Interreg North-West Europe
DGE-ROLLOUT

Uncertainties related to the depth mapping of the Dinantian aquifer

Deliverable WP LT D3.2

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Contents

Summary

In the framework of the DGE Rollout consortium, the geothermal potential of the Carboniferous Dinantian carbonates in the North-Western Europe has been investigated.

The current deliverable describes the uncertainties related to the constructed Top Dinantian depth map. It also provides recommendations for decreasing the uncertainties should additional data become available. Derisking and reducing uncertainties will provide more robust estimates of the spatial distribution of the deep limestone reservoirs. Using learnings from other mapping programs, recommendations are provided to better integrate cross-border mapping studies.

Various sources of error contribute to uncertainties in the Top Dinantian depth map. They relate to various stages of the interpretation and map making process, from interpretation through time-depth conversion to interpolation (e.g., data error in seismic data (processing), structural complexity, depth, velocity model and data density).

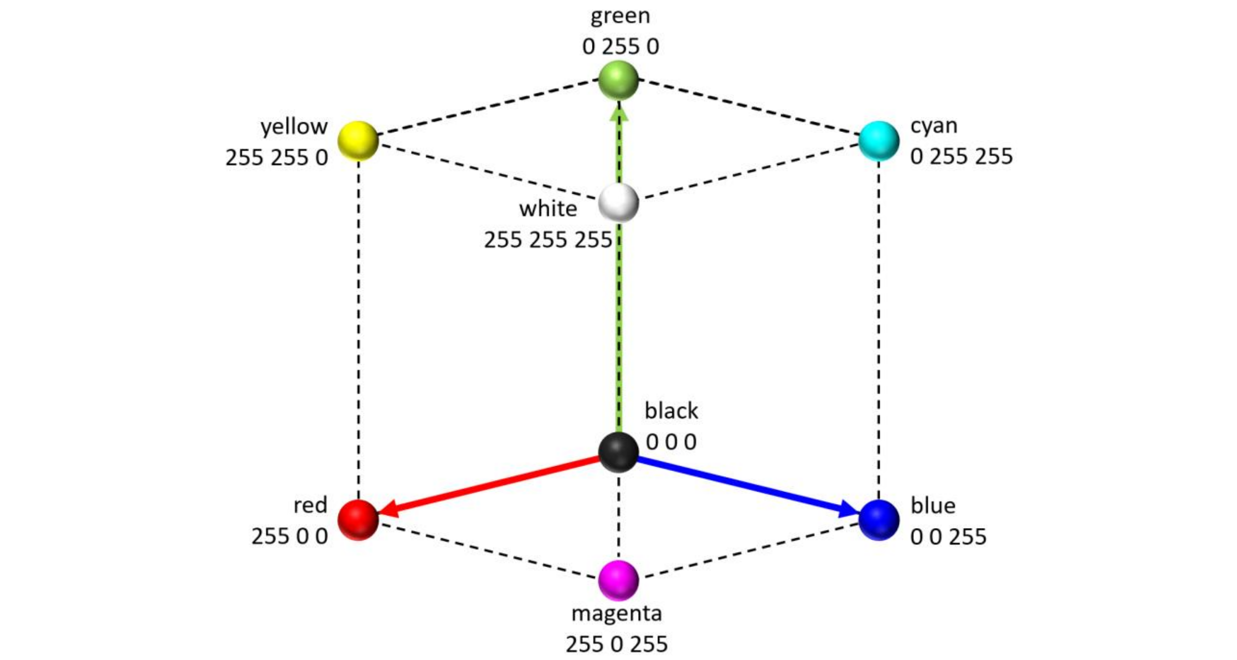
Based on learnings from other integrated geothermal studies, three main qualitative indicators for uncertainty were identified that determine the uncertainty in Top Dinantian depth map:

1. Data quality and density
   Seismic data is often of different vintage with varying quality, and is either 2D (digital or analogue lines) or 3D seismic. In addition, seismic data density varies within a country, but also between countries. Also, the seismic was interpreted by multiple individuals over longer periods of time, applying varying methods with different geological models in mind.

