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Evaluation of sandstone aquifers of the North German Basin: a contribution to the „Geothermal Information System of Germany"

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ABSTRACT

Numerous boreholes were drilled for the exploration for hydrocarbons in the eastern part of the North German Basin (NGB). These data and the results of geophysical investigations are used for the characterization of the geothermal potential of Mesozoic sandstone layers in NE Germany. Important aquifers for geothermal applications are the sandstones of the Middle Bunter, the Schilfsandstein (Middle Keuper), the sandstone complex of the Rhaetian and Liassic, the Dogger-ß sandstone (Aalenian) and the Lower Cretaceous sandstones. These horizons are distributed basin-wide and reach often the required thicknesses. They display good geothermal properties with temperatures > 60°C, porosities > 20% and permeabilities > 500mD. The utilization of geothermal energy of deep aquifers is currently performed in several localities in NE Germany. Geothermal heating plants operate successful for more than 10-20 years. Further installations use thermal water for balneological purposes or they are established as deep seasonal heat storage.

1. INTRODUCTION

The systematic exploration for hydrocarbons in NE Germany during the second half of the 20th century proved a high geothermal potential for the eastern part of the North German Basin. Mesozoic aquifers containing thermal water with temperatures between 40 and 120°C in depth's from approximately 1.000 to 3.000m are widespread in this area. As a consequence, three geothermal heating plants were built producing district heating since more than 10 to 20 years. A few other installations are planned.

During the late 1980 and early 1990, a group of geologists compiled all data of the hydrocarbon investigation in NE Germany considered as relevant for geothermal applications. Short description of the aquifers are given in several reports and maps in the scale of 1 : 200.000 and 1 : 100.000 respectively contain information about their distribution, depth and prospectivity (Brückner et al. 1990, Diener et al. 1988-1992, Wormbs et al. 1988-1989). These data will be evaluated using borehole databases and new results of the State Geological Surveys. The goal is to build up an ArcGIS based information system, that provide the public authorities as well as private investors with a tool for the investigation of the geothermal potential of the Mesozoic aquifers of NE Germany and for the characterization of potential sites for geothermal purposes. Besides, the digital information system can be used to find opportunities for other than geothermal applications as, e.g. the storage of gas or CO_2 in the subsurface.

The area of investigation includes the territory of the NE German state Mecklenburg-Vorpommern and adjacent parts of the states Brandenburg and Sachsen-Anhalt. It is bounded by the Baltic Sea to the north, Poland to the east and the NW German states Schleswig-Holstein and Niedersachsen to the west. The southern limit is formed by the elevated parts of the pre-Zechstein basement, south of the NW-SE trending deep Gardelegen and Wittenberg faults and the Lusatian anticlinal zone respectively.

2. REGIONAL GEOLOGY

The territory of NE Germany belongs geologically to the North German Basin (NGB), a sub-basin of the Central European Basin System containing up to 12km of Permian to Cenozoic deposits (Gast et al. 1998). The evolution of the North German Basin was initiated by intensive volcanism at the beginning of the Autunian (Lower Rotliegend). The subsidence started slightly later in the late Saxonian (Upper Rotliegend) and lasted until the end of the Cretaceous (Ziegler 1990, Katzung 2004).

During this time the basin deepened successively. The stage of main subsidence lasted until the end of the middle Bunter (Triassic), and is followed by the stage of basin differentiation until the early Upper Cretaceous. This latter stage is characterized by the development of smaller sub-basins with increased sediment thicknesses. Consequences are varying basin configurations and changing lithofacial conditions. Marine ingressions occurred several times from the Arctic ocean in the north and from the Tethyan ocean in the south (cf. Ziegler et al. 1990, Walter 1995, Katzung 2004). The sediments were supplied from the north (Fennoscandian landmass) as well as from the southeast (Bohemian High) and from the southwest (London-Brabant High). The NNW situated Rinkøbing-Fyn High acted as a further source area from the middle Jurassic until the early Cretaceous (cf. Katzung 2004).

A compressive, approximately N-S-oriented stress field at the end of the Cretaceous caused the uplift of large basin parts finishing the basin evolution.

