Z. Dt. Ges. Geowiss. (J. Appl. Reg. Geol.), **172 (3)**, p. 307–324, 8 figs., 1 table
Published online November 2021

3D modelling of the Lower Carboniferous (Dinantian) as an indicator for the deep geothermal potential in North Rhine-Westphalia (NRW, Germany)

Martin Arndt*

Arndt, M. (2021): 3D modelling of the Lower Carboniferous (Dinantian) as an indicator for the deep geothermal potential in North Rhine-Westphalia (NRW, Germany). – Z. Dt. Ges. Geowiss., 172: 307–324, Stuttgart.

Abstract: Geothermal energy will play a major role in the forthcoming energy and heat transition in Europe. In the scope of the Interreg-funded project DGE-ROLLOUT ("Roll-out of Deep Geothermal Energy in North-West Europe"), the hydrothermal potential of Lower Carboniferous (Dinantian) carbonate rocks is being investigated.

There are five areas in North Rhine-Westphalia (NRW), Germany, which provide information about the Lower Carboniferous potential reservoirs: the Aachen region, the Velbert Anticline, the Northern Rhenish Massif, the Lower Rhine Embayment, and the Münsterland Basin. Much is known about the Tournaisian and Viséan facies from field investigations of the first three areas, however, the deep subsurface of the last two areas lies in the focus of this investigation. Structural models and borehole information played a major role in the modelling process.

In early Carboniferous times, a tropical shallow-water platform developed in the south of the Laurussian shelf forming thick carbonate deposits, which were often affected by karstification. The shelf edge of the large so-called Kohlenkalk platform is located in the transition zone between the Lower Rhine Embayment and the Münsterland Basin. The karstified platform carbonate rocks of the Kohlenkalk facies in the Lower Rhine Embayment provide ideal aquifers for hydrothermal energy exploitation, whereas proximal calciturbiditic deposits and their respective source areas may provide suitable reservoirs within the Kulm facies of the Münsterland Basin.

A lithostratigraphic overview of the Lower Carboniferous formations in NRW has been summarised from the current literature, aiming to assist in the quick characterisation of drill cores and outcrop equivalents in NRW and surrounding areas.

A digital 3D model of the subsurface was generated providing information about the depth, thickness and structure of the Lower Carboniferous strata in NRW. Consequently, an estimation of the temperature in the deep subsurface was calculated based on an average geothermal gradient of 30 °C/km. Temperatures above 100 °C are expected in the western part of the Lower Rhine Embayment (Roer Valley Graben) and throughout the Münsterland Basin. Here, it appears to be possible to implement hydrothermal heat and power generation depending on the geotectonic setting.

Keywords: DGE-ROLLOUT, Mississippian, Tournaisian, Viséan, Kohlenkalk, Kulm, Rhenohercynian Basin, hydrothermal, energy

1. Introduction

Climate-neutral energy production is one of the key issues of the future. The imminent fossil fuel phase-out and the decommissioning of nuclear power plants demand a broader use of alternative "green" energy sources. About half of the gross energy product is used for heat, which could be substantially covered by the implementation of geothermal energy. Although the application of shallow geothermal systems is already well-established in North Rhine-Westphalia[1], the potential of deep geothermal reservoirs remains largely unknown. Promising reservoirs are, for instance, the Lower Carboniferous carbonate rocks, the large Condroz sandstones, or the Devonian reefs, all deposited within the Rhenohercynian Basin – an extensive Palaeozoic basin in the equatorial zone between Laurussia and Gondwana.

The project DGE-ROLLOUT ("Roll-out of Deep Geothermal Energy in North-West Europe"), funded by the Interreg NWE programme, investigates the geothermal potential of the Lower Carboniferous carbonate rocks. Their depth, thickness, structure, and reservoir qualities will help to characterise their geothermal potential for Northwest Europe (NWE). Most of the information is presented in a 3D map containing the combined models of Northern France, Wallonia and Flanders (Belgium), the Netherlands, and North Rhine-Westphalia (NRW, Germany). The digital 3D model of NRW has been constructed in the scope of this project and serves as a working base for the forthcoming geothermal ex-

*Address of the author:
Geological Survey of North Rhine-Westphalia, De-Greiff-Str. 195, 47803 Krefeld, Germany (martin.arndt@gd.nrw.de)

DOI: 10.1127/zdgg/2021/0279
E. Schweizerbartsche Verlagsbuchhandlung, Stuttgart, Germany, www.schweizerbart.de

ploration. It was mainly constructed using the 3D modelling software MOVE (v2019.1.0; Petroleum Experts Ltd) and contains all current information of the Geological Survey of NRW, including maps, cross sections, boreholes, vintage 2D seismic data and other 3D models that were constructed earlier.

2. Geological overview: the Lower Carboniferous in NRW

In early Carboniferous times (361–327 Ma; STG 2016), NRW was at the position of a marginal basin of the Rheic Ocean: the Rhenohercynian Basin. It was situated in a tropical belt between the passive continental margin of Laurussia in the north and the advancing continent Gondwana from the south, before they collided to form Pangaea.

Climatic conditions were ideal for carbonate production, leading to the formation of a large platform on the southern shelf of Laurussia. Especially around the London-Brabant Massif – a palaeogeographic high that stretched from Ireland and Great Britain over Northern France, Belgium and the Netherlands to the Lower Rhine Embayment in NRW (Broothaers et al. 2021; Laurent et al. 2021; Mijnlieff 2020; Pharaoh et al. 2021; Pracht et al. 2021). Further to the east, the platform carbonate rocks gradually pass into the deep basinal Kulm facies – an environment dominated by mostly starved, siliciclastic sedimentation interrupted by turbiditic inputs from sources all around the basin and within. The geological situation of NRW provides the unique possibility to study both the platform carbonate rocks of the Kohlenkalk facies and the condensed shales and turbidites of the Kulm facies.

The Lower Carboniferous in NRW crops out in the areas of Aachen, the Velbert Anticline, and on the northern and eastern flank of the Rhenish Massif. Further north, it extends into the subsurface of the Lower Rhine Embayment and the Münsterland Basin, where the information on depth, thickness and lithology is only accessible from deep boreholes. According to their expected low geothermal potential, the Eastern Westphalia-Lippe region and the Kulm greywackes of the Eastern Rhenish Massif will not be discussed in this study (Fig. 1).

2.1 The platform carbonate rocks of the Aachen region

The carbonate rocks of the Aachen region form the north-eastern extension of the Belgian Dinant and Namur basins. Their thickness ranges from 140 to 220 m (Wrede & Zeller 1988), which is thin compared to the thick successions of more than 1000 m in, for example, Great Britain, and Ireland (Pharaoh et al. 2021; Pracht et al. 2021). However, the WSW–ENE striking outcrops, which follow the direction of the Midi-Aachen Thrust Fault, clearly represent a well-developed platform environment with distinctive erosional interruptions. It has been described in detail by Kasig (1980a, b), who divided the deposits into a sevenfold succession, which has been transferred to the recent stratigraphic subdivision of the German subcomission of the Carboniferous by Amler & Herbig (2006). The deposits cover the lowermost Tournaisian up to the Middle Viséan strata. More recent findings of Poty (2016) indicate that most of the deposits in the Aachen region are of Tournaisian age. However, the stratigraphic chart presented here still refers to the official version according to Amler & Herbig (2006).

The **Hastière Formation** ("Lower [bright] Dolomite" after Kasig 1980a, b) is described as a mainly fine-grained and bright dolomite that reaches thicknesses of 7 to 30 m. The completely altered micro-sparite left no trace of the former matrix. It developed from a very fine-grained calcilutite that is still recognisable in the underlying Strunian deposits. Locally, for instance in the Hastenrath quarry or in the nearby borehole Hast 1, cavernous structures can be observed. The cavities are filled with calcite, which shows subsequent dissolution structures. The lowermost 0.5 m consist of laminated lenses of marly material with beds gradually increasing in thickness. The uppermost centimetres of the formation appear darker and contain thin layers of shale (Kasig 1980b). The Hastière Formation is subdivided into three members. The prominent member around Aachen and in the Lower Rhine Embayment is referred to as Binsfeldhammer Member (Amler & Herbig 2006; Fig. 2).

The **Pont d'Arcole Formation** ("Pont d'Arcole Shale" after Kasig 1980a, b) continues on top of the Hastière Formation with a sharp basal contact. It consists of dark-grey to greyish-black shales with greyish-green, fine-grained sandstone intercalations. Throughout the area, the thickness remains constant and never exceeds more than 6 m. No reworked material could be found at the base. Occasionally, the upper part of the shales may include some dolomite layers. Their thickness increases towards the top, thus blurring the transition towards the Vesdre Formation. Except for isolated remains of the brachiopod *Spiriferrelina peracuta*, the fauna of the shales remains very scarce (Kasig 1980b).

The **Vesdre Formation** ("Upper [dark] Dolomite" after Kasig 1980a, b) is distinguished from the Binsfeldhammer Member by its darker colour and coarser texture. The latter makes it more prone to weathering, which results in numerous cavernous structures from a few mm to cm in diameter. Particularly in the vicinity of fault zones, these alterations may reach very deep into the rock. The fossil content of the homogenous formation comprises scattered crinoids. Its thickness reaches up to 80 m. At the top of the formation, large cavities (up to 2 m) of the irregular erosion surface with fibrous or palisade calcite can be observed (Kasig 1980b).

Amler & Herbig (2006) divided the early Viséan **Terwagne Formation** into three members: the Hastenrath Member ("*Vaughanites* Oolite"), the Bärenstein Member ("Lower Cyclic Succession"), and the Bernhardshammer Member ("Upper Cyclic Succession"), which relates to the previous subdivision of Kasig (1980a, b). As mentioned before, Poty (2016) proposes a different subdivision in which these members represent independent Tournaisian units. They could be correlated to the Ourthe Formation, Martin-