2. Total depth
   Seismic data is acquired in time. This is the time required for an acoustic wave to travel into the subsurface where it is reflected by different rock layers, and subsequently recorded on the surface by geophone. Next, the recorded travel time is converted to depth using a velocity model that defines the varying relationship between depth and acoustic wave velocity. With cross-border interpretations, differences in the velocity models used will result in different depth conversions, introducing additional uncertainties.

3. **Tectonic complexity**
   Structural complexity introduces a significant source of error when interpreting (seismic) data. In certain areas (e.g., the Netherlands and North Rhine-Westphalia NRW), the structural setting of the Dinantian is relatively simple, with predominant normal faulting defining horsts, grabens and half grabens. Other areas are significantly more complex (e.g., northern France and Wallonia), as thrust sheets and duplexes (structural duplications) are present.

For each of those three qualitative indicators, uncertainty maps have been produced that are overlain to generate a total uncertainty depth map. In order to visualise the total (combined) uncertainties, the colour composition technique is used (adopted from the field of remote sensing, see figure below).



Maps for the three qualitative contributors are constructed in the primary colours red, green and blue. **Data quality and density** is depicted in shades of blue ranging from black to full blue. **Total depth map** is depicted in shades of green (black to full green) whereas **structural complexity** contains shades of red (black to full red). In all the three maps, the colour shades depict the same confidence levels: black (or no colour) represents high uncertainty, whereas full red, green or blue equals a low uncertainty.

When the three maps are overlain, the resulting composite colours depict the joined uncertainty. Dark shades indicate a large joined uncertainty, i.e., all three contributing maps have a high uncertainty whereas light shades indicate a low uncertainty. Non-primary colours depict relative contributions of the uncertainties. Yellow shades (red + green) indicate a high uncertainty in structural complexity but at shallow depth and high data density. Cyan (green + blue) is indicative of low data density, shallow and tectonically less complex. Magenta (red + blue) depicts areas of large depth, high data density and low structural complexity.

In the final chapter of this report, recommendations are made to reduce the uncertainties in the Top Dinantian depth map.

Note

The complexity maps shown in this report are based on the depth and data maps that were available during the writing of the report prior to June 2023. This means that both the data distribution and depth maps can be slightly different from the final versions delivered within the DGE Rollout project.

1 Introduction

In the framework of the DGE Rollout consortium, the geothermal potential of the Carboniferous Dinantian limestones in the North-western Europe is being investigated. The carbonate rocks of the Lower Carboniferous are known in the Netherlands by various names: Carboniferous Limestone Group, Zeeland Formation, 'Kohlenkalk', Dinantian, or sometimes as 'Kulm'. For this report we use the term Dinantian when referring to this stratigraphic interval. Previous DGE Rollout deliverables include, among others, maps of the depth of the top and base of the Dinantian, thickness, map and workflows used for determining geothermal potential (temperature, heat in place and geothermal power, e.g., Arndt et al., 2021; Veldkamp, 2021; Nelskamp et al., 2022).

The depth, thickness and temperature maps are based on a variety of subsurface data. Some of those data can be considered 'hard' (e.g., well tops for depth or thickness, core data for lithological properties, borehole temperature measurements for the temperature map) whereas other sources can be considered 'soft' (e.g., seismic data processing and interpretation, velocity models for time-depth conversions, conceptual geological models). The latter comprise data sources of varying quality and areal density, that have been interpreted by multiple individuals over long periods of time, and for which different geological methods and concepts have been used over regions which had variable geological evolution.

