100 % renewable energies by the year 2040. Since there are few renewable alternatives in the urban environment, geothermal energy will provide the main load. Preliminary surveys (primarily 2D and 3D seismic surveys in the urban area of Munich) have been completed and further surveys are planned. It is anticipated that the relevance of deep geothermal energy will increase in the long term and that geothermal will become one of the cheapest forms of energy for supplying heat by 2040 (Greller & Bieberbach 2015).

The partially karstified Malm limestones and dolomites make up the most important geothermal aquifer in the Bavarian part of the Molasse Basin because of their usually high productivity combined with sufficiently large depths stretching over wide areas. North of the Danube, the Malm crops out at the surface in the Swabian Alb and Franconian Alb. South of the Danube, this formation dips down below the Molasse Basin to depths exceeding 5,000 m at the margin of the Alps.

The Malm (including the Purbeck) reaches its greatest thickness of over 600 m to the south of Munich between the Lech and Inn rivers. In this area, it consists of massive sponge limestones with thicknesses of up to 500 m, as well as the overlying light, porous coral detritus limestone (Meyer & Schmidt-Kaler 1996). Until the Upper Cenomanian transgression several hundred metres of Malm sediments were eroded in the north-eastern part of the Malm platform which has been dragged up by the uplift of the Bohemian Massif. Therefore, the thicknesses of the Malm in today's eastern part of the Bavarian Molasse Basin decrease north-eastwards to less than 100 m.

The groundwater in the Malm largely moves along karst cavities, fissures and fault zones, and to a lesser extent also along bedding planes. The facies differentiation of the Malm also has a direct influence on the hydraulic conductivity because the facies are affected differently by karstification processes. The dolomitised massive limestones are usually very permeable because the porosity is enhanced by recrystallisation, and karstification preferentially affected the grain boundaries (Andres 1985). In contrast, the rocks of the Helvetian facies of the Malm in the south-west can be classified overall as having low to very low permeability. The net thickness of the Malm aquifer largely depends on the depth of karstification, and is therefore usually much smaller than the total thickness. Details on net thicknesses, porosities or the effective pore volumes are very difficult to assess in a karst/fissure aquifer and have to be interpreted as statistical values.

In the central and eastern Molasse Basin average porosities of 2.5 % are expected for the Malm sequence without any overlying Cretaceous beds and of 2.0 % in the remaining areas (Hänel et al. 1984).

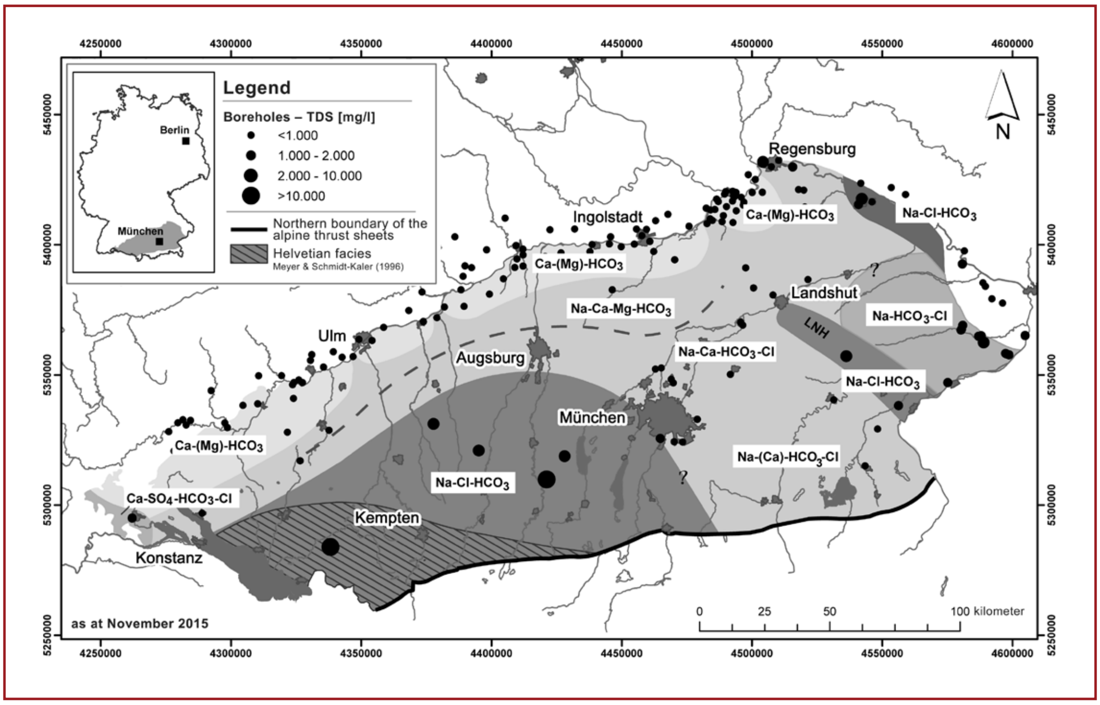

Fig. 37: Hydrochemistry of the Malm aquifer (modified after Birner 2013)