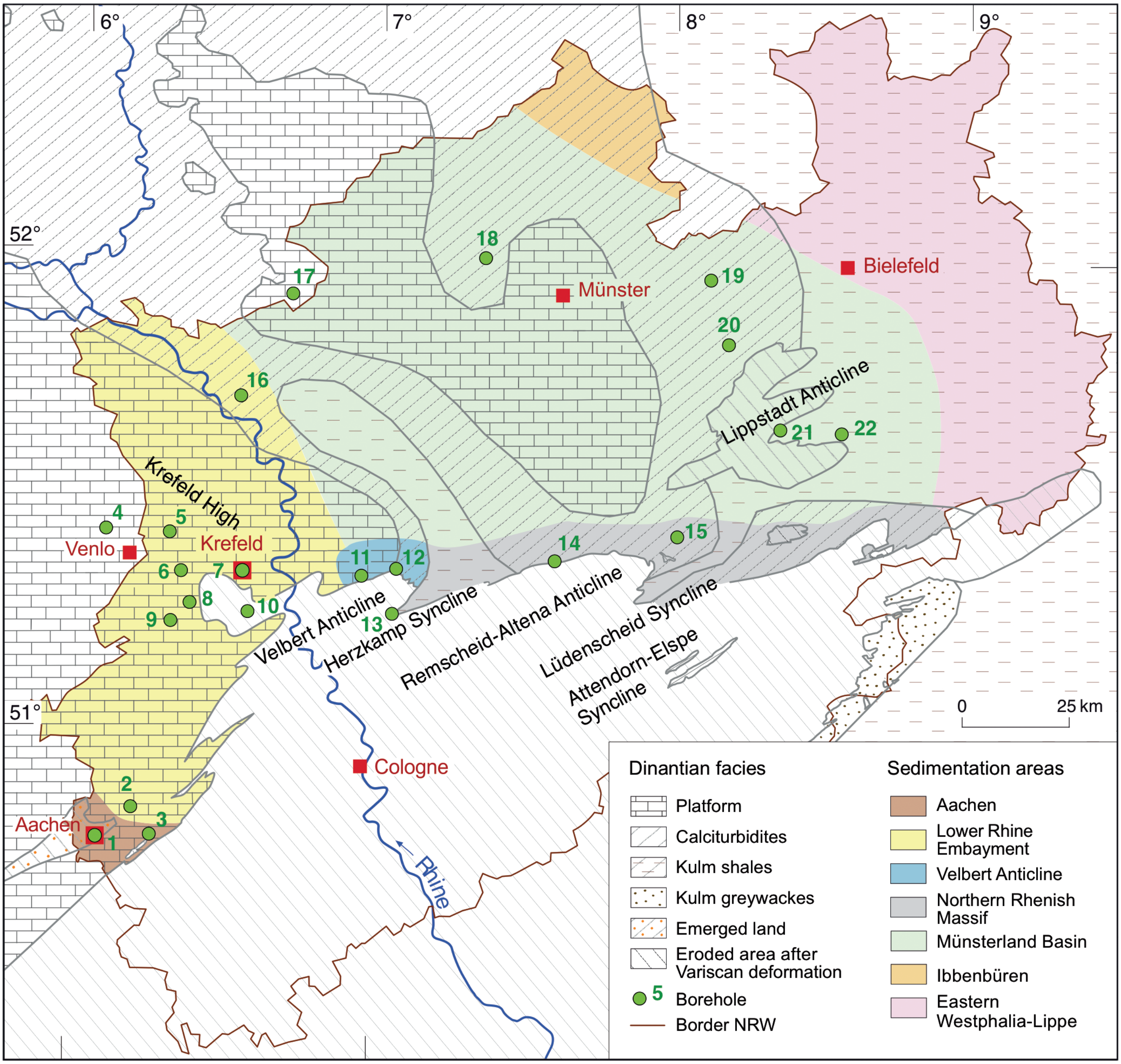

Fig. 1: Facies distribution and sedimentation areas of the Lower Carboniferous in NRW. The numbered borehole locations are listed in Table 1.

rive Formation and Flémalle Member in Belgium and are therefore not related to the Belgian Terwagne Formation.

The Hastenrath Member starts in the east with a bright yellow, fine- to medium-grained, calcareous sandstone with embedded, rounded pebbles of sandstone and dolomite at its base. It has a maximum thickness of 0.6 m (Amler & Herbig 2006) and is overlain by calcirudites and calcarenites with crinoid debris passing gradually into a bright-grey oolitic limestone. In the southern area, the sandy base is missing. Throughout the usually medium-grained limestone, the coral *Vaughanites flabelliformis* occurs, forming small colonies of up to 10 cm in diameter. Generally, the colonies appear corroded and displaced from their life position. There is also a strong lateral and vertical variation in grain size. Towards the northwest, the oolite becomes replaced by finer-grained sediments. The lowermost parts of the oolite laterally fill the karstic cavities of the Vesdre Formation or cover the intermediary fibrous palisade calcite. The upper part is more fine-grained and shows “minute cross-bedding alternating with clearly fine-laminated beds” and many thin fining-upward sequences with thicknesses from mm to cm range (Kasig 1980b). In the topmost part, crinoidal limestones become more abundant. The transition towards the overlying member is gradual (Kasig 1980b).

The Bärenstein Member is subdivided into three major cycles, which include several minor carbonate sequences. The lower part consists of dark-grey to black calcilutites alternating with marly shales containing large plant fragments, smooth-shelled ostracods and finely disseminated pyrite. They are overlain by fine-grained calcarenites and calcilutites with slumping structures. They form small cycles, often starting with fine-grained breccias at the bottom. The upper part is marked by a sedimentary breccia with varying thicknesses that consists of greyish-green marls and isolated limestone pebbles. The cycles of this member appear incomplete and the total thickness varies from a few metres to more than 10 m. The top contact appears gradually if it is not eroded (Kasig 1980b).

The Bernardshammer Member begins with a synsedimentary breccia that Kasig (1980b) correlates with the Banc d'Or in Belgium and France. However, according to Devuyst et al. (2005), this marker bed is correlated with the top of the Neffe Formation. The thickness of the member varies from 0.8 to 1.2 m and consists of unsorted, head-sized limestone pebbles in a greyish-green to yellow, marly matrix. Unlike the Bärenstein Member, the Bernhardshammer Member consists of well-developed and complete cycles with five successive phases: (1) a sedimentary breccia (calcirudite) resting on an irregular erosion surface; (2) homogenous layers of calcarenites containing foraminifera, algae, and coated grains; (3) a gradually finer-grained grainstone with intraclasts, lenses of coated grains and oncolite horizons; (4) finely laminated micrites and microsparites with isolated thin beds of calcarenites and frequent occurrences of smooth-shelled ostracods and algae; (5) finely laminated calcilutites and thin algal mats alternating with clay laminae, comprising smooth-shelled ostracods, calcispheres, and bird's-eye structures. Desiccation cracks may be observed at the top layers of the latter phase. Phases 1 to 3 represent the transgressive part of each cycle, while phase 4 and 5 display the regressive part, which is usually much thicker (Kasig 1980b).

The **Neffe Formation** barely shows any signs of cyclicity. It consists mainly of ooids and coated grains, similar to the Hastenrath Member, but with finer-grained material and large productids. Therefore, it could be compared to the upper Viséan *Gigantoproductus* beds in Belgium. The rest of the uppermost Viséan strata are missing in the Aachen region. Erosion and karstification are widespread throughout the area. This uneven surface has later been covered by the Namurian shales and sandstones of the Walhorn Formation (Kasig 1980b; Steingrobe 1987).

Apart from the shales of the Pont d'Arcole Formation and the sandstones of the Hastenrath Member, the succession consists mainly of carbonate rocks. The total Tournaisian and Viséan succession has a reduced thickness compared with the surrounding areas in Belgium and the Lower Rhine Embayment, where the borehole Wachtendonk 1 encountered the thickest known succession in NRW with 425 m along the borehole. Erosional surfaces, karstification, desiccation cracks, and obvious gaps in Tournaisian and Viséan strata suggest a frequently exposed shoal in a shallow-water environment. Syngenetic dolomites, abundant grainstones, and algal deposits support this suggestion. The Bärenstein Member further indicates a depositional phase of a relatively restricted lagoonal environment (Kasig 1980b). It is possible that only the sequence stratigraphic high stand system tracts and a few transgressive system tracts were deposited in the Aachen region, considering the elevated morphology in the early Carboniferous.

Similar deposits are expected to occur in the depths of the Wurm and Inde synclines lying north and south of the Midi-Aachen Thrust Fault, respectively. The thickness of the Lower Carboniferous succession is expected to reach 250 to 300 m according to Wrede & Zeller (1988).

Surprisingly, none of these deposits have been found in the subsurface of Aachen City. The 2,544.3 m MD (Measured Depth) deep borehole RWTH 1 did not encounter Lower Carboniferous strata. Instead, a paraconformity of horizontally stratified Famennian and Namurian deposits has been recognised in a depth of 849 m MD (Ribbert et al. 2008). This suggests that this area belonged to a palaeogeographic high during the early Carboniferous, where no or little sedimentation occurred. This paraconformity has also been recognised in Belgium near the village of Val-Dieu and in the Boland borehole (Graulich 1975). This suggests a larger extension of this palaeogeographic high, which is referred to as the Booze-le Val Dieu Ridge (Bless et al. 1980). It is the easternmost documented offshoot of the London-Brabant Massif and separates the Lower Carboniferous deposits of NRW from the Campine Basin in Flanders (Belgium). Further south, the borehole Kinzweiler 1 located the Lower Carboniferous within the Midi-Aachen Thrust Fault. Ribbert & Wrede (2005) argue that there is no major thrust sheet in NRW as known from the Belgian side. However, the boreholes Boland, Soumagne, and Soiron (Graulich 1975, Graulich et al. 1975) as well as the borehole Ensival-Lambermont (Graulich & Vandenven 1973) suggest a large allochthonous thrust fault with underlying Lower Carboniferous limestones in the deep subsurface of the Walloon region in Belgium. As long as there are no further findings, the geological situation at the border region remains a matter of debate.

2.2 The shelf edge along the Velbert Anticline

The easternmost remnants of the Kohlenkalk platform can be found on the northern flank of the Velbert Anticline. Here, the Viséan deposits of the Heiligenhaus Formation form a shelf edge facies proximal to the platform. Numerous calciturbidites gradually pass into the deeper parts of the Rhenohercynian Basin. Outcrops (e.g. Conil, Paproth & Lys 1968) and boreholes (Heiligenhaus 1, Velbert 4) indicate an east-southeastern sedimentation trend towards a basinal facies of the Herzkamp Syncline.

The early Tournaisian is introduced by the equivalents of the **Hastière Formation**, which are subdivided in the Steinkothen Member in the western part of the Velbert Anticline and the Laupen Member further east (Fig. 2). The

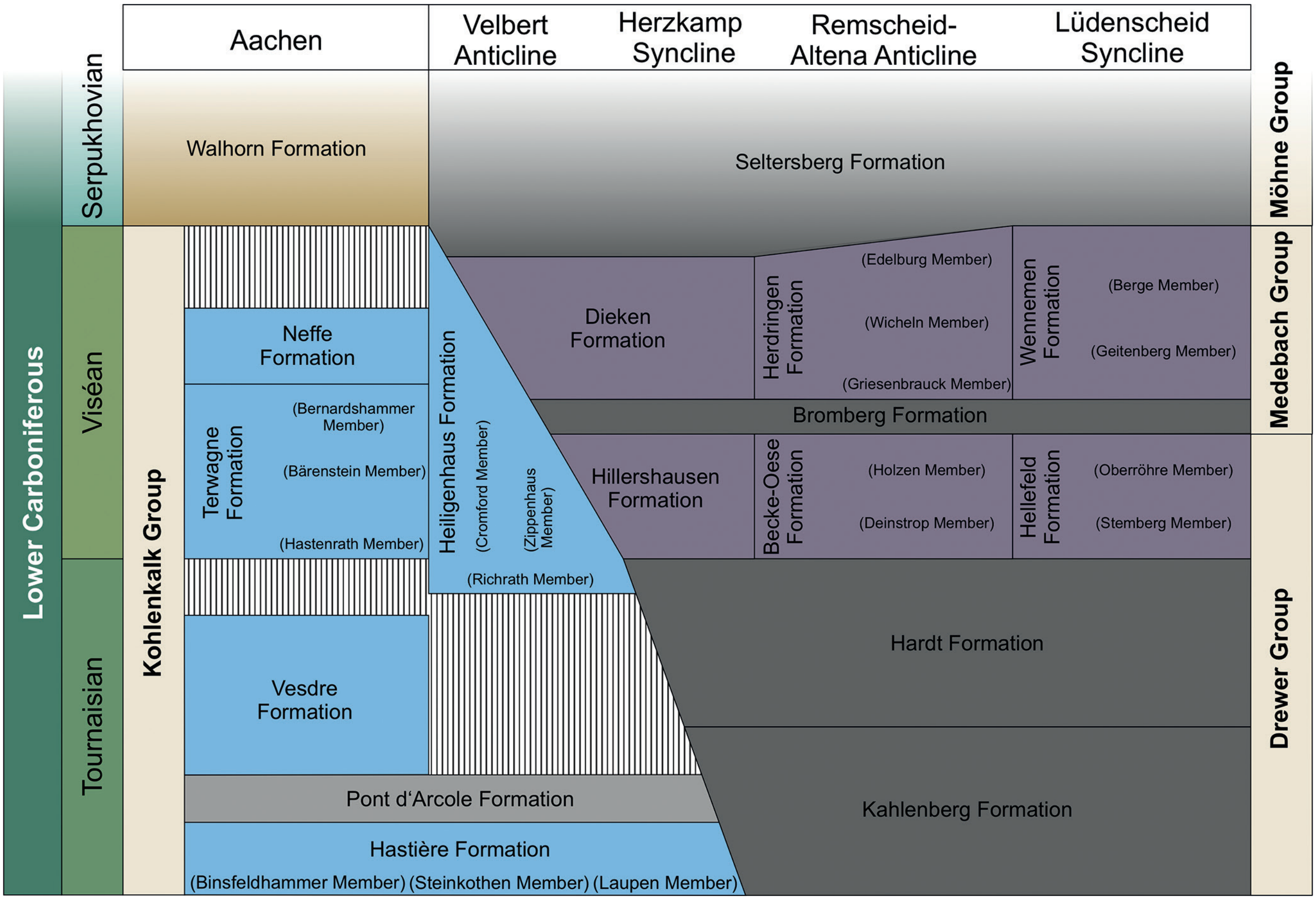

Fig. 2: Stratigraphic subdivision of the Lower Carboniferous in the Aachen region, the Velbert Anticline, the Herzkamp Syncline, and the Northern Rhenish Massif of NRW; after Kasig (1980a, b), Amler & Herbig (2006), Korn (2008, 2010), GD NRW (2016), STG (2016).