The Mesozoic succession of the NGB is intersected by many faults and fault zones. A major structure zone is the NNW-SSE striking Vorpommern fault system stretching from E Mecklenburg to the island Rügen (figure 2). It has been developed during the Early Kimmerian tectonic pulses and represents typical features of extension tectonics (Krull 2004). Similar striking faults occur in the Fürstenwalde-Guben and the Gross Köris-Merzdorf structure zones, respectively, in the south-eastern part of the basin. In contrast, the Altmark-Fläming depression and the Prignitz elevation in the south-western part are characterized by WNW-ESE striking fault systems. Further faults occuring only locally and preferred in the vicinity or on top of salt structures trend in different directions.

Mesozoic tectonic phases led not only to differentiation of the NGB but also triggered the mobilisation of the Zechstein salt which strongly influenced its structural evolution. Thus, the NGB displays a wide variety of salt structures with structural amplitudes of up to 8 km. Salt structures with mainly NNE-SSW striking axes occur in the western part of basin. They border genetically related Triassic-Jurassic graben structures of similar orientation. Furthermore, salt structures aligned along NW–SE striking axes dominate the eastern part of the NGB. The numerous salt diapirs and salt pillows have an important influence on the geothermal conditions of the NGB. The temperatures increase remarkably on top and in the surrounding of the salt structures, due to the higher heat conductivity of rock salt and anhydrite.

3. MESOZOIC AQUIFERS IN NE GERMANY

3.1 Criteria for the geothermal utilization of aquifers

Aquifers are water-saturated sediment layers, mostly sandstones, with a very low content of matrix or cement. Their thermal capacity forms the interesting energy potential.

Based on the requirements of the utilization of geothermal energy and of previous experiences of operated geothermal heating plants as well as on economic aspects, the following criteria were used for the classification as a geothermal aquifer (cf. Wormbs et al. 1992). The temperature should be between 40°C and 100°C or even higher, which can be expected in a depth interval of about 1000-3000m. A supposed minimum productivity of 50m³/h requires aquifer thicknesses of at least 10-15m and an effective porosity of more than 20% and preferably 25%. The permeability of the rock should exceed the minimum value of 0,25-05 Darcy.

3.2 Aquifers

Figure 1 displays the Mesozoic aquifers of NE Germany which are suited for geothermal energy uses. The most important horizons are the sandstones of the Middle Bunter, the Schilfsandstein (Middle Keuper), the sandstone complex of the Rhaetian and Liassic, the Dogger-ß sandstone (Aalenian) and the Lower Cretaceous sandstones. These horizons are distributed basin-wide and reach often the required thicknesses and minimum permeabilities. They are described in detail below.

Other aquifers are distributed only regionally or even locally in the area of investigation. The Pelitröt formation (Upper Bunter) consisting normally of fine grained sediments contains sandy intervals of a considerable thickness, e.g. on northern Rügen island. Another locally distributed aquifer is the Lower Callovian sandstone from the area Wolgast-Usedom in the northeastern part of the investigation area. This sandstone is evaluated for restricted geothermal purposes due to its varying silt content and the relatively shallow depth.

3.3 Middle Bunter sandstones (Lower Triassic)

The Middle Bunter is subdivided into the formations Volpriehausen, Detfurth, Hardegsen and Solling. This succession is widespread in the NGB The depth of its basis varies from more than 3500 m in the basin centre to less than 200 m at the southern basin margin. On Rügen island the succession is buried below 800-1000m younger sediments. The thickness of the Middle Bunter differs considerably, depending on regional stratigraphic failures below the Solling formation and on the basinal position. While an about 500 m thick succession occurs in the central parts of the basin (W Mecklenburg and NW Brandenburg) the thickness of the Middle Bunter decreases to less than 50 m at the basin margins in the NE (Rügen island) and in the S (S Brandenburg).