Information on permeabilities within the Malm is also based on values which have to be interpreted statistically because they can partly be subject to extreme local fluctuations. Hydraulic tests from over 60 wells which tapped waters with temperatures of over 20 °C in the Malm within the Bavarian Molasse Basin were evaluated. The transmissivities (T) range from $6.9 \cdot 10^{-8}$ m^2/s to $1.6 \cdot 10^{-1}$ m^2/s, with most wells showing transmissivities ranging from $1.0 \cdot 10^{-4}$ m^2/s to $1.0 \cdot 10^{-2}$ m^2/s (Birner et al. 2012). The hydraulic conductivities (T/H) of the formation derived from the latter values vary from $5.8 \cdot 10^{-11}$ m/s to $5.2 \cdot 10^{-4}$ m/s. The maximum of the frequency distribution lies in the range of $1.0 \cdot 10^{-6}$ m/s to $1.0 \cdot 10^{-5}$ m/s. In the eastern part of the Bavarian Molasse Basin the area with higher hydraulic conductivities seems to extend far to the southeast. In the western part hydraulic conductivities decrease towards the south-west (Birner et al. 2012; Fig. 36).

The confined water level in the Malm in the central part of the Molasse Basin lies below ground level and is usually below the Tertiary confined water level, i.e. "sub-hydrostatic pressures" dominate.

Confined water levels of 100 to 200 m below ground level are expected in the Greater Munich area. The potential conditions remain largely unresolved to the south-east in the Wasserburg depression.

In the south of the Braunauer Trough (northeast of the Landshut-Neuöttinger-Hoch) the groundwaters of the Malm, Cretaceous and the Lower Tertiary are in hydraulic contact with each other (Prestel 1991, Bayer. Landesamt für Wasserwirtschaft 1999). The waters there are under artesian pressure over wide areas.

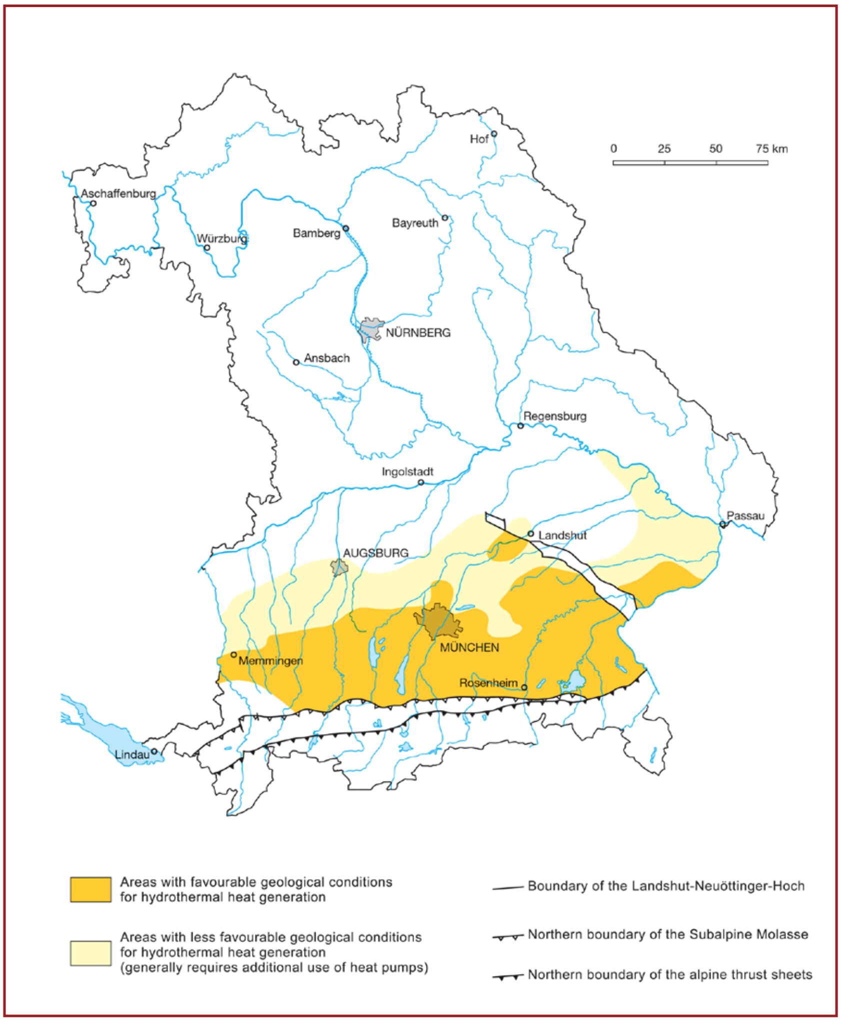

Fig. 38: Areas in Bavaria with favourable geological conditions for hydrothermal heat generation (Source: Bayerisches Landesamt für Umwelt)

