Geological atlas of the Ruhr Area

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Martin Arndt (GD NRW)

Gabriela de los Angeles Gonzales de Lucio (GD NRW)

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Disclaimer

The information provided in this report are based on available data and current scientific knowledge. It is intended to provide initial information for potential deep geothermal energy users. The results presented herein do not replace the own independent research on this topic. Any decision based on this report should be evaluated by an expert of the respective field.

We cannot guarantee the accuracy, reliability, correctness or completeness of the information and materials given in this report and accept no legal responsibility.

Contents

1. Introduction

The objective of this deliverable is to investigate the structure of the deep subsurface of the Ruhr Area from a deep geothermal perspective. Within the framework of DGE-ROLLOUT, an updated 3D model has been constructed for the Middle Devonian and Lower Carboniferous target horizons. Their carbonate rock formations are regarded as candidates for the development of deep geothermal energy (DGE). The geological and geothermal characteristics are briefly described and supplemented by depth, thickness and estimated temperature maps. This is intended to provide DGE users with decision support for initial planning steps.

Around 18 million people live in North Rhine-Westphalia and more than 6 million of them in the Ruhr Area, the largest metropolitan area in North-West Europe (NWE). The Ruhr Area covers about 4,400 km^2 and is framed by the rivers Rhine to the west, Lippe to the north, and Ruhr to the south. It includes the cities and municipalities of Bochum, Bottrop, Dortmund, Duisburg, Enneppe-Ruhr-Kreis, Essen, Gelsenkirchen, Hagen, Hamm, Herne, Mühlheim an der Ruhr, Oberhausen, Recklinghausen, Unna and Wesel (https://www.rvr.ruhr/politik-regionalverband/staedte-kreise/).

Initially, larger cities, such as Bochum, Dortmund, Duisburg and Essen have grown together to this metropolitan area, which gained first importance with the onset of industrialization at the end of the 19th century. Here, the hard coal of the Upper Carboniferous occurs close to the surface and was mined extensively due to its easy accessibility. As coal mining expanded northwards following the inclination of the coal seams into greater depths, smaller cities such as Bottrop, Gelsenkirchen and Herne gained more importance, too. The Ruhr Area is known for its mining and heavy industry ever since. However, due to a political resolution, coal mining has ceased in 2018 and numerous industrial sites have been transformed into, e.g., residential and business locations. Nowadays, these sites often comprise recreational areas into which their industrial past has been cleverly integrated. With regard to existing district heating networks, DGE could be implemented to provide renewable heat to a large number of households.

In the frame of the DGE-ROLLOUT project, the existing geological data of the deep subsurface of the Ruhr Area has been revised and included into a new 3D model, which is harmonized with the recently published 3D models of the Lower Rhine Embayment and the Northern Rhenish Massif in an online application of the Geological Survey of North Rhine-Westphalia (GD NRW): https://www.geothermie.nrw.de/. The project area of the atlas of the Ruhr Area was defined to cover the cities and municipalities of Bochum, Bottrop, Dortmund, Essen, Gelsenkirchen, Hamm, Herne, Mühlheim an der Ruhr, Oberhausen, Recklinghausen, Unna, the southeastern part of Coesfeld (Nordkirchen, Ascheberg) and the southwestern part of Warendorf (Ahlen, Drensteinfurt, Sendenhorst) (Figure 1). Since the cities and municipalities of Duisburg, Hagen, Enneppe-Ruhr-Kreis, and Wesel were already included in the published 3D models of the Lower Rhine Embayment and the Northern Rhenish Massif, they were not included in the project area of the atlas of the Ruhr Area.

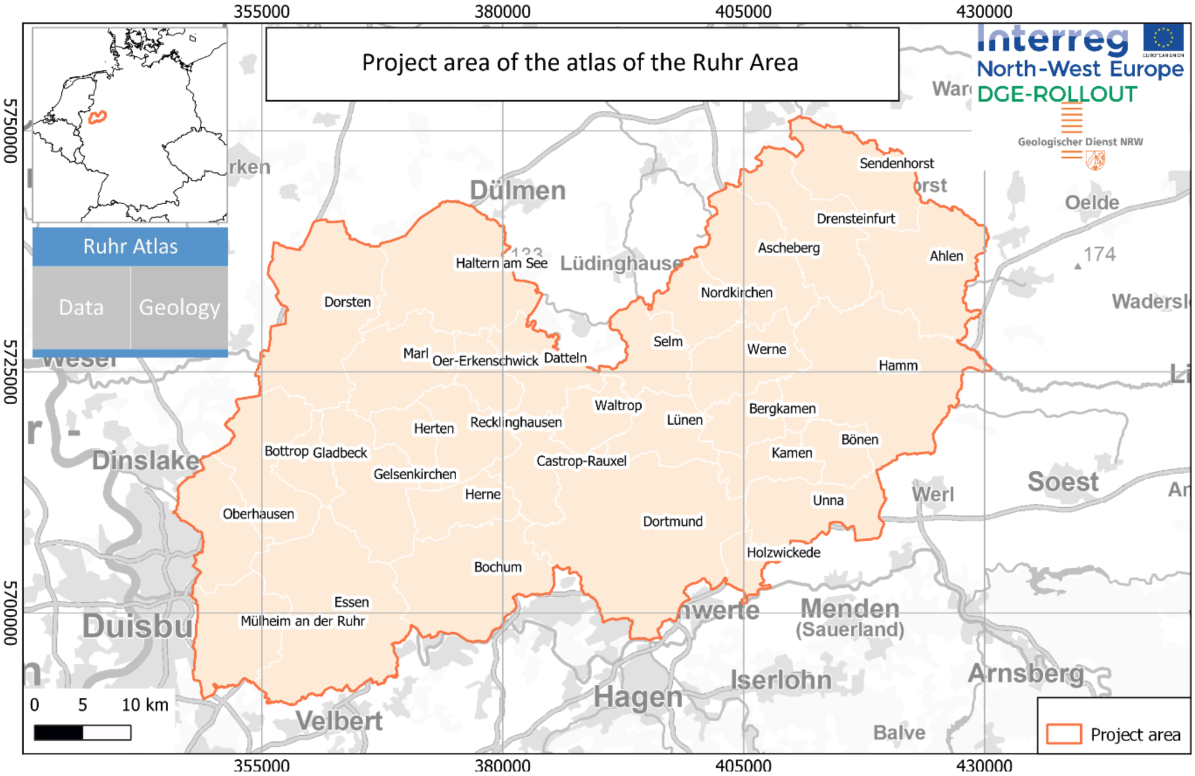

Figure 1: Map of the project area of the atlas of the Ruhr Area with the cities and municipalities considered in this report.