Both hard and soft data types have varying degrees of associated uncertainties. Well tops (formation depth) are usually identified from well logs (e.g., gamma ray, sonic, density), cores and drilling cuttings, but interpretation errors may result in wrongly picked tops. These errors are incorporated when producing seismic-to-well ties and are subsequently propagated into the seismic interpretation of a specific surface. The uncertainties related to seismic processing, interpretation and time-depth conversion of the surfaces depend on many factors (quality and resolution of seismic surveys, structural complexity of the studied area, the seismic interpreter, reliability of velocity model, etc.), and generally will introduce the largest uncertainty with respect to the picked horizon. All these factors may contribute to the total error in the final map(s).

The current study summarises the specific uncertainties related to the geological mapping of the Top Dinantian and provides a provisional data confidence map. Furthermore, it provides recommendations for future derisking and decreasing uncertainties in updated versions of the Dinantian maps, based on learnings from other mapping programs.

1.1 Goal of the study

The aim of the current study is to provide insights in the uncertainties in the depth map of the Top Dinantian, and provide recommendations for decreasing the uncertainties. Derisking and reducing uncertainties will provide more robust estimates of the spatial distribution of these deeply buried carbonate reservoirs. Using learnings from other mapping programs, recommendations are provided to better integrate cross-border mapping studies.

2 Sources of uncertainty

In statistics, two types of uncertainties or errors are distinguished: **accuracy** and **precision**. Accuracy reflects the proximity of a model results to the true value. Precision gives information on the reproducibility of the model results, neglecting the accuracy of the underlying input data.

There are various sources of data uncertainty when it comes to creating maps. Uncertainties may arise from the source of the data (e.g., digital *vs.* analogue, 2D *vs.* 3D seismic, legacy *vs.* recent processing) or areal coverage of the seismic data. In addition, some other data may aid in seismic interpretation, such as the availability of well data to tie to the seismic, outcrop data, pre-existing maps, and geological cross sections.

Regarding the interpretation of the data, one may think of different seismic interpretation techniques, on analogue or digital data. Regarding the methods, one may think of different time-depth conversion techniques, and different interpolation techniques. Regarding the geological differences, the maps may cover areas for which their geological evolution was very different from one another. In structurally complex regions, the uncertainty in the depth map could be larger compared to areas that more simple structural evolution.

The variety of sources of input data have effects on the robustness and reliability of the interpreted top and base depth, thickness and temperature maps, and ultimately the heat in place and geothermal potential of the Dinantian. Assessing the uncertainty of the resulting maps will provide the end-user with a first order assessment of the reliability of the maps.

In this report, we provide:

1. a first order assessment of the uncertainties in the Top Dinantian depth map,
2. recommendations to reduce the uncertainty (beyond the obvious 'more data is needed')
3. a visualization of the uncertainties in the depth map.

The need to visualize uncertainty stems from end user demands: if the map shows a certain depth, what is the reliability of the estimate, meaning: how much deeper (or shallower) should drilling engineers consider the target to be. Depth differences also have influence on the expected temperature of the production water.

Various sources of error have been identified for the Top Dinantian depth map. The relate to various stages of the interpretation and map making process, from interpretation through time-depth conversion to interpolation.

1. Data error (in seismic data: processing, vertical shifting, and resolution errors)
   - The error increases with depth
   - The error in 3D seismic interpretations is generally less than for 2D seismic
   - Can be added as a noise factor to the original horizon picks using a short correlation distance (<1 km).
2. Structural complexity
   - Areas with low structural complexity can be interpreted with larger confidence than areas with large structural complexity. The correlation length, used in interpolation, is generally lower for areas with large structural complexity.
3. Depth

- At the location of data points, i.e., well data or seismic interpretations, the 'true' depth varies within the data error bandwidth. Further away from data points the error gradually increases to the maximum interpolation error, for instance defined by the Kriging interpolation error, or in the case of a set of gaussian simulations, to the standard error of the realizations.