Steinkothen Member is a succession of dark-grey to black argillaceous micrite with greyish-brown marl intercalations. Some horizons contain ostracods, algae, and solitary corals. Its thickness decreases from 15 m at Ratingen to 8 m at Steinkothen (Amler & Herbig 2006). The Laupen Member consists of greyish-blue oosparite with thin intercalations of marl and siltstone. Its components comprise ooids, oncoids, detrital fossils, and quartz grains. The thickness ranges between 1 to 6 m (max. 10 m; Amler & Herbig 2006).

The **Pont d'Arcole Formation** is recognised by its dark-coloured, marly shales. The finely laminated succession is intercalated with lenses of mica-bearing sand and siltstone, dolomitic marl and clay-rich limestone beds. In the south-eastern part of the Velbert Anticline, the formation becomes bituminous and contains less sand and siltstone intercalations. The average thickness is 2.5 m in this area. The upper contact with the Heiligenhaus Formation is erosive (Amler & Herbig 2006).

The **Heiligenhaus Formation** represents the deposits on the shelf edge of the Kohlenkalk platform. It is subdivided in the basal Richrath Member and the overlying Cromford and Zippenhaus members (Fig. 2). The Richrath Member is a dark, pyrite-rich, bituminous limestone with rich bioclastic content. Its partly reworked base features condensed sedimentation with a high concentration of phosphorite nodules. Grain size and carbonate content decrease from west to east. The average thickness of 4.3 m is reduced to 0.4 m in this direction. The top contact is gradual (Amler & Herbig 2006). The Cromford Member is a thickly bedded bioclastic limestone in the western part of the Velbert Anticline. It consists of coarse-grained fossil debris (brachiopods, rugose corals, foraminifera, algae) mixed with boulder-sized limestone intraclasts and well-sorted oosparites (Franke et al. 1975; Amler & Herbig 2006). At its type locality, the degree of dolomitisation increases towards the eroded and completely altered top. A precise stratigraphic age is not known. The thickness reaches 160 m. The Cromford Member represents the platform carbonate rocks in the Velbert Anticline which are passing eastwards into the Zippenhaus Member ("Velberter Kalk"), a succession of graded or massive bioclastic calciturbidites, locally containing metre-sized clasts. Their diameter varies from a few mm up to 2.5 m. The background sedimentation is rarely observed in the form of tuff layers and black shales. Dolomitisation is a prominent feature. The average thickness of the member decreases from about 100 m to 6.5 m in the southeast of the Velbert Anticline. Here the nodular limestone barely resembles the proximal calciturbiditic facies (Amler & Herbig 2006).

The Upper Viséan **Dieken Formation** ("Posidonienschiefer") consists of dark-grey shales with fine sandstone intercalations, black alum shales, dark cherts, and calciturbiditic limestones. It is only documented in the eastern part of the Velbert Anticline with a thickness between 4 and 8 metres. The abundant fauna comprises conodonts, brachiopods, goniatites, bivalves, trilobites, ostracods, and rare rugose corals (Amler & Herbig 2006).

The general east-southeast trending reduction in bed thickness and carbonate content indicates a transitional zone between the calcareous Kohlenkalk facies and the basinal, mostly starved siliciclastic Kulm facies. Herbig et al. (2013) interpreted the succession of the borehole Velbert 4 as a distal, steepened ramp or platform margin, which became deeply drowned in Mid-Tournaisian times (Pont d'Arcole Formation) and a widely flooded platform with massive calciturbiditic shedding in Viséan times (Zippenhaus Member). The overlying Dieken Formation indicates another deepening of the platform into the foreland basin of the advancing Variscan Orogen (Herbig et al. 2013).

2.3 The basinal and calciturbidite facies of the Northern Rhenish Massif

In the Herzkamp Syncline, south of the Velbert Anticline (Fig. 1), the deposits continue with the Kulm facies of the Drewer and Medebach Group (Fig. 2). Here, the mostly starved basinal facies within the Rhenohercynian Basin contains numerous marker horizons and volcaniclastic layers. The abundance of index fossils enables a detailed stratigraphic subdivision (Korn 2010). However, the correlation to the nearby platform deposits in the Velbert Anticline is complicated due to a change from benthic to planktonic fauna assemblages (Amler & Herbig 2006). An extensive overview of the Kulm facies is given by Korn (2003, 2006, 2008, 2010).

Above the grey shales with occasional carbonate lenses or a pyritised ammonoid fauna, that indicates the Devonian/Carboniferous transition, the Tournaisian sedimentation begins with an abrupt colour change from grey to black. The upper and lower parts comprise dark and partly siliceous shale and alum shale, whereas the middle part contains intercalated, light-grey, and nodular limestone ("Steinberg Formation" in Korn 2010).

These sediments are succeeded by the Viséan **Hillershausen Formation** ("Kulm-Kieselkalk"), a 10 m thick succession that mainly consists of greenish-grey cherts with interbedded siliceous limestones interpreted as distal turbidites. They are concentrated in the middle of the formation. The top is marked by a fossil-rich trilobite fauna ("Grimmeri Bed") and a slightly siliceous shale with mica flakes (Korn 2010).

The overlying **Bromberg Formation** ("Kieselige Übergangsschichten") has a thickness of four to five metres at the Aprath section. It consists of extremely condensed, slightly siliceous shales and black shales with phosphoritic nodules and is well known for its outstanding fossil content (Korn 2010).

The **Dieken Formation** ("Posidonienschiefer") also resembles condensed sedimentation of fossil-rich, slightly siliceous shales. It begins above a slightly siliceous, crinoid-rich horizon and reaches a maximum thickness of 5 m. The top is marked by the "Actinopteria Shale", which introduces the Serpukhovian Seltersberg Formation (Korn 2010).

The recent drilling Herzkamper Mulde 1 (Fig. 1) encounters a nearly 200 m thick succession of the aforementioned formations. The drill cores are completely penetrated by calcite-bearing fissures and polished fault surfaces, which indicate a tectonic overprint. Current investigations on the cores will soon reveal new insights for the Herzkamp Syncline.

Further to the east, the Tournaisian deposits consist of the black alum shales of the **Kahlenberg Formation** ("Liegende Alaunschiefer") and the black cherts of the **Hardt Formation** ("Kulm Lydite"; Korn 2003, 2010). Additionally, limestone turbidites become increasingly more dominant and continue above the Hardt Formation with two Viséan sequences: The Herdringen Sequence of the Remscheid-Altena Anticline and the Hellefeld Sequence of the Lüdenscheid Syncline (Figs. 1 and 2). They have been thoroughly described by Korn (2008), who divided each sequence into three formations, respectively.

The Herdringen Sequence comprises (from bottom to top) the Becke-Oese Formation, the Bromberg Formation, and the Herdringen Formation (Fig. 2).

The **Becke-Oese Formation** – a lateral equivalent of the Hillershausen Formation – comprises two members: the lower oolitic Deinstrop Member with a thickness of about 50 m and the upper Holzen Member, which consists of siliceous shales and limestones as well as detrital limestone. Almost all shales have a light-grey to greenish colour and lack bituminous content. The fossil content (ammonoids, orthocone nautilids, brachiopods, bivalves, trilobites, sponges) decreases from bottom towards the top of the 50 m thick succession (Korn 2008).

The **Bromberg Formation** (STG 2016; "Retringen Formation" in Korn 2006, 2008, 2010) consists mainly of dark shales, which can be subdivided into several lithological subunits according to their colour changes. The formation contains abundant macrofossils and reaches a maximum thickness of 33 m (Korn 2008).

The **Herdringen Formation** ("Kulm-Plattenkalk") is up to 155 m thick and is divided into three members. The lower Griesenbrauck Member with a thickness of 25 m consists of grey shales with increasingly dominant calciturbidites. Distinct fossil horizons and tuff layers are rarely preserved. The overlying 110 m thick Wicheln Member is dominated by calciturbiditic deposits. The shaly background sedimentation is almost missing. The turbiditic beds range in thickness from 2 cm up to 2 m. At the top of the member, the beds become increasingly thinner. In the uppermost Edelburg Member, the autochthonous sedimentation reappears with an increased number of dark-grey to black shales, which contain numerous macrofossils. The modal Formation has a diachronous Late Viséan to early Serpukhovian boundary from west to east in the Northern Rhenish Massif (Fig. 2).

The Hellefeld Sequence is subdivided (from bottom to top) into the Hellefeld Formation, Bromberg Formation, and Wennemen Formation (Fig. 2).

The **Hellefeld Formation** is further subdivided into the lower Stemberg Member, which consists of 100 metres of thick-bedded limestones and the upper Oberröhre Member, which is similar to the Holzen Member of the Becke-Oese Formation, but with a reduced thickness of maximum 25 m and without coarse-grained limestone beds (Korn 2008).

The **Bromberg Formation** (STG 2016; "Lineppe Formation" in Korn 2006, 2008, 2010) resembles the background sedimentation of dark shales but also includes numerous limestones. Some of these massive crinoidal packstones may reach thicknesses of 2.5 m. The total thickness of the formation reaches 25 m (Korn 2008).

The **Wennemen Formation** consists of the lower Geitenberg Member with a thickness of up to 40 m, which is composed of fossiliferous laminated shales and numerous crinoidal grainstone beds and the upper Berge Member with a thickness of up to 30 m, which has a similar composition, but does not include beds of crinoidal grainstone (Korn 2008).

The calciturbiditic sequences of Herdringen and Hellefeld have two different source areas. This is indicated by starved basin deposits that separate the two sequences from each other and by the internal facies distribution and thickness variations within the two sequences (Korn 2008). Massive debrites with 10 cm sized clasts are restricted to the western part of the Herdringen Sequence, whereas the eastern part consists mainly of "modal calciturbidites" with graded beds and medium to fine-grained intraclasts (Korn 2008). Coarse-grained bioclastic limestone beds with thicknesses between 0.5 and 1 m were almost exclusively documented in the Hellefeld Sequence. Korn (2008) suggested the Attendorn-Elspe Syncline as sediment source for the Hellefeld Sequence and a northwestern source for the Herdringen Sequence, which is hidden underneath the Pennsylvanian and Cretaceous deposits of the Münsterland Basin. This is also supported by the investigations of Eder et al. (1983) who determined a southward sediment transport based on sole marks. A significant increase in thickness within the Herdringen Sequence further indicates that this sediment source was close to the eastern end of the Remscheid-Altena Anticline (Korn 2008).