1.1 Geological overview

The subsurface of the project area of the atlas of the Ruhr Area can be divided into two major geological units: the Variscan basement consisting of folded Devonian and Carboniferous rocks, and the overburden of the Münsterland Cretaceous Basin and the Lower Rhine Embayment. Sedimentation and erosion within the project area of the atlas of the Ruhr Area were controlled by sea level changes caused by trans- and regressional events, climatic conditions and tectonic processes.

The sedimentary succession of the Devonian derived from the former Old Red Continent and was deposited on its southern shelf in the Rhenohercynian Basin. Thus, sandstone, clay and limestone successions can be expected in the deep subsurface below the Ruhr Area (GD NRW 2020). Carbonate rocks originating from coral reefs may also occur, however, they are only exposed in the northern part of the low mountain ranges of the 'Bergisches Land' and 'Sauerland', which form the Rhenish Massif in NRW (GD NRW 2012, GD NRW 2017).

During the Early Carboniferous, the ocean trough of the Rhenohercynian Basin began to sink as the Variscan mountain chain successively moved northwestwards. This resulted in different depositional areas: In the west of the basin, shelf deposits including a carbonate platform developed. In the center, sediment rocks of the Kulm basin facies accumulated comprising shale and alternating turbiditic limestone successions. The latter originated from the western carbonate platform or a carbonate platform that is expected below the Münsterland Cretaceous Basin (Korn 2008). In the southeastern part of the basin, flysch deposits consisting of sandstone layers accumulated. With increased shortening of the basin during the Late Carboniferous, the ocean trough became a flat coastal plain known as the Subvariscan

Foredeep (Drozdzewski & Wrede 1994). Climate conditions favoured the development of an extensive marshland, from which today's hard coals in the Ruhr Area derive.

Later, the Upper Carboniferous strata were folded, traversed by faults and incorporated into the orogenic belt. Their uplift and erosion during the Variscan Orogeny formed the Rhenish Massif. The project area of the atlas of the Ruhr Area was part of this paleogeographic high and therefore only has younger sedimentary deposits at its margins.

The Rhenish Massif was located in the south of the North German Basin and was bounded on the west by the Lower Rhine Embayment and the east by the Hesse Basin ('Hessische Senke'). In the western part of the Ruhr Area, Permian, Lower Triassic, Cretaceous, Tertiary and Quaternary deposits are found. Further to the east, the Carboniferous is unconformably overlain by thick layers of Upper Cretaceous sediments with a thin Quaternary cover (GD NRW 2020).

Permian and Triassic sedimentary rocks were only deposited in the Lower Rhine Embayment, northwest of the project area. They consist of a series of Permian Zechstein evaporates that were subsequently covered by Early Triassic continental clay and sand deposits from a desert-like environment with only episodically water-bearing rivers, the Buntsandstein. No sedimentary deposits are known from mid-Triassic times until the Early Cretaceous (GD NRW 2020).

Towards the end of the Lower Cretaceous, the sea level began to rise significantly, which shifted the northern coastline far onto the Rhenish Massif, forming the Münsterland Cretaceous Basin. Until the end of the Cretaceous, sedimentation prevailed in the project area of the atlas of the Ruhr Area. The sedimentary succession comprises green sandstone deposits of the Essen and Duisburg formations (Cenomanian), clay marlstones and sandy marlstones of the Emscher Formation (Coniacian) as well as sands and sandy marlstones of the Haltern and Bottrop formations (Santonian), (GD NRW 2020).

Tertiary sediments are only known from the western part, where marine fine sands, silts and clays were deposited into the subsiding Lower Rhine Embayment. Quaternary sediments lie in patchy distribution on top of the Palaeozoic and Mesozoic deposits. Often, they are thin and reach only a few meters, sometimes they are missing. Only in the Lower Rhine Embayment, they can reach several tens of meters in thickness (GD NRW 2020).

1.2 Tectonic setting

During the Variscan Orogeny, the Carboniferous strata were folded into southwest-northeast striking anticlines and synclines, which subsequently experienced secondary folding. The Carboniferous strata can be divided into three horizontal units with different internal structures ('Stockwerkbau', Drozdzewski & Wrede 1994): in the upper unit, flat stratification prevails; in the middle unit, folds and overthrusts occur; and the lower unit consists of narrow folds with a few overthrusts. Overthrusts occur in all units and strike southwest-northeast in close mechanical relation to the overall fold structures and may dip to the northwest as well as to the southeast.

Northwest-southeast striking faults have all sorts from normal to strike-slip character with varying displacements, which created horst and graben structures during the Variscan Orogeny. The less pronounced the folding, the higher is the number of faults and their respective displacement within the project area of the atlas of the Ruhr Area. As the intensity of folding decreases from south to north, the intensity of faulting increases in the same direction (GD NRW 2020).

After the Variscan Orogeny, sedimentary deposits of the Münsterland Cretaceous Basin and the Lower Rhine Embayment unconformably overlaid the Devono-Carboniferous basement. In both of these major geological units, intense faulting can be recognized. The main tectonic movements occurred at the end of the Variscan folding, at the end of the Triassic and at the transition from the Jurassic to the Cretaceous. The repeated crustal movements resulted from transregional strains in connection with the opening of the Atlantic Ocean (GD NRW 2020). Widespread uplift of the crust led to partial erosion of the previously deposited strata. The uplift was accompanied by reactivation of existing faults and the formation of new faults. Reactivation of major faults within the Carboniferous basement also affected the overburden during the Late Cretaceous to the Early Tertiary (Wesche 2017).

During the Tertiary, another extensional phase took place in which Cretaceous faults were reactivated. They partially or completely reversed the uplift of Cretaceous units and older strata. Tectonic subsidence in the Lower Rhine Embayment lasted until the Quaternary (GD NRW 2020).

1.3 Hydraulic properties of fault zones

The hydrogeological assessment of rock units significantly depends on the characteristics of the present fault zones, which may function as aquifers, barriers, or a combination of both. The heterogeneous and complex internal structures result in directional hydraulic properties within fault zones and structural units.