4. Velocity model (V0-k)
   - The velocity model uses a V0-k approach to seismic velocities, in which k is assumed constant for a layer, and V0, the velocity at time or depth zero of the rock at the datum, as if it had been decompacted, is assumed to vary spatially. For each map of V0, a set of sequential gaussian simulation (SGS) realizations has been calculated using the same interpolation and variogram settings as used in the VELMOD-3 model.
5. Data density
   - Although not strictly a source of error, the (distance to) available data strongly influences the reliability of the interpolated map.
6. Geological model
   - In parts of the mapped area, the available data is very sparse. Therefore, the modelled depth of the top of the Dinantian is largely determined by geological concepts and models, like for instance the thickness of the overlying strata. The error of the modelled depth is not easily quantified.

Although uncertainty maps can also be made for the Base Dinantian depth map, the thickness map and temperature map, we have not addressed them in this report. In large parts of the Netherlands, the Dinantian is buried deeper than the vertical seismic coverage, and proper base and thickness maps cannot be properly constructed. The lack of well penetration in the Dinantian makes that temperature control is also limited. Hence, constructing uncertainty maps for base, thickness and temperature is of limited added value beyond the uncertainties described in the various reports (see Veldkamp, 2021; Nelskamp et al., 2022).

3 Learnings from other studies

This chapter describes various Dutch national mapping projects in which attention was paid to evaluating the uncertainty of maps generated from combined seismic and well data.

3.1 DGM-Deep

For the TNO developed DGM-Deep model of the Dutch subsurface, an integrated workflow has been developed for modelling the uncertainties related to occurrence and depth of the various layers in the model (Maljers et al., 2015). This workflow entails modelling in which multiple realizations for each horizon in the subsurface model are generated using a stochastic simulation algorithm (Sequential Gaussian Simulation, SGS). This produces a Standard Deviation that gives information on probability of the model. In addition, residual grids are generated in order to determine the correctness of the model at locations where well data is available. By adopting this workflow, uncertainties resulting from seismic interpretations (in time) that are subsequently converted to the depth by using an acoustic velocity model are incorporated.

In the DGM-Deep workflow, the following uncertainties are incorporated (adopted from Maljers et al., 2015):

- **Data error**: This error takes into account errors related to the picking of a horizon within a seismic dataset. It includes vintage, processing errors, vertical shifting errors and resolution errors. In general, the data error is relatively small for shallow horizons, but increases with depth due to decreasing seismic data quality downward (e.g., lower resolution and more problematic processing). In addition, the data error also incorporates errors resulting from interpretations on 2D or 3D seismic; a larger error is assumed for 2D picks versus 3D seismic picks.
- **Structural complexity error**: Areas characterized by low to moderate structural complexity (e.g., platforms and highs; normal faulting) will produce small errors with interpolation. On the other hand, in structurally complex areas (e.g., large fault offsets, salt doming or thrusts and duplexes), a significant error is introduced when large gaps exist between data points. Therefore, structural complexity importantly affects the uncertainty. In the DGM-Deep workflow, the structural complexity error is incorporated by calculating moving standard deviation maps for the depth of each layer. These maps represent the regional variation of potential interpolation errors. For locations near datapoints, the error is small and increases moving away from datapoints.
- **Velocity model error**: In the DGM-Deep workflow, a countrywide velocity model (VELMOD model) is used for the time-depth conversion. The values of the velocity model include a large uncertainty, especially for the deeper geological units, as they are based on a relatively sparse borehole dataset and the determination of acoustic velocities in itself often incorporates a lot of uncertainties. Furthermore, the errors generated with the time-depth conversion of shallow layers will propagate to the depth conversion of deeper layers. In the DGM-Deep workflow, the velocity model error is incorporated by generating a set of SGS realisations for each mapped horizon using similar settings as in the original velocity (VELMOD) model.

The above discussed errors are combined to generate a depth error. Additional uncertainty modelling steps include adding a random depth-dependent data error to all picked seismic horizons, picks, generation of a random realization of a set of depth domain maps from time-depth conversion and Kriging interpolation of residual well marker mismatches (and subsequent correction) so that the maps are conditioned to the wells used.

