Interreg
EUROPEAN UNION
North-West Europe
DGE-ROLLOUT

Deliverable T2.1.13 – Interpretation of seismic data in NRW

Part 2 - Results of the reprocessed seismic lines DEK86-2N and DEK86-2Q

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Disclaimer

The purpose of this report is to summarize the interpretation results of a reprocessed deep seismic reflection survey. It is not a peer-reviewed paper and therefore does not replace the own independent research on this topic.

The results presented herein are the authors' subjective opinions based on the research which has been done for this report.

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

Contents

1. Introduction

The objective of this deliverable is to investigate the structure of the deep subsurface of North Rhine-Westphalia (NRW) and parts of Belgium for carbonate rocks that are candidates for the development of deep geothermal energy. Within the framework of the DGE-ROLLOUT project, three seismic lines of the German Continental Seismic Reflection Programme (DEKORP) were reprocessed and reinterpreted focussing on the Middle Devonian and Lower Carboniferous carbonate rocks.

The DEKORP seismic lines were acquired in the 1980's with the aim to investigate deep crustal structures and targets like the Mohorovičić Discontinuity. They reached depths of approximately 50,000 to 60,000 m. The vintage seismic data was reprocessed by DMT GmbH & Co. KG to enhance the resolution of shallow targets in depths of up to 6,000 m. Further details about the reprocessing can be found in Appendix 1.

This report presents the new results on the interpretation of the seismic lines DEK86-2N and DEK86-2Q. The interpretation was done with the software Petrel (Schlumberger Information Solutions) to determine the depth and thickness of the Lower Carboniferous and Devonian carbonate rocks in the Palaeozoic basement below the Münsterland Cretaceous Basin. These carbonate rocks are considered as target horizons for deep geothermal energy exploitation.

The reprocessed seismic line DEK86-2N generally trends from northwest to southeast and has a length of 153.7 km. It starts in the north near Altenburg and continues past the deep borehole Münsterland 1 southeast towards Unna and Iserlohn and ends at the border between the German federal states of North Rhine-Westphalia and Rhineland-Palatinate near Siegen (Figure 1). The original seismic line of the DEKORP Research Group continued further southeast and ended c. 20 km before Frankfurt am Main (Franke et al. 1990). This latter part was not reprocessed.

The reprocessed seismic line DEK86-2Q has a length of 60 km and passes through the vicinity of the deep borehole Versmold 1 in the northeast. It starts near Selm and is directed towards northeast, crosses the seismic line DEK86-2N near Ascheberg and ends south of Versmold. The whole line has been reprocessed and interpreted within this investigation.