In addition to the vertical offset, the width and shape of the fault zones and the nature of the individual deformation paths are decisive. Fault zones often show strongly fractured or fissured transitions to the intact host rock with crushed or pulverized rock material of varying grain size and consolidation. The unconsolidated material has a higher permeability, which is why fault zones can become an important migration pathway for subsurface waters and/or gases. Nonetheless, sorting processes may also lead to the accumulation of particularly fine-grained clayey material which then may act as a seal in parts of the fault zone.

Clayey material within the host rock may also be passively dragged into a fault zone or laterally injected by pressure differences between the host rock and the fault zone. Therefore, high permeabilities are not expected in faults near clay-rich formations, such as the Emscher Formation in the Cretaceous succession.

In the project area of the atlas of the Ruhr Area, numerous fault systems have been identified that penetrate the Devono-Carboniferous basement and the sedimentary overburden. They either reach the surface or terminate upwards within the Cretaceous strata.

The hydraulic effectiveness of fault zones within the Upper Carboniferous may vary. On the one hand, mineralized thermal waters are known from mining activities to emerge from several faults. On the other hand, hydraulic connections do not occur along large fault zones due to their heterogenic internal structures and complex water pathways.

There are only limited studies available on the hydraulic properties of fault zones in the Cretaceous strata. According to recent studies (Wesche 2017), most fault systems of the Münsterland Cretaceous Basin can be characterized as predominantly sealed. Only local hydraulic pathways are to be expected.

2. Methodology

Although the Ruhr Area has been extensively explored for its Upper Carboniferous coal deposits, there is little known from the underlying strata of the Lower Carboniferous and Devonian. Deep boreholes and seismic surveys only reach depths relevant for coal exploration. Deep boreholes that reach into the Lower Carboniferous and Devonian strata, such as Münsterland 1 and Versmold 1, may provide insights into the depth and facies of carbonate rocks, however, they are located too far outside the project area (Figure 2).

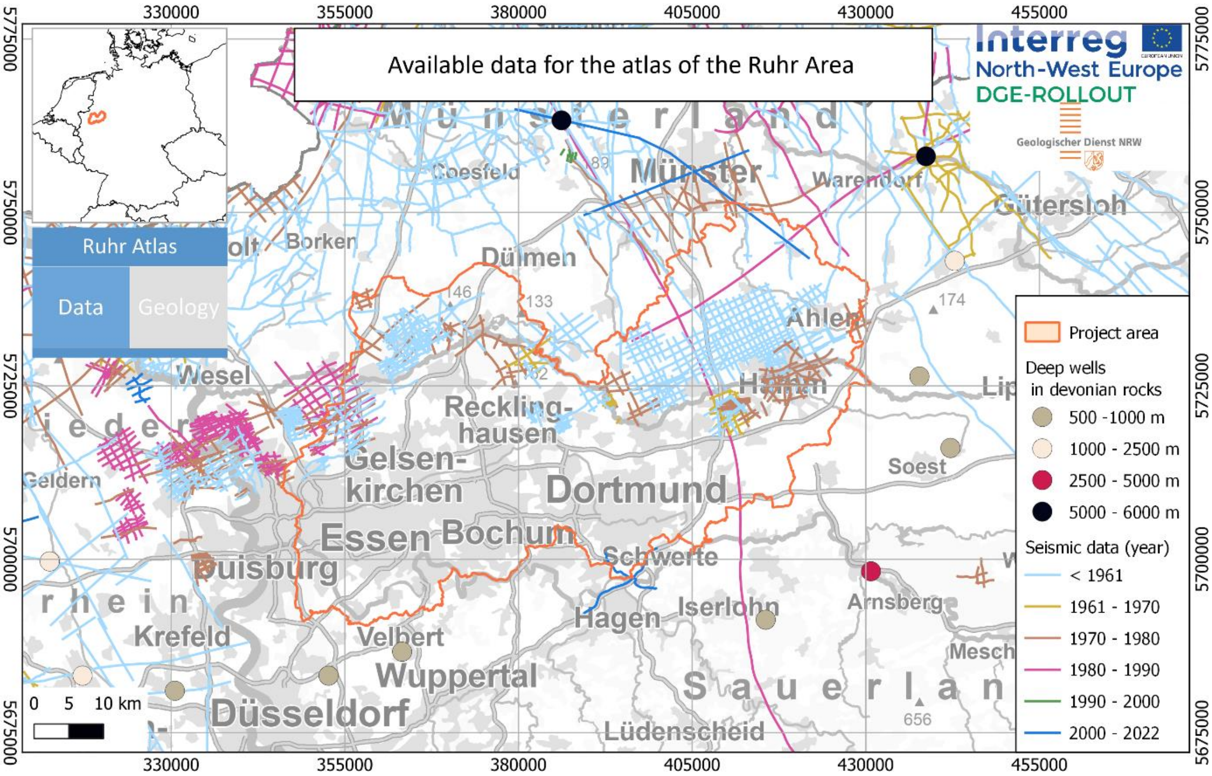

Figure 2: Overview of available data for the atlas of the Ruhr Area. No borehole in the project area (orange outline) reached the Lower Carboniferous or Devonian strata. Seismic data only reached depths relevant for coal exploration in the Upper Carboniferous succession.

Therefore, data of the structural model of the Upper Carboniferous (SMOK) were used for the construction of the target horizons. This model is formerly known as 'Kohlenvorratsberechnung' (KVB) and provides structural 3D information about all coal seams in the subsurface of NRW (Juch et al. 1994). Tectonic structures can be obtained from the location of the coal seam surfaces and their boundaries. Since original mining data were used, the reference horizons in the model have a high degree of accuracy.

The Geological Survey of North Rhine-Westphalia (GD NRW) constructed 3D models of the Lower Carboniferous and Devonian target horizons in the Lower Rhine Embayment and the Northern Rhenish Massif in the scope of the project for geothermal characterization of North Rhine-Westphalia (GTC). The data are available in an online application: https://www.geothermie.nrw.de/. Since the project areas of GTC and this deliverable overlap, the target horizons of the Ruhr Area can be correlated and connected with the GTC models. In addition, a structural 3D model for the overburden exists for parts of the project area known as the 'Strukturmodell Deckgebirge Ruhrgebiet'.