The final, calculated uncertainties are represented as standard deviations (SD), which is a statistical measure for the spread of values. In the DGM-Deep workflow, the SD is calculated using the above workflow from the multiple realizations of two-way travel time (TWT) and well-tied depth (TVD) maps. After the SD are calculated for each horizon, the SD is disseminated as the final result of the uncertainty procedure.

3.2 SCAN Dinantian

Within the SCAN Dinantian[1] framework, a geological characterization of the Dinantian in the Dutch subsurface has been carried out The SCAN (https://www.nlog.nl/en/scan) program is a multi-year, integrated program that comprehensively studied the Dinantian in the Netherlands. It included (for the geological aspects) renewed seismic interpretation, temperature modelling, petrophysical analyses, carbonate diagenesis studies, burial evaluation and structural restorations (e.g., ten Veen et al., 2019; Veldkamp and Hegen, 2020; Carlson; 2019; Mozafari , 2019; Bouroullec et al., 2019;). In addition, multiple new seismic lines were acquired, some with the aim of better imaging the Dinantian. Further, vintage digital seismic data was also recently reprocessed.

Previous results of this multi-year program have been included in various deliverables of the DGE-ROLLOUT project (top/base/thickness and temperature maps of the Dinantian). Dinantian interpretations of the new seismic will eventually be integrated in the DGE Rollout top Dinantian map.

The main learnings for generating the depth and thickness maps were:

- Poor data quality for deep interpretation and sparse data (wells and seismic) onshore in the Central and Southwestern Netherlands made interpretations challenging. Interpretations had to be corroborated via offshore data and model interpretations.
- Vertical seismic coverage in large parts of the west and central Netherlands, was insufficient for imaging the Dinantian. In these regions, the Dinantian sits at 4 seconds TWT or deeper, which is deeper than vertical seismic coverage. It was proposed that energy content, source strength and spread length allowing, new migrated 2D vertical coverage should be extended to at least 5-7 seconds TWT.

Following the SCAN Dinantian project, over 50 seismic lines were acquired in data-sparse areas, some of them aiming at the Dinantian.

3.3 WarmingUP project

Within the WarmingUP project funded by the Dutch Enterprise Agency (Rijksdienst voor Ondernemend Nederland RVO) (www.warmingup.info), several studies have been conducted to improve the knowledge and understanding of the Paleogene Brussels Sand Member and Breda Formation (de Haan et al., 2020).

Like the Dinantian, the Brussel Sand Member and Breda Formation (buried to shallow depths between 100 and 1000 m) were of little interest to hydrocarbon exploration. Therefore, no detailed studies were available on the geological characterization of these units. Existing maps of the top/base and thicknesses of these units were based on well-to-well interpolation using stratigraphic

[1] SCAN: Seismische Campagne Aardwarmte Nederland (Seismic Campaign Earth Heat Netherlands), www.scanaardwarmte.nl (in Dutch), results downloadable from https://www.nlog.nl/en/scan

interpretations (well tops). Depending on the well density, those maps lacked spatial detail in between the wells.

The depth and distribution of these units, however, made them of interest for geothermal exploration. Hence in recent years, several new geological studies were carried out integrating seismic data, evaluation of the interpreted lithostratigraphic well markers and a detailed petrophysical evaluation of selected wells (e.g., de Haan et al., 2020; Geel and Foeken, 2021; Peters et al., 2022).

Main learnings from these studies include:
- Seismic interpretation resulting in major improvements in characterizing the thickness and top/depth maps compared to previous well based maps.
- New seismic interpretation that improved the definition of the boundary polygon enclosing the various units.
- Well log based petrophysical evaluations, combined with core measurements significantly improving the understanding of reservoir properties.