Most of the Malm waters can be classified as fresh water, with almost exclusively low mineralised (below 1 g/l) waters of Ca-Mg-HCO_3 type occurring at the northern basin margin, and usually also only low mineralised waters of Na-(Ca-)HCO_3-Cl type in the centre of the basin (Birner et al. 2011). The sulphate concentrations decrease from the northern margin of the basin towards the basin centre because sulphate is reduced to sulphide here. The H_2S resulting from this process is detectable in all Malm waters of the basin. There is an increase in the dissolved constituents with increasing basin depth so that in the south – at least in the areas where there is only little inflow – one can also expect the presence of higher mineralised waters and elevated chloride concentrations (Fig. 37).

High maximum temperatures of well over 100 °C are reached in the Malm in the south whereas the temperatures decrease towards the north (Fig. 38). Power generation using hydrothermal energy is therefore only feasible to the south of Munich because the temperatures should be above 100 °C for this purpose (Fig. 39).

Further information on hydrothermal energy utilisation in Bavaria can be found in the Bavarian geothermal atlas (Bayerisches Staatsministerium für Wirtschaft, Infrastruktur, Verkehr und Technologie 2012).

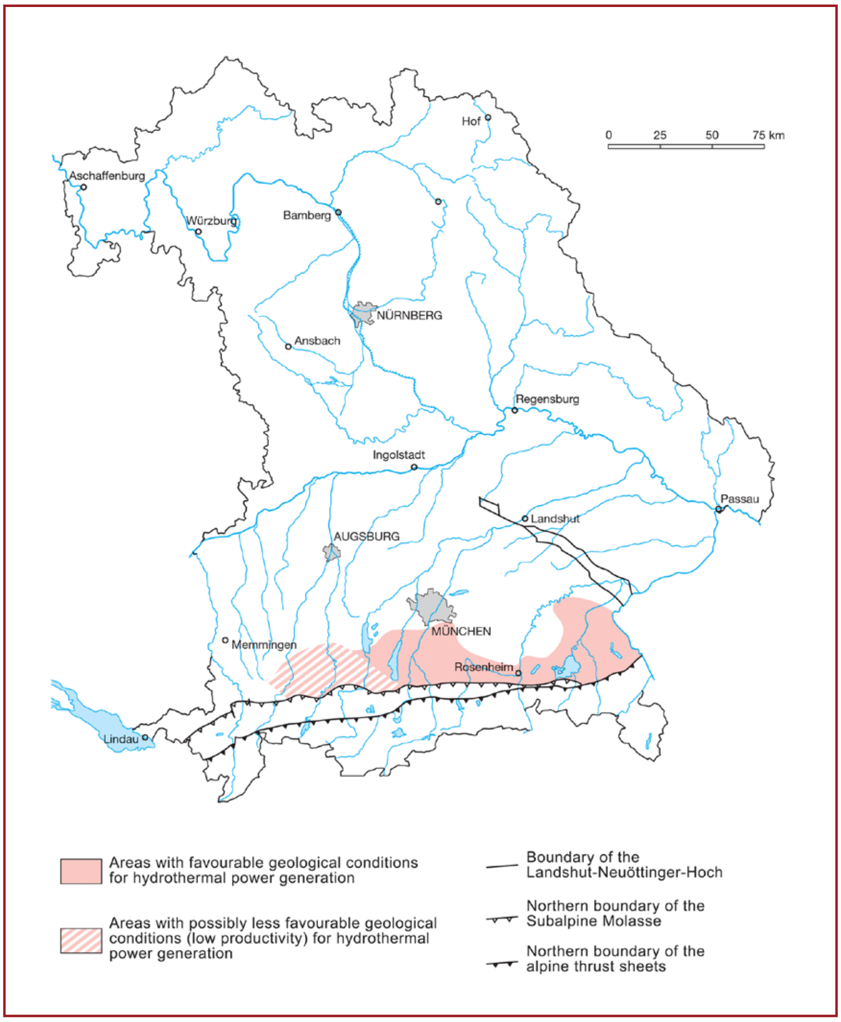

Fig. 39: Areas in Bavaria with favourable or possibly less favourable geological conditions for hydrothermal power generation (Source: Bayerisches Landesamt für Umwelt)

8 Deep Geothermal Projects

The deep geothermal projects described in the following are examples of successful geothermal energy supply in the regions with the most significant geothermal potential for utilisation in Germany. In addition, the European geothermal project in Soultz-sous-Forêts (Alsace, France) is briefly described as an example of an EGS plant.