The 3D model of the Ruhr Area was constructed with the 3D modelling software MOVE (v2022; Petroleum Experts Ltd). In the first step, the faults were constructed using data of SMOK and the 'Strukturmodell Deckgebirge Ruhrgebiet". In the second step, the top and base of each of the Lower Carboniferous and Devonian target horizons were interpolated using SMOK data, borehole data, and thickness data from literature as well as from the adjacent GTC 3D models of the Lower Rhine Embayment and the Northern Rhenish Massif.

2.1 Construction of faults

All faults in the project area of the atlas of the Ruhr Area refer to the open dataset 'Großtektonik Ruhrgebiet'. The lines of this dataset were vertically projected onto the standard reference horizon of the Variscan basement, which is the pre-Permian horizon of the 3D model of NRW ('Landesmodell'). From these projected lines, the faults were constructed in two approaches, depending on data availability.

In the first approach, faults from the 'Strukturmodell Deckgebirge Ruhrgebiet' were imported into the MOVE project. They refer to the pre-Permian reference horizon of the 'Landesmodell' and the dataset 'Großtektonik Ruhrgebiet', which is why the fault surfaces only needed to be extended to the lower limit of the 3D model, which was set at 10,000 m. Statistical values of dip and azimuth were calculated with the SCAT tool in MOVE ('Mean Principal Orientation') and used for each fault surface individually.

All remaining faults were constructed using a more complex approach. Starting from the fault lines of the dataset 'Großtektonik Ruhrgebiet' projected onto the pre-Permian reference horizon, a fault surface was created by extending the lines to surfaces. Data for dip and azimuth were determined in a separate step: a narrow set of cross sections was created along each fault to create fault lines between the displaced coal seams of the SMOK. Based on these lines, a surface was created which was then used to calculate statistical dip and azimuth values with the SCAT tool in MOVE ('Mean Principal Orientation'). In a final step, the projected fault lines were also extended to the lower limit for the 3D model, which was set at 10,000 m.

All constructed faults were connected or cut along their intersection lines to finalize the fault model.

2.2 Construction of the target horizons

The target horizons are the top and the base of the Lower Carboniferous carbonate rocks as well as the top and the base of the Devonian carbonate rocks. Since no primary exploration data are available for these target horizons within the project area of the atlas of the Ruhr Area, their surfaces had to be interpolated from available data, such as boreholes and published thickness maps (e.g. Drozdzewski 1992, Arndt 2021).

As a reference horizon for the interpolation, the well-constrained coal seam 'Sarnsbank' of the SMOK was used. It marks the Namurian-Westphalian boundary within the Upper Carboniferous succession. For interpolating the Namurian, the thickness map of Drozdzewski (1992) was used. The remaining thickness maps of the Lower Carboniferous, the Upper Devonian, and the Devonian 'Massenkalk' were taken from the adjoining 3D models of the Lower Rhine Embayment and the Northern Rhenish Massif, as well as from data of the deep boreholes Münsterland 1 and Versmold 1. Finally, the surfaces were cut at fault intersections, and their displacement was adapted according to the offset values of each fault according to the existing data of the 'Strukturmodell Deckgebirge Ruhrgebiet'.

3. Results

In the following chapters, the Lower Carboniferous and Devonian carbonate rocks in the subsurface of the project area of the atlas of the Ruhr Area are characterized. The focus is on the description of the stratigraphic succession, lateral facies changes as well as distinctive features of the underlying and overlying strata. Additionally, information on the hydrogeological, reservoir and geothermal evaluation is provided.

3.1 The Lower Carboniferous carbonate rocks in the project area of the atlas of the Ruhr Area

Carboniferous strata occur throughout the subsurface of the project area of the atlas of the Ruhr Area. The Upper Carboniferous is well known from surface outcrops, numerous boreholes, and underground mining, whereas the Lower Carboniferous is mainly known from surface outcrops and shallow wells in the Rhenish Massif, south of the project area.

The Lower Carboniferous has an average thickness of 175 to 200 m and includes the Medebach and Drewer groups comprising the basin deposits of the Kulm facies (Figure 3). In the western part of the project area of the atlas of the Ruhr Area, the strata interfingers with the Heiligenhaus Formation of the Kohlenkalk Group. The latter forms the marginal facies of a carbonate platform extending further west (GD NRW 2020).

Along the Velbert Anticline, the formations translate into the Kulm facies towards east, which is predominantly composed of clastic rocks, such as dark mudstones and siltstones, and subordinated sandstones and dark siliceous shales. North of the Remscheid-Altena Anticline, these rocks alternate with turbiditic limestone sequences. Changes in thickness of the turbiditic limestone sequences of the Herdringen Formation possibly indicate the existence of a carbonate platform beneath the Cretaceous and Upper Carboniferous strata further north (Korn 2008). This platform may have supplied the material for the turbidites.

The base of the Lower Carboniferous comprises a major extinction event which is evident within the black shale and sandstone succession of the Hangenberg Formation. Below, fine sandy turbidites and shales of the Upper Devonian are found. The top of the Lower Carboniferous is indicated by the transition of the Kulm facies or the carbonate rocks of the Kohlenkalk Group to the Seltersberg Formation of the Upper Carboniferous, which consists of organic and pyrite-rich shales and siltstones (GD NRW 2020).