Learnings from evaluation of the uncertainties in the mapping exercises include:
- Uncertainties in the polarity and phase picked for seismic interpretation (peak, trough, zero crossing or different) could lead to an error of 20-35 meters in the depth of the top/base of the units.
- Seismic resolution results in uncertainties in interpretation, especially in areas where the units are thin and pinching out.
- Vertical mismatches up to 15-30 ms TWT (15-30 meters at 2000 m/s) are observed at intersections of crossing 2D seismic lines. They result from imperfect migration (of 2D seismic lines) in combination with uncertainty in statics (topography and reference to seismic datum).
- Uncertainties in velocity model building and time-depth conversion could lead to some 50 meters uncertainty at a depth of 1000 meters.

By integrating various data sets, better well-ties and cross-correlation between lithostratigraphic well tops and better alignment of seismic data sets, uncertainties in the spatial distribution (depth, thickness and reservoir properties) have been reduced. The new maps provide better insights in the reservoir characterization for geothermal applications.

3.4 Conclusions from other studies

Although important knowledge had been gained from various national mapping projects, it is doubtful if the learnings from these projects can be applied to the DGE Rollout mapping results. The reason is that for the projects mentioned the source data were very coherent i.e., originating from a single source, the data were well known, i.e., the accuracy of the data, and that the seismic interpretation was done by a single team of interpreters, and therefore the applied techniques e.g. interpretation and time-depth conversion, were the same. A Sequential Gaussian Simulation which incorporates the well and seismic interpretation error, the time-depth conversion uncertainty and the interpolation between data points described in section 3.1, although attractive from a data modelling point of view, is considered to be too far-fetched for the current Top Dinantian study.

The most valuable findings therefore include the identification of potential sources of error, especially data density, depth, and structural complexity. For the top Dinantian mapping they are described in the following chapter.

4 Top Dinantian depth uncertainty mapping

4.1 Uncertainties

Following the conclusions of the previous chapter, the following major qualitative indicators for uncertainty were identified that determine the uncertainty in depth for the Top Dinantian:

1. Data quality and density
2. Total depth
3. Tectonic complexity

Various uncertainties result from the source of data that has been used to interpret the Top Dinantian. Seismic data is often of different vintage with varying quality and is either 2D (digital or analogue lines) or 3D seismic. In addition, seismic data density varies within a country, but also between countries. Also, the seismic was interpreted by multiple individuals over longer periods of time, applying varying methods with different geological models in mind.

Seismic data is acquired in time and converted to depth using velocity models of the for the overlying units. With cross-border interpretations, differences in the used velocity models will result in different depth conversions. This adds to the uncertainties.

In areas where seismic data is unavailable, the depth of the Top Dinantian may be derived from available well data of from geological concepts. Nearby wells, uncertainties in interpreting the top/base are less than away from the wells. There are also areas where no seismic and no well data is available. Here, depth to the Top Dinantian may be inferred from regional geological knowledge and trends.

The structural complexity introduces another source of uncertainty. In The Netherlands and North Rhein-Westphalia, the structural setting of the Dinantian is relatively simple, with block faulting present. Further south in Northern France and Wallonia, the Dinantian is more complex with thrust sheets and structural duplications present. South/below the Faille du Midi, the Dinantian is deeply buried and the structure is still poorly understood. Additional seismic acquisition (e.g., resulting from the SCAN seismic acquisition [2]and within the DGE-ROLLOUT project) is currently being processed/interpreted and will contribute to better understanding of the structural setting.

Maps were constructed for the above mentioned three indicators.

4.2 Data density

Figure 1 shows the available data. For wells, a maximum distance of 5 kilometers is assumed around the well in which the interpreted well top can be extrapolated with high degree of confidence. The ideal combination is a combination of 3D seismic and well control - this combination only occurs in the northernmost part of the Netherlands around the Uithuizermeeden well. The combinations that occur, in decreasing order of certainty, are:

1. 3D seismic + well < 5 km
2. 2D seismic + well < 5 km
3. 3D seismic
4. Well < 5 km, no seismic coverage

[2] https://scanaardwarmte.nl/english/
https://www.nlog.nl/en/scan-2d-seismic-data)

5. 2D seismic

The approach presented here is a simple one which could be extended using various distances to the data source and/or a distinction between 'old' (low quality) and 'new' data (high quality), but for the current purpose, a simple approach is preferred.