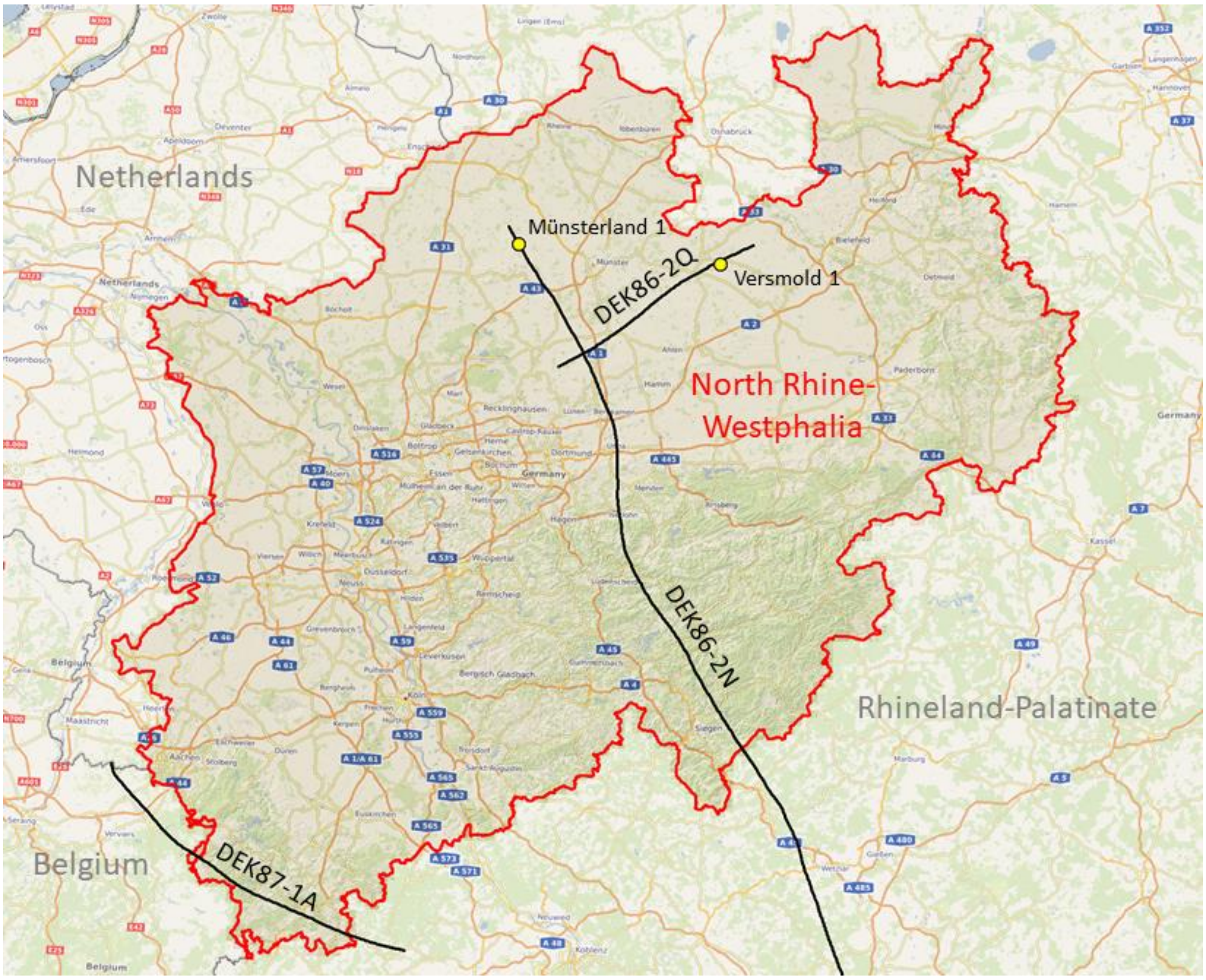

Figure 1: Base map of the DEKORP seismic lines in North Rhine-Westphalia. The seismic line DEK87-1A was interpreted in part 1 of this deliverable. The interpretations of seismic lines DEK86-2N and DEK86-2Q are presented in this report. The deep boreholes tied to the seismic lines are indicated as yellow circles.

1.1 Geological overview

The geological history of the investigated area reaches back about 400 million years into the past (GLA NRW 1995). The sedimentary succession of its subsurface can be subdivided into two major geological units: (1) the Variscan basement consisting of folded Palaeozoic rocks and (2) the overburden, which mainly consists of up to more than 2,000 m thick Cretaceous strata. Since the latter are so prominently represented in this area, it is also referred to as the Münsterland Cretaceous Basin (MCB). Since this study focuses on the Palaeozoic rocks of the Devonian and Lower Carboniferous, they are described more detailed than the other geological units in this report.

The Devonian succession derived from the former Old Red Continent and was deposited on its southern shelf in the Rhenohercynian Basin. Thus, sandstones, clays and limestones are expected in the deep subsurface below the MCB. Thick carbonate rocks originating from coral reefs (also referred to as ‘Massenkalk’) may also be among them. Information about the Devonian is known from the adjacent deep boreholes Münsterland 1 and Versmold 1 as well as from the near-surface outcrops of the Rhenish Massif in the south (Figure 2).