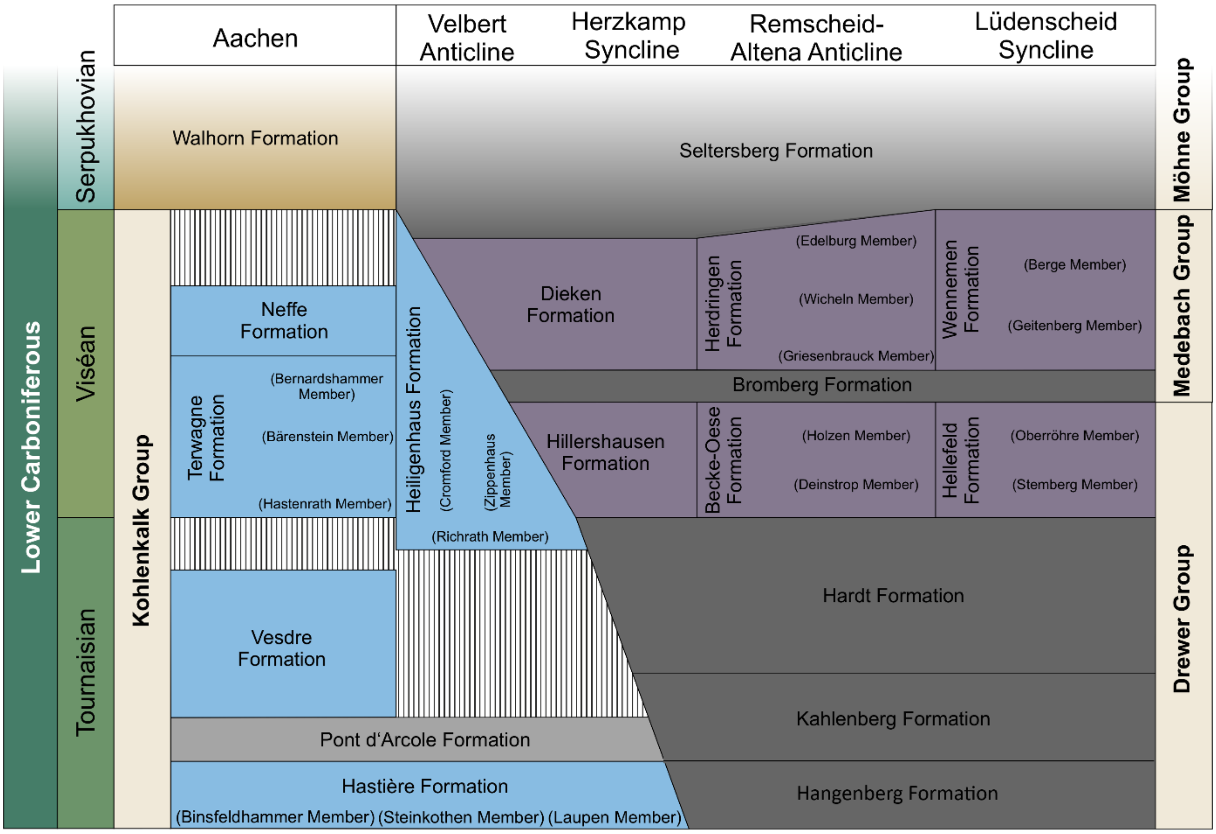

Figure 3: Stratigraphic overview of the Lower Carboniferous in North Rhine-Westphalia according to the outcrops of in western NRW (Aachen) and the Northern Rhenish Massif in central NRW (Velbert Anticline, Herzkamp Syncline, Remscheid-Altena Anticline, Lüdenscheid Syncline), modified after Arndt (2021): blue formations consist of carbonate rocks; purple formations consist of alternating successions of shale and turbiditic limestone sequences.

The Kulm facies contains fissure and karst aquifers with very low to low permeabilities, whereas the carbonate rocks of the Lower Carboniferous Kohlenkalk Group have medium to high permeabilities, depending on their degree of karstification. They are a main target for deep geothermal exploration in NRW. In particular near fault zones these rocks are expected to have a sufficiently high flow rate to allow geothermal exploitation with open well systems (doublets). Closed well systems with thermal conductivities between 3.0 and 5.5 W/(m*K) also appear to have a good geothermal potential (GD NRW 2020).

There are a number of risks that should be considered when drilling into the carbonate rocks of the Lower Carboniferous: karstification could cause the drill pipe to sag and drilling fluid to be lost. In addition, there is a risk of methane escaping from the coal-bearing layers of the Upper Carboniferous, especially beneath sealing rock layers such as the Cretaceous Emscher Formation.

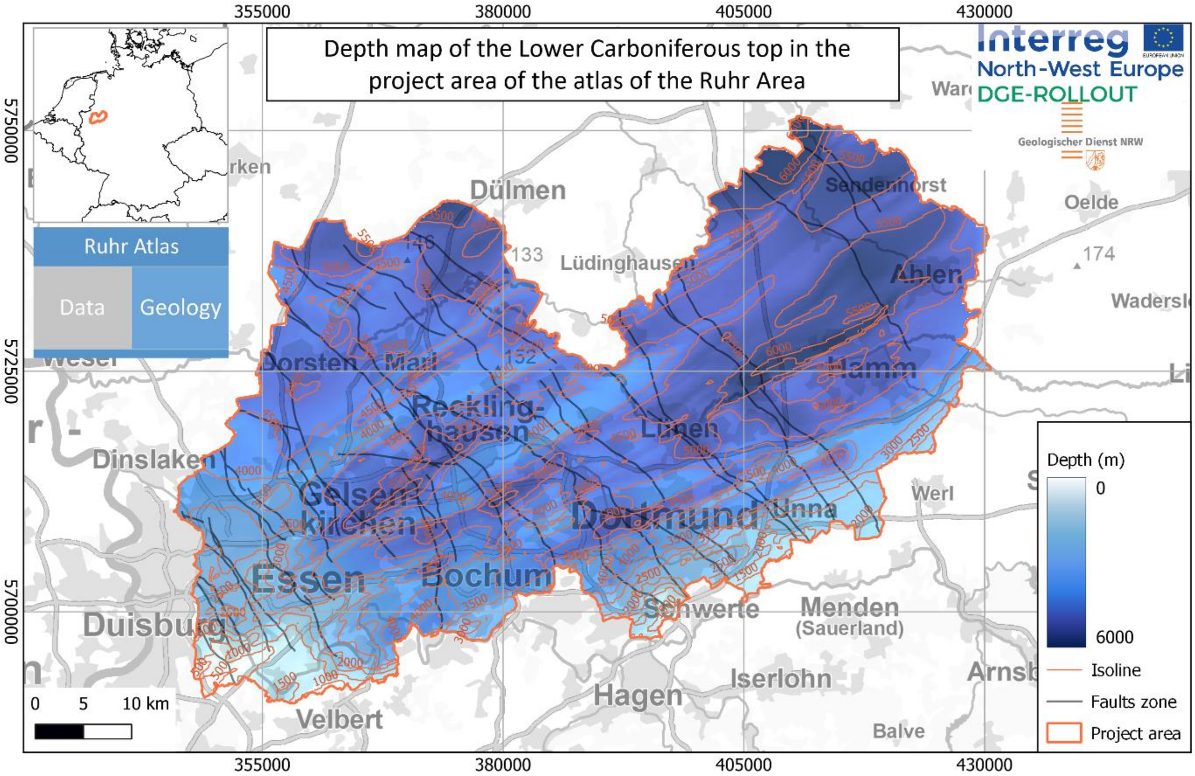

Figure 4: Depth map of the top of the Lower Carboniferous in the project area of the atlas of the Ruhr Area. The depth increases towards northeast from approximately 500 m down to 6,000 m. Regional and supra-regional faults are indicated with black lines. They trend northwest-southeast and have a dip of ≥ 60°.

