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Deep geothermal energy potential at Weisweiler, Germany: Exploring subsurface mid-Palaeozoic carbonate reservoir rocks

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Abstract: Carboniferous and Devonian carbonate rocks are present in the subsurface of the Weisweiler lignite-fired power plant near Aachen, Germany. The utilisation of these rocks for the purpose of deep geothermal energy extraction using hydrothermal techniques is currently being explored. First steps are undertaken as green field exploration in the course of the transnational EU-Interreg-funded "Roll-out of Deep Geothermal Energy in North-West Europe" (DGE-ROLLOUT) project, which aims to provide solutions to reduce carbon-dioxide emissions using a variety of geoscientific approaches.

As a result of multiphase deformation and faulting through Variscan and Alpine (post-)orogenic processes, a complex geological setting has emerged in the Weisweiler subsurface. However, considering the formation of both syncline-anticline and horst-graben structures the geological setting appears to exhibit favourable conditions for deep geothermal exploitation at several depth levels.

Besides ongoing mapping campaigns, as well as lithological and structural studies, a preliminary geological 3D model of the subsurface of the Weisweiler area has been constructed on the basis of which a first drilling operation is currently being planned. At the same time, the subsurface 3D model is currently being transferred into a thermohydraulic 3D model to obtain first impressions on possible fluid pathways within the targeted carbonate horizons. In addition, a variety of petrophysical and (isotope) geochemical analyses of analogue rock samples are also underway.

Keywords: DGE-ROLLOUT, Interreg NWE, Kohlenkalk Group, Massenkalk facies, hydrothermal geothermics, seismic observatory, exploration drilling, 3D modelling

1. Introduction

Hydrothermal aspects of karstified carbonate rocks of the Molasse Basin in southern Germany and Austria have been under investigation since the 1970's (Homuth 2014, and references therein). Commercial hydrothermal exploitation of these Jurassic aquifers in Germany is in operation since the late 1990's[1]. However, to date, subsurface Devonian and Carboniferous carbonate rocks occurring in the Rhenohercynian Basin of northwest Europe have largely eluded deep geothermal investigation in the German federal state of North Rhine-Westphalia[1,2]. Based on the experiences gained from the operations in the German part of the Molasse Basin (e.g. Dorsch 2012; Steiner et al. 2014; Dirner & Steiner 2015), the "Roll-out of Deep Geothermal Energy in North-West Europe" (DGE-ROLLOUT) project, funded through the EU-Interreg North-West Europe Programme, was initiated by the Geological Survey of North Rhine-Westphalia in 2018 (Salamon & Thiel 2019; Fritschle et al. 2021).

A major activity within the DGE-ROLLOUT project revolves around the geothermal characterisation of the subsurface of the lignite-fired power plant in Weisweiler, westernmost Germany, where carbonate rocks of the Devonian Massenkalk facies and the Carboniferous Kohlenkalk Group are present in some thousand metres depth. In the course of this activity it is currently being tested whether the geological characteristics of these carbonate rocks, e.g. depth, karstification and fracturing, allow for the implementation of hydrothermal energy extraction. Assuming suitable conditions in the potential geothermal reservoirs, it is aimed to replace (parts of) the nowadays conventionally obtained energy sup-

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plying the regional district heating network (Oswald et al. 2021).

Hydrothermal exploitation of the Lower Carboniferous Kohlenkalk horizon, for example, is currently in test operation in the nearby Balmatt site in Belgium (Bos & Laenen 2017; Broothaers et al. 2019; Broothaers et al. 2021, this issue) and in Californië in the Netherlands (Reith 2018; Mijnlieff 2020). At Balmatt, the production well is situated at a depth of 3,609 m, operating at a flow rate of 140 m^3/h and yielding a production temperature of 128 °C (Bos & Laenen 2017). At Californië, where production has been stopped in 2018 due to induced seismicity[3], two production wells (GT-01 and GT-04) reach depths of 2,082.00 and 3,037.20 m[4], respectively, yielding production temperatures of about 75–80 °C for GT-01 and c. 88 °C for GT-04 (Vörös & Baisch 2019; Broothaers et al. 2021, this issue).

The first investigations at Weisweiler include the drilling of a c. 1,500 m deep borehole on the premises of the Weisweiler power plant and will determine the actual temperature depth profile, as well as the depth and thickness of the topmost geological formations, providing crucial information for the arrangement and scheduling of the subsequent undertakings. In parallel, petrophysical and geochemical analyses of the samples being obtained, in conjunction with borehole geophysical measurements, will support the further geothermal characterisation of the potential reservoir and cover rocks. These data will prove to what extend the geothermally relevant parameters are in agreement with data obtained from analogue samples of the regional geological formations. First studies of samples from the Devonian Massenkalk facies, e.g. thermal conductivity (2.2 to 3.3 W/mK), total porosity (4.7 to 10.0%) and permeability (5.9×10^{-17} to 2.8×10^{-16}) (Pederson et al. 2021, this issue), indicate that geothermal parameters are well in accordance with and partly surpass data from samples of the Molasse basin (Homuth 2014; Bär et al. 2020; Weydt et al. 2021).

In preparation of the drilling operation, a geological/geotectonic 3D model of the subsurface of the Weisweiler area was prepared to elucidate the general geological setting of the potential geothermal reservoirs (Fritschle et al. 2020). This model is currently being transformed into a thermohydraulic 3D model in order to investigate the potential fluid pathways in the distinct carbonate aquifers.

In the following we present the current status of the activities at Weisweiler, depict the framework which leads to the first arrangements, and outline the effects of the first developments for the further progress of the overall objective. The stratigraphic nomenclature throughout the text uses the Stratigraphic Table of Germany 2016 developed by the German Stratigraphic Commission.

2. Timeline and concept of the Weisweiler deep geothermal prospect

To date, the Weisweiler power plant has a total capacity (lignite) of about 1,900 MW as well as 400 MW gas, and generates 9,706 GWh power per year through coal and gas combustion. The connected district heating network (DHN) supplies households in the city of Aachen, Inden and Jülich. Nearly the complete DHN is fed by the energy produced by the Weisweiler power plant, which sums up to a total of c. 376 MW_{th} (ZfK 2020). With regard to the forthcoming fossil fuel phase-out, the lignite-fired power plant will terminate its conventional operation in 2029. Nonetheless, it is intended to uphold large parts of the supply by feeding geothermal energy into the DHN.

The general idea behind the current project is to use hydrothermal techniques for the extraction of geothermal heat. Therefore, both of the subsurface carbonate units, the Lower Carboniferous Kohlenkalk Group as well as the Middle to Upper Devonian Massenkalk facies, are potential targets for geothermal exploitation. As outlined below, both of these carbonate horizons may be present at various depth levels in the Weisweiler area, opening up the possibility to also extract distinct temperature levels from the subsurface.

Expecting suitable geothermal characteristics of the carbonate reservoirs in the subsurface of the Weisweiler power plant, as indicated by lithological features of nearby analogues and drill core samples, and as anticipated from extensive geological studies, 3D modelling and available geothermal parameters, it is planned to start with a first exploration drilling by the beginning of 2022. Whereas the current drilling survey is being financed through the Interreg DGE-ROLLOUT project, further activities revolving around the geothermal prospect Weisweiler will be undertaken after the project's end in October 2022.

A decisive next step in the exploration of the geothermal potential of the Weisweiler subsurface envisages seismic surveys in 2022 to 2023 (Oswald et al. 2021) under the lead of Fraunhofer IEG. Major results of this seismic investigation in conjunction with the green field exploration undertaken within the DGE-ROLLOUT project will assess whether and to what extent the current model approaches match the actual geological/geotectonic conditions. These additional data will provide crucial insight into the geometry of the underground structures and the hydrothermal suitability of the targeted reservoir rocks.

Assuming further progress of the geothermal prospection at Weisweiler, the subsequent work will include complementary drilling campaigns into the crest of the Inde Syncline, down to a depth of c. 4,000 m, sampling both the Kohlenkalk and Massenkalk potential reservoirs. The installation of a geothermal doublet in envisaged for 2023 to 2025. If the results of the geothermal doublet is suitable, it is envisioned to implement geothermal heat production into a planned Fraunhofer IEG research power plant by the end of 2026, and subsequently into the DHN, if applicable.

3. Geological background

Marine transgressive-regressive cycles during mid-Palaeozoic times enabled the formation of extensive reef complexes on the southerly continental shelf of the Laurussian palaeocontinent. Supported by favourable climatic conditions including warm, clear and shallow waters, the Givetian to Frasnian Massenkalk facies and the Lower Carboniferous Kohlenkalk Group, each several hundred metres thick, evolved in North-West Europe around the London Brabant Massif and as isolated platforms (Arndt 2021; Arndt et al. 2021; Broothaers et al. 2021; Laurent et al. 2021; Pharaoh et al. 2021; Pracht et al. 2021, all this issue).

Prerequisite for the deposition and manifestation of the Palaeozoic carbonate platforms and debris was the initial formation of the Rheic Ocean (Nance et al. 2010) following the onset of subduction within the pre-existent northerly outboard Iapetus Ocean in early Ordovician (McConnell & Morris 1997). The latter process initiated the separation of several Neoproterozoic arc terranes (Avalonia, Ganderia, Carolinia and Meguma) from the northern margin of Gondwana which rapidly drifted northwards, enabling the development of the Rheic Ocean (Fig. 1). By the closure of the Iapetus Ocean in Silurian times and consequential terrane amalgamation to Laurentia (McConnell et al. 2020) the Rheic Ocean had reached its maximum extension of c. 4,000 km. Subsequent subduction of Rheic Ocean lithosphere beneath the emerged Laurussian Palaeocontinent started in early Devonian.