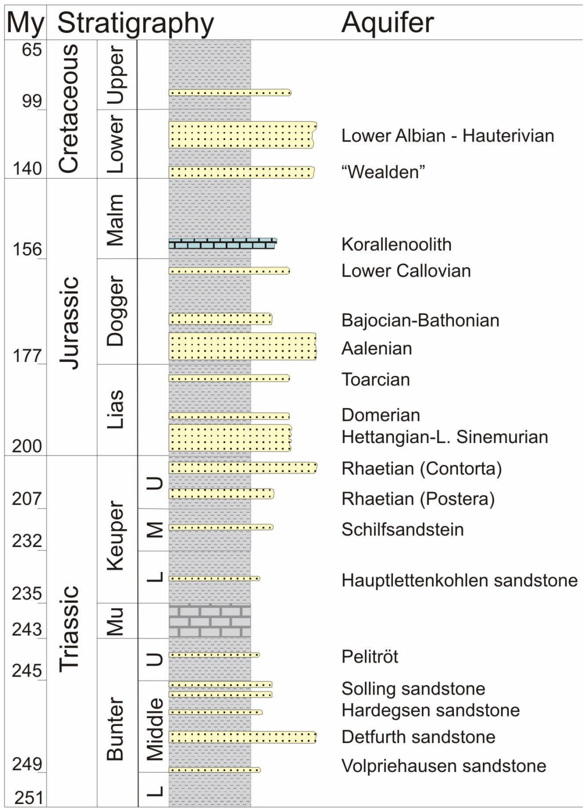

Figure 1: Stratigraphic position of the aquifers in the Mesozoic succession of NE Germany (Wolfgramm et al. 2004, modified). Mu – Muschelkalk.

The formations of the Middle Bunter show a cyclic development. A basal sandstones is followed by siltstones and claystones with partly intercalated sandstone layers (Detfurth) and anhydrite (Hardegsen). The Solling formation is, in general, composed of an about 15-20m thick sandstone, which is overlain by 20 m of claystone and a further 25 m thick sandstone. Maximum thicknesses occur in the Altmark with up to 50m thick Solling sandstones. Beutler (2004) suggests that the sand content in the Detfurth, Hardegsen and Solling successions increases continuously NE of the Rostock-Gramzow deep fault in the NE part of the basin as well as in SE Brandenburg. The thickness of the sandstones of the other formations varies as well. The mostly 2-10m thick Volpriehausen sandstone reaches more than 25m in the vicinity of Usedom island. The Detfurth sandstone is often 5-12m thick, but in the NE part of the basin (Vorpommern, Usedom) thicknesses of 20-40m can be reached. The basal sandstone of the Hardegsen formation is basin-wide about 2-12m and in the Vorpommern area between 20 and 50m thick.

The porosity of the sandstones was determined on core samples and with borehole measurements. They range between 10 and 30%, whereas the higher values occur in the northeastern part of the NGB. In this area the permeabilities are estimated as moderate to good.

About 150 temperature measurements were carried out in the sandstones of the Middle Bunter, mainly in the

Vorpommern area. They vary from 30°C (Rügen island, 960m depth) to 120°C (Altmark, 2700 m). High temperatures are measured also sporadically in E Mecklenburg (95°C, 2250m).

The productivity of the Solling sandstone in Vorpommern is estimated about 100m³/h/MPa, on basis of porosity measurements and productivities of geothermal wells.

3.4 Schilfsandstein (Middle Keuper, Upper Triassic)

The Schilfsandstein beds (Stuttgart-Formation) represent a sandy to muddy succession of the Middle Keuper. They are distributed over the entire basin, with exception of the areas of Rügen island and the Altmark, typical swells regions during the Middle Keuper. A characteristic feature of the formation is the changing facial development. Up to 60m thick channels filled with fine to medium grained sandstones cut erosive into the underlying beds. They interfinger laterally with clayey and silty sediments. The width of the sandstone channels vary between 1km and 15km. They form linear elements in NE-SW to NW-SE direction which can be followed from N Germany to S Germany and SE Poland (Beutler 2004, Göthel 2006).

The thickness of the Schilfsandstein formation is about 80-100m in Mecklenburg-Vorpommern and reduces to the south to about 40-60m (Beutler 2005). The basis of the Schilfsandstein occur at depth between 400-700m near the southern and northeastern margins of the NGB and more than 2500m in the basin centre. The deepest occurrence of the Schilfsandstein formation basis has been discovered in rim synclines of salt diapirs in S Mecklenburg as well as in N Sachsen-Anhalt and N Brandenburg (2,900-3,100m). According to borehole data the thickness of the sandstones ranges from 5 to 60m, sometimes split up into several distinct beds. A higher thickness of 30m and more has been observed in the northeastern part of the NGB and in gaben structures on top of single salt pillows (e.g. Schlieven).