In Early Carboniferous times, the ocean trough of the Rhenohercynian Basin began to sink as the Variscan Orogen successively moved northwards. This resulted in different depositional areas. A carbonate platform, which belongs to the Kohlenkalk Group, extended to the west of the basin. In the center, sedimentary deposits of the Kulm basin facies accumulated comprising shales alternating with turbiditic limestones. The latter originated from the western carbonate platform or a carbonate platform that is expected below the MCB (Korn 2008). In the southeastern part of the basin, flysch deposits consisting of sandstone layers accumulated.

With increased shortening of the basin during the Late Carboniferous, the ocean trough became a flat coastal plain known as the Subvariscan Foredeep (Drozdzewski & Wrede 1994). Climate conditions favoured the development of an extensive marshland, from which the hard coals of Ruhr Area derive. They are also present in the deep subsurface below the MCB.

The Rhenish Massif was located in the south of the North German Basin and was bounded on the west by the Lower Rhine Embayment and the east by the Hesse Basin ('Hessische Senke'). Due to its elevated position, Permian, Triassic and Jurassic sedimentary deposits were only accumulated at its margins.

During the late Early Cretaceous, a significant sea level rise shifted the northern coastline towards the south and flooded the northern part of the Rhenish Massif, forming the first deposits of the MCB. The Cretaceous sediments unconformably overlie the Palaeozoic basement.

Tertiary deposits are only known from the subsiding Lower Rhine Embayment, which adjoins the MCB to the west. Quaternary sediments lie on top of the Cretaceous strata in patchy distribution. Often, they are thin and only reach a few meters, sometimes they are missing.

1.1 Tectonic setting

During the Variscan Orogeny, the Palaeozoic strata were folded, traversed by faults and uplifted. At the same time, their erosion began. The degree of deformation decreases to the northwest with an increasing distance from the orogen, which formed the Rhenish Massif.

Tectonic structures can be recognized in both the Palaeozoic basement and the Cretaceous overburden. The main tectonic movements occurred at the end of the Variscan folding, at the end of the Triassic and at the transition from the Jurassic to the Cretaceous. The repeated crustal movements resulted from transregional strains in connection with the opening of the Atlantic Ocean (GD NRW 2020).

Widespread uplift of the crust led to partial erosion of the previously deposited strata. The uplift was accompanied by reactivation of existing faults and the formation of new faults. Reactivation of major faults within the Carboniferous basement also affected the overburden during the Late Cretaceous to the Early Tertiary when another compressional phase reactivated Cretaceous faults. Uplift induced movements partially or completely reversed the former depositional amounts by erosion in the Cretaceous and older strata, which lead to complex setting of reverse faults ('Umkehrverwurf', Wolansky 1960, Wesche 2017).