At the time of deposition of the Massenkalk facies and the Kohlenkalk Group, the Rheic Ocean had developed to an aggregation of separate terranes and narrow oceans, each of which underwent distinct Wilson Cycles (Franke et al. 2017). One of these narrow oceans, the short-lived Rhenohercynian Ocean (Franke et al. 2017, 2019), opened in Emsian times triggered through subduction of the Rheic Ocean rift underneath Franconian (North Armorican) continental lithosphere. By mid- to late Devonian, closure of the Rhenohercynian Ocean had already started with collision of the northerly Avalonian and the southerly Franconian continental plates in the course of the Variscan Orogeny.

In the following, ideal conditions for the widespread formation of extensive reef complexes evolved through narrowing and uplift of the Rhenohercynian Ocean (Arndt et al. 2020), in connection with the shallowing of the ocean due to

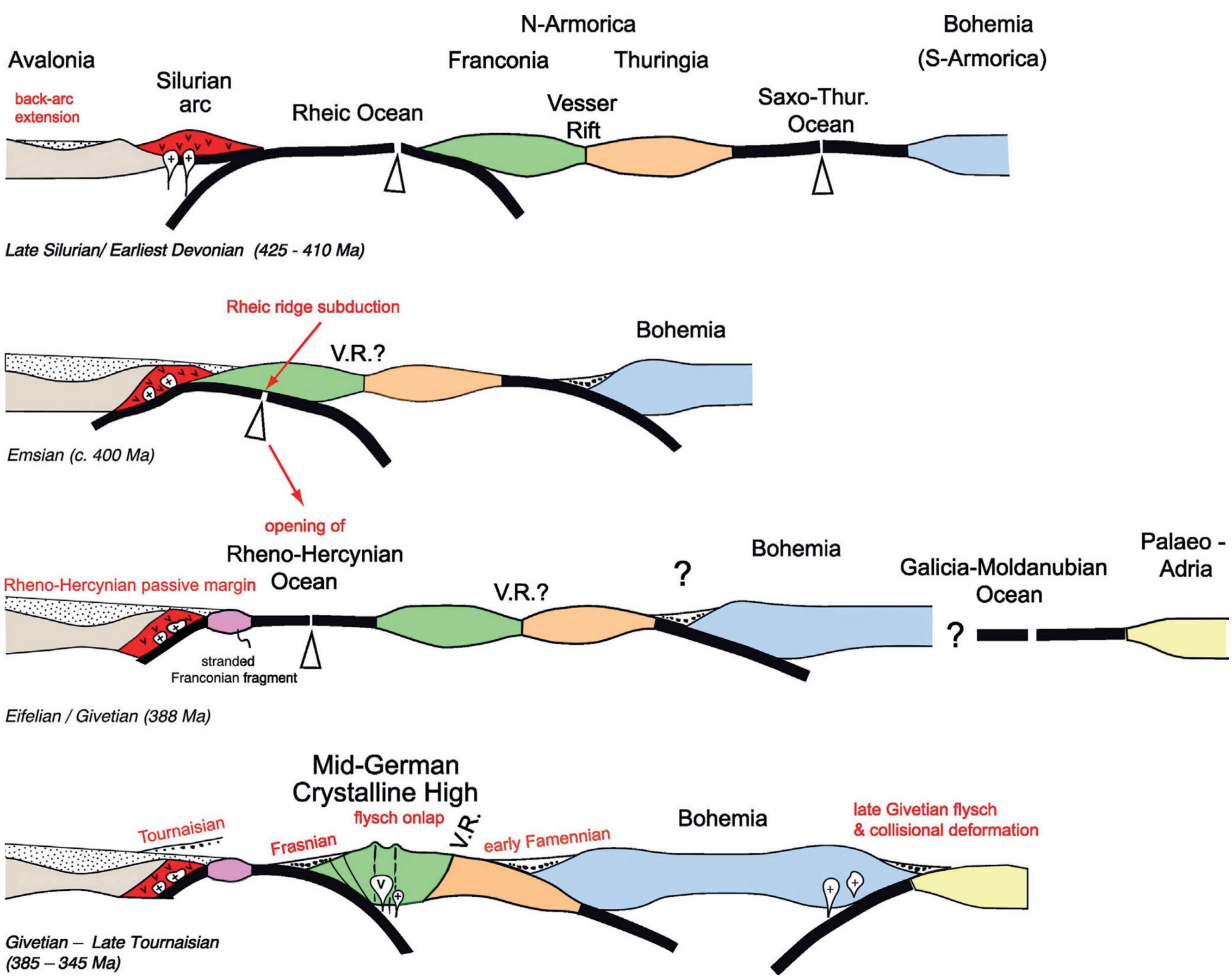

Fig. 1: Cartoon of the plate-tectonic evolution in the central European segment of the Variscides during the late Silurian through to early Carboniferous including the formation and closure of the Rhenohercynian Ocean (Franke et al. 2017).

deposition of high volumes of material eroded from the Laurussian palaeocontinent. Within only a few million years from Givetian to Frasnian the partly more than thousand metres thick Massenkalk facies emerged, favourably at the continental shelf in the northerly parts of the shallow ocean basin. Main constituents of these fossil rich carbonate rocks include corals and stromatopores.

Renewed deepening of the Rhenohercynian Ocean in late Devonian resulted in the deposition of clay-rich sedimentary rocks and reef debris on top of the Massenkalk before a new phase of reef formation commenced in earliest Carboniferous times. Formation of the Kohlenkalk Group, predominantly carbonate rocks comprising a rich fauna consistent of brachiopods, goniatites, bryozoans and corals, lasted until late Viséan times. These reef carbonates reach a thickness up to three hundred metres nearby the Weisweiler area of interest (e.g. Wrede & Zeller 1988).

4. Tectonic setting

Subsequent to their deposition, the Devonian and Carboniferous carbonate rocks were covered by voluminous paralic sedimentary rocks of Westphalian and Namurian age, and the complete strata was deformed to large-scale, generally southwest–northeast trending, syncline-anticline structures during the main phase of the Variscan Orogeny, in late Carboniferous times. Contemporaneously, similarly-directed thrust faults, which may have developed displacements of more than 1,000 metres, emerged in the Weisweiler area (Ribbert & Wrede 2005). Sedimentation during Meso- and Cenozoic times, together with tectonic processes during the Alpine Orogeny, further modified the structure and depth of the carbonate rocks. Importantly, these mainly Tertiary Alpine orogenic processes induced significant faulting and strike-slip movements resulting in extensive northwest–southeast directed fault block tectonics including horst-graben structures. Displacements along these structures may range from neglectable extents up to several hundreds of metres. However, it has to be considered that several of the normal faults may have been originally created in Permian to Cretaceous times and have been reactivated through Alpine processes (e.g. Wrede 1985; Knaak et al. 2020). After all, the Weisweiler geological setting in the present day is largely determined by Tertiary (Alpine) northwest–southeast directed fault block tectonics compartmentalising the older southwest–northeast trending syncline-anticline structures and parasitic folds in an area of still active tectonic subsidence, i.e. the Lower Rhine Embayment.

Current seismic activities in the area are generally minor, however, at least some of the Tertiary northwest–southeast trending faults associated with the opening of the Rhine Valley are known as being seismically active (see overview of earthquakes in Pelzing 2008). These Tertiary faults which cross-cut earlier Variscan thrust faults, and which occur in a spacing of several hundred metres to a few kilometres, have produced historic earthquakes with magnitudes >6, i.e. a M6.1 earthquake in Düren in 1756 (Grünthal 2004). The most significant earthquake in the area which occurred during the past few decades was situated c. 50 km to the northwest of Weisweiler, in the subsurface of the Dutch city Roermond. This earthquake of 1992 had its epicentre at c. 18 km in the subsurface and resulted in a magnitude of 5.3 (Braunmiller et al. 1994).

The most recent, noticeable (about M2.1 to M2.8) earthquakes in the area occurred between January and February 2021 with a series of shakings in Roetgen, c. 20 km southwest of Weisweiler[5]. Other minor and not noticeable earthquakes occur regularly in the area and can be followed through the information provided by the Landeserdbebendienst NRW[6] (State Earthquake Service of North Rhine-Westphalia, affiliated to the Geological Survey of North Rhine-Westphalia, GD NRW). The earthquake foci in the area are mainly located in depths between 5 and 15 km, and are assumed to trace major northwest–southeast trending faults in the subsurface. This earthquake activity, together with a constant seismic tremor of minor earthquakes was classified to represent a seismic hazard risk zone 3 (Grünthal et al. 2018).

5. Weisweiler site

The town of Weisweiler is located in the Rhenish lignite area in the federal state of North Rhine-Westphalia in westernmost Germany (Fig. 2: inset). The site of the power plant lies in the immediate vicinity to the open pit mine Inden from which it is provided with lignite. The geological setting at the Weisweiler power plant site is determined by two major faults, the Weisweiler and Merode faults, which span a 1.2 to 1.5 km wide horst on the surface, edging the designated spot for the first exploration drilling to the west–southwest and east–northeast (Fig. 2). The designated target for geothermal extraction, the crest of the northwest-vergent Inde Syncline, lies in the south-southeast of the latter spot.