The storage properties of these sandstones are very good in the north-eastern and eastern parts of the basin with effective porosities varying between 20 and 35%. Slightly lower porosities (15-25%) display the sandstones in the western part. Furthermore, good permeabilities (> 1D) can be expected in the eastern part, while moderate (to good) permeabilities appear in the western part. The productivity of the aquifers reaches up too 100m³/h/MPa.

Temperature measurements were carried out only rarely in the Schilfsandstein beds. They range from 33°C (SW Mecklenburg, 480m) to 92°C (N Brandenburg, 2350m).

3.5 Rhaetian-Liassic aquifer complex (Upper Triassic – Lower Jurassic sandstones)

The sandstones of the Rhaetian and the lower Liassic were deposited under similar conditions. Partly the stratigraphic border can not be distinguished due to the lack of fossils. Therefore they are regarded in practice often as one aquifer complex.

The Rhaetian is subdivided into three units, which consist of coloured and black mudstones and light to brownish mature sandstones (Beutler 2005). Sandstones occur in the Lower Rhaetian (Postera beds), in the Middle Rhaetian (Contorta beds) and locally in the Upper Rhaetian (Triletes beds). The thickness of the whole Rhaetian succession ranges from 50m at the NGB margins (SW Rügen and S Brandenburg) to 150-170m in SW Mecklenburg. Up to 250m thick sequences occur only locally (Beutler 2004, Beutler 2005).

The lower Liassic succession (Hettangian to Pliensbachian) consists of claystones, siltstones and sandstones. The claystones contain often thin intercalations of siderite and sandstone. Thin lignite beds are locally developed. The thickness of this succession varies between 270 and 400m. Maximum values of more than 500m occur only in SW Mecklenburg as well as in downfaulted segments within the Vorpommern fault system (Petzka 1999, Petzka et al. 2004). Massive sandstone layers appear in the Hettangian sequence. Fine grained sandstones deposited during the Sinemurian, especially at the bases of the Lower and Upper Pliensbachian, respectively, are widespread in the NGB (Petzka 1999, Göthel 2006). In Mecklenburg-Vorpommern the total thickness of sandstone layers increases from W to E (Petzka et al. 2004).

Both, the deposits of the Upper Rhaetian and of the Liassic are distributed over the whole investigation area, except of N Rügen (palaeogeographic swell region). The basis of the Liassic rests at depths between 100-2800m (figure 2). Rather shallow positions of the basis are known from the southern parts of the NGB, from the top of a few salt pillows and from the area of the Vorpommern Fault system. Deeper occurrences below 2500m are bound to some rim synclines of salt structures in the basin centre (SW Mecklenburg and NW Brandenburg).

The individual sandstone beds display mostly thicknesses between 10 and 30m. Higher thicknesses of up to 120m occur especially in the northeastern to eastern parts of the NGB. In some boreholes, up to 12 sandstone beds separated by thin mudstones have been distinguished in the Rhaetian-Liassic complex. These can reach a cummulative sandstone thickness of about 230m. On the other hand, the number and thickness of sandstones in the southern to southwestern parts of the basin are less.

The sandstones of the Rhaetian and Liassic are mostly very good aquifers, because of their low content of matrix and cement. The high quality especially of the Rhaetian aquifers is proven by geothermal installations in Waren, Neustadt-Glewe and Neubrandenburg. Numerous laboratory measurements and the interpretation of the well logs imply porosities of 20-35% as well as good and rarely moderate to good permeabilities (500 - 1000 mD), respectively. The productivity is estimated of about 50 – 250m³/h/Mpa.

The temperature logs (n=150) display values from 21°C (Vorpommern, 490m) to 90°C (S Mecklenburg, 1700m). The Contorta sandstone in Neustadt-Glewe shows a temperature of 99°C in 2250m depth (figure 3).

3.6 Dogger-ß sandstone (Upper Aalenian, Middle Jurassic)

The Dogger-ß sandstone belongs stratigraphically to the Upper Aalenian of the Middle Jurassic. It represents the reservoir horizon of many oil fields in the western part of the NGB. The formal name is *Altmark sandstone* (Deutsche Stratigraphische Kommission 2002). According to Petzka et al. (2004) an about 80m thick succession of silty sands in the Möckow-Dargibell Fault zone, known as *Wusterhusen beds*, is assigned to the Aalenian as well. During the early Middle Jurassic, the eastern part of the NGB was affected by continental conditions of deposition passing into deltaic to shallow marine conditions towards the west. This is reflected by the lithology of the successions. Marine mudstones of the Toarcian and Lower Aalenian occur in the west western part of the NGB but getting more and more sandy to the east as well as to the above lying Upper Aalenian succession (Petzka et al 2004, Göthel 2006).