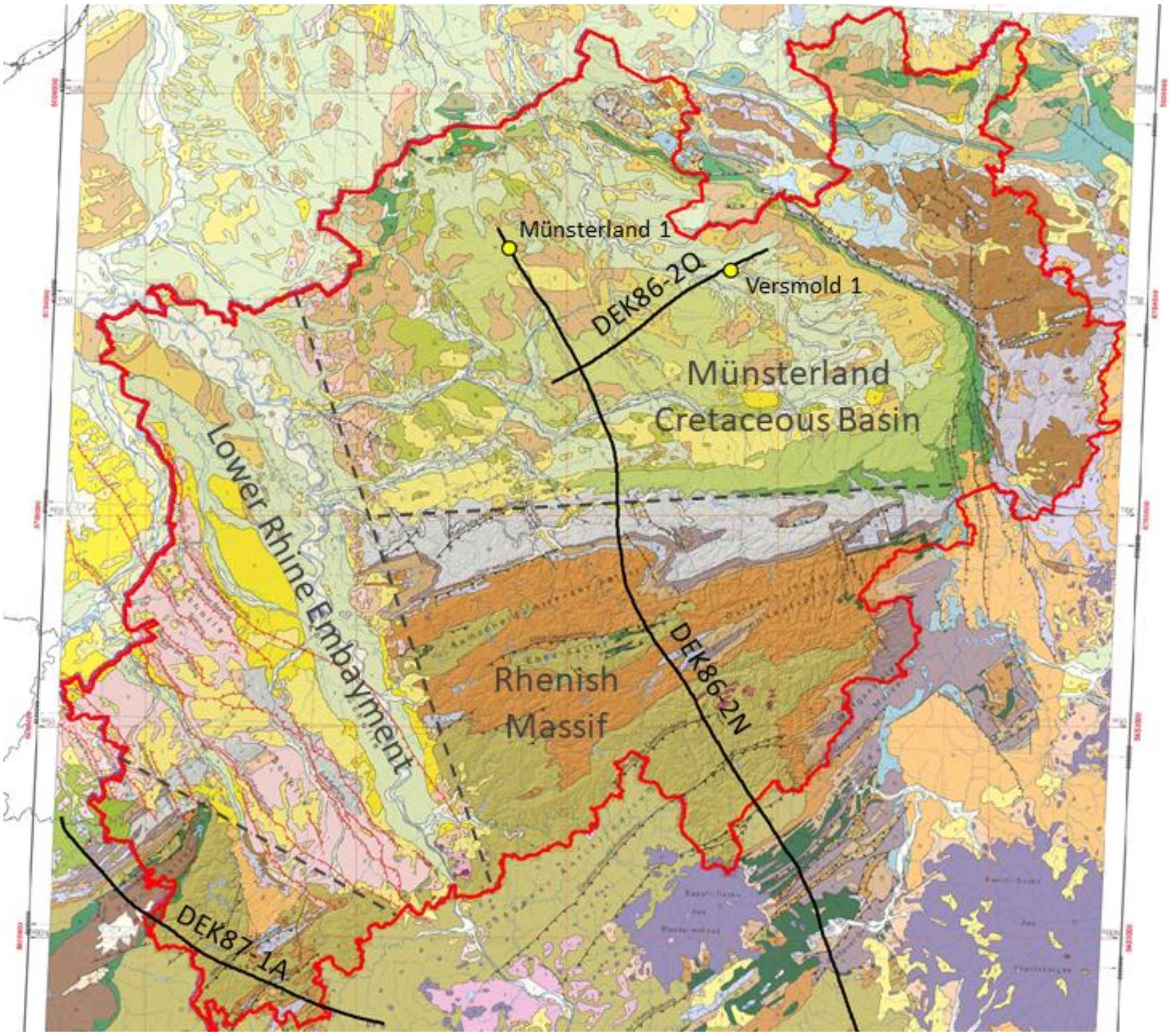

Figure 2: Geological map of North Rhine-Westphalia showing the seismic lines DEK87-1A, DEK86-2N, and DEK86-2Q as well as the major geological areas: the Lower Rhine Embayment, the Münsterland Cretaceous Basin, and the Rhenish Massif.

2. Methodology

The Devonian and Lower Carboniferous carbonate rocks are the main target of this study. During the interpretation process characteristic reflections were marked and followed laterally (picking process). Faults can be recognized by sharp offsets of strong reflectors. Small scale faulting often shows inclined reflectors rather than clear offsets. Lateral changes in the seismic wave attributes (e.g. frequency, phase or amplitude force) may indicate weak zones due to fractures, karstification or facies changes.

2.1 Geological database: stratigraphy and borehole correlation

The Palaeozoic rocks of the basement were drilled by the deep boreholes Münsterland 1 and Versmold 1. Formation top data and synthetic seismograms from the former boreholes were used to age-calibrate the key seismic horizons on line DEK86-2N. A direct seismic-to-well correlation of the borehole Versmold 1 with line DEK86-2Q was not possible due to a substantial distance to the seismic line and the absence of borehole velocity data. Instead, a qualitative correlation was conducted by projecting the borehole formation tops orthogonally onto the line DEK86-2Q in depth domain. New data from a recent seismic survey in Münster were included. The seismic lines of the latter contributed to a better understanding of the deep subsurface of the MCB.