The most important geological constraints for the subsurface geology of the Weisweiler site were provided by the nearby drilling "Frenzer Staffel 1" (cf. Fig 2) which was drilled in 1985/86, and which reached a depth of 434 m (Muller et al. 1991). The drilling which targeted the fold axis of the Inde Syncline is located c. 1.5 km east of the designated drilling spot for the current geothermal exploration.

The drill core of the Frenzer Staffel 1 revealed that the subsurface geology in the first few hundred metres below the Weisweiler area is determined by a thick sequence of Upper Carboniferous layers which are situated below a thin cover of c. 160 m of Quaternary and Tertiary sedimentary rocks. Despite controversaries on the stratigraphic interpretation of the drilled sequence (Wrede & Zeller 1991, and references therein), mainly due to the lack of distinctive marker horizons, Wrede & Zeller (1991) attribute the entirety of the drilling Frenzer Staffel 1 to the uppermost Westphalian A on the basis of palynological investigations (Streel & Loboziak 1991).

A critical factor with regard to the geothermal exploitation using hydrothermal techniques is the availability of fluid pathways in the carbonate horizons. Therefore, signifi-

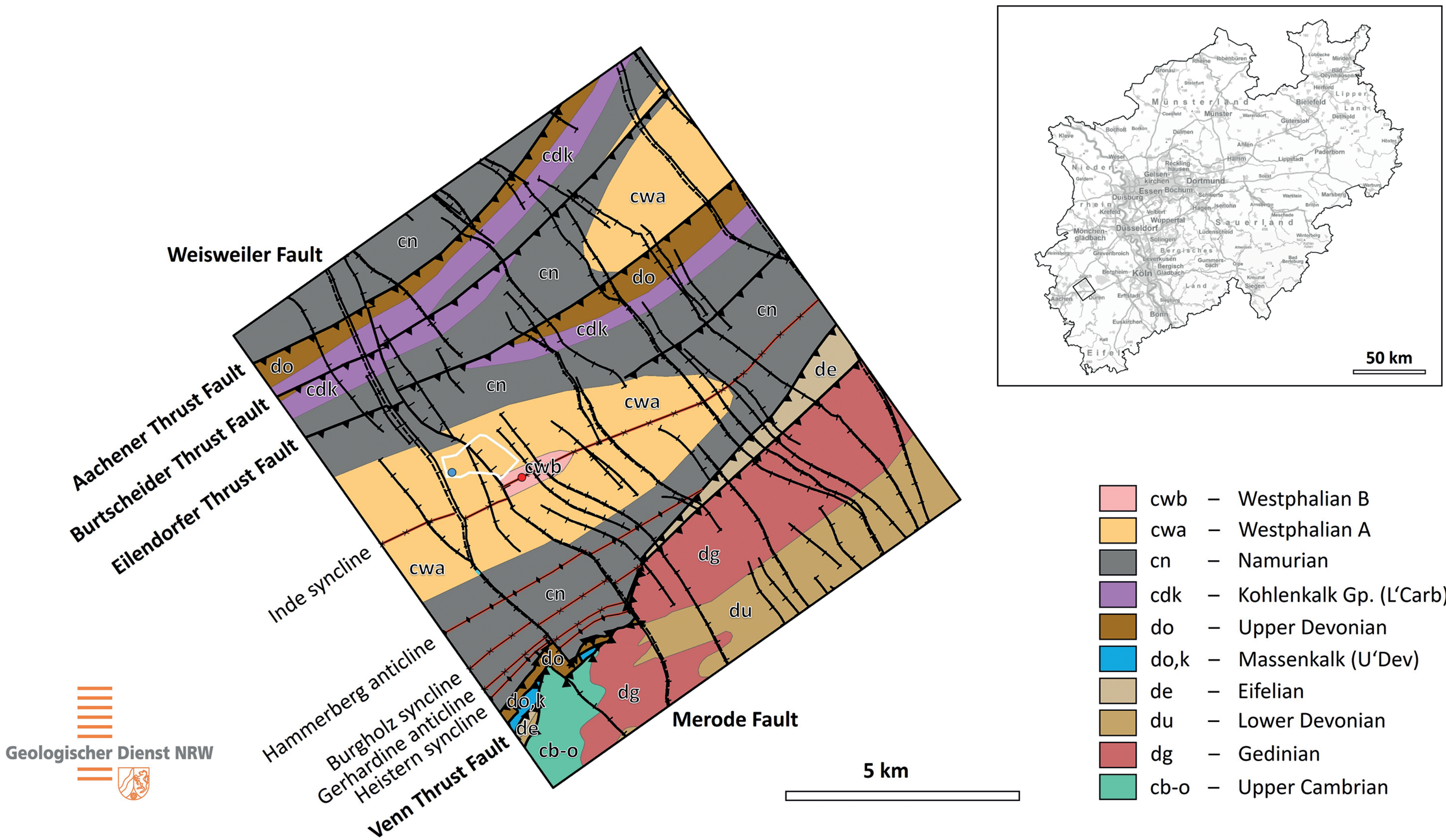

Fig. 2: Simplified geological map at the base of the Tertiary including the major structural features (modified after Ribbert & Wrede 2005) and the locations of the Weisweiler power plant (white outline), the drilling spot for the drilling Frenzer Staffel 1 (red spot), and the designated drilling spot for the exploration drilling on the premises of the Weisweiler power plant (blue spot, see text). Inset: Large-scale topographic map of the German federal state of North Rhine-Westphalia including the location of the Weisweiler area (black frame).

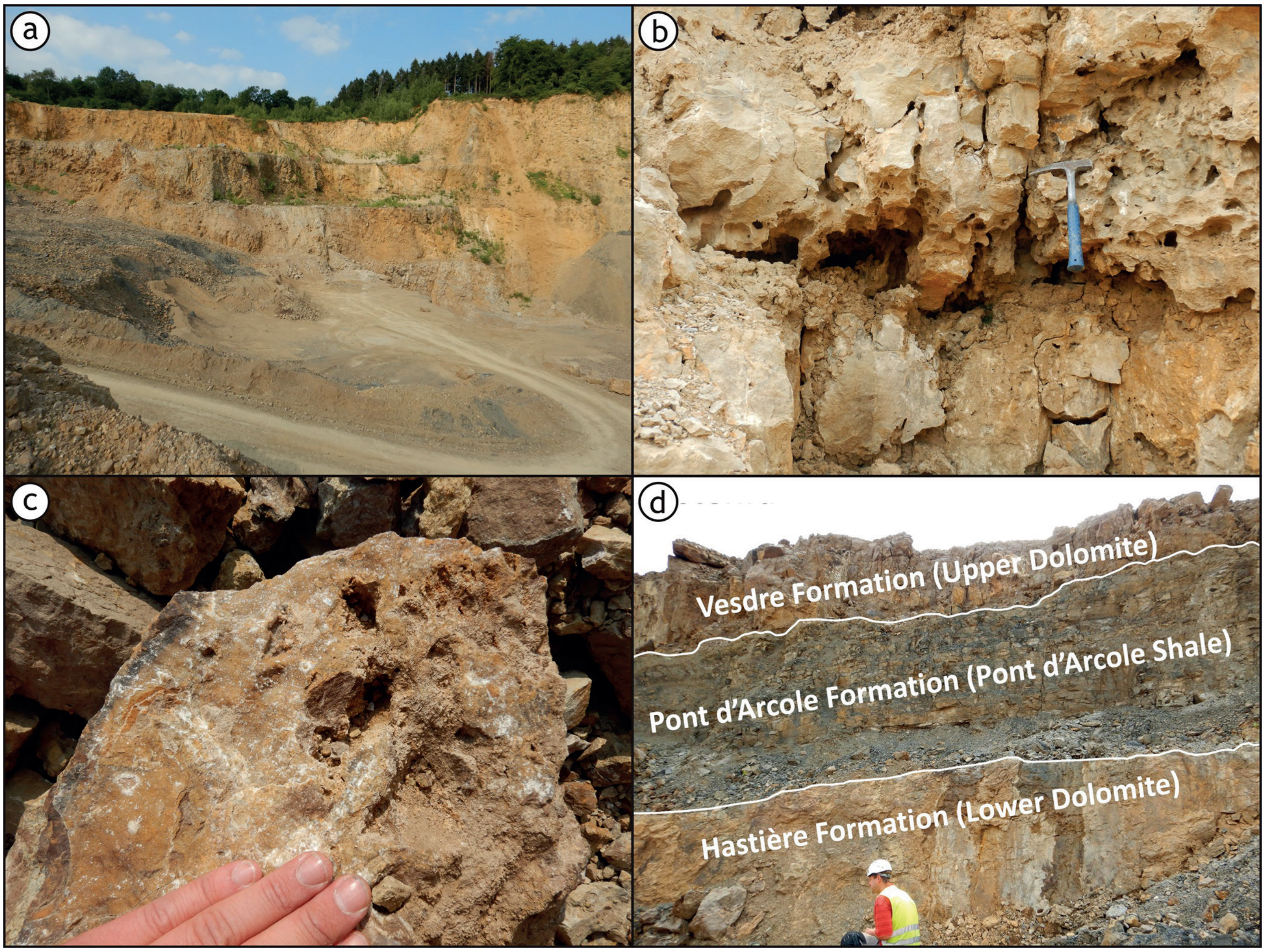

Fig. 3: Photographs of the Hastenrath Quarry in the immediate vicinity of the Weisweiler power plant: (**a**) Viséan and Tournaisian rocks of the Kohlenkalk Group just on top of the Pont d'Arcole Formation; (**b**) karstification in the Hastière Formation; (**c**) hand specimen of the Hastière Formation demonstrating dolomitisation and karstification; (**d**) Vesdre to Hastière formations of the Kohlenkalk Group.

cant karstification in the potential reservoirs may be a prerequisite for the successful realisation of the Weisweiler geothermal prospect. Whereas carbonate rocks of the Kohlenkalk Group are exposed in nearby outcrops, e.g. Hastenrath Quarry of the Lhoist Germany Rheinkalk GmbH (Fig. 3a), which is located c. 6.5 km to the south-southeast of the designated drilling spot at the Weisweiler premises. Exposures of the Massenkalk facies are rare in the vicinity of the Weisweiler power plant.