2.4 The subsurface of the Lower Rhine Embayment and the Münsterland Basin

The Lower Rhine Embayment is the northwestern continuation of the Upper Rhine Graben rift system reaching from the Rhenish Massif into the North German Basin. It separates the Aachen region on its western side from the outcrops of the Velbert Anticline on its eastern side (Fig. 1). The greatest subsidence is known from the Dutch German Central Graben with 1,300 m of accumulated Cenozoic sediments at the southwestern side of the Erft Fault on the German side, and up to 2,000 m at the southwestern side of the Peel Fault on the Dutch side (Schäfer et al. 2005). These sediments cover the Palaeozoic basement and thus the extensions of the Kohlenkalk platform. They also disguise the Variscan deformation structures that change from west to east: from steeply sheeted thrust faults in the Aachen region to dominantly folded structures at the Velbert Anticline and the Northern Rhenish Massif. The Velbert Anticline is considered to be the northeastern equivalent of the Midi-Aachen Thrust Fault (Drozdzewski & Wrede 1994; Wrede 1998).

The areas of highest subsidence are located at the Roer Valley Graben in the west of the Lower Rhine Embayment. Despite the known thickness of the Cenozoic sediments, the actual depth of the Lower Carboniferous remains uncertain for this region. Nevertheless, some boreholes of a drilling campaign and a seismic survey provide information about the Lower Carboniferous in the eastern part of the Lower Rhine Embayment. In 1965, a seismic survey in the area of Krefeld and Mönchengladbach determined the depth of the Lower Carboniferous top. It has later been verified by the drilling Schwalmtal 1001, which reached the Lower Carboniferous top at 1,614.9 m MD. The lower Viséan part of the borehole comprises limestone similar to the Aachen region, whereas the upper part resembles equivalents of the calciturbiditic units of the Velbert Anticline (Fig. 3). The deep geothermal well California-GT-03 confirms that the platform carbonate rocks also continue in the Netherlands (Broothaers et al. 2021; Mijnlieff 2020). Other boreholes further revealed the offset of the Viersen normal fault system and proved the continuation of the carbonate platform in the subsurface of the Lower Rhine Embayment. The Lower Carboniferous deposits east of the Viersen Fault resemble strongly karstified platform carbonate rocks, which occur in depths of about 293 m MD (Wachtendonk 1, Krefeld GLA 1), 264.5 m MD (Grefrath 2) and 224.5 m MD (Süchteln-Sittard 1). The different values in depth relate to a Variscan axial structure known as the Krefeld High ("Krefelder Achsenaufwölbung"; Fig. 1). Its NNW–SSE directed axis passes from Krefeld to Süchteln, from where it slightly dips towards the north-northeast and south-southwest, respectively (Drozdzewski & Wrede 1994; Wrede 1998). The vertex of the fold axis is documented in the borehole Willich 1001, which reached the Upper Devonian strata at a depth of 220 m MD. The borehole Isselburg 3, which lies northeast of the aforementioned boreholes, marks an abrupt change from the Kohlenkalk facies into a more basinal environment. Therefore, the edge of the Kohlenkalk platform is considered to lie west of the line between Isselburg 3 and Velbert 4 (Fig. 1). East of this line and north of the Rhenish Massif, the realm of the Münsterland Basin is characterised by a rather basinal facies with intercalated calciturbidites, which is indicated by the boreholes Münsterland 1, Versmold 1, and Vingerhoets 93 (Figs. 1 and 3). It is unlikely that all the turbidites derived from the western Kohlenkalk platform. Thus, another carbonate source is expected in the subsurface of the Münsterland Basin. Evidence is given by the calciturbidites in the

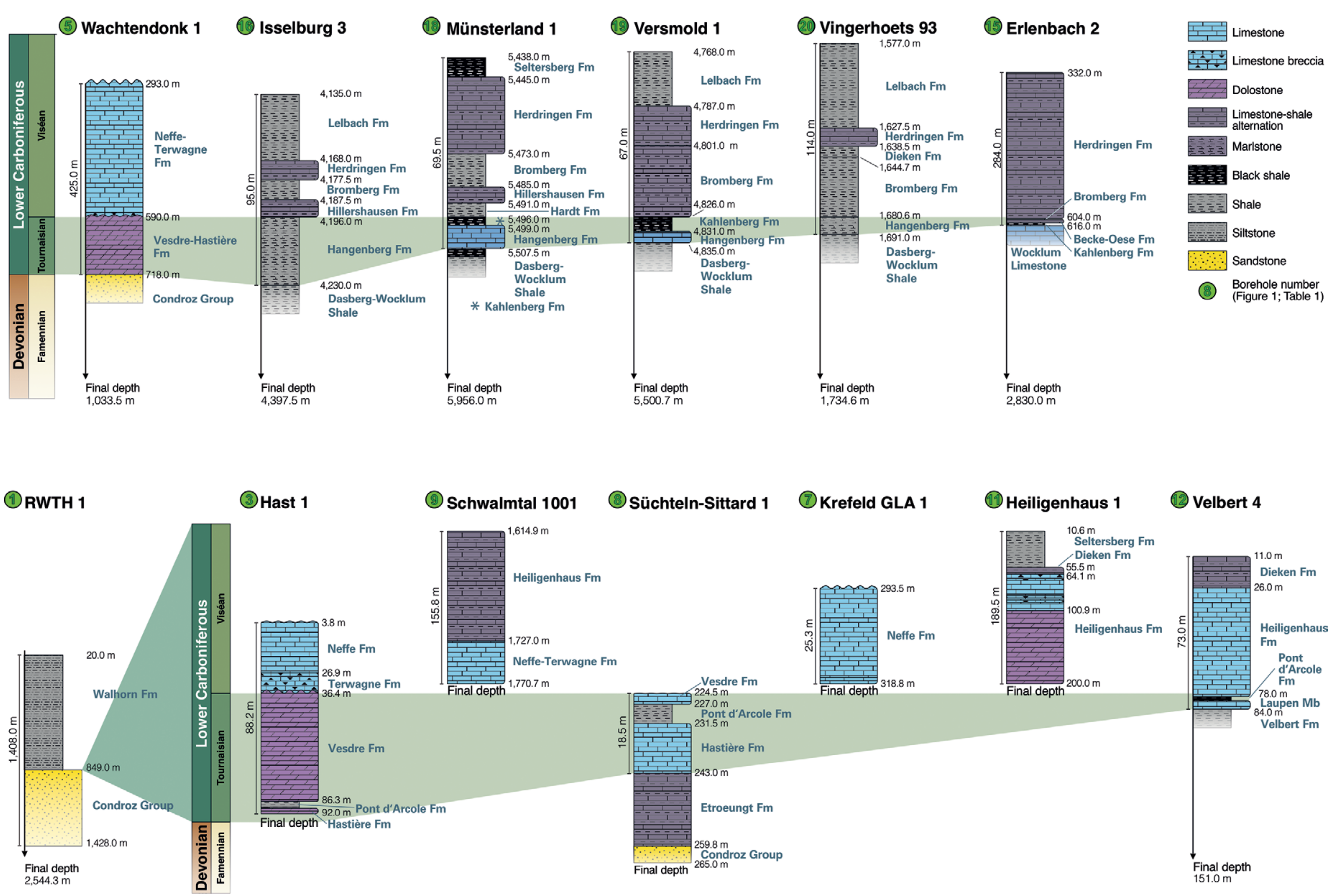

Fig. 3: Simplified lithologic columns of selected boreholes in NRW. The Lower Carboniferous deposits are displayed in relation to their time of deposition with reference to the Tournaisian/Viséan boundary. The measured depth of lithologic boundaries is indicated on the right side of each column; total thickness (along borehole) on the left side. Additional information about the stratigraphic units is available on the Litholex website [7].

Table 1: Relevant boreholes for the 3D construction of the Lower Carboniferous top and base of NRW; numbers indicate the borehole locations in Fig. 1. *Data acquired from: https://www.nlog.nl/en/map-boreholes

No.	Borehole name	Depth Lower Carboniferous top [m MD]	Depth Lower Carboniferous base [m MD]	Thickness along borehole [m]	Facies
1	RWTH 1	Paraconformity Famennian/Namurian A at 849 m MD			
2	Kinzweiler 1	25.95	Not reached	41.55	Platform
3	Hast 1	3.75	Not reached	88.25	Platform
4	Californie-GT-03*	1,562.00	1,966.00	404.00	Platform
5	Wachtendonk 1	293.00	718.00	425.00	Platform
6	Grefrath 2	264.50	Not reached	33.50	Platform
7	Krefeld GLA 1	293.50	Not reached	25.30	Platform
8	Süchteln-Sittard 1	224.50	243.00	18.50	Platform
9	Schwalmtal 1001	1,614.90	Not reached	155.80	Platform
10	Willich 1001	Unconformity Upper Famennian/Palaeogene at 220 m			
11	Heiligenhaus 1	10.55	Not reached	189.45	Calciturbidites
12	Velbert 4	11.00	84.00	73.00	Calciturbidites
13	Herzkamper Mulde 1	27.20	Not reached	174.10	Kulm shales
14	Schälk 1	22.15	Not reached	69.50	Calciturbidites
15	Erlenbach 2	332.00	616.00	284.00	Calciturbidites
16	Isselburg 3	4,135.00	4,230.00	95.00	Calciturbidites
17	Winterswijk-01*	4,275.00	4,461.00	186.00	Platform
18	Münsterland 1	5,438.00	5,507.50	69.50	Calciturbidites
19	Versmold 1	4,768.00	4,835.00	67.00	Calciturbidites
20	Vingerhoets 93	1,577.00	1,691.00	114.00	Kulm shales
21	Lippstadt	402.00	Not reached	88.00	Kulm shales
22	Tölle	318.70	Not reached	80.80	Kulm shales

boreholes Münsterland 1, Versmold 1 and the Herdringen Sequence in the Remscheid-Altena Anticline described by Korn (2008). This hidden carbonate platform could be located somewhere in the centre of the Münsterland Basin. Furthermore, the Dutch borehole Winterswijk-01 verifies the presence of another – or even the same – platform at a depth between 4,275 m and 4,461 m (Mozafari et al. 2019; Fig. 1, Table 1).

3. Digital modelling of the Lower Carboniferous top and base in NRW

The systematic collection of geological data in NRW goes back to the 19th century when Prussian geologists produced the first geological maps and cross sections (Wiegel 1973). Although the techniques of data management have increasingly improved since then, the availability of outcrop data became rather scarce in the last century. The "traditional" maps relied on a much greater number of open quarries. Most of the modern maps and cross sections are based on these original Prussian maps. For modern exploration, however, a 3D model of the subsurface is almost inevitable. Maps, sections, seismic lines, and borehole data need to be digitised, georeferenced, and mutually related to each other to create a conclusive overall model. This chapter will explain the data basis and construction of the Lower Carboniferous top and base in NRW with the modelling software MOVE (v2019.1.0; Petroleum Experts Ltd) and SKUA-GOCAD 17 (GOCAD).

3.1 Data basis

In addition to the maps of the Geological Survey of NRW (scale 1:100,000), the following geological maps have been used to outline the Lower Carboniferous in NRW:

- The Geological Map of the Ruhr Area ("Geologische Karte des Ruhrkarbons") 1:100,000 (Drozdzewski et al. 1981)
- The tectonic map of the pre-Permian surface in the Lower Rhine Embayment ("Abgedeckte tektonische Übersichtskarte der Oberfläche des Präperms in der Niederrheinischen Bucht" (Wrede 1998)

– The geological map of the central Lower Rhine Embayment ("Abgedeckte geologische Karte der zentralen Niederrheinischen Bucht") 1:100,000 (Ribbert & Wrede 2005)
– The Pre-Permian map of North West Germany (Drozdzewski et al. 2009)

Furthermore, the Namurian thickness map of Drozdzewski (1992) was used for the interpolation of the Dinantian top underneath the Carboniferous coal reserves, as well as the information from the GOCAD-based 3D models of NRW, the Information System Deep Geothermal of the Ruhr Area, and "SMOK", which are introduced hereinafter.