The massive, medium to fine grained Dogger-ß sandstone is distributed over a much smaller area than the above mentioned aquifers. It is absent in wide parts of W and N Mecklenburg, Vorpommern N Sachsen-Anhalt, and S Brandenburg. The basis of the Aalenian occurs at depth´s between 100m near the basin margins in the NE and SW and on top of the salt pillow Marnitz, and 2400m in several rim synclines in N Brandenburg and S Mecklenburg.

The thickness of the Dogger-ß sandstone varies remarkably. Often it is more than 30m and in the rim synclines up to 270m thick (cf. Petzka et al. 2004). The borehole Gt Nn 2/87 in N Brandenburg exposes a 100m thick Upper Aalenian sandstone (Göthel 2006). Low thicknesses are bound to the eastern, southern and southwestern margins of the NGB.

The sandstones of the Aalenian represent excellent aquifers predominantly with porosities of 25-30% and occasionally more. The permeability of the Aalenian is interpreted in about 70 boreholes as good (to very good) with values of 500-1000mD and often more (Diener et al 1988, 1992). Therefore, productivities of 150 – 300m³/h/MPa can be expected.

Temperatures of the Aalenian were measured in about 75 boreholes. They correlate mostly with the normal geothermal gradient. Anomalous high values occur rarely in the vicinity of salt structures.

3.7 Lower Cretaceous aquifers

The distribution of the Lower Cretaceous sediments in NE Germany reflects the palaeogeographic situation during this epoch. Pre-Middle Albian rocks occur in the SW Mecklenburg-Prignitz-Altmark-Brandenburg depression and in the Usedom depression. Both sedimentation areas are separated by several palaeogeographic swell regions: Pompeckj Scholle, N Mecklenburg Scholle and E Brandenburg uplift (Diener 2000a, 2000b, Diener et al. 2004). The Usedom depression as a part of the Danish-Polish through can be understand as a bight with a sandy facies. The relatively narrow SW Mecklenburg-Prignitz-Altmark-Brandenburg depression represents the eastern continuation of the Lower Saxony Basin.

According to Diener (2000a, 2000b) and Diener et al. (2004) the succession of the Lower Cretaceous is characterized by clayey and marly sediments in the central parts of the NGB (N Altmark, SW Mecklenburg) whereas sandstones with intercalated thin mudstones and marls occur at the marginal parts of the basin (S Altmark, W Brandenburg) and in the Usedom Senke. The thickness of the whole succession (Berrias – lower Middle Albian) ranges from few metres at the swell regions to maximum values of more than 1000m in rim synclines in W Brandenburg. Sandstones of the Wealden and Valanginian appear only locally in very active rim synclines in SW Mecklenburg and the Altmark as well as in the Usedom depression and in the Prerow and Samtens fault zones, respectively. They are up to 50m thick. Furthermore, sandstones of the Hauterivian to Aptian succession occur in the Prerow fault zone (c. 50m) in the Usedom depression (c. 100m) and in SW and NW Brandenburg. Very thick sandstones of the Lower Cretaceous are exposed in boreholes in N Brandenburg (100-200m) and in the Altmark (up to 90m).

The basis of the Lower Cretaceous rests mainly at depth´s between 500m and 1500m. Maximum depth of up to 3000m occur in rim synclines in W Mecklenburg and minimum depth´s less than 500m are known the margins of the NGB and above some salt pillows.

The porosities of the sandstones are relatively high with values of 20-38%. The permeabilities is interpreted as good to moderate (250-1000mD). However, the temperatures are relatively low, due to the shallow depth of the Lower Cretaceous. The measured temperatures (n=59) ranges from 23°C (W Mecklenburg, 700m) to 70°C (N Brandenburg, 1700m). A remarkably high temperature of more than 100°C occur in a rim syncline in W Mecklenburg (2700m).