In the Hastenrath Quarry, a large part of the sequence of the Kohlenkalk Group can be observed. Although the general thickness of this horizon is expected to be substantially greater in the Weisweiler subsurface (the Kohlenkalk Group of the Hastenrath Quarry shows a combined thickness of c. 95 m, see below) it is notable that the rocks have suffered large-scale karstification and dolomitisation (Figs. 3b and 3c), in particular in the lower Kohlenkalk, the Tournaisian Vesdre and Hastière formations (Fig. 3d), and that an extensive fracture network is present.

Drozdzewski et al. (2017) discuss the karstification in the Hastenrath Quarry and describe caves with extensions up to a width of 30 and a height of 20 metres. They also investigated the fillings of these caves which often consist of lignite and siliciclastic material, and which may include ore accumulations or ore lodes. With regards to the fillings, the minimum age for the karst caves was reported to Upper Cretaceous (Santonian). The presence of significant palaeokarst at the top of the Kohlenkalk Group has also been reported by Kasig (1980a, b) and Steingrobe (1987) from various outcrops in the area, as well as by Ribbert & Wrede (2005) from the nearby drilling Kinzweiler 1.

The extensive fracture network in the Hastenrath Quarry was described by Becker et al. 2014 who identified two dominant northeast–southwest and northwest–southeast striking fracture sets, as well as several minor fracture sets with various orientations. The highest rate of fracturing exhibited up to 65 fractures per metre, whereas an averaged density of 8 ± 1 fractures per metre (95% confidence interval) is reported. In general, the fracture planes showed relatively steep dipping angles of more than 55°.

6. Geological 3D modelling

The 3D modelling of the depths and dimensions of the potential Weisweiler subsurface carbonate reservoirs is carried out over an area of c. 120 km^2 using the commercial software Move [v2019.1.0; Petroleum Experts Ltd], and is constrained by lithostratigraphic data obtained from shallow drilling operations, extensive geological mapping, and interpretation of vintage seismic profiles. The latter, however, did not have relevant implications for 3D modelling considering their insufficient resolution in the deeper subsurface. Significant constraints for the upper few hundred metres of the 3D model can be deduced from the stratigraphic interpretation of the drilling "Frenzer Staffel 1" (Wrede & Zeller 1991) as well as from extensive geological mapping campaigns carried out over the last few decades by GD NRW including the data published by Ribbert & Wrede (2005) and Wrede & Zeller (1988). Major results from geological field work and mapping campaigns including the description of key locations and outcrops were published in Salamon (2008) and Herbig & Salamon (2009)[7].

In addition, the major structural features at the base of the Tertiary in the Weisweiler area have been well determined (Fig. 2). These features also include abundant values for the dip and dipping direction of the particular lithologies implemented in the 3D model. Accordingly, the south-easterly limb of the Inde Syncline exhibits a very steep (and locally overturned) dipping angle, whereas the north-westerly limb of the syncline shows a comparatively shallow dip (Figs. 4 and 5). Further to this, several southwest to northeast trending fold axes have been observed to the southwest of the Inde Syncline, pointing towards parasitic folding of the steeply dipping south-easterly limb. This is also illustrated in the schematic geological cross-section which was deduced from the geological 3D model at the designated drilling spot (Fig. 5).

Against the background of these boundary conditions, and in combination with limited vintage 2D seismic profiles, and constraints from other shallow drilling operations undertaken by GD NRW, the known surface exposures of the various lithologies, folds, faults, and thrusts were interpolated 9,000 m into the subsurface of the Weisweiler area.

When modelling the structural framework, the faults with the larger displacement noted at the base of the Tertiary were generally assumed to cut off those faults with the comparatively smaller displacement if a timewise distinc-

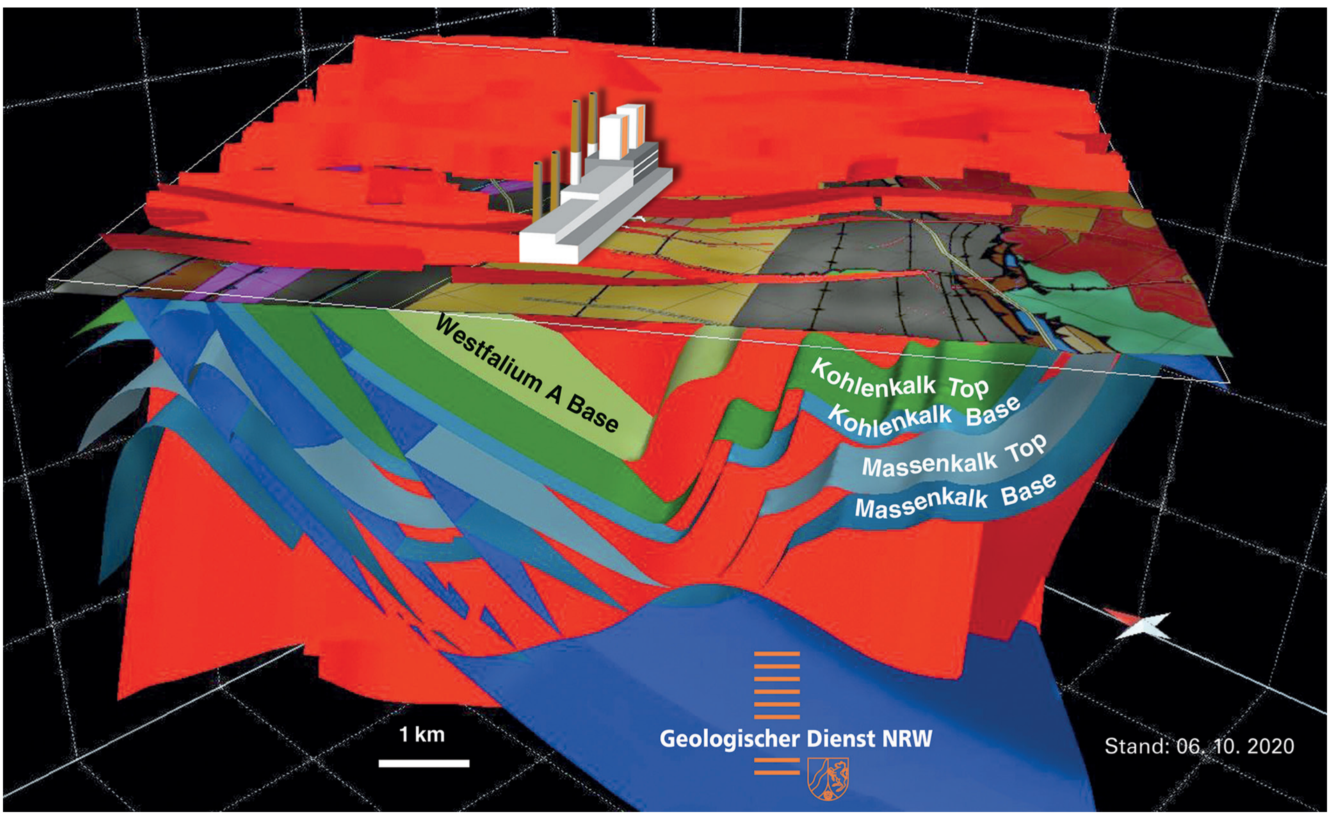

Fig. 4: Geological/geotectonic 3D model of the subsurface of the Weisweiler power plant including the geological map at the base of the Tertiary (see Fig. 2), as well as the tops and bases of the Kohlenkalk and Massenkalk potential geothermal reservoirs. Tertiary faults in red; Variscan thrust faults in blue. For an animation of the 3D model, please visit https://www.gd.nrw.de/ew_pj_interreg-dge-rollout_gdnrw.htm.