Thanks to extensive mining activities in the 20th century, a large pool of spatial and structural data is available for the coal reserves in NRW, especially in the Ruhr Area. This information has already been gathered and published in a series of volumes (Drozdzewski et al. 1980; Drozdzewski et al. 1985; Kunz et al. 1988) and further developed into an internally used structural model of the Upper Carboniferous ("Strukturmodell Oberkarbon" or "SMOK"), formerly known as KVB model ("Kohlenvorratsberechung" – Coal Reserve Estimation; Juch et al. 1994). It is based on geometrical approximations of well-known coal seams in the shape of planar polygonal elements and interposed minor coal seams calculated from thickness values of the country rock. The database comprises about 240,000 single surfaces and provides extensive data for 3D modelling on a larger scale in NRW. Despite the simplified visualisation, the model provides detailed information about the tectonic structures in the deep subsurface of the Palaeozoic basement. Although it covers large areas of NRW, the most reliable information is limited to the former coal mining districts in the Ruhr Area, the Wurm and Inde synclines in the Aachen region, and the horst structures in Erkelenz and Ibbenbüren (Fig. 4).

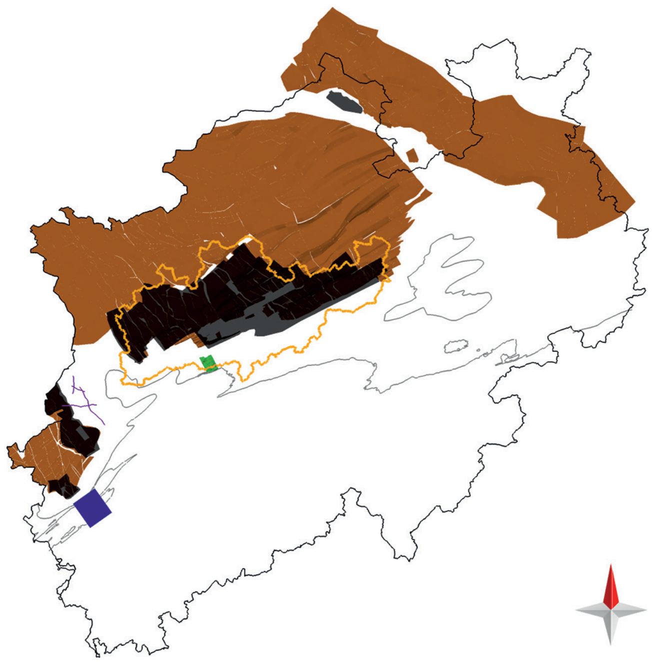

Fig. 4: Data used for the construction of the Lower Carboniferous top in NRW: the project area of the Information System Deep Geothermal is outlined in orange; the extends of the case study Kettwig is indicated in green; the project area of the Weisweiler model is indicated in blue; the position of the seismic lines at Krefeld-Mönchengladbach are indicated in purple; the distribution of the coal seam "Finefrau" in the Lower Rhine Embayment and the coal seam "Sarnsbank" in the Münsterland Basin and adjacent areas is indicated in brown; dark shaded areas mark the coal mining districts with most reliable data.

The Information System Deep Geothermal ("Informationssystem Tiefengeothermie"; Holl-Hagemeier 2003)[2] is a project based on outcrop and borehole data, isolines, geological maps and sections published in Drozdzewski et al. 1980, Drozdzewski et al. 1985 and Kunz et al. 1988, and the structural information of SMOK. It is a stratigraphic 3D model within the limits of the Ruhr Area (Fig. 4), which includes the horizons from the Quaternary down to the Carboniferous base. The lowermost horizons (base of Namurian AB, base of Namurian C, and the base of the Lower Carboniferous) have been interpolated from SMOK data and thickness models of their respective stratigraphic units.

Further data was included from the generalised 3D model of NRW and two local 3D models in the regions Kettwig and Weisweiler. They are important cornerstones providing detailed structural information about the Lower Carboniferous in the subsurface of the Velbert Anticline and the Aachen region (Fig. 4).

The generalised 3D model of NRW mainly comprises the Cenozoic and Mesozoic horizons constructed with GOCAD, including the transregional faults in NRW. It is based on the geological maps and sections (scale = 1:100,000)[3]. The most important reference horizons are the pre-Permian horizon – a merged surface from all the bases of the Cenozoic and Mesozoic horizons that resembles the Palaeozoic basement – and the DEM with a rectangular mesh width of 500 m.

The case study Kettwig was initiated in 2019 to link and improve the workflows between geological mapping and digital modelling with MOVE. It covers an area of 30 km² northeast of the Velbert Anticline and was constructed from field data, geological maps and sections (scale = 1:25,000 and 1:100,000) and from the information of Drozdzewski et al. (1980) and Drozdzewski et al. (1985).

As part of the exploration work package of the DGE-ROLLOUT project (see Fritschle et al. 2021a), a geotectonic 3D subsurface model of the Weisweiler region (c. 120 km²) has been constructed using MOVE (v2019.1.0; Petroleum Experts Ltd). This model is mainly based on lithostratigraphic data obtained from shallow drilling operations and geological mapping campaigns (Fritschle et al. 2021b and references therein). The authors interpolated the utilised data down to a depth of 9,000 m below the Weisweiler site and modelled parts of the Inde Syncline.

Primary data on the depth and thickness of the Lower Carboniferous were obtained from boreholes (Table 1) and a seismic survey in the area of Mönchengladbach-Krefeld.

The latter specifically targeted the location of the Lower Carboniferous carbonate rocks in the survey area of the Lower Rhine Embayment (Fig. 4). It was evaluated by stacking and filtering the field data from single shots as well as the application of statistic and dynamic corrections on magnetic films. This method enabled multiple stacking of seismic reflection and refraction data from a former seismic survey in this area to eliminate multiple reflections, and to define the position of the Palaeozoic basement and the Lower Carboniferous limestones (Prakla-Seismos GmbH 1965). The depth of the Lower Carboniferous carbonate rocks was later verified by the borehole Schwalmtal 1001 in 1986.

3.2 Construction of the Lower Carboniferous top

Although the aforementioned data comprise various kinds of information and levels of precision, they form an almost complete data coverage for the construction of the Lower Carboniferous in the subsurface of North Rhine-Westphalia. The 3D model of these horizons was constructed in four steps using the commercial softwares MOVE (v2019.1.0; Petroleum Experts Ltd) and SKUA-GOCAD 17 (GOCAD):

- Extension of the fault model into the deep subsurface (MOVE)
- Interpolation of the Lower Carboniferous top in the Lower Rhine Embayment (MOVE)
- Interpolation of the Lower Carboniferous top in the Münsterland Basin and adjacent areas (MOVE)
- Interpolation of the Lower Carboniferous base from the merged surface of the Lower Carboniferous top horizon (GOCAD)

First of all, the fault model, and main reference horizons were included from the generalised 3D model of NRW, the Information System Deep Geothermal, SMOK, the case study Kettwig, and the Weisweiler model (Fig. 4). Then, the geological maps and sections have been added to the project. The outlines of the Dinantian in these maps were then digitised as lines and projected to the pre-Permian surface. Finally, the borehole data was inserted to the MOVE project as well as the digitised vintage seismic lines in the Lower Rhine Embayment. All data were referenced to the coordinate system ETRS 1989 – UTM 32N (EPSG: 25832).

Furthermore, the Dutch 3D model of the Dinantian[4] and borehole data have been downloaded, transformed to the UTM reference system and inserted to the MOVE project for the construction at the Dutch/German border region. Since the 3D modelling of the Walloon region in Belgium was carried out simultaneously, the Belgian/German border region has been constructed in frequent consultation with the responsible modeller of the Walloon counterpart.

Extension of the fault model into the deep subsurface

The generalised 3D model of NRW already contains fault models for regional and transregional faults, which are distinguished by their offset. If the offset is higher than 100 m, the faults are considered as transregional. To find a compromise between a realistic representation and a practicable realisation, all transregional faults and a selection of regional faults were included into the model. Not all of them reached the depth in which the Dinantian was expected. Therefore, they had to be extended to a depth of 9,000 m below sea level. Strike and dip values were taken from statistical values of each respective fault. Depending on the difference in orientation of the original fault and its extension, the strike and dip values have been adjusted manually by some degrees, if necessary. When all extended faults had been created, they were cut along their intersection lines or extended towards their branched appendages.

Some additional faults, such as the SW–NE trending Oranje and Willem-Adolf faults and the NW–SE trending faults Carolus, Settericher Graben and Sandgewand (Wrede & Zeller 1988), had to be constructed in the area of the Wurm Syncline using SMOK information. Basically, the model already includes the different fault blocks so that the intermediate fault surfaces could be constructed using the corner points around the different polygons of the coal seams.

The transregional Viersen Fault – a NNW–SSE striking normal fault system with a length of c. 150 km and an offset of partly up to 1000 m – was used as a separator between the structural 3D model of the Lower Rhine Embayment in the southwest and the Münsterland Basin in the northeast of NRW.

Interpolation of the Lower Carboniferous top in the Lower Rhine Embayment

The top of the Lower Carboniferous carbonate rocks in the subsurface of the Inde and Wurm synclines (Lower Rhine Embayment) was constructed using the digitised maps and sections of Ribbert & Wrede 2005 and Herbig & Salamon 2009 as well as the recently constructed 3D model of the Weisweiler Site (Fritschle et al. 2021a). Further north, in the Dutch German Central Graben, only the polygonal coal seam data of SMOK provide spatial information of some marker horizons. The coal seam "Finefrau", which is lying c. 150 m above the Namurian/Westphalian boundary (Wrede & Zeller 1988, 2005), covers most of the area. It was chosen as a template for the interpolation of the Lower Carboniferous top.