According to borehole data, the Lower Carboniferous strata lie in depth of 5,438 to 5,512 m (borehole Münsterland 1) and 4,768 to 4,832 m (borehole Versmold 1). The alternating sequences of partly silicified shales and limestones indicate the Kulm facies with turbiditic limestones. A carbonate platform within the basin is assumed to be the source area of these turbidites (Korn 2008).

The Devonian limestones lie in depth of 5,757 to 5,930 m (borehole Münsterland 1) and 5,247.5 to 5,500.7 m (total depth of borehole Versmold 1). These massive Devonian limestones are micritic and rich in fossils, which is typical for the Middle Devonian Massenkalk facies.

2.2 Seismic imaging of carbonate rocks

In the seismic images, carbonate rocks can be recognized by a strong reflection or a series of strong reflections at the top followed by a series of weak reflections (or even a transparent zone) below.

Other geological settings may produce similar seismic images: water-filled carbonates, for instance, often indicate higher velocities and/or densities; interbedding with siliciclastics and coal seams may also generate strong multiple reflections. Therefore, it is also important to include the indirect indicators into the interpretation.

Thus, the alternating sequences of the Lower Carboniferous Kulm facies and the Middle Devonian Massenkalk should be identified as strong reflections in the seismic image.

3. Interpretation

The interpretation of the reprocessed seismic lines DEK86-2N and DEK86-2Q was carried out by identifying the strong reflectors close to the deep boreholes Münsterland 1 and Versmold 1.

Strong reflections are clearly visible at the Cretaceous base, which lies unconformably above the Palaeozoic basement at a maximum depth of c. 1,800 m in the borehole Münsterland 1 and 1,500 m near the borehole Versmold 1. The seismic data clearly depict the flat-lying Cretaceous overburden. In particular, the Turonian and Cenomanian carbonate formations at the base of the Cretaceous overburden exhibit distinct reflections (Figures 3 and 4).

In the Upper Carboniferous, undisturbed areas with shallow to moderately inclined bedding, typically up to a maximum of 40º, are generally well imaged and are seismically characterized by a series of strong reflections that can be followed down to depths of up to 4000 m. Such a reflection pattern represents the alternating successions of coal seams and sandstones of the succession of the Westphalian A and B. Tectonic structures with angles exceeding 40º and tight folding are either not imaged at all or display shallow phantom horizons.

Neither steep nor shallow faults (thrusts and normal faults) are directly imaged in the Upper Carboniferous by the seismic data. They can only be perceived when layers with different inclinations adjoin one another or when reflections abruptly terminate.

It was only possible to discriminate between Devonian and Lower Carboniferous strata near the deep boreholes Münsterland 1 and Versmold 1. Therefore, the interpretation only defined the top of the Lower Carboniferous and the base of the Middle Devonian Massenkalk, based on visible reflections and the expected thickness of the strata.

Strong reflectors which can be associated with the Devonian and Lower Carboniferous carbonate rocks can be recognized in the seismic line DEK86-2N at km 5.5 in depths from 5,200 to 6,000 m, between km 17 and 21 in depths from 6,000 to 7,000 m, and between km 30.5 and 33 in depths from 4,900 to 5,700 m (Figure 3). The reflector is not continuous and cut off by several faults. In other places of the seismic image, no good reflection can be seen in the expected depths (e.g. between km 7 and 8.5, km 22 and 23, and from km 42 onwards).

In the seismic line DEK86-2Q, a series of strong reflections could be identified as the top of the Lower Carboniferous (Figure 4) in the northeastern part between km 52.5 and 59.5 in depths from 4,800 to 5,800 m. Near the deep borehole Versmold 1, the reflections are rather inconsistent. Further to the southwest, only weak reflections could be identified.