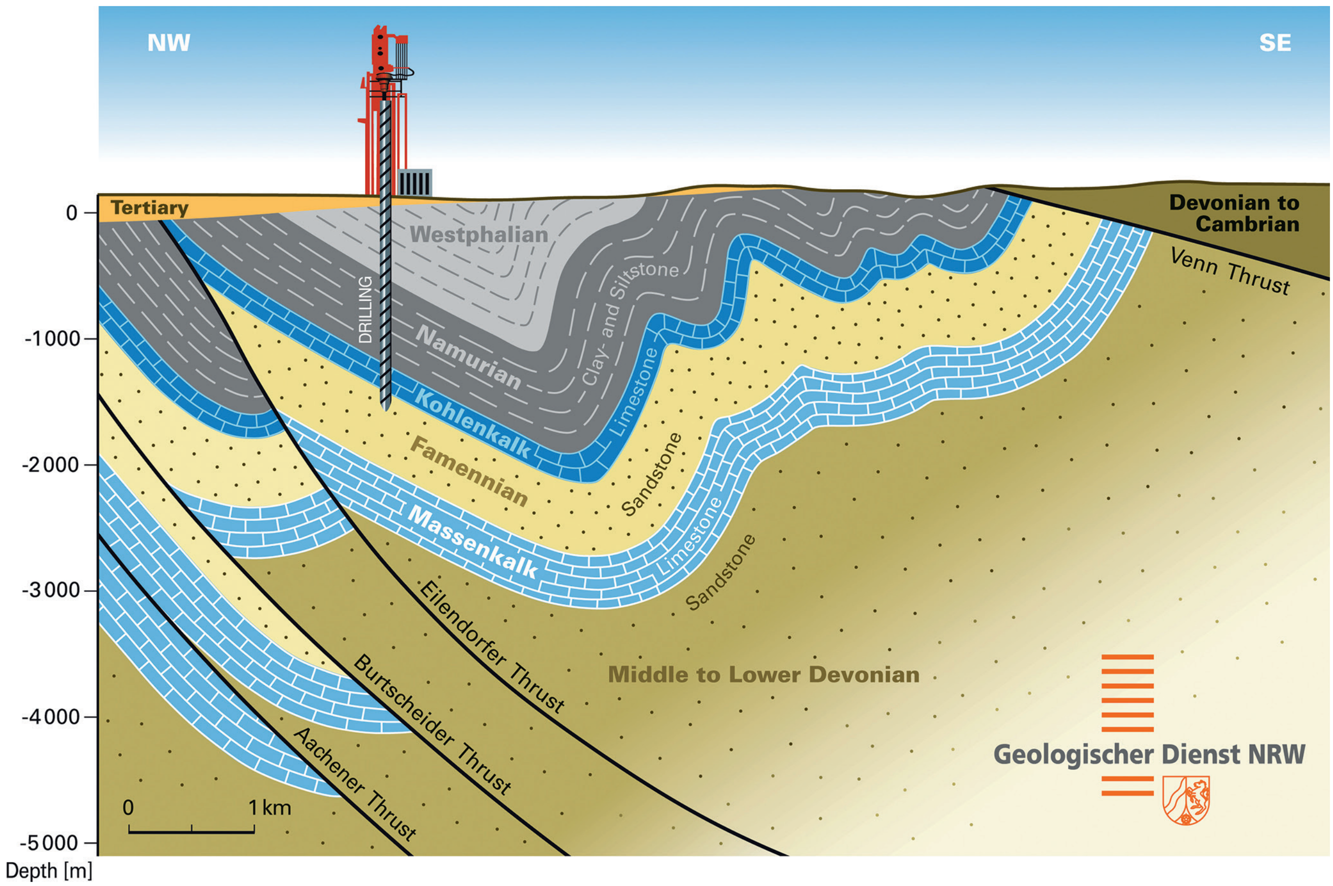

Fig. 5: Schematic geological section at the designated drilling spot at the premises of the Weisweiler power plant. The section is deduced from the geotectonic subsurface 3D model (Fig. 4), and illustrates the prognosed geological formations down to a depth of c. 5,000 m including their principal lithologies. In addition, the Variscan thrust faults and the Inde Syncline with its crest to the south-southeast of the designated drilling spot, are shown.

tion between the faults could not be determined. This applies for the northwest to southeast oriented Tertiary faults, which are shown in red in the model (Fig. 4). In addition, the older southwest to northeast trending and south-eastwards dipping Variscan thrust faults (shown in blue in the model, Fig. 4) were assumed to have been displaced by the younger Tertiary faults. The various Carboniferous and Devonian horizons (shown in various colours in the model, Fig. 4) were taken to have experienced displacement by both the Variscan thrust faults, first, and by the Tertiary faults, subsequently. These processes, however, were accepted to have occurred strictly in the aftermath of any folding for simplification of the modelling. The base of the Tertiary, naturally, was anticipated to have been affected through displacement by the Tertiary faults, but not by the Variscan thrust faults.

Considering maximum thicknesses of c. 900 m for the Westphalian A and c. 700 m for the underlying Namurium in the Inde area, the depths of the tops of the potential carbonate reservoirs are situated below c. 1,300 m for the Carboniferous Kohlenkalk Group and below c. 2,100 m for the Devonian Massenkalk facies at the designated drilling spot on the premises of the Weisweiler power plant. In the following we present more details on the ongoing and planned activities in the course of the exploration of the deep geothermal energy potential at Weisweiler including a prognosis of the lithostratigraphic conditions in the Weisweiler subsurface which were deduced from the generated 3D model.

Following the evaluation of the planned drilling operation the current 3D model will be updated with the latest information in order to reflect a more comprehensive picture of the Weisweiler geotectonic setting. In addition, the 3D model is currently being transformed into a thermohydraulic 3D model to obtain a first impression on possible fluid pathways within both the Kohlenkalk and Massenkalk potential geothermal reservoirs (see below).

7. Drilling operation

Based on the 3D model and on the current literature, a prognosis for the depth and thickness of the geological units occurring in the subsurface of the Weisweiler power plant was conducted (Fig. 6). In particular the abundant hard coal layers and a few conglomerate horizons included in the prognosis are expected to function as important marker horizons during the conducted drilling operation.

Major constraints for the drilling prognosis were deduced from the data published by Ribbert & Wrede (2005) and Wrede & Zeller (1988). Together with interpretations from geological field work, in particular from structural measurements of exposed Carboniferous rocks in nearby exposures and drillings (Salamon 2008; Herbig & Salamon 2009[7]), and in conjunction with constraints from the drilling Frenzer Staffel 1 (Wrede & Zeller 1991; Muller et al. 1991), it can be inferred that the topmost samples underlying the Quaternary and Tertiary cover can be attributed to the uppermost Westphalian A.

The comprehensive description of the depths and depth-relations between the locally occurring hard coal layers of Wrede & Zeller (1988 and 2005) has been applied as the basis for the transition from Westphalian to Namurian rocks in a depth of c. 650 m within the Krebs-Traufe Formation. The thickness of the underlying Namurian rocks, and hence the depth of the unconformity between the Upper and the Lower Carboniferous was estimated from the aforementioned data sources in connection with the thicknesses on the various Namurian Formations provided in the entries in the LithoLex database[8] (Federal Institute for Geosciences and Natural Resources, Germany). The same sources were used for the remainder of the depth prognosis. However, with regard to the presumably relatively steep dipping angles of the various geological horizons within the Inde Syncline, and naturally also in the subsurface of the Weisweiler premises, a significant deviation from the here estimated depths may occur within a short lateral distance.

Taking these limitations into account, the top of the Kohlenkalk Group is expected to occur in the drilling in a depth below c. 1,300 m. The total thickness of these carbonate rocks is approximated to 200 to 250 metres. However, it has to be noted that surface exposures of the Kohlenkalk Group were reported to vary significantly in thickness from only a few or some tens of metres (e.g. Kasig et al. 1978; Kasig 1980a and b) to about 300 m in the south of the Aachener thrust (Wrede & Zeller 1988). Likewise, Walter (2010) states a range for the thickness of the Kohlenkalk Group between 180 and 300 metres in the greater Aachen area. Besides, it has also to be noted here that the 2,544 m deep drilling RWTH-1 to the northwest of the Aachener thrust (cf. Fig. 2), and c. 18 km west-southwest of the Weisweiler power plant, did not recover any Lower Carboniferous carbonate rocks beneath a c. 1,000 m thick cover of Westphalian and Namurian rocks (e.g. Becker et al. 2011).

Below the Kohlenkalk Group the transition from Carboniferous to Devonian rocks is expected to be apparent by the thin Etrœungt Formation comprising alternating layers of dolostone, sandstone and claystone. Underneath a further c. 500 m of mainly Condroz Group sandstone the approximately 500 m thick Devonian Massenkalk facies is expected to be present in a depth below c. 2,100 m.

The drilling will be performed under the lead of Fraunhofer IEG on the premises of the RWE power plant Weis-