4. GEOTHERMAL ENERGY USES IN NE GERMANY

The geothermal potential of deep aquifers of the NGB is used in several localities in NE Germany, which are described below. The chapter gives an overview over the geothermal applications, despite the information may be incomplete, especially because some projects are running or in the stage of planning (see table 1).

Geothermal heating plants with doublet systems operate successful in Waren and Neustadt-Glewe, both situated in Mecklenburg. They are in operation since 1984 and 1995, respectively. The productive horizon is the Raethian Contorta sandstone. Additionally, the plant in Neustadt-Glewe generates power with an ORC installation.

The about 1200m deep sandstone horizons of the Upper Postera (Rhaetian) and Hettangian are used for storage and recovery of excessive heat of power generation for a district heating system in Neubrandenburg (E Mecklenburg).

A geothermal heating plant using a deep vertical heat exchanger was installed in Prenzlau NE Brandenburg in 1994. The VHE is about 2800m deep.

Thermal water from a depth of about 850m is used for a thermal spa in Belzig (S Brandenburg). The spa in Binz (Rügen island) benefits from 34°C warm thermal water from about 1200m depth. Furthermore thermal water from deep aquifers is used in spas in Templin and Bad Wilsnack.

An about 300m deep aquifer below the parliament buildings in Berlin is used for the storage of excessive heat arising from power generation during summer. The heat will be recovered through winter times.

Currently under construction is a geothermal installation in Neuruppin (N Brandenburg). Here, the about 60m thick Dogger-ß sandstone is selected to deliver energy for a district heating system and watr for a thermal spa and for balneological purposes.

Another project in progress is the in-situ geothermal laboratory in Groß Schönebeck, situated about 60km NE of Berlin. The target of this R&D project is to develop a technology for the generation of geothermal electricity from low-enthalpy reservoirs. Until now two more than 4km deep boreholes have been drilled, reaching the Rotliegend.

Further geothermal projects are planned in several regions of NE Germany.

5. CONCLUSIONS

The condition for a geothermal use of saline aquifers in the NGB can be considered as good, evaluating data from more than 1500 boreholes in NE Germany.

The most important aquifers for geothermal applications are the sandstones of the Middle Bunter, the Schilfsandstein (Middle Keuper), the sandstone complex of the Rhaetian and Liassic, the Dogger-ß sandstone (Aalenian) and the Lower Cretaceous sandstones. These horizons are distributed basin-wide and reach often the required thicknesses.

The geothermal properties of these main aquifers vary remarkably, depending on the depth and the lithological composition. However, temperatures > 60°C, porosities > 20% and permeabilities > 500mD occur in wide parts of NE Germany.

Besides the "first class" aquifers, several minor sandstones layers can be considered as local suppliers for the geothermal heat production. However, lateral facies changes documented by a great number of boreholes can be considered as a limiting factor for real applications.

The salt structures play an important role for the temperature field of the NGB. Increased sandstone thicknesses and higher temperatures occur often in the rim synclines of salt diapirs and salt pillows.

The great number of geothermal installations in NE Germany show, that the use of geothermal energy is feasible under economic aspects, even with temperatures between 60-100°C.

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location	purpose	project status	aquifer	depth [m b.s.]	$T_{aquifer}$ [°C]
Arendsee	district heating, balneology	planned	Lower Cretaceous	1548	75
Bad Wilsnack	spa, balneology	in operation	Rhaetian	1000	39
Belzig	spa, balneology	in operation	Rhaetian	730	27
Berlin	heat storage	in operation	Hettangian	320	19
Binz	spa, balneology	inoperative	Middle Bunter	1020	29
Groß Schönebeck	in-situ geothermal lab power generation	under construction	Rotliegend	4400	150
Karlshagen	heat, balneology	planned	Middle Bunter	1780	58
Neubrandenburg	heat storage	in operation	Rhaetian	1250	53
Neubrandenburg	balneology	planned	Aalenian	822	32
Neuruppin	district heating, spa, balneology	under construction	Aalenian	1620	63
Neuruppin	district heating	inoperative	Rhaetian	2340	81
Neustadt-Glewe	district heating, power generation	in operation	Rhaetian	2250	99
Prenzlau	deep borehole VHE	in operation	Rotliegend	2800	108
Pritzwalk	spa, balneology	planned	Aalenian	2036	78
Rheinsberg	spa, balneology	planned	Rhaetian	1626	68
Sassnitz	balneology	inoperative	Middle Bunter	1081	30
Stralsund	district heating	planned	Middle Bunter	1530	58
Templin	spa, balneology	in operation	Hettangian	1620	67
Velten	district heating	inoperative	Hettangian	1550	63
Waren	district heating	in operation	Rhaetian	1540	61
Wartenberg	spa, balneology	inoperative	Schilfsandstein	960	38

Table 1: Geothermal installations and areas with activities for the use of geothermal energy in NE Germany.