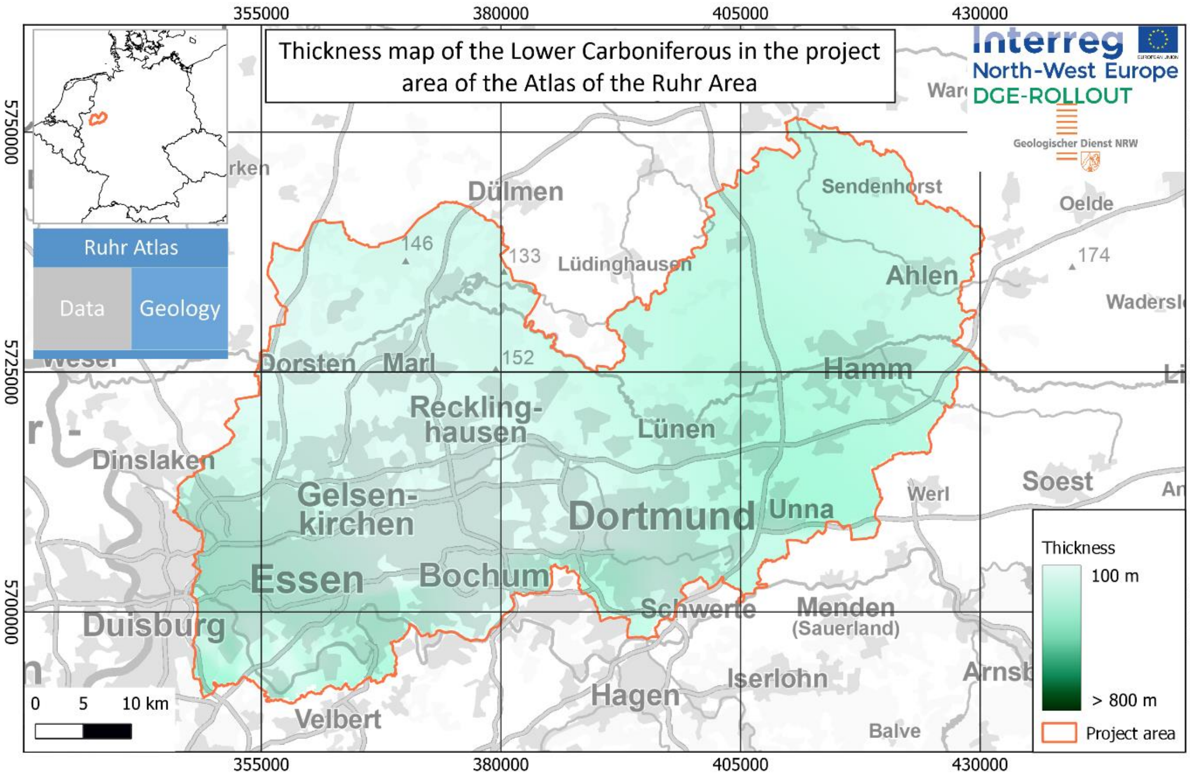

Figure 5: Thickness map of the Lower Carboniferous in the project area of the atlas of the Ruhr Area. The thickness was estimated from the boreholes Münsterland 1 and Versmold 1 as well as from 3D mapping data of the Lower Rhine Embayment and the Northern Rhenish Massif.

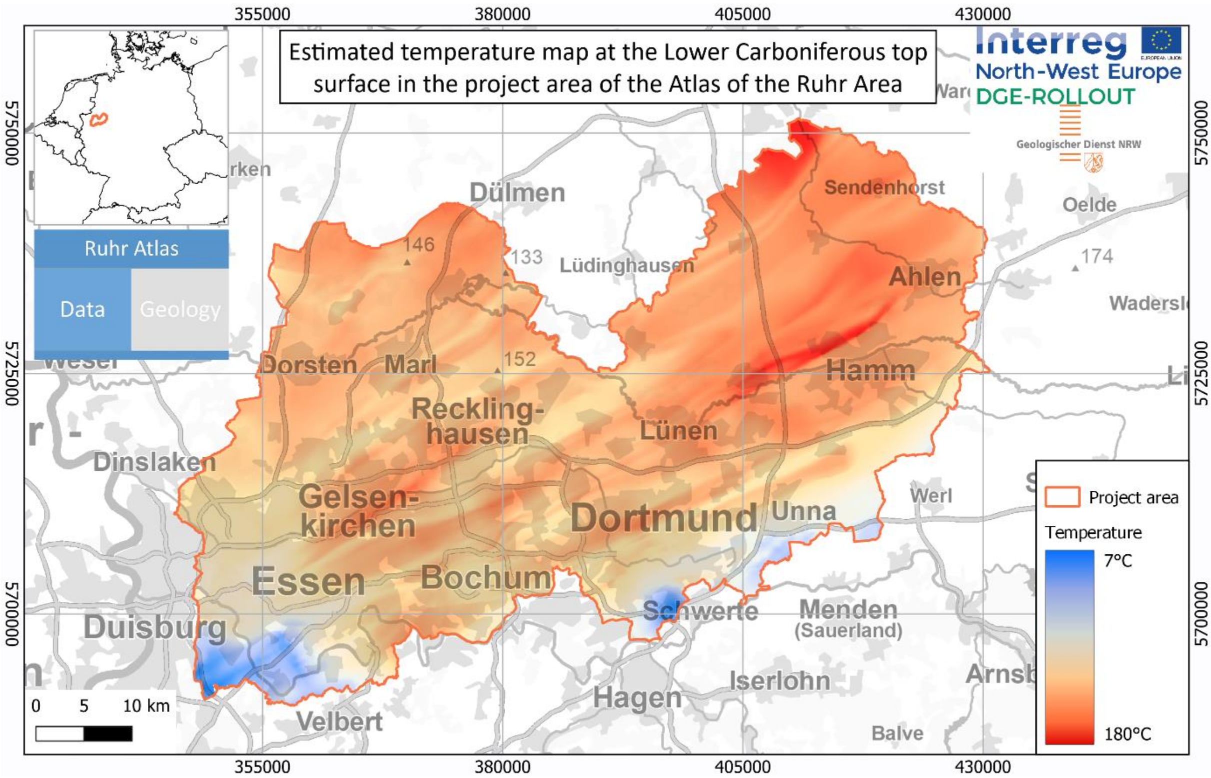

Figure 6: Estimated temperature map of the Lower Carboniferous in the project area of the atlas of the Ruhr Area. The temperature was estimated using an average geothermal gradient of 30 °C/km, starting at an average annual temperature of 10 °C at the surface. The highest temperatures are expected in the northeast.