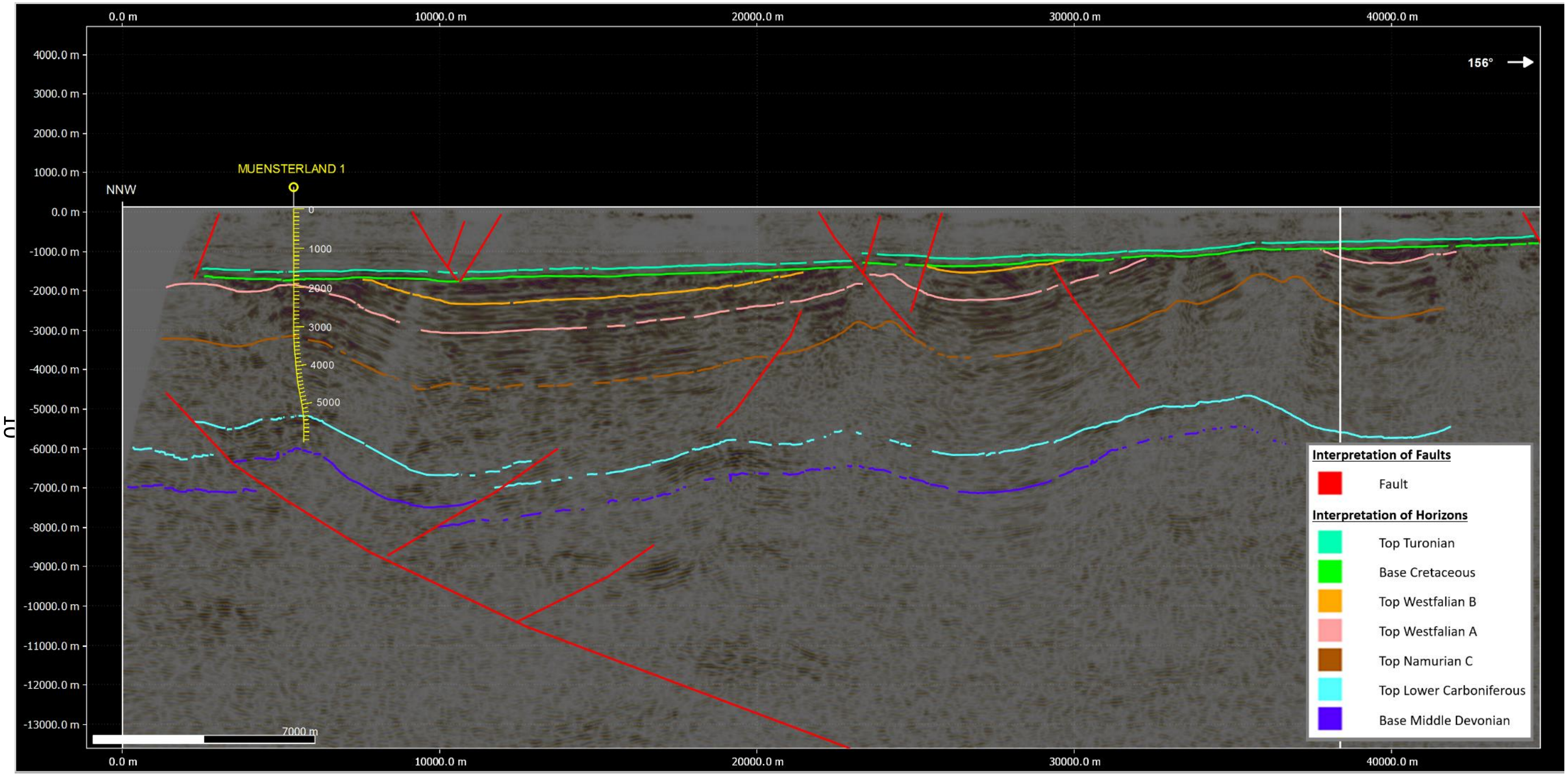

Figure 3: Interpretation of the seismic line DEK86-2N (2x vertical exaggeration). The thick vertical line (in white) indicates the intersection with seismic line DEK86-2Q. See also Figure 4, Appendix 2 and Appendix 3.