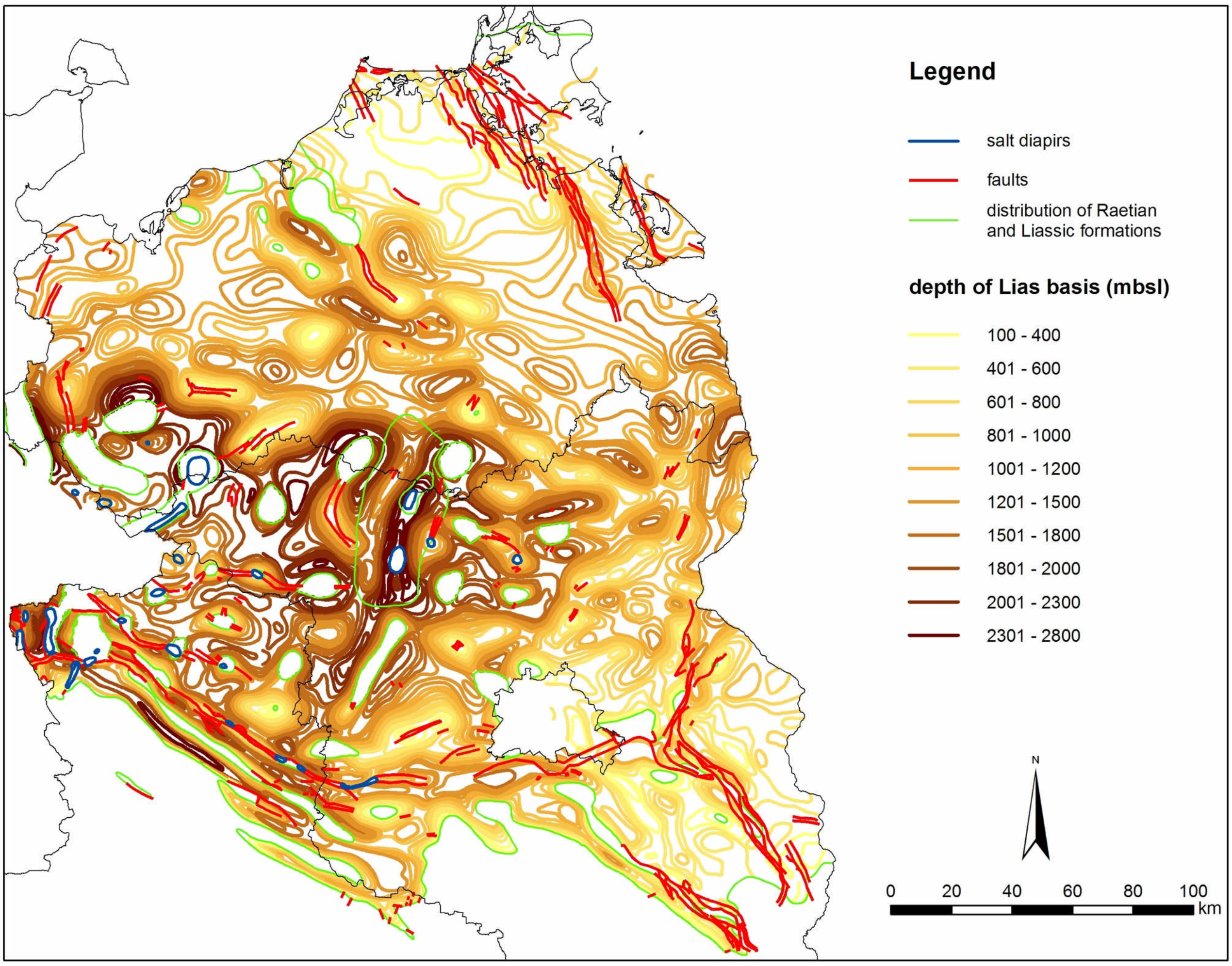

Figure 2: Distribution and depth of the Rhaetian and Liassic formations in NE Germany.