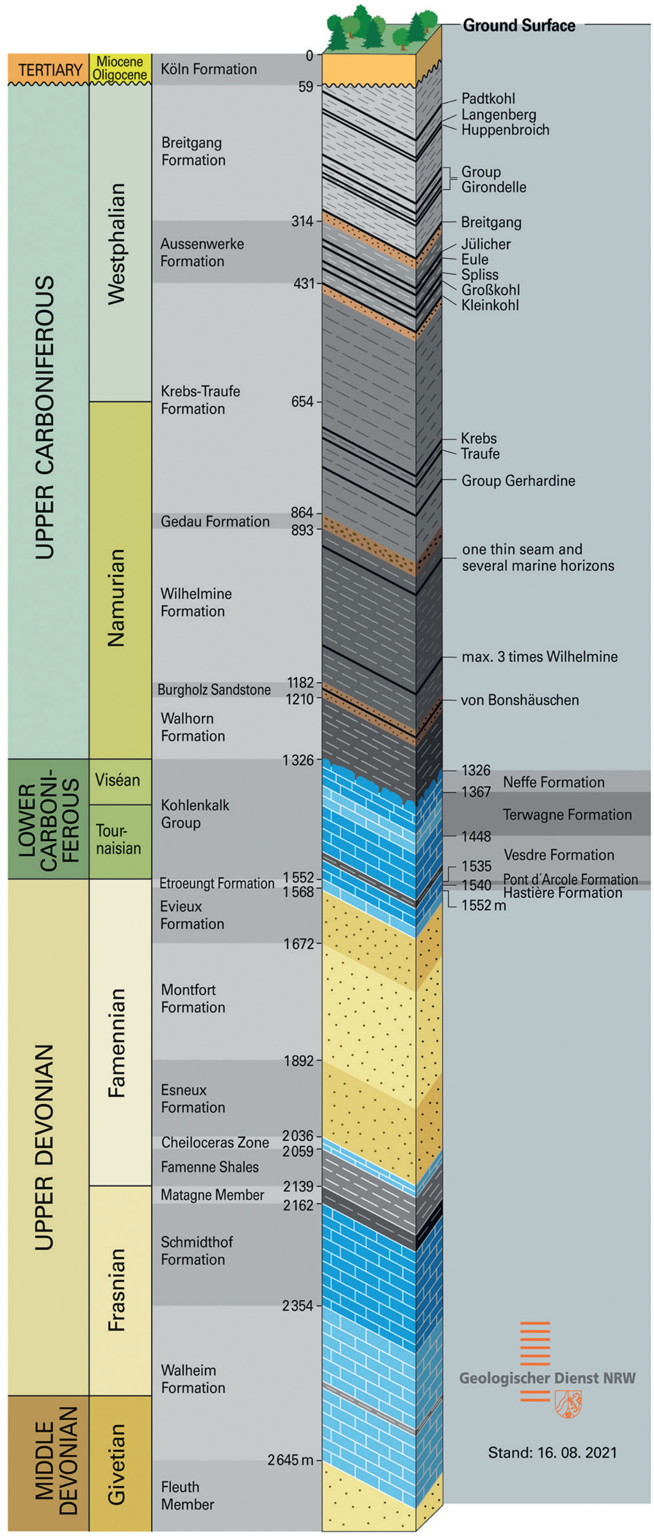

Fig. 6: Prognosis for the geological units expected in the subsurface of the Weisweiler power plant at the designated drilling spot including stratigraphic units, geological formations, estimated depths and the expected relevant hard coal beds. Notation of the stratigraphic units and geological formations after the Stratigraphic Table of Germany 2016; notation of the hard coal beds after Wrede & Zeller (2005).

weiler. It is planned to reach an overall depth of c. 1,500 m through the drilling operation, which will allow for a first recovery and detailed study of samples directly obtained from the Kohlenkalk potential geothermal aquifer. Moreover, the drilling campaign will enable to recover a complete section through the lowermost Westphalian and the entire Namurian stratigraphic units for the first time in the greater Aachen area to the southeast of the Aachener thrust.

Besides, the highly valuable data for litho-stratigraphic interpretation and more precise subsurface modelling, the planning of the further exploration strategy will largely depend on the actual depths and thicknesses of the recovered rock units. Only through this crucial first-hand knowledge of the geological and tectonic features in the Weisweiler subsurface, it will be possible to plan future exploration campaigns and attempted exploitation activities.

Eventually, this here drilled first exploration well is envisaged to be utilised by Fraunhofer IEG as an observatory for all future exploration and exploitation activities up to the eventual geothermal energy production through a number of geothermal doublets. The observatory will then be expanded into a regional seismic monitoring network for continuous seismological measurements (see below). This is of particular importance considering the location of the Weisweiler power plant in an area of active seismicity[5, 6].

In addition, the data obtained through the deep drilling will contribute to a generally better understanding of the large-scale geological structure at the front of the Variscan northern Eifel region, and the still controversially discussed formation of folds, faults and thrusts in the wider Aachen region (e.g. Sindern et al. 2012; Chatziliadou 2009; Wrede et al. 1993; von Winterfeld 1994).

It appears worth mentioning that besides the Weisweiler drilling, GD NRW has just completed a drilling campaign in the Hastenrath Quarry in June 2021. Complementing an earlier drilling, GD NRW has now acquired 95 m of drill core representing the entirety of the Kohlenkalk Group in Hastenrath. These Lower Carboniferous rocks are supplemented by a further 82.5 m of drill core comprising the Carboniferous/Devonian boundary, Etrœungt Formation and the uppermost Evieux Formation of the Condroz Group. In addition to the drilling, borehole geophysical measurements have been undertaken and are currently being evaluated. A preliminary lithostratigraphic description as well as a first short article have been completed by Becker et al. (2021). At the same time, petrophysical, geochemical and geological laboratory measurements are underway through GD NRW and the project partners within the DGE-ROLLOUT project. All information obtained in this respect will aid the planning of the drilling Weisweiler and support the interpretation of the obtained samples.

8. Thermohydraulic 3D modelling

Once the essential input data are available, a thermohydraulic 3D model is generated for the area of the geological 3D model. The primary objective of the thermohydraulic modelling is to obtain first impressions on possible fluid pathways within the targeted carbonate horizons. It may also be used in finding an optimal location for production or identifying possible risks. Both risks for production and originating from production may result from the geological or geochemical setting of the site. Later the operation of production can be optimised.

The numerical modelling and simulation is carried out with the HEATFLOW software (DMT GmbH & Co. KG). HEATFLOW is part of the BoxModel simulation software for 3D modelling of mine and groundwater flow, heat and (reactive) mass transport even in coupled systems. BoxModel contains the complete modelling workflow from geometry to postprocessing including conversion of several geological tools. One aspect of the HEATFLOW software for modelling deep geothermal reservoirs is the transfer of geological structural models directly from Move (v2019.1.0; Petroleum Experts Ltd) into models for heat transport simulations including chemical processes. The contained improvement of the fault description ensures a high accuracy modelling flow in fault systems.

Basic requirements for the preparation of a reliable thermohydraulic 3D model are a description of the modelled geological body as accurate as possible and an initial concept of its hydraulic and geothermal conditions. The geological 3D model already summarises the entire required knowledge about the geological structure of the subsurface. The geometries contained in this model are transferred into a 3D mesh in which the numerical operations can take place (process of discretisation). To calculate the hydraulic, thermal and hydrochemical processes, several parameters have to be assigned to this 3D mesh. These parameters include conductivities, porosities, fracture opening widths, material-specific thermal parameters, the hydro- and geochemical composition of the modelled aquifer and groundwater, and several others. Some of these parameters can be gained directly on site from the drillings, whereas others may need to be estimated reasonably from literature data and empirical values from other sites. The whole model area needs to be parameterised for the modelling setup. Therefore, the parameters gained from field measurements are regionalised accordingly. Finally, boundary conditions (e.g. constant heat or no-flow boundaries) and initial conditions (e.g. spatial distribution of water levels or pressure, temperature and dissolved substances in groundwater) are defined in the model.

Following the described model setup, a 3D numerical model is generated that is ready to use for simulating groundwater flow, heat- and (reactive) mass-transport in the subsurface of the Weisweiler site.

Especially in the early phase of exploration there is not enough information available for the deep aquifers to allow a calibration of the model. Thus, the focus of further modelling is on the verification of the initial concept and the plausibility of the model results. Uncertainties regarding the input data used in the model will be identified and their relevance for the future geothermal usage of the reservoir will be analysed and quantified. Finally, a comprehensive and reliable concept of the hydraulic and geothermal conditions in the model area will be developed with the aid of this numerical model. Future findings, whether from drillings, hydraulic testing or operation, might be used to improve the model, to calibrate it and to verify model results.

Using this workflow from Move to BoxModel, a thermo-hydraulic 3D model is created that plausibly reproduces the hydraulic, geothermal and hydrochemical conditions in the model area. Taking the uncertainties into account, this model can then be used to analyse and optimise a wide range of production scenarios.

9. Seismic monitoring

Besides the long-term set-up of seismic monitoring from the prospective borehole, a number of existing monitoring stations of the State Earthquake Service (Landeserdbebendienst) NRW[6] will be supplemented by new stations, built up and operated by Fraunhofer IEG. All of these stations will be integrated into a dense network of seismological observatories which will aid Fraunhofer IEG to differentiate a naturally occurring seismic tremor with frequent earthquakes, which occurs in greater depths along seismically active northwest–southeast trending faults, from an ambient, artificial seismic tremor caused by the lignite-fired power plant, the nearby highway, and the numerous wind power plants in this region. First measurements close to the power plant Weisweiler have started in early summer 2021. Long-term seismic monitoring of deep-seated natural events will also allow to map the deeper geological structures in this region, and to improve existing models of seismic velocities in the subsurface. Furthermore, in the context of the Geothermica project "DEEP" (Innovation for de-risking enhanced geothermal energy[9]) by Fraunhofer IEG, all data from the regional seismic observatory networks will be used for an innovative technique (Löer et al. 2020; Finger & Saenger 2021) of analysing subsurface structures and movements with a focus on seismic activity along poorly imaged or even unknown fault zones.

10. Summary and conclusions

Both the Mid- to Upper Devonian Massenkalk facies and the Lower Carboniferous Kohlenkalk Group are considered as potential geothermal reservoirs for the exploitation of hydrothermal energy. In NRW, this assumption is based on the investigation of exposed analogue rocks as well as on characteristic geothermal data obtained therefrom. In addition, these carbonate rocks are already being exploited with hydrothermal techniques in both Belgium and the Netherlands.