8.1 Neustadt-Glewe (North German Basin)

In the 1980s, twenty wells were drilled at six project locations in Mecklenburg-Vorpommern (Waren, Neubrandenburg, Neustadt-Glewe, Stralsund, Karlshagen and Schwerin) with the aim to utilise thermal waters from deep productive aquifers for district heating systems. The Geothermal Heating Plant in Waren started operations in 1984 as the first of its kind in Germany. It proves that a hydrothermal doublet system operates successfully even after 30 years. Starting in 1988 Germany's second Geothermal Heating Plant in Neubrandenburg produced geothermal energy using the usual doublet technology for ten years. After conversion to store waste heat from a Combined Cycle Gas Turbine (CCGT) plant, it is now the world's largest heat storage system with a capacity of 3.0 to 3.5 MW_{th}. The Neustadt-Glewe Geothermal Heating Plant which has been operated since 1995, was converted in 2003 to a combined heat and power plant by installing an additional ORC system (Fig. 32). With an installed electric capacity of 230 kW_{el}, it could be seen as pilot plant for the low enthalpy sector in Germany. Although geothermal electricity production stopped in 2010, it demonstrated that an installation of this type could also be operated even at relatively low aquifer temperatures.

Already back in 1984 the geothermal project in Neustadt-Glewe was launched on behalf of the former leather factory. The aim was to supply the factory with thermal and process heat, as well as a neighbouring new housing estate with thermal heat. The existing geological and geophysical data generated during oil and gas exploration was initially evaluated to provide a first assessment of the geothermal resources in the Neustadt-Glewe area. The location lies on the western flank of a passive salt uplift primarily caused by migration of salt into the neighbouring Kraak salt dome in the north-west and the Werle salt dome to the south.

Vibroseis surveys were conducted from the middle of 1988 to evaluate the local structure and to define the locations of the drilling sites. Well Gt NG 1/88 was drilled down to a depth of 2,450 m in the Lower Gipskeuper in 1989, and well Gt NG 2/89 reached a final depth of 2,335 m in the Dolomitmergelkeuper in 1990. The distance between the two wells is about 1,400 m. Three or four potential geothermally exploitable horizons were identified in the wells of which the Contorta sandstone of the Rhaetian proved to have the best properties as a compact, massive and statically stable reservoir. Over 400 metres of core were recovered in total, and more than 1,100 core samples were investigated by Geothermie Neubrandenburg. The productivity and injectivity parameters were determined by performing different tests. As a result it was decided to use well Gt NG 1/88 as the production well and well Gt NG 2/89 as the injection well.

The geothermally exploitable Contorta sandstone is located at a depth between 2,218 m and 2,278 m in the Gt NG 1/88 well. In the Gt NG 2/89 well, it occurs 40 m deeper. The reservoir consists of fine- to medium-grained sandstones with an effective thickness of approximately 50 m. The average porosity is about 25 % as determined from well logs. The porosities measured in the laboratory from core samples reach almost 22 %. The average permeability also determined in the laboratory is around 500 mD. The permeability derived from the test results was much higher and estimated with 1,400 mD. The temperatures in the aquifer reach almost 100 °C. This is therefore the warmest hot water reservoir developed in North Germany so far. As usual in the Mesozoic aquifers of the North German Basin, the salinity is also very high and amounts to 220 g/l.

The Erdwärme Neustadt-Glewe GmbH was established in 1992 to construct and operate a geothermal facility. The project was funded by the German Ministry for Research and Technology, the State of Mecklenburg-Vorpommern, and the Hamburger Elektrizitätswerke AG. After further expanding the existing wells in 1993 and constructing the heating plant, the Neustadt-Glewe Geothermal Heating Plant began regular operations in 1995. Depending on the customer's heat demand, the amount of thermal water produced ranges from 40 to 110 m^3/h (11 – 35 l/s).

Because the water temperature at the wellhead of the production well is 97 °C and therefore adequate for heating purposes, heat can be supplied without using a heat pump. The maximum installed geothermal capacity is 5.3 MW_{th} when cooling the thermal water down to 50 °C. In practice, a capacity of 4 to 4.5 MW_{th} is achieved. The total installed capacity is 14 MW_{th} (including gas- and fuel oil-fired boilers). The annual production lies between 16 GWh and 21 GWh of which more than 90 % is generated geothermally. The connected district heating system supplies 1,325 housing units as well as nine small and medium-sized enterprises.