3.2 The Devonian carbonate rocks in the project area of the atlas of the Ruhr Area

Devonian rocks occur only in the deeper subsurface of the project area of the atlas of the Ruhr Area. Little is known about their lithology and facies distribution, therefore most of the information is taken from near-surface outcrops of the Rhenish Massif. The Middle Devonian (Eifelian and Givetian) carbonate rocks, also referred to as 'Massenkalk', are of particular interest for the implementation of DGE in NRW.

The Devonian Massenkalk consists of mudstones, siltstones and marls with limestone beds, partly also with massive reef limestone deposits and subordinated sandstone layers. They were deposited in a marine basin at varying depths, flow and sedimentation conditions. Within the Eifelian, claystones and siltstones of a deeper shelf area predominate, whereas several 100 m thick reef limestone deposits are known from the Givetian succession. The latter laterally translates into clayey-carbonaceous debris flow deposits, known as the Flinz layers (GD NRW 2020).

The Devonian Massenkalk is considered as a fissure aquifer with very low to low rock permeabilities. Low to moderate rock permeabilities are expected in these karstified carbonate rocks. Middle Devonian carbonate rocks occurring at greater depths are of high interest as a deep geothermal target in NRW. In particular near fault zones these rocks are expected to have a sufficiently high flow rate to allow exploitation with open well systems (doublets). The implementation of closed deep well systems is possible. Thermal conductivity measurements in carbonate rocks, claystones and siltstones show a range of 2.5 to 3.5 W/(m*K). The subordinate sandstone horizons have thermal conductivities of 3.0 to 5.0 W/(m*K) due to their high density (GD NRW 2020).

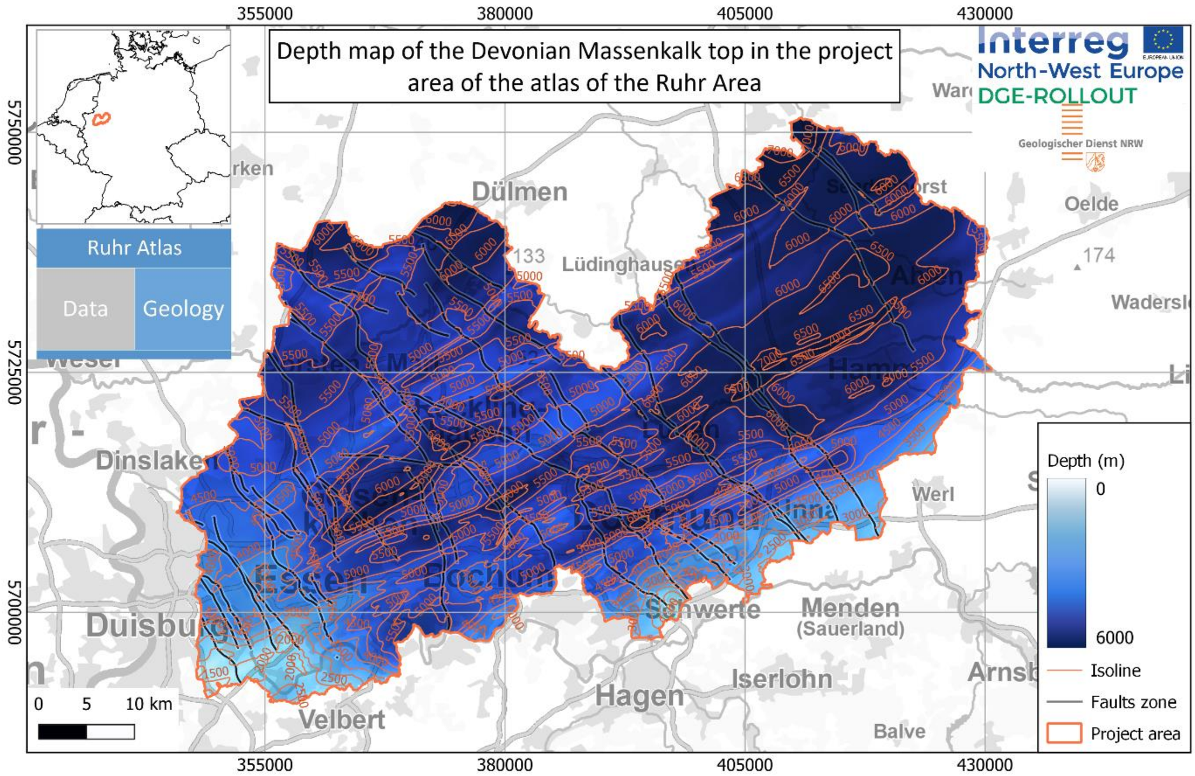

Figure 7: Depth map of the Devonian Massenkalk top in the project area of the atlas of the Ruhr Area. The maximum depth of more than 6,500 m is reached in the northeastern part. Regional and supra-regional faults are indicated with black lines. They trend northwest-southeast and have a dip of ≥ 60°.