To interpolate the depth of the Lower Carboniferous carbonate rocks, 17 parallel SW–NE striking sections (perpendicular to the majority of the faults in this region) with a distance of 2 km have been created containing the intersection lines with the reference horizon "Finefrau" (Figs. 5a–c). These intersection lines were used as template for the creation of a line set of the Lower Carboniferous top by adding the difference to the Namurian/Westphalian boundary (= 150 m) and the Namurian thickness values of Drozdzewski (1992) to the depth of the reference horizon (Fig. 5c). These interpolated lines were then manually joined, smoothed, and extended towards and cut off at the next fault line. This work step was repeated for each of these sections creating a scaffold of lines, which was used on the 3D level to create the surface of the Lower Carboniferous top for every single

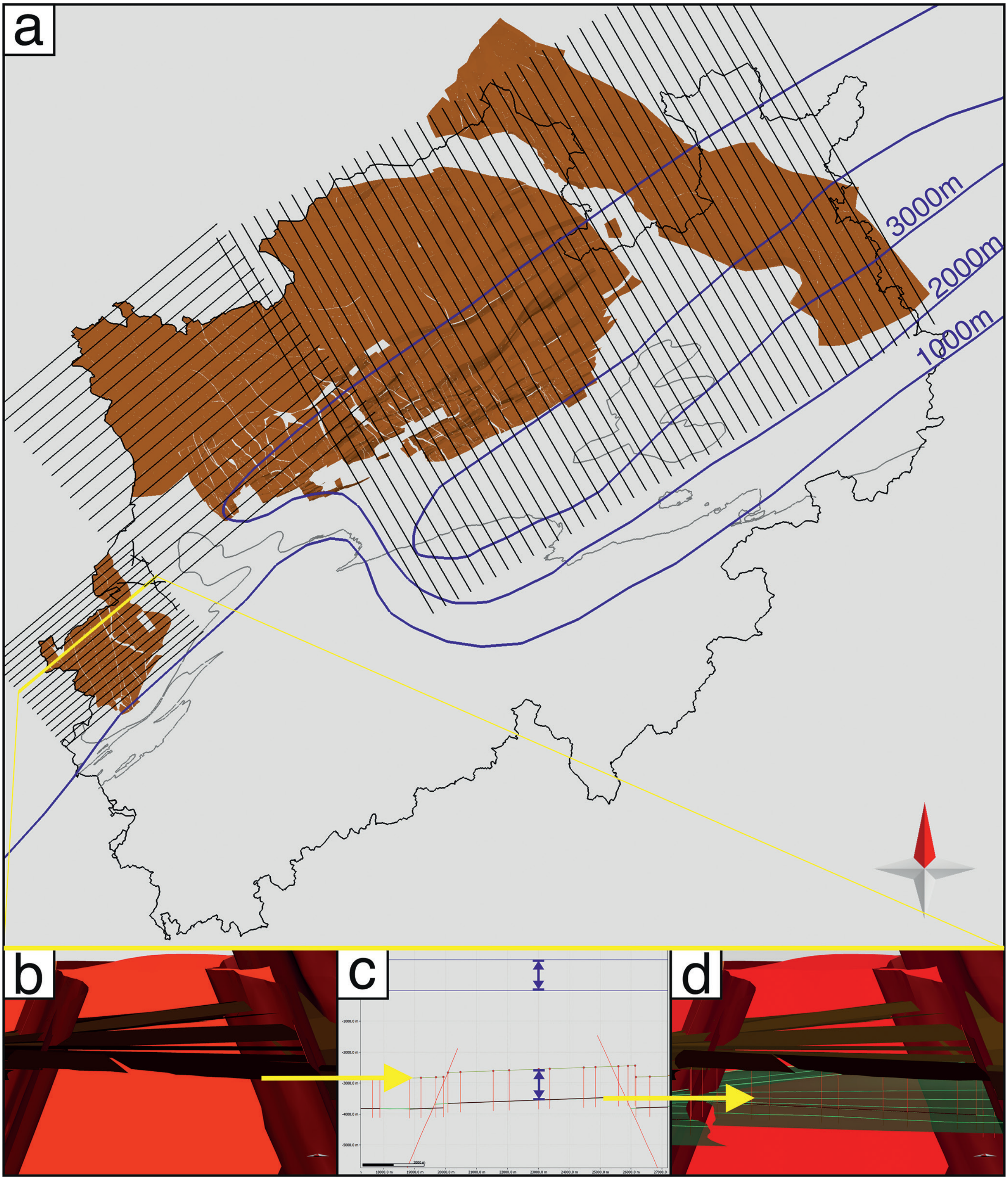

Fig. 5: Construction of the Lower Carboniferous top with the data from SMOK and Drozdzewski (1992). (**a**) Sections used for the construction (in black) and thickness isolines of the Namurian (in blue); an exemplary workflow for the yellow section is presented in the pictures below: (**b**) intersection lines from the coal seams "Finefrau" or "Sarnsbank" with each section were used as templates; (**c**) depth of the Lower Carboniferous top was interpolated by adding the Namurian thickness values to the depth of the templates (blue arrows); (**d**) the interpolated lines were used to create the surface of the Lower Carboniferous top.

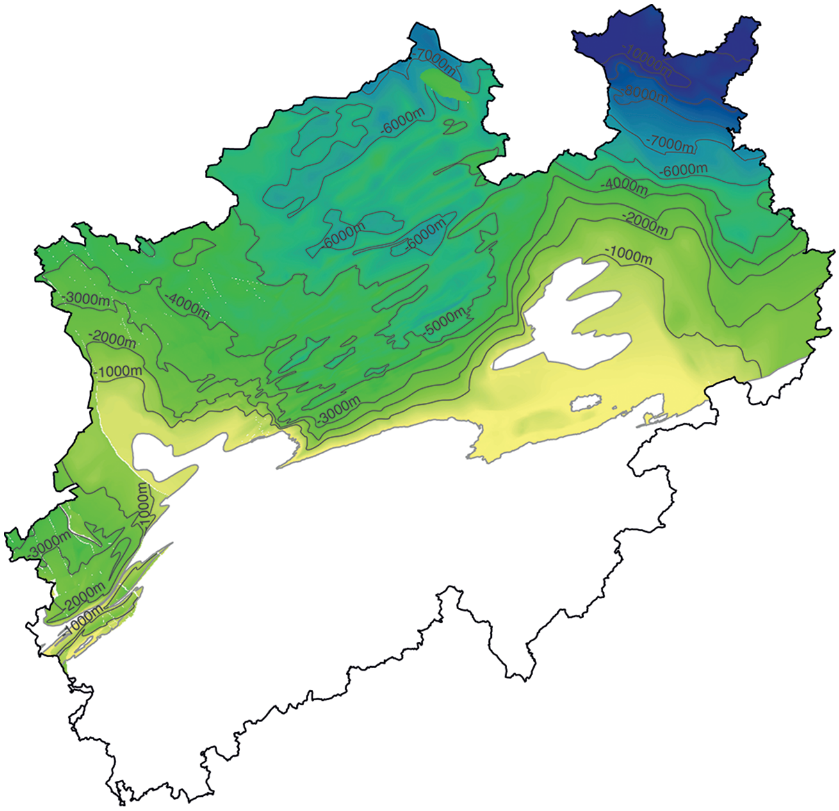

Fig. 6: Depth map of the Lower Carboniferous top in NRW.

fault block of the Dutch German Central Graben. In 3D view, these surfaces were then extended, resampled, cut at the adjacent fault surfaces, and finally merged to a single surface (Fig. 5d). Two different resampling methods were used depending on the inclination of the surfaces. For a sub-horizontal surface, grid resampling was applied with a cell width of 500 m. This value is an economic compromise between computing power and visualisation of larger scaled structures. For steeper and more strongly folded surface structures, adaptive resampling was applied using 500 m as maximum edge length and 20 m as maximum approximation distance. Although the whole procedure was quite laborious, the final result delivered a detailed surface including fold structures and offsets.

Northeast of the Dutch German Central Graben, the depth of the Lower Carboniferous carbonate rocks is located by the seismic survey at Krefeld-Mönchengladbach, as well as the boreholes Schwalmtal 1001 and California-GT-03 (Table 1, Figs. 1 and 3). Here, the top surface has been modelled with linear interpolation, resampled with a cell width of 500 m, and cut at the adjacent fault surfaces.

In the northeast, the Viersen Fault and the associated Krefeld High separate the Lower Rhine Embayment from the Münsterland Basin. The more elevated position of the Krefeld High is defined by the boreholes Grefrath 2, Krefeld GLA 1, Süchteln-Sittard, and Wachtendonk 1, which coincide with the pre-Permian horizon of the generalised 3D model of NRW. From the Krefeld High to the Münsterland Basin, a stepwise transition is determined by a NW–SE trending fault set.

Interpolation of the Lower Carboniferous top in the Münsterland Basin and adjacent areas

The southern part of the Münsterland Basin is largely included in the 3D model of the Information System Deep Geothermal and the case study Kettwig. The two models have been combined and extended with linear interpolation towards the outline of the Lower Carboniferous at the pre-Permian horizon. Towards the north, again the SMOK data and the Namurian thickness map of Drozdzewski (1992) provided the main spatial information for the interpolation of the Lower Carboniferous top, except for the Ibbenbüren region, where there are additional sections available (Drozdzewski 1985). This time, the coal seam “Sarnsbank” served as template for the interpolation, since it is defined as the Namurian/Westphalian boundary (Wrede & Ribbert 2005). The Lower Carboniferous top was constructed by adding the Namurian thickness to the depth of the template in 18 NE–SW trending sections and 41 NW–SE trending sections with a distance of 4 km from each other (Fig. 5a). The orientation of the sections was determined according to the main structural elements: NE–SW because of predominating fault structures and NW–SE due to a majority of folds in the eastern part of NRW. Additional information was taken from the Dutch 3D

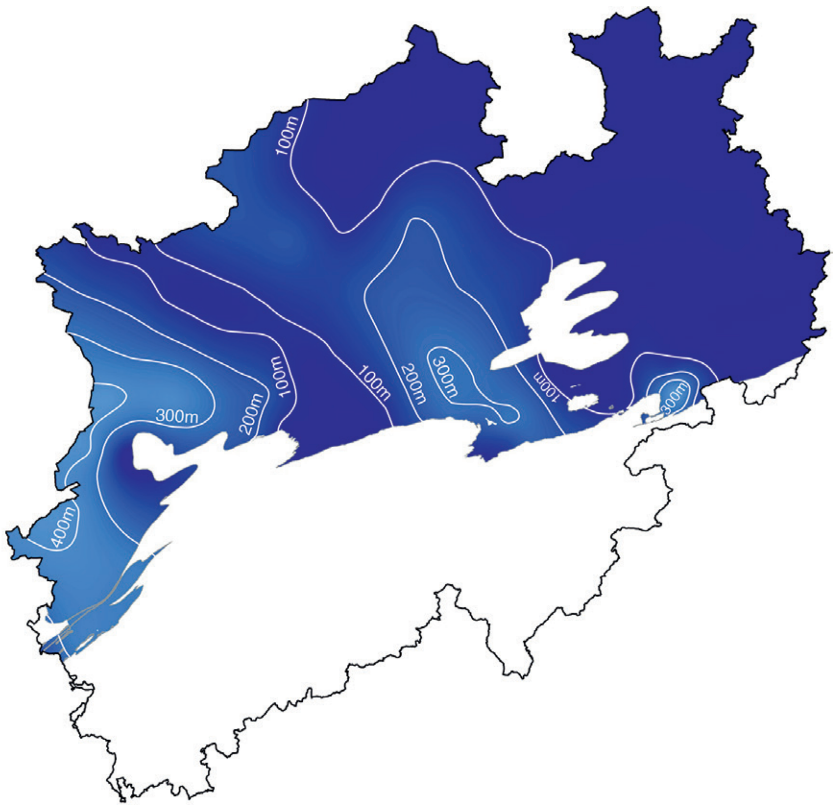

Fig. 7: Thickness map of the Lower Carboniferous in NRW.

model of the Dinantian and the boreholes Isselburg 3, Münsterland 1, Versmold 1, Vingerhoets 93 and Winterswijk-01. The interpolated line set was then used for the construction of the surfaces of the Lower Carboniferous top, similar to the procedure that was used for the Lower Rhine Embayment.

Compared to the depths in the Münsterland Basin, the Lower Carboniferous rocks appear quite shallow in the area around the Lippstadt Anticline. Here, they are mainly associated with the pre-Permian horizon of the generalised 3D model of NRW and were only adjusted by shallow borehole data, if necessary.

To the northeast, the Münsterland Basin is bordering the Osning Fault – an approximately 200 km long dextral NW–SE trending strike-slip fault zone, which is separating the basin from the regions of Ibbenbüren and Eastern Westphalia-Lippe (Drozdzewski & Dölling 2018; Fig. 1). There is not much structural information available for the latter region. Even the SMOK data are not confirmed by any boreholes or depth migrated seismic data. Nevertheless, the 3D model has been extended to this region based on this sparse data basis. Here, the Lower Carboniferous Kulm shales are expected in depths of up to more than 10 km (Fig. 6), which is why the area is not considered for geothermal exploration. Further improvement of the model could be achieved with additional borehole data from the federal German state Lower Saxony.