Due to the low demand for heat in the summer months, a concept was sought for using the excess geothermal energy to generate electricity. When the Renewable Energy Act (EEG) came into force in 2000, and the provision of funding by the German Ministry for the Environment, Nature Conservation and Nuclear Safety was secured, the first geothermal heat and power plant in Germany was constructed in Neustadt-Glewe to realise the combined supply of power and heat. The geothermal power plant used the Organic Rankine Cycle (ORC), i.e. an organic medium with a low boiling point circulates in a secondary circuit in the surface facilities, which enables power to be generated from heat sources with low temperatures of about 90 °C (Fig. 40).

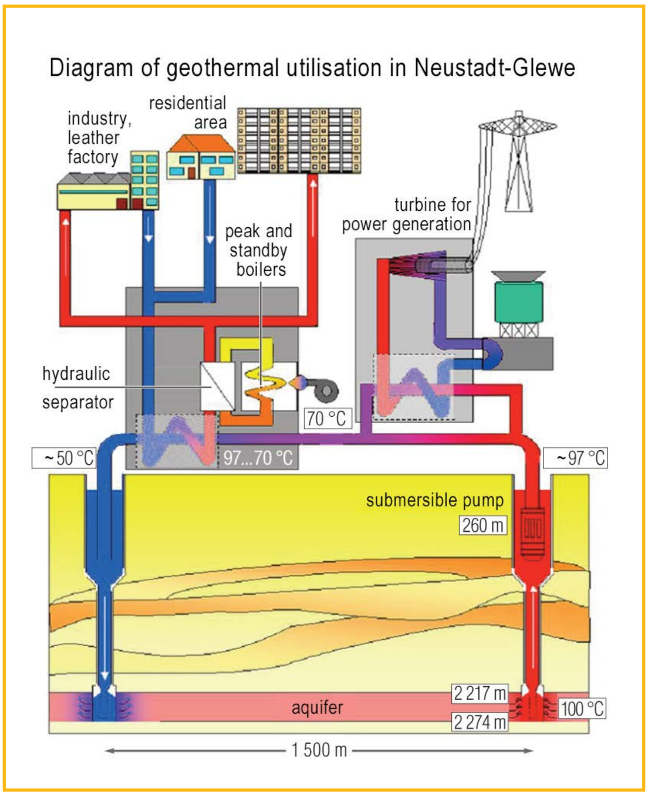

Fig. 40: Sketch showing the principle behind the Neustadt-Glewe combined heat and power plant

Because a capacity of only 140 kW_{el} could usually be reached in practise, and heat generation has priority at low outside temperatures, the power production was shut down for economic reasons and the ORC plant was dismantled in 2012.

The Geothermal Heating Plant Neustadt-Glewe is operated by the WEMAG AG Schwerin together with the municipality of Neustadt-Glewe and the Geothermie Neubrandenburg GmbH. The ORC plant was operated by the Erdwärme-Kraft GbR, a subsidiary of Vattenfall Europe Berlin, and the WEMAG AG.

8.2 Bruchsal (Upper Rhine Graben)

Although the power plant in Bruchsal, located at the eastern margin of the Upper Rhine Graben around 30 km north of Karlsruhe, did not begin operations until the end of 2009, initial work on this project dates back to 1983. Because of the high oil price at the time, the municipality of Bruchsal decided to drill the first deep well (GB1) in 1983. The 1,874 m deep well produces highly mineralised thermal water from the Bunter. The second deep well (GB2) was drilled to a total depth of 2,542 m in 1985. GB2 produces thermal water from the Bunter and the Permian. Falling oil prices in the 1990s made the geothermal project economically unattractive. The project was only revived in 2002 with the adoption of the Renewable Energy Act.

Fig. 41: Pump installation in deep well GB2 (Bruchsal)

The two vertical wells have a distance of about 1,400 m. The temperature at the base of GB2 is 131 °C, and around 20 °C lower in GB1. Hydraulic tests carried out in the 1980s revealed that the transmissivity is slightly higher in GB2 ($T = 1 \cdot 10^{-3}$ m^2/s) than in GB1. Thermal water is currently produced at a rate of 24 l/s from GB2. Both wells tap the highly saline Na-Cl water with total dissolved solids (TDS) of approximately 127 g/kg and a gas-water ratio of around 1.5:1. The main gas components are CO_2 and N_2. Because of the high TDS and gas content, the water pumped to the surface is very strongly oversaturated with respect to various minerals due to reduction in temperature and pressure. This means that minerals, especially aragonite and calcite, can spontaneously precipitate particularly in the case of gas exchange. This problem is counteracted by maintaining a pressure of approximately 22 bar in the surface facilities of the power plant and the pipelines. The thermal water is also corrosive because of the high chloride and CO_2 concentrations. The pH value is approximately 5.0.