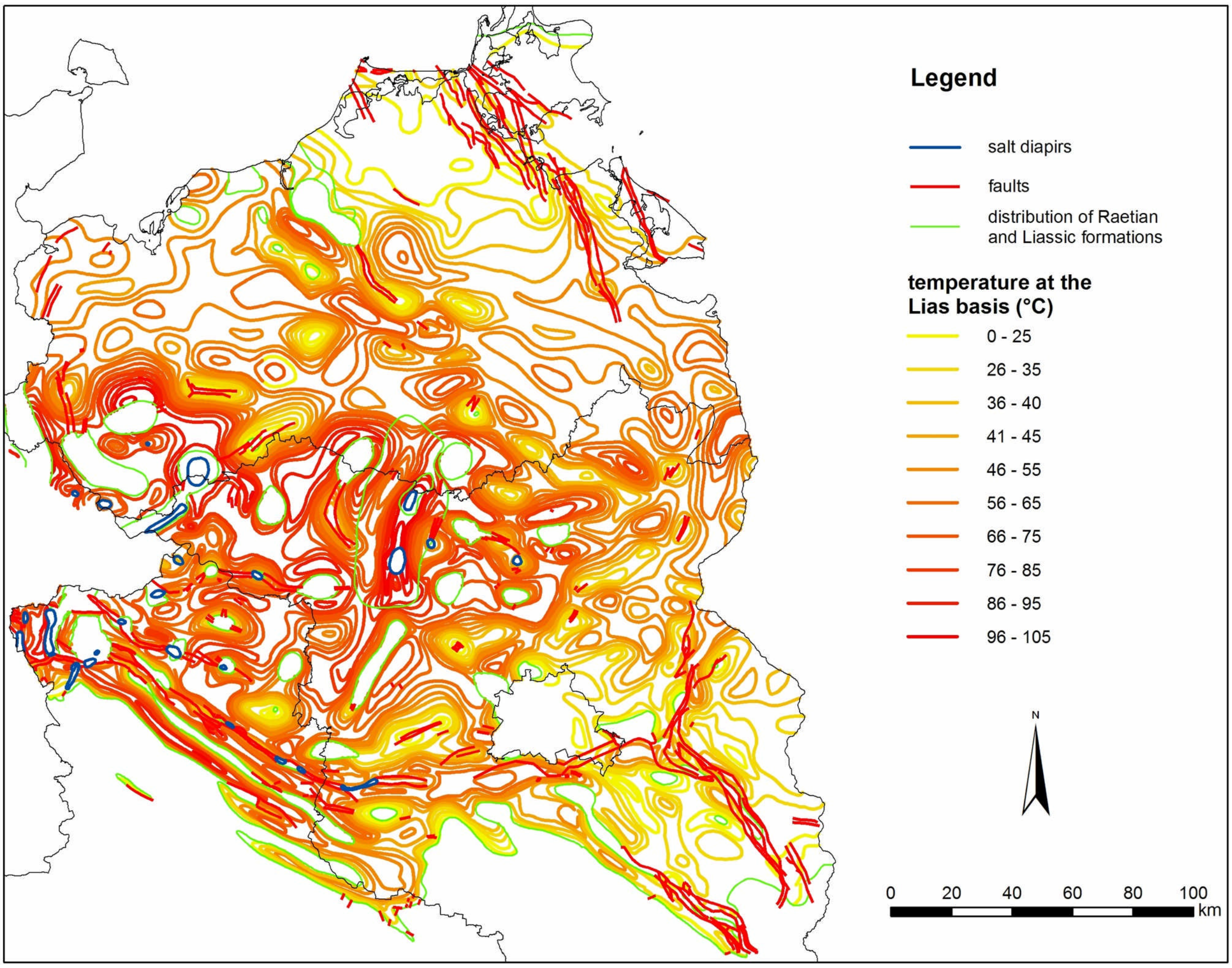

Figure 3: Temperature at the basis of the Liassic in NE Germany. The isotherms are interpreted from temperature measurements in boreholes in combination with the depth of the Liassic and the thickness of the Zechstein salt below.