Interpolation of the Lower Carboniferous base from the merged surface of the Lower Carboniferous top horizon

The construction of the Lower Carboniferous base required much less effort compared to the top horizon. After the finalisation of the Lower Carboniferous top, the base has been created using a synoptic thickness map based on borehole data, outcrops, and a facies map (Table 1; Korn 2010; Arndt et al. 2020). When there was no borehole information available, the platform facies was attributed with depth values of 200 to 300 m, the calciturbiditic facies with 200 to 100 m and the Kulm facies with 100 to 70 m (Fig. 7). The facies-related thickness was subtracted from the merged top horizon of the Lower Carboniferous in NRW for any vertex point of the surface (depth base [mNN] = depth top [mNN] – thickness [m]). This work step was performed with GOCAD. Subsequently, the calculated surface of the Lower Carboniferous base had to be edited, especially along the outlines of fold structures at the pre-Permian surface and at the contacts of the extended fault model.

4. Discussion

The geothermal potential of the Lower Carboniferous rocks depends on various characteristics. In the first place a reservoir is defined by its depth, dimension, and geotectonic setting, together with its petrophysical features, including thermal conductivity, porosity, and transmissivity (Homuth 2014 and references therein). The Tournaisian and Viséan carbonate rocks provide such beneficial characteristics as demonstrated, for instance, at the geothermal sites of Saint-Ghislain and Balmatt in Belgium, or Californië in the Netherlands (Broothaers et al. 2021; Mijnlieff 2020).

According to borehole data in NRW, the platform carbonate rocks which are present throughout the Lower Rhine Embayment, seem to be an ideal aquifer for hydrothermal energy exploitation due to available fracture networks and karstification. This area experienced several stages of thrusting, faulting and/or folding during the Variscan Orogeny and during subsequent crustal movements that enabled the generation of favourable hydraulic conditions. Outcrop analogues in the Aachen region and in the Velbert Anticline further support this assumption.

However, the ubiquitous presence of platform carbonate rocks in the Lower Rhine Embayment does not imply their general presence in the Münsterland Basin. It appears more likely that only smaller isolated carbonate platforms or intrabasinal heights exist, and that the majority of the subsurface carbonate rocks comprise the here often exposed calciturbidites and Kulm shales. The presence of such heights or isolated platforms in the Münsterland subsurface seems plausible considering the findings of Korn (2008) and Mozafari et al. (2019), who described a facies close to a carbonate source in outcrops of the Northern Rhenish Massif and in the Dutch borehole Winterswijk-01. With regard to the limited amount of data, however, more exploration in this intermediate area is highly desirable.

The shales and cherts of the Kulm facies generally appear to have an unfavourable geothermal potential considering their low permeabilities. Nonetheless, the intercalated calciturbidite facies and the isolated platforms of intra-basinal heights as their source areas, may still serve as a suitable reservoir. The presence of an intra-basinal high or isolated platform seems likely according to the findings of Korn (2008) and Mozafari et al. (2019), which is why further exploration in this area could provide gratifying results.

The depth of the potential reservoir rocks is crucial for the energy outtake. However, the likelihood of locating a suitable deep reservoir is problematic considering the increasing limitations of the data with increasing depth. This study provides a depth and thickness model for the Lower Carboniferous of NRW based on the current knowledge about the deep subsurface (Figs. 6 and 7). Major information, however, relies on SMOK data and thickness interpolations.

The results of this virtual mapping campaign might be applied with regard to the calculated temperature estimations of the aforementioned potential carbonate reservoirs. Münsterland 1 is the deepest and best documented borehole in NRW. Log data with temperature measurements to a depth of c. 4,500 m (MD) revealed a geothermal gradient between 33

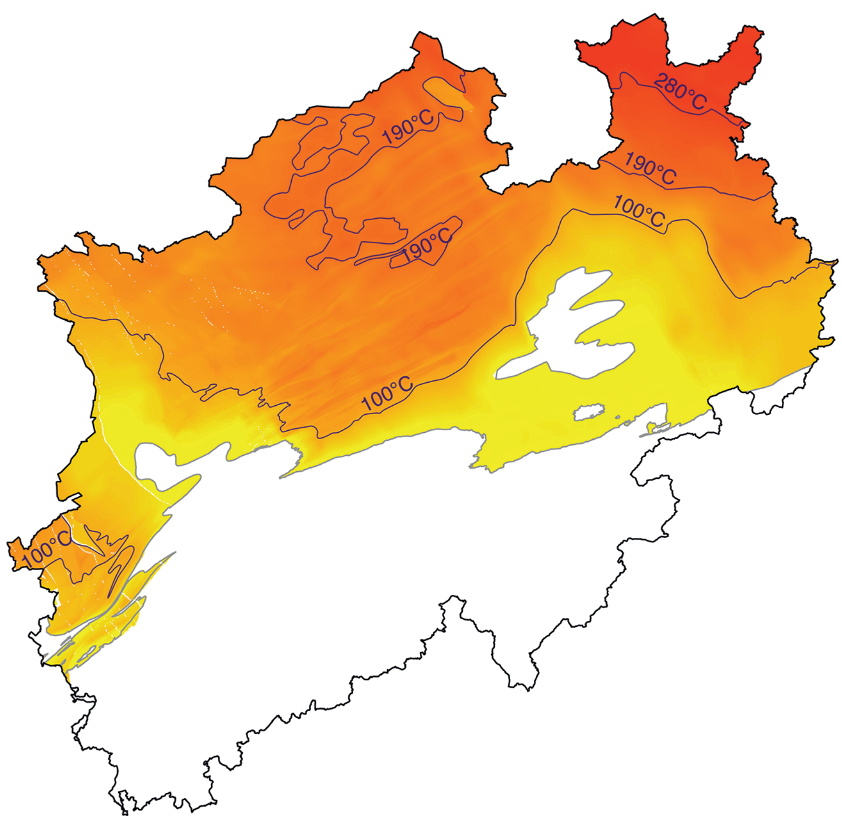

Fig. 8: Heat map at the Lower Carboniferous top in NRW, assumed from the total depth below the surface with a starting temperature of 10 °C and a geothermal gradient of 30 °C/km.

and 35 °C/km. Nevertheless, more conservative values were chosen here for the estimated heat map of the Lower Carboniferous top, starting with an average surface temperature of 10 °C and continuing downwards with a general geothermal gradient of 30 °C/km (Fig. 8). Temperature anomalies may occur in the vicinity of faults, resulting in a higher or lower geothermal gradient caused by uprising hydrothermal fluids or cold ground water flowing downwards, respectively.

Low-enthalpy deep geothermal systems may be subdivided into warm (60–100 °C) and hot (100–180 °C) categories (LIAG 2017). Warm hydrothermal systems can find implementation for district heating purposes, whereas hot hydrothermal systems allow the generation of electricity through the implementation of a binary systems, such as the Kalina Type or the Organic Rankine Cycle (ORC). Although hydrothermal systems above 180 °C may have higher efficiencies, no geothermal well has ever exceeded these temperatures in Germany (LIAG 2017).

Another important point to mention in this discussion is the uncertainty of the generated 3D subsurface model. Considering its widespread extent and limited first-hand subsurface data, it should be regarded as a contribution towards illuminating the geothermal potential of the aforementioned target areas.

The integration of manyfold sources of information with various precisions noticeably complicates a proper quantification of the errors of this model. A comparison with the Dutch 3D subsurface model of the Dinantian horizons revealed discrepancies of sometimes 500 m to 800 m in depth in areas where there were no data available. These values seem surprisingly high, but when related to the expected depths of the Lower Carboniferous of 5 to 6 km, the error lies somewhat between 10 and 16 percent.

Borehole data provide the most precise information about the depth of the Lower Carboniferous strata. Therefore, they are regarded as the most important anchor points in the subsurface model of NRW. The acquisition of seismic data, which are limited in NRW, in particular in comparison to the available input parameters in the Dutch model (SCAN), will play a major part in the improvement of the model. In the next phase of the DGE-ROLLOUT project, the current model will be adjusted. Subsequently the NRW subsurface model will be merged with its counterparts of the Netherlands and Belgium. Especially newly acquired SCAN data[5] and the recently reprocessed lines DEK-1A, DEK86-2N, and DEK86-2Q of the DEKORP programme (Meissner & Bortfeld 1990)[6] will play a significant role in this process.

5. Conclusion

The presented 3D subsurface model of NRW enables more precise statements on the expected depth, thickness and temperature of the Lower Carboniferous in NRW. A substantial potential for the hydrothermal production of heat and electricity in both the Lower Rhine Embayment and the Münsterland Basin is anticipated with regard to the widespread occurrence of platform carbonate rocks. However, there are Further aspects that need to be considered for the implementation of hydrothermal energy are the energy infrastructure, the geology in the subsurface (e.g. facies, rock type), and the geotectonic setting, in which these suitable rocks occur.

Although this study comprises more than a century of geological data acquisition, combined with modern modelling and mapping methods, further geoscientific exploration such as deep drilling or seismic acquisition, is still irreplaceable. Data gaps are particularly apparent in the centre of the Münsterland Basin and at the border regions to Belgium, the Netherlands and Lower Saxony. A major step towards a better understanding of the geothermal potential of the Lower Carboniferous in NWE will be provided once the transnational data from Belgium, France, NRW and the Netherlands are combined.

Finally, the Lower Carboniferous which is investigated exclusively in the scope of the DGE-ROLLOUT project, is only one of several potential hydrothermal reservoirs which occur widespread in the subsurface of NRW. The Devonian sandstone and reef deposits, for instance, provide additional potentials in greater depths.

6. Acknowledgements

The author gratefully thanks the editor and reviewers for their constructive remarks that helped to improve the manuscript. Many thanks also go to Kim Nokar, Markus Pracht, Sascha Sandmann, Daniel Schrijver, Sören Stichling, Burcu Tasdemir, and Volker Wrede for additional remarks and proofreading of the manuscript as well as to Ulrike Mittler for assistance in creating the figures. Further appreciation is dedicated to my colleagues Martin Salamon, Bernd Linder, Anna Thiel and Tobias Fritschle for their advice and help in modelling and enhancing the manuscript. This study was supported by the Interreg NWE Programme through the Roll-out of Deep Geothermal Energy in North-West Europe (DGE-ROLLOUT) Project (www.nweurope.eu/DGE-Rollout), NWE 892. The Interreg NWE Programme is part of the European Cohesion Policy and is financed by the European Regional Development Fund (ERDF).

7. References

Amler, M. R. W., & Herbig, H.-G. (2006). Ostrand der Kohlenkalk-Plattform und Übergang in das Kulm-Becken im westlichsten Deutschland zwischen Aachen und Wuppertal. In Deutsche Stratigraphische Kommission (Ed.), Stratigraphie von Deutschland, VI. Unterkarbon (Mississippium). *Schriftenreihe der Deutschen Gesellschaft für Geowissenschaften, 41*, 441–447.

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

Bless, M. J. M., Bouckaert, J., Conil, R., Groessens, E., Kasig, W., Paproth, E., . . . Walter, R. (1980). Pre-Permian depositional environments around the Brabant massif in Belgium, The Netherlands and Germany. *Sedimentary Geology, 27*(1), 1–81. https://doi.org/10.1016/0037-0738(80)90031-7

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, 172*(3), 211–225. https://doi.org/10.1127/zdgg/2021/0285

Conil, R., Paproth, E., & Lys, M. (1968). Mit Foraminiferen gegliederte Profile aus dem nordwest-deutschen Kohlenkalk und Kulm. *Decheniana, 119*(1/2), 51–94.

DEKORP Research Group. (1990). Results of deep-seismic reflection investigations in the Rhenish Massif. In J. H. Leven, D. M. Finlayson, C. Wright, J. C. Dooley, & B. L. N. Kennett (Eds.), Tectonophysics: *Vol. 173*. *Seismic probing of continents and their margins* (pp. 507–515).