The heat extracted from the thermal water is transferred to a secondary cycle. The working fluid used in this cycle is a binary mixture of ammonia and water (Kalina cycle). The plant is designed for an electric capacity of about 550 kW_{el}. Taking a runtime of 8,000 full load hours per year as a basis, the power plant can theoretically generate about 4,400 MWh per year.

8.3 Unterhaching (South German Molasse Basin)

The geothermal energy project of the Unterhaching municipality to the south of Munich was the first project in the Bavarian Molasse Basin in which power generation was realised in addition to local and district heating. It was also the first project of its kind in the world for which a private exploration risk insurance policy could have been taken out (Schulz et al. 2004).

The Unterhaching geothermal project was initially conceived as a power generation plant. District heating only played a subordinate role in the initial planning phase because the price of fossil fuels at the time did not suggest that a more comprehensive supply of heat from geothermal energy resources would be economically viable. However, this view changed completely in the face of enormous rises in the price of fossil fuels starting from 2003, so the priority changed towards district heating.

The first well at the site of the planned power plant was finished in September 2004 with a final depth of 3,350 m TVD (3,445 m MD) tapping the Malm target horizon (Upper Jurassic) with a vertical thickness of approximately 380 m. The temperature in the thermal water horizon exceeded 120 °C and was therefore well above the most optimistic expectations. However, the production rate was initially unsatisfactory. After acid stimulation, a production rate could be achieved which indicated a possible flow rate of up to 150 l/s during operation.

The second well was spudded 3 km to the east in order to target a remarkable structural discontinuity identified by the reprocessing of seismic data. In January 2007 the deviated well reached its final depth at 3,580 m TVD (3,863.7 m MD) along with a total loss of drilling mud. A total thickness of approximately 650 m of Malm was drilled through, attributable to a vertical increase in the thickness of the sequence as a result of faulting. Tests carried out after acid stimulation produced even better results than in the first well in terms of thermal (reservoir temperature) as well as hydraulic (production rate) properties.