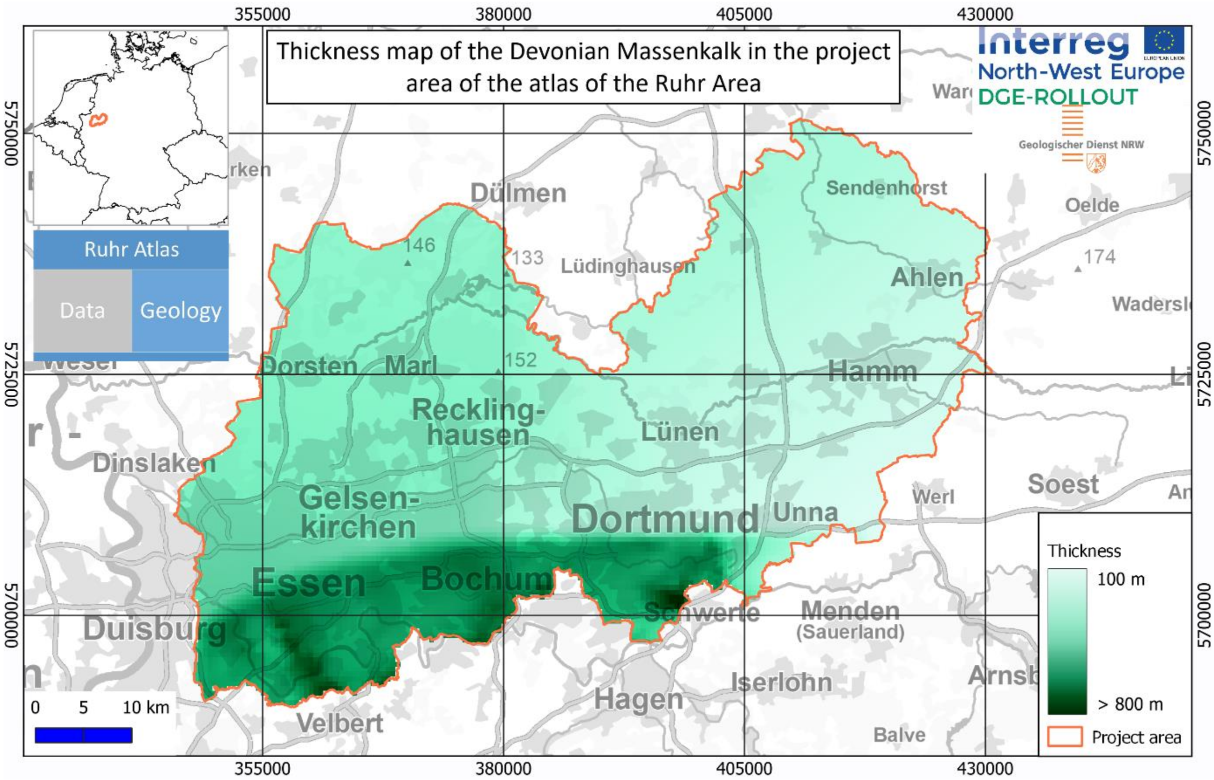

Figure 8: Thickness map of the Devonian Massenkalk in the project area of the atlas of the Ruhr Area. It was estimated from the boreholes Münsterland 1 and Versmold 1 as well as from 3D mapping data of the Lower Rhine Embayment and the Northern Rhenish Massif.

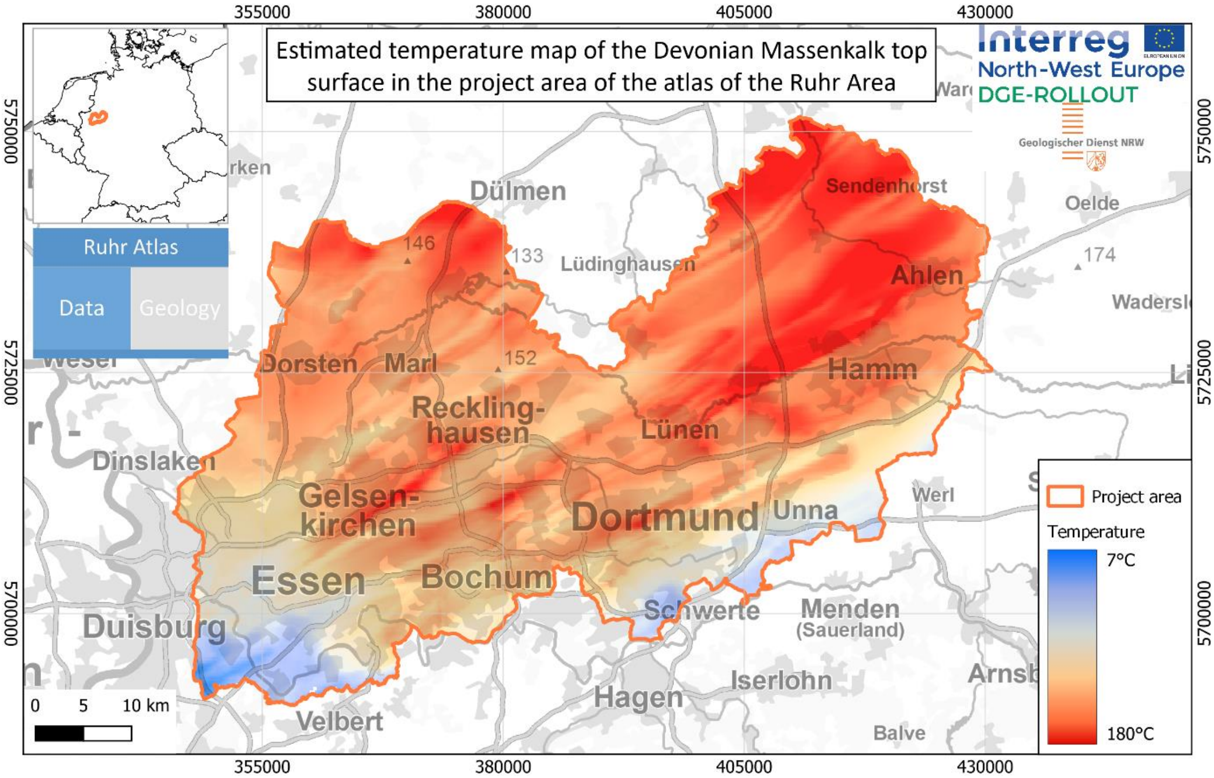

Figure 9: Estimated temperature map of the Devonian Massenkalk top surface in the project area of the atlas of the Ruhr Area. The temperature was estimated using an average geothermal gradient of 30 °C/km, starting at an average annual temperature of 10 °C at the surface. The highest temperatures are expected in the northeast.

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PROJECT PARTNERS

PROJECT SUBPARTNERS

MORE INFORMATION

Anna Thiel (Project Manager)

Anna.Thiel@gd.nrw.de

+49 2151 897 460

Vb.nweurope.eu/DGE-Rollout

@DGE-ROLLOUT

SUPPORTED BY

europiZe UG

Dr. Daniel Zerweck

+49 176 62 51 58 41

www.europize.eu