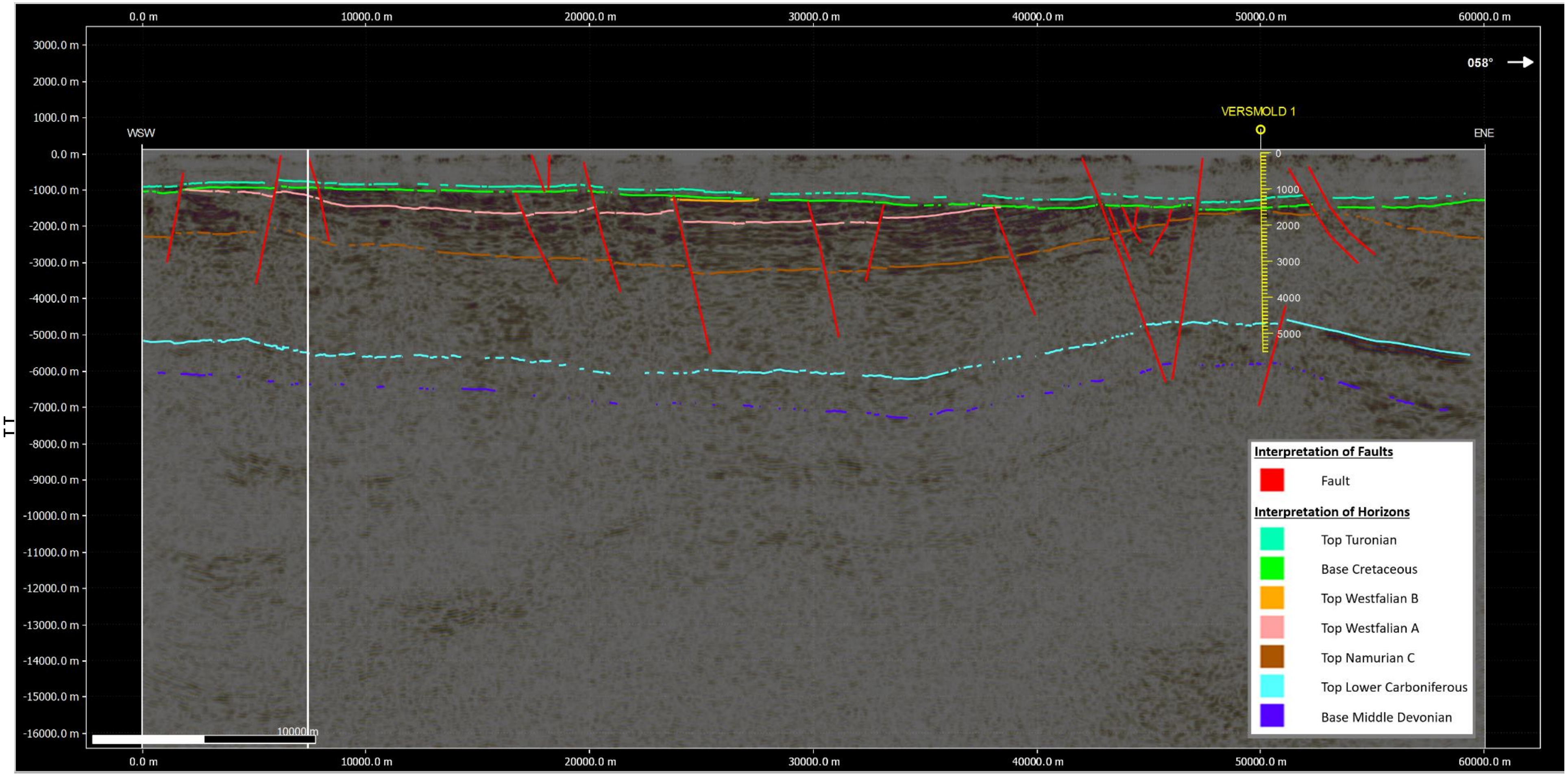

Figure 4: Interpretation of the seismic line DEK86-2Q (2x vertical exaggeration). The thick vertical line (in white) indicates the intersection with seismic line DEK86-2N. See also Figure 3, Appendix 2 and Appendix 3.