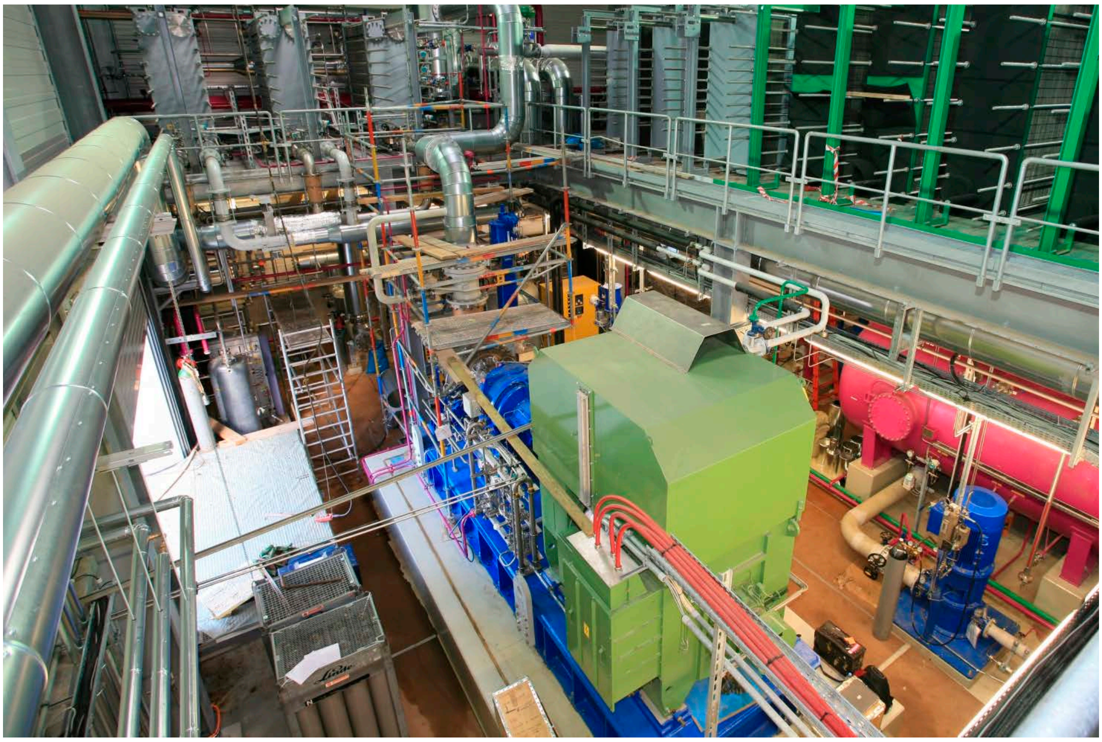

Fig. 42: Unterhaching geothermal power plant

The water tapped in the reservoir at Unterhaching has a very low mineralisation (< 1 g/l) and almost drinking water quality. Therefore, it is relatively unproblematic with respect to precipitation and corrosion. After completion of the heating plant, redundancy and peak load boilers, as well as the first construction phase of the new district heating network, the supply of district heat started in the 2007/2008 heating season. By the end of 2010, the connected heat load was already 38 MW_{th} and reached 58 MW_{th} on 1 May 2015. The expansion target has been set to about 90 MW_{th} from which a maximum of 38 MW_{th} can be provided by the production well.

At the beginning of the project, the technology available for power generation involved the already frequently applied ORC technology (Organic Rankine Cycle) and the less well tested Kalina cycle (with an ammonia-water mixture). The latter was considered to have a slightly higher efficiency at comparatively low temperatures. The Kalina plant was therefore chosen and funded by the German government as a demonstration plant. The first kWh of electricity generated geothermally in Bavaria was fed into the grid on 8 May 2008. The power plant started continuous operation in February 2009 with an electric capacity of 3.36 MW_{el} (Knapek 2009, Rödl 2009).

In 2012, the Geothermie Unterhaching GmbH & Co KG and the Erdwärme Grünwald GmbH established the first Bavarian geothermal district heating cooperation. Within the framework of this cooperation, both geothermal plants in Unterhaching and Oberhaching/Laufzorn are connected by a new district heating pipeline since April 2013. This so far unique cooperation enables the mutual use of excess heat of both plants and therefore a most efficient utilisation of the facilities. This situation opens up the possibility of an increased power production in Unterhaching because excess heat from Laufzorn can be used if required. Furthermore, in the case of a plant downtime both partners are able to compensate, at least in part, for the loss by heat provided by the other plant and do not have to fall back on fossil fuels to generate heat (Lederle & Geisinger 2014). Such joint use of existing and neighbouring plants could have positive economic effects for many operators and should serve as a positive example for future projects.

8.4 Unterföhring (South German Molasse Basin)

The geothermal project in Unterföhring located northeast of Munich is the first project in Bavaria which has been extended by a second doublet and this at remarkably low drilling costs. Prior to this, the geothermal plant in Pullach (south of Munich, west of Unterhaching) has been extended by a third well which acts as new injection well; the former injection well is now used as second production well.

The geothermal plant in Unterföhring was planned as a heating project without power production since water temperatures below 100 °C had to be expected. In November 2006, own seismic surveys have been carried out in the preliminary stage of a geothermal project for the first time in Bavaria. The planned wells should be completed from a single well site by deviated drilling and reach a distance of 2 km at the final depth.

Drilling of well TH 1 started in November 2008 and reached its final depth at 3,042 m MD (2,512 m TVD) in February 2009. The subsequent pumping test indicated a reservoir temperature of 86 °C and a flow rate of at least 50 l/s. A considerably higher flow rate could be expected, because the performance of the pump was limited to 50 l/s. Thus, the minimum expectations of 80 °C and 35 l/s have been clearly exceeded.

Starting mid-March 2009, the second well TH 2 was drilled and reached its target depth of 2,578 m MD (2,124 m TVD) at the beginning of May 2009. After completion of the pumping tests, it was decided to use the second borehole as production well, because it delivered slightly better results with a reservoir temperature of 87 °C and a flow rate of at least 75 l/s.

A connected heat load of about 4.5 MW_{th} was contractually secured already prior to the drilling operations. As of 3 December 2009, the first 1,200 housing units were supplied with geothermal heat. As at February 2014, the district heating network for the "supply area North" has reached a length of 22 km with a connected heat load of about 24.3 MW_{th}. The production well provides a geothermal capacity of about 10 MW_{th}. It is generally possible to provide the network without additional peak load capacity because of the favourable customer structure and the resulting low diversity factor.

Due to the high degree of acceptance of the geothermal project and the large demand for geothermal heat, the GEOVOL Unterföhring GmbH, a 100 % subsidiary of the municipality of Unterföhring, has advanced the planning of a second hydrothermal doublet in order to double geothermal capacity and to supply district heating to a further area ("supply area South"). In preparation of the new project, a further 2D seismic survey was carried out in the claim. In addition, it was tried to find the optimal target points for the two new wells to minimise possible hydraulic and thermal interactions between the old and the new wells.