Field observations and interpretation of mapping campaigns indicate the presence of both of these carbonate horizons at some thousand metres depth in the subsurface of the lignite-fired power plant Weisweiler. The complex geological and geotectonic situation in this area further suggests that these lithologies may also be present in greater depths considering possible tectonic doubling below the Variscan thrust faults. In addition, the potential reservoir rocks reach depths suitable for geothermal exploitation in the crest of the Inde Syncline in the immediate vicinity of the Weisweiler power plant.

First steps in testing the feasibility of a transformation of the lignite-fired power plant Weisweiler into a geothermal power plant are currently being undertaken within the Interreg DGE-ROLLOUT Project. A geological/geotectonic 3D model of the subsurface has been created on the basis of mapping campaigns, drilling operations and vintage seismic data. This model is currently being transferred into a thermo-hydraulic 3D model to obtain first impressions on possible fluid pathways within the targeted carbonate horizons. The final preparations for an exploration drilling targeting the Kohlenkalk potential geothermal aquifer in a depth below c. 1,300 m are underway.

Assuming favourable perspectives for the extraction of geothermal energy based on the planned drilling and seismic operations, it is aimed to construct a geothermal power plant relying on parts of the infrastructure of the existing lignite-fired power plant, and to supply the connected district heating network with green energy following the forthcoming fossil fuel phase-out before the end of the decade.

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12. References

Arndt, M. (2021). 3D modelling of the Lower Carboniferous (Dinantian) as an indicator for the deep geothermal potential in North Rhine-Westphalia (NRW, Germany). [Journal of Applied and Regional Geology] [this issue]. *Zeitschrift der Deutschen*

Gesellschaft für Geowissenschaften, 172(3), 307–324. https://doi.org/10.1127/zdgg/2021/0279

Arndt, M., Fritschle, T., Salamon, M., & Thiel, A. (2020). Das Rhenoherzynische Becken – Ein hydrothermales Reservoir für NRW und Nordwesteuropa? *scriptumonline, 16*, 1–11. https://www.gd.nrw.de/pr_bs_scriptumonline.htm

Arndt, M., Fritschle, T., Thiel, A., & Salamon, M. (2021). The DGE-ROLLOUT project: Deep Geothermal Energy potential of Carboniferous carbonate rocks in North-West Europe – History, characterisation, modelling and exploration. [Journal of Applied and Regional Geology] [this issue]. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 172*(3), 205–210. https://doi.org/10.1127/zdgg/2021/0309

Bär, K., Reinsch, T., & Bott, J. (2020). The PetroPhysical Property database (P^3) – A global compilation of lab-measured rock properties. *Earth System Science Data, 12*(4), 2485–2515. https://doi.org/10.5194/essd-12-2485-2020

Becker, S., Hilgers, C., Kukla, P. A., & Urai, J. L. (2011). Crack-seal microstructure evolution in bi-mineralic quartz-chlorite veins in shales and siltstones from the RWTH-1 well, Aachen, Germany. *Journal of Structural Geology, 33*(4), 676–689. https://doi.org/10.1016/j.jsg.2011.01.001

Becker, S., Nguyen, H. T., Nollet, S., Fernandez-Steeger, T. M., Laux, D., & Hilgers, C. (2014). Methods to analyse fracture orientation patterns in a Lower Carboniferous carbonate reservoir analogue in the Voreifel, Germany. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 165*(3), 319–330. https://doi.org/10.1127/1860-1804/2014/0078

Becker, S., Fritschle, T., Mighali, S., & Stichling, S. (2021). Bohren für saubere Energie aus der Tiefe. *gdReport, 2021*(2).

Bos, S., & Laenen, B. (2017). Development of the first deep geothermal doublet in the Campine Basin of Belgium. *European Geologist, 43*, 16–20.

Broothaers, M., Bos, S., Lagrou, D., Harcouët-Menou, V., & Laenen, B. (2019). Lower Carboniferous limestone reservoir in northern Belgium: Structural insights from the Balmatt project in Mol. *European Geothermal Congress, 11–14 June 2019, The Hague, the Netherlands. Conference proceedings.*

Broothaers, M., Lagrou, D., Laenen, B., Harcouët-Menou, V., & Vos, D. (2021). Deep geothermal energy in the Lower Carboniferous carbonates of the Campine Basin, northern Belgium: An overview from the 1950's to 2020. [Journal of Applied and Regional Geology] [this issue]. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 173*(3), 211–225. https://doi.org/10.1127/zdgg/2021/0285

Braunmiller, J., Dahm, T., & Bonjer, K.-P. (1994). Source mechanism of the 1992 Roermond earthquake from surfacewave inversion of regional data. *Geophysical Journal International, 116*(3), 663–672. https://doi.org/10.1111/j.1365-246X.1994.tb03288.x

Chatziliadou, M. (2009). Rb-Sr Alter und Sr-Pb Isotopencharakteristik von Gangmineralisationen in paläozoischen Gesteinen am Nordrand des linksrheinischen Schiefergebirges (Raum Stolberg–Aachen–Kelmis) und Vergleich mit den rezenten Thermalwässern von Aachen-Burtscheid. *Dissertation Technische Hochschule Aachen* (311 pp.).

Dirner, S., & Steiner, U. (2015). Assessing reservoir uncertainty with stochastic facies modeling of a hydrothermal medium enthalpy reservoir (Upper Jurassic carbonates of the southern German Molasse Basin). *Proceedings World Geothermal Congress*, 2015, *Melbourne*.

Dorsch, K. (2012). *10 Jahre geothermische Exploration im süddeutschen Molassebecken – Ein Fazit. Geothermie in Bayern* (pp. 28–32). München: Media Mind.

Drozdzewski, G., Richter, D. K., & Wrede, V. (2017). Hydrothermalkarst im nördlichen Rheinischen Schiefergebirge. *Jahrbuch Karst und Höhle, 2015–2017*, 1–88.

Finger, C., & Saenger, E. H. (2021). Determination of the time-dependent moment tensor using time reverse imaging. *Geophysics, 86*(2), KS63–KS77. https://doi.org/10.1190/geo2020-0348.1

Franke, W., Cocks, L. R. M., & Torsvik, T. H. (2017). The Palaeozoic Variscan oceans revisited. *Gondwana Research, 48*, 257–284. https://doi.org/10.1016/j.gr.2017.03.005

Franke, W., Huckriede, H., O'Sullivan, P., & Wemmer, K. (2019). Zircons to the front: Accretionary history of the Rheno-Hercynian active margin (Variscides, Germany). *Canadian Journal of Earth Sciences, 56*(12), 1375–1397. https://doi.org/10.1139/cjes-2018-0255

Fritschle, T., Salamon, M., Bißmann, S., Arndt, M., & Oswald, T. (2020). Exploring the deep geothermal energy potential at Weisweiler, Germany: 3D-modelling of subsurface Mid-Palaeozoic carbonate reservoir rocks. *EGU General Assembly Conference Abstracts, 2020*, 16953. https://doi.org/10.5194/egusphere-egu2020-16953

Fritschle, T., Petitclerc, E., van Melle, T., Broothaers, M., Passamonti, A., Arndt, M., . . . Salamon, M. (2021). DGE-ROLLOUT: Promoting deep geothermal energy in North-West Europe. *Proceedings World Geothermal Congress*, 2021, *Reykjavik*.

German Stratigraphic Commission (Ed.; editing, coordination and layout: Menning, M. & Hendrich, A.) (2016). Stratigraphic Table of Germany 2016. Potsdam: German Research Centre for Geosciences.

Grünthal, G. (2004). Erdbeben und Erdbebengefährdung in Deutschland sowie im europäischen Kontext. *Geographie und Schule, 151*, 14–23.

Grünthal, G., Stromeyer, D., Bosse, C., Cotton, F., & Bindi, D. (2018). The probabilistic seismic hazard assessment of Germany – version 2016, considering the range of epistemic uncertainties and aleatory variability. *Bulletin of Earthquake Engineering, 16*(10), 4339–4395. https://doi.org/10.1007/s10518-018-0315-y

Homuth, S. (2014). Aufschlussanalogstudie zur Charakterisierung oberjurassischer geothermischer Karbonatreservoire im Molassebecken. *Dissertation Technical University Darmstadt* (314 pp.).

Kasig, W. (1980a). Zur Geologie des Aachener Unterkarbons (Linksrheinisches Schiefergebirge, Deutschland). Stratigraphie, Sedimentologie und Paläogeographie des Aachener Kohlenkalks und seine Bedeutung für die Entwicklung der Kulturlandschaft im Aachener Raum. *Habilitation RWTH Aachen* (253 pp.) [unpublished].

Kasig, W. (1980b). Dinantian carbonates in the Aachen region, F.R.G. In M. J. M. Bless, J. Bouckaert, J., & E. Paproth (Eds.), Pre-Permian around the Brabant Massif in Belgium, the Netherlands and Germany. *Mededelingen Rijks Geologische Dienst, 32*(6), 44–52.

Kasig, W., Spaeth, G., Stoltidis, I., & Walter, R. (1978). *Stratigraphie, Paläogeographie und Tektonik des nördlichen linksrheinischen Schiefergebirges. Exkursionsführer, 130*. Aachen: Hauptversammlung DGG.

Knaak, M., Becker, S., Strauss, R., Wrede, V., Hürtgen, J., Paillard, R., & Reicherter, K. (2020). Beobachtungen zur Ausbildung des Kleingladbacher Sprungs bei Wassenberg-Myhl. *scriptumonline, 11* (24 pp.).