4. Discussion

Typical interpretation problems like noise, multiples, fault shadows, as well as surface and topography influences were identified. Additionally, the seismic lines DEK86-2N and DEK86-2Q are only suitable to a limited extent for the interpretation and mapping of shallow targets because of their original acquisition design, which was intended to image very deep crustal structures. Some mis-ties occurred where the seismic lines crossed each other. At some parts, the seismic image did not show any good reflection signals. This could be due to several reasons, of which the main ones are explained in the following:

(1) The deeper strata experienced a strong tectonic overprint: seismic reflection signals are especially weak near larger fault zones and irregularly folded surfaces. The complex tectonic structures of the Subvariscan Foredeep are known from mining activities of the Ruhr Area and have been described in detail by Drozdzewski & Wrede (1994): the upper parts of the Palaeozoic basement have few folds with high amplitudes, whereas the lower parts have many folds with low amplitudes creating a disharmonic folding structure. The former structures are clearly visible in the seismic image, whereas the latter could explain the low reflectivity. The decrease in reflectivity within the steeply dipping anticlines can be explained by an increased density of fractures that attenuate seismic energy.

(2) Lateral changes in facies (e.g. from massive platform carbonate rocks to sand and siltstone deposits) may cause the target horizons to blend into the monotonous layering of the overlying and underlying strata. Thus, no seismic signal could be reflected.

(3) The Cretaceous sediments and Upper Carboniferous coal seams absorbed most of the stimulation energy and caused a blurring of the strata below. Franke et al. (1990) explained a paucity of reflections in the deeper crust by a shielding influence of the Cretaceous sediments, especially for higher frequencies. However, the Mohorovičić Discontinuity was still visible. Nonetheless, no reliable statement can be made on the condition of the subsurface for certain areas without additional studies.

It is worth mentioning that, parallel to the seismic line DEK86-2N, a magnetotelluric survey was executed, which indicates with a fair degree of certainty that there is a conductive zone below the MCB in depths between 6 and 8 km (Volbers et al. 1990). They determined electron conduction as the most likely explanation and interpreted the good conductor as a black shale. However, an electrolytic conduction (e.g. by a brine) was also considered as likely. This zone coincides with our interpretation of the Lower Carboniferous or Devonian target horizons, where black shales are known from the Lower Carboniferous Kulm facies and brines could occur in faulted or karstified areas of the Middle Devonian Massenkalk.

5. Conclusion

The seismic lines DEK86-2N and DEK86-2Q have been reprocessed and interpreted with the aim to determine the depth and thickness of the Devonian and Lower Carboniferous target horizons below the Münsterland Cretaceous Basin. Despite the reprocessing, it was not possible to show the areas with low reflectivity more clearly, for different reasons.

The target horizons from the top of the Lower Carboniferous to the base of the Middle Devonian were interpreted and lie in depths between 4,500 and 8,000 m in the seismic line DEK86-2N and between 4,500 and 7,500 m in the seismic line DEK86-2Q, respectively.

There is evidence of carbonate rocks in the target horizons, but they cannot be traced throughout the profiles. If these are considered for deep geothermal energy exploitation, further investigations will be necessary.

6. References

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7. Appendices

Appendix 1 – Report on seismic reprocessing ‚2D-Seismik DEKORP Land Nordrhein-Westfalen‘

Appendix 2 – Interpretation DEK86-2N

Appendix 3 – Interpretation DEK86-2Q

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