Fig. 43: Pumping test in well Unterföhring TH 4 (© GEOVOL Unterföhring GmbH)

Work on the new doublet started mid-February 2014 with drilling well TH 4. Drilling was deviated to the South and reached a final depth of 3,879 m MD (2,340 m TVD) at the beginning of April 2014. The following pumping test indicated a reservoir temperature of 93 °C and a flow rate of 85 l/s (Fig. 43). The actual drilling time was only 48 days. The subsequent well tests including cleaning run, acid stimulation, short-term pumping test, liner installation, second acid stimulation and long term (four weeks) production test took another 28 days, so that in total only 76 days were needed for completion (Lentsch et al. 2014).

Drilling the forth well TH 3 started in May 2014 and reached the final depth of 3,050 m MD (2,053 m TVD) in June 2014 after only 39 days. Well TH 3, intended to be the potential injection well because of a known negative temperature anomaly in the East, showed as expected a considerably lower reservoir temperature of about 84 °C. Well TH 3 is ideally suited as injection well and ranks among the best wells in Greater Munich with regard to its hydraulic properties with a productivity of 12.5 l/(s·bar) in the final expansion and a flow rate of at least 87 l/s proven by the long term (four weeks) production test (Lentsch et al. 2014).

Construction of the second geothermal plant began in November 2014, the topping-out ceremony was celebrated in July 2015. The aim is to supply also the south of the municipality with geothermal heat by 2020 and thus covering the whole municipality.

Moreover, the first two office buildings are cooled by geothermal heat since mid-2015. A so-called absorption chiller is used for this purpose, which provides cooling by the use of thermal energy and a saline solution of water and lithium bromide. The principle is based on cooling by evaporation of water and the ability of the saline solution to absorb the resulting water vapour. The geothermal heat removes the water from the solution and the cycle can start again.

The chiller was installed directly to one of the two office buildings and replaces the previous air conditioning powered by electricity. With a cooling capacity of 200 kW the chiller provides cooling for about 4,500 m^2 of office space in normal operation. An additional electrically powered air conditioning is ready to cover the peak load on very hot days.

8.5 The European EGS project at Soultz-sous-Forêts

The European geothermal project in Soultz-sous-Forêts, France, is located about 40 km to the north of Strasbourg and approximately 30 km southwest of Karlsruhe at the western border of the Upper Rhine Graben. The three 5,000 m deep wells reached the granitic basement in a depth of 1,400 m. The fracture system in the 200 °C hot rock was expanded by massive water injection (stimulation) in the lowest part of the boreholes and connected to create a geological heat exchanger. The deep boreholes were drilled as deviated wells. Although they are close together at the surface, their bottom hole sections are actually about 600 m apart from each other.

Hot water is produced from two of the three wells. The water contains total dissolved solids of approximately 100 g/kg as well as gases, mainly CO_2 and N_2. The main constituents are sodium and chloride. Just like in Bruchsal, the water has corrosive properties. At the surface facilities the thermal water is therefore circulated within a closed primary circuit kept under overpressure. The heat is extracted and transferred to an organic working medium using tubular heat exchangers. The water is then reinjected through the third well. The organic working medium is expanded in a turbine connected to a generator before being cooled down and again liquefied in a condenser attached to an air cooling system equipped with fans (ORC plant).

The world's first EGS project started test operations in June 2008. The plant has a net electric capacity of 1.5 MW_{el} at a flow rate of 30 l/s and a production temperature of about 165 °C. In 2015/16 the surface part of the facility was newly constructed and the plant is now in commercial operation.

Fig. 44: Soultz-sous-Forêts geothermal power plant (source: Groupement Européen d´Interêt Économique (GEIE) - Exploitation Minière de la Chaleur)

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9.2 Guidelines

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9.3 Atlases and maps

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9.4 Links

Geothermal Information System GeotIS:	http://www.geotis.de
German Geothermal Association (BVG):	http://www.geothermie.de
Swiss Geothermal Society (SVG):	http://www.geothermie-schweiz.ch
International Geothermal Association (IGA):	http://www.geothermal-energy.org

The integration of deep geothermal energy into power and heat supply is of great importance for achieving the climate protection goals and offers best chances for a sustainable development. Due to its relatively low subsurface temperatures, Germany is not considered a traditional geothermal country. However, deep geothermal heat is already used for wide-ranging applications. Geothermal energy is not only environmentally and climate friendly but also available throughout the year with only a small demand of land.

The purpose of this brochure is to provide a technical overview as well as to give recommendations useful for public and private investors. The authors offer a profound introduction to deep geothermal energy, present the state of the art using German projects as examples, and present the geological, physical and technical interrelationship in a comprehensive way.

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