Laurent, A., Beccaletto, L., Averbuch, O., Graveleau, F., Lacquement, F., Caritg, S., . . . Capar, L. (2021). Modelling the 3D geometry of the Dinantian carbonate geothermal reservoir in Northern France. [Journal of Applied and Regional Geology] [this issue]. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 172*(3), 293–305. https://doi.org/10.1127/zdgg/2021/0284

Löer, K., Toledo, T., Norini, G., Zhang, X., Curtis, A., & Saenger, E. H. (2020). Imaging the deep structures of Los Humeros geothermal field, Mexico, using three-component seismic noise beamforming. *Seismological Research Letters, 91*(6), 3269–3277. https://doi.org/10.1785/0220200022

McConnell, B., & Morris, J. (1997). Initiation of Iapetus subduction under Irish Avalonia. *Geological Magazine, 134*(2), 213–218. https://doi.org/10.1017/S0016756897006626

McConnell, B., Riggs, N., & Fritschle, T. (2020). Tectonic history across the Iapetus suture zone in Ireland. *Special Publication – Geological Society of London, 503*, 333–345. https://doi.org/10.1144/SP503-2019-233

Mijnlieff, H. F. (2020). Introduction to the geothermal play and reservoir geology of the Netherlands. *Netherlands Journal of Geosciences, 99*, e2. https://doi.org/10.1017/njg.2020.2

Muller, A., Steingrobe, B., & Wrede, V. (1991). Die Forschungsbohrung Frenzer Staffel 1 (1985) (Inde-Mulde, Aachener Steinkohlerevier). *Geologisches Jahrbuch, A 116*, 1–145.

Nance, R. D., Gutiérrez-Alonso, G., Keppie, J. D., Linnemann, U., Murphy, J. B., Quesada, C., . . . Woodcock, N. H. (2010). Evolution of the Rheic Ocean. *Gondwana Research, 17*(2–3), 194–222. https://doi.org/10.1016/j.gr.2009.08.001

Oswald, T., Salamon, M., & Strozyk, F. (2021). Erkundung der Potenziale für die Tiefengeothermie am Standort des Kraftwerkes Weisweiler der RWE Power AG. *Erdöl, Erdgas, Kohle, 3*, 24–26.

Pederson, C., Mueller, M., Lippert, K., Igbokwe, O., Riechelmann, S., Lersch, S., . . . Immenhauser, A. (2021). Impact of a regional fault zone on the properties of a deep geothermal carbonate reservoir unit (Devonian of NRW). [Journal of Applied and Regional Geology] [this issue]. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 172*(3), 339–364. https://doi.org/10.1127/zdgg/2021/0281

Pharaoh, T., Jones, D., Kearsey, T., Newell, A., Abesser, C., Randles, C., . . . Kendall, R. (2021). Early Carboniferous limestones (ECL) of southern and central Britain: Characterisation and preliminary assessment of deep geothermal prospectivity [Journal of Applied and Regional Geology] [this issue]. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 172*(3), 227–249. https://doi.org/10.1127/zdgg/2021/0282

Pracht, M., Rogers, R., & McConnell, B. J. (2021). Mississippian (Dinantian) of Ireland and its geothermal potential. [Journal of Applied and Regional Geology] [this issue]. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 172*(3), 267–292. https://doi.org/10.1127/zdgg/2021/0280

Pelzing, R. (2008). *Erdbeben in Nordrhein-Westfalen*. Krefeld: Geologischer Dienst NRW.

Reith, D. F. H. (2018). Dynamic simulation of a geothermal reservoir: Case study of the Dinantian carbonates in the Californië geothermal wells, Limburg, NL. *M.Sc. thesis Technical University Delft* (119 pp.).

Ribbert, K.-H., & Wrede, V. (2005). Stratigrafische und tektonische Ergebnisse der Grundgebirgsbohrungen im Umfeld des Braunkohle-Tagebaus Hambach. s*criptum, 13*, 33–60.

Salamon, M. (2008). Stratigraphy and tectonics of the Aachen-Region – Results of a recent mapping project of the Geological Survey of Northrhine-Westfalia. In P. Kukla, & R. Littke (Eds.), Geo2008 – Resources and risks in the earth system. *Schriftenreihe der Deutschen Gesellschaft für Geowissenschaften, 60*, 158.

Salamon, M., & Thiel, A. (2019). Heißes Wasser aus der Erde. *gdReport, 2019*(1), 4–7.

Sindern, S., Meyer, F., Lögering, M., Kolb, J., Vennemann, T., & Schwarzbauer, J. (2012). Fluid evolution at the Variscan front in the vicinity of the Aachen thrust. *International Journal of Earth Sciences, 101*(1), 87–108. https://doi.org/10.1007/s00531-011-0662-2

Steiner, U., Savvatis, A., Böhm, F., & Schubert, A. (2014). Explorationsstrategie tiefer geothermischer Ressourcen am Beispiel des süddeutschen Oberjuras (Malm). In M. Bauer, W. Freeden, H. Jacobi, & T. Neu (Eds.), *Handbuch Tiefe Geothermie* (pp. 429–461). Berlin: Springer; https://doi.org/10.1007/978-3-642-54511-5_13

Steingrobe, B. (1987). Zum Sedimentationsbeginn des Oberkarbons im Aachener Steinkohlenrevier. *Facies, 17*(1), 231–235. https://doi.org/10.1007/BF02536787

Streel, M., & Loboziak, S. (1991). Westphalian A and B miospore zones in boreholes from the Inde and Wurm synclines and the Erkelenz horst near Aachen, Federal Republic of Germany. *Geologisches Jahrbuch, A 116*, 67–72.

Vörös, R., & Baisch, S., (2019). Seismic hazard assessment for the CLG-Geothermal system – Study Update March 2019. *Report CLG006_190322* (63 pp.). Q-con GmbH.

Von Winterfeld, C.-H. (1994). Variszische Deckentektonik und devonische Beckengeometrie der Nordeifel – Ein quantitatives Modell. *Dissertation RWTH Aachen / Aachener Geowissenschaftliche Beiträge, 2*, 1–319.

Walter, R. (2010). Aachen und südliche Umgebung: Nordeifel und Nordost-Ardennen. *Sammlung geologischer Führer, 100* (360 pp.). Berlin: Borntraeger.

Weydt, L. M., Ramírez-Guzmán, Á. A., Pola, A., Lepillier, B., Kummerow, J., Mandrone, G., . . . Sass, I. (2021). Petrophysical and mechanical rock property database of the Los Humeros and Acoculco geothermal fields (Mexico). *Earth System Science Data, 13*(2), 571–598. https://doi.org/10.5194/essd-13-571-2021

Wrede, V. (1985). Tiefentektonik des Aachen-Erkelenzer Steinkohlengebietes. In G. Drozdzewski, H. Engel, R. Wolf, & V. Wrede (Eds.), *Beiträge zur Tiefentektonik westdeutscher Steinkohlenlagerstätten* (pp. 9–103). Krefeld: Geologischer Dienst Nordrhein-Westfalen.

Wrede, V., & Zeller, M. (1988). *Geologie der Aachener Steinkohlelagerstätte (Wurm- und Inde-Revier)*. Krefeld: Geologischer Dienst NRW.

Wrede, V., & Zeller, M. (1991). Die stratigraphische Einstufung der Bohrung Frenzer Staffel 1. In A. Muller, B. Steingrobe, & V. Wrede, V. (Eds.), Die Forschungsbohrung Frenzer Staffel 1 (1985) (Inde-Mulde, Aachener Steinkohlerevier). *Geologisches Jahrbuch, A 116*, 73–86.

Wrede, V., & Zeller, M. (2005). Eifelnordrand, Aachen – Erkelenz und Untergrund der Niederrheinischen Bucht. In Deutsche Stratigraphische Kommission (Ed.): Stratigraphie von Deutschland, V. Das Oberkarbon (Pennsylvanium) in Deutschland. *Courier Forschungsinstitut Senckenberg, 254*, 199–224.

Wrede, V., Drozdzewski, G., & Dvorak, J. (1993). On the structure of the Variscan front in the Eifel-Ardennes area. In R. A. Gayer, R. O. Greiling, & A. K. Vogel (Eds.), *Rhenohercynian and Sub-*

variscan fold belts (pp. 267–296). Braunschweig: Vieweg & Teubner.

ZfK – Zeitung für kommunale Wirtschaft (2020). *Stawag plant Wärmewende für Aachen*, 11200, 19.

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Internet References

[1] https://www.geothermie.de/fileadmin/user_upload/Projektliste_Tiefe_Geothermie_2020_KS.pdf, 26.03.2021

[2] https://iea-gia.org/about-us/members/germany/, 26.03.2021

[3] https://www.californie.nu/nieuws/archief/negatieve-reactie-sodm-op-verzoek-clg-geothermie-bv-om-weer-te-mogen-op-starten/109, 09.07.2021

[4] https://www.nlog.nl/kaart-boringen, 09.07.2021

[5] https://www.gd.nrw.de/gg_le_erdbebenmeldung.php?id=318, 24.03.2021

[6] https://www.gd.nrw.de/gg_le.htm, 24.03.2021

[7] https://karbonstratigraphie.unikoeln.de/fileadmin/einrichtungen/karbon/Exkursionsfuehrer/Aachen2009_1-15.pdf, 13.07.2021

[8] https://litholex.bgr.de/, visited on daily base between January and April 2020

[9] https://www.ieg.fraunhofer.de/de/referenzprojekte/deep.html, 24.03.2021