Devuyst, F. X., Hance, L., & Poty, E. (2005). The Dinantian of Southern Belgium revisited: Sedimentary history and biostratigraphy. A guidebook of key sections. *SCCS field trip 24-28.05.2005*.

Drozdzewski, G. (1985). Tiefentektonik der Ibbenbürener Karbon-Scholle. In G. Drozdzewski, H. Engel, R. Wolf, & V. Wrede (1985). *Beiträge zur Tiefentektonik westdeutscher Steinkohlelagerstätten*. Krefeld: Geologisches Landesamt Nordrhein-Westfalen.

Drozdzewski, G. (1992). Zur Faziesentwicklung im Oberkarbon des Ruhrbeckens, abgeleitet aus Mächtigkeitskarten und lithostratigraphischen Gesamtprofilen. *Zeitschrift für Angewandte Geologie, 38*(1), 41–48.

Drozdzewski, G., & Dölling, M. (2018). Elemente der Osning-Störungszone (NW-Deutschland) – Leitstrukturen einer Blattverschiebungszone. *scriptumonline, 7*, 1–39. www.gd.nrw.de/pr_bs_scriptumonline.htm

Drozdzewski, G., & Wrede, V. (1994). Faltung und Bruchtektonik – Analyse der Tektonik im Subvariscikum. In G. L. Nordrhein-Westfalen (Ed.), *Das Subvariscikum Nordwestdeutschlands. Fortschritte in der Geologie von Rheinland und Westfalen, 38, 7–188*.

Drozdzewski, G., Bornemann, O., Kunz, E., & Wrede, V. (1980). *Beiträge zur Tiefentektonik des Ruhrkarbons*. Krefeld: Geologisches Landesamt Nordrhein-Westfalen.

Drozdzewski, G., Jansen, F., Kunz, E., Pieper, B., Rabitz, A., Stehn, O., & Wrede, V. (1981). *Geologische Karte des Ruhrkarbons 1:100 000, dargestellt an der Karbonoberfläche*. Krefeld: Geologisches Landesamt Nordrhein-Westfalen.

Drozdzewski, G., Engel, H., Wolf, R., & Wrede, V. (1985). *Beiträge zur Tiefentektonik westdeutscher Steinkohlelagerstätten*. Krefeld: Geologisches Landesamt Nordrhein-Westfalen.

Drozdzewski, G., Henscheid, S., Hoth, P., Juch, D., Littke, R., Vieth, A., & Wrede, V. (2009). The pre-Permian of NW-Germany – Structure and coalification map. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 160*(2), 159–172. https://doi.org/10.1127/1860-1804/2009/0160-0159

Eder, W., Engel, W., Franke, W., & Sadler, P. M. (1983). Devonian and Carboniferous limestone-turbidites of the Rheinisches Schiefergebirge and their tectonic significance. In H. Martin & W. Eder (Eds.), *Intracontinental fold belts* (pp. 93–124). Berlin: Springer. https://doi.org/10.1007/978-3-642-69124-9_5

Franke, W., Eder, W., & Engel, W. (1975). Sedimentology of a Lower Carboniferous shelf-margin. *Neues Jahrbuch für Geologie und Paläontologie, 150*(3), 314–353.

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

Fritschle, T., Strozyk, F., Oswald, T., Stubbe, H., & Salamon, M. (2021b). Deep geothermal energy potential at Weisweiler, Germany: Exploring subsurface mid-Palaeozoic carbonate reservoir rocks. [Journal of Applied and Regional Geology] [this issue]. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 172*(3), 325–338. https://doi.org/10.1127/zdgg/2021/0292

GD NRW – Geologischer Dienst Nordrhein-Westfalen (Ed.). (2016). *Geologie und Boden in Nordrhein-Westfalen*. Krefeld: Geologischer Dienst NRW.

Graulich, J.-M. (1975). Le sondage de Boland. *Professional Paper of the Geological Survey of Belgium, 122*(9), 1–38.

Graulich, J.-M., & Vandenven, G. (1973). Le sondage d'Ensival-Lambermont. *Service Géologique de Belgique, 90*(7), 1–37.

Graulich, J.-M., Coen-Aubert, Mme., & Conil, M. R. (1975). Le sondage de Hermalle-sous-Argenteau. *Service Geologique de Belgique, 117*(4): 1–15.

Herbig, H.-G., & Salamon, M. (2009). *Stratigraphie und Fazies des späten Oberdevons und Karbons am Südost-Rand des Brabanter Massivs (Aachen/westlichstes Deutschland und Vesdre-Massiv/Ostbelgien). Tagung der Subkommission für Karbon-Stratigraphie, Stolberg-Vicht, 25.–26. April 2009*. Köln: Deutsche Stratigraphische Kommission, Subkommission für Karbonstratigraphie.

Herbig, H.-G., Lobova, D., & Seekamp, V. (2013). Tales of a core: Sea-level history, global crises and changing depositional architecture – The Famennian-Viséan of "Velbert 4", westernmost Rhenish Massif, Germany. In J. Žák, G. Zulauf, & H.-G. Röhling (Eds.), *Crustal evolution and geodynamic process in Central Europe. Schriftenreihe der Deutschen Gesellschaft für Geowissenschaften, 82, 49*.

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

Juch, D., Roos, W.-F., & Wolff, M. (1994). Kohleninhaltserfassung in den westdeutschen Steinkohlelagestätten. In G. L. Nordrhein-Westfalen (Ed.), *Das Subvariscikum Nordwestdeutschlands. Fortschritte in der Geologie von Rheinland und Westfalen, 38, 189–307*.

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, & E. Paproth (Eds.), Pre-Permian around the Brabant Massif in Belgium, the Netherlands and Germany. *Mededelingen Rijks Geologische Dienst, 32*(6), 44–52.

Korn, D. (2003). Die Formationen der Kulm-Fazies im Rheinischen Schiefergebirge. In M. R. W. Amler & M. Gereke (Eds.), *Karbon-Korrelationstabelle (KKT). Senckenbergiana lethaea, 83(1–2), 236–242*.

Korn, D. (2006). Lithostratigraphische Neugliederung der Kulm-Sedimentgesteine im Rheinischen Schiefergebirge. In M. R. W. Amler, & D. Stoppel (Eds.), Stratigraphie von Deutschland, VI.

Unterkarbon (Mississippium). *Schriftenreihe der Deutschen Gesellschaft für Geowissenschaften, 41*, 379–383.
Korn, D. (2008). Early Carboniferous (Mississippian) calciturbidites in the northern Rhenish Mountains (Germany). *Geological Journal, 43*(2–3), 151–173. https://doi.org/10.1002/gj.1100
Korn, D. (2010). Lithostratigraphy and biostratigraphy of the Kulm succession in the Rhenish Mountains. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften, 161*(4), 431–453. https://doi.org/10.1127/1860-1804/2010/0161-0431
Kunz, E., Wolf, R., & Wrede, V. (1988). *Ergänzende Beiträge zur Tiefentektonik des Ruhrkarbons*. Krefeld: Geologisches Landesamt Nordrhein-Westfalen.
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
LIAG – Leibniz Institute for Applied Geophysics. (2017). *Deep geothermal energy*.
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
Mozafari, M., Gutteridge, P., Riva, A., Geel, K., Garland, J., & Dewit, J. (2019). Facies analysis and diagenetic evolution of the Dinantian carbonates in the Dutch subsurface: overview and synthesis. *SCAN Dinantian Report*. https://www.nlog.nl/scan/
Pharaoh, T., Jones, D., Kearsey, T., Newell, A., Abesser, C., Randles, T., . . . & Kendall, R. (2021). Early Carboniferous limestones 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
Poty, E. (2016). The Dinantian (Mississippian) succession of southern Belgium and surrounding areas: Stratigraphy improvement and inferred climate reconstruction. *Geologica Belgica, 19*(1–2), 177–200. https://doi.org/10.20341/gb.2016.014
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
Prakla-Seismos GmbH (1965). *Bericht über seismische Messungen im Arbeitsgebiet Krefeld-Mönchengladbach 1964/1965*. Archiv-Nr.: 1517.
Ribbert, K.-H., & Wrede, V. (2005). Stratigrafische und tektonische Ergebnisse der Grundgebirgsbohrungen im Umfeld des Braunkohle-Tagebaus Hambach. In N. R. W. Geologischer Dienst (Ed.), *Der tiefere Untergrund der Niederrheinischen Bucht. scriptum, 13,* 33–60.
Ribbert, K.-H., Wrede, V., Oesterreich, B., Hartkopf-Fröder, C., Piecha, M., & Veith, A. (2008). The geothermal well „RWTH-1“ – Basic geological results and interpretation. In P. Kukla, & R. Littke (Eds.), Geo2008 – Resources and risks in the earth system. *Schriftenreihe der Deutschen Gesellschaft für Geowissenschaften, 60*, 316.
Schäfer, A., Utescher, T., Klett, M., & Valdivia-Manchego, M. (2005). The Cenozoic Lower Rhine Basin – Rifting, sedimentation, and cyclic stratigraphy. *International Journal of Earth Sciences, 94*(4), 621–639. https://doi.org/10.1007/s00531-005-0499-7
Steingrobe, B. (1987). Zum Sedimentationsbeginn des Oberkarbons im Aachener Steinkohlenrevier. *Facies, 17*(1), 231–235. https://doi.org/10.1007/BF02536787
STG 2016 (German Stratigraphic Commission) (Ed.; Editing, coordination and layout: M. Menning, & A. Hendrich) (2016). *Stratigraphic Table of Germany 2016*. Potsdam: German Research Centre for Geosciences.
Wiegel, E. (1973). Die Entwicklung der staatlichen geologischen Kartierung in Nordrhein-Westfalen vor 1873. *Fortschritte in der Geologie von Rheinland und Westfalen, 23*, 11–54.
Wrede, V. (1998). Die Tektonik des präpermischen Untergrundes von Krefelder und Venloer Scholle. In N. R. W. Geologischer Dienst (Ed.), *Der Untergrund der Niederrheinischen Bucht. Fortschritte in der Geologie von Rheinland und Westfalen, 37,* 333–380.
Wrede, V., & Ribbert, K.-H. (2005). Das Oberkarbon (Silesium) am Nordrand des Rheinischen Schiefergebirges. In D. S. Kommission (Ed.), *Stratigraphie von Deutschland, V. Das Oberkarbon (Pennsylvanium) in Deutschland. Courier Forschungsinstitut Senckenberg, 254,* 215–254.
Wrede, V., & Zeller, M. (1988). *Geologie der Aachener Steinkohlelagerstätte*. Krefeld: Geologisches Landesamt Nordrhein-Westfalen.
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.

Manuscript received: 16.03.2021
Revisions required: 05.05.2021
Revised version received: 06.10.2021
Accepted for publication: 07.10.2021

Internet References

[1] https://www.geothermie.nrw.de/
[2] https://www.energieagentur.nrw/geothermie/geothermie/potenzialstudie-zur-tiefengeothermie-im-ruhrgebiet
[3] https://www.gd.nrw.de/ge_eb_3d_modelle.htm
[4] https://www.nlog.nl/en/scan-2d-seismic-interpretation-and-depth-conversion-dinantian.
[5] https://www.nlog.nl/en/scan-2d-seismic-data
[6] https://www.gfz-potsdam.de/en/section/geophysical-imaging/projects/past-projects/dekorp/dekorp-2/
[7] https://litholex.bgr.de/pages/MainApp.aspx?_sys_params=Nr8PDn_4fNCQfZiUX8sxJCnDDD2DVQI3nlWJAMb_HEYXPvzDP6bZu0751vshIgRu5xpu9ybBjw