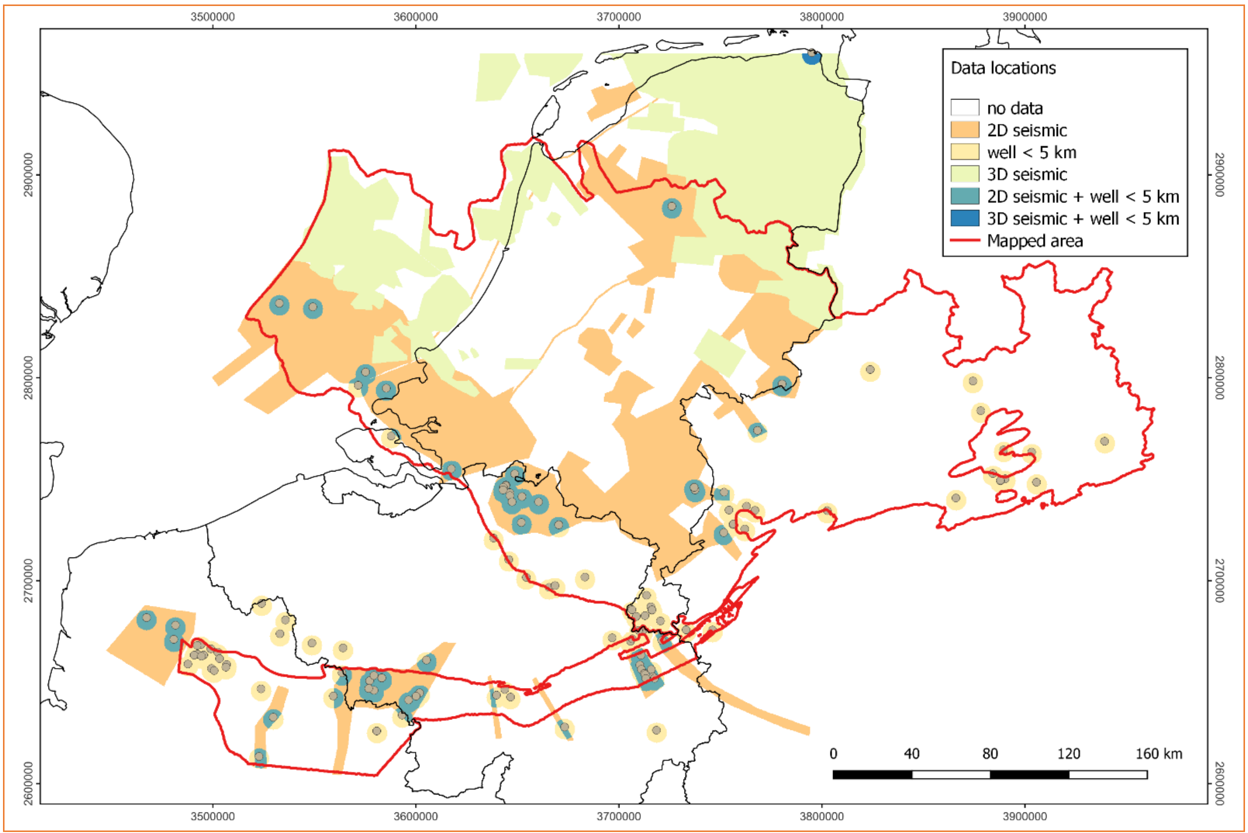


Figure 1 *(Distance to) Data distribution. Orange: least uncertain, blue: most uncertain. The red polygon is the intersection of the Interreg Northwestern Europe and mapped area polygons.*

4.3 Depth of the top of the Dinantian

Figure 2 shows the depth of the Top Dinantian. A detailed description of the mapping is given in DGE Rollout deliverable (Veldkamp, 2021). The depth ranges between +500 and -10000 meter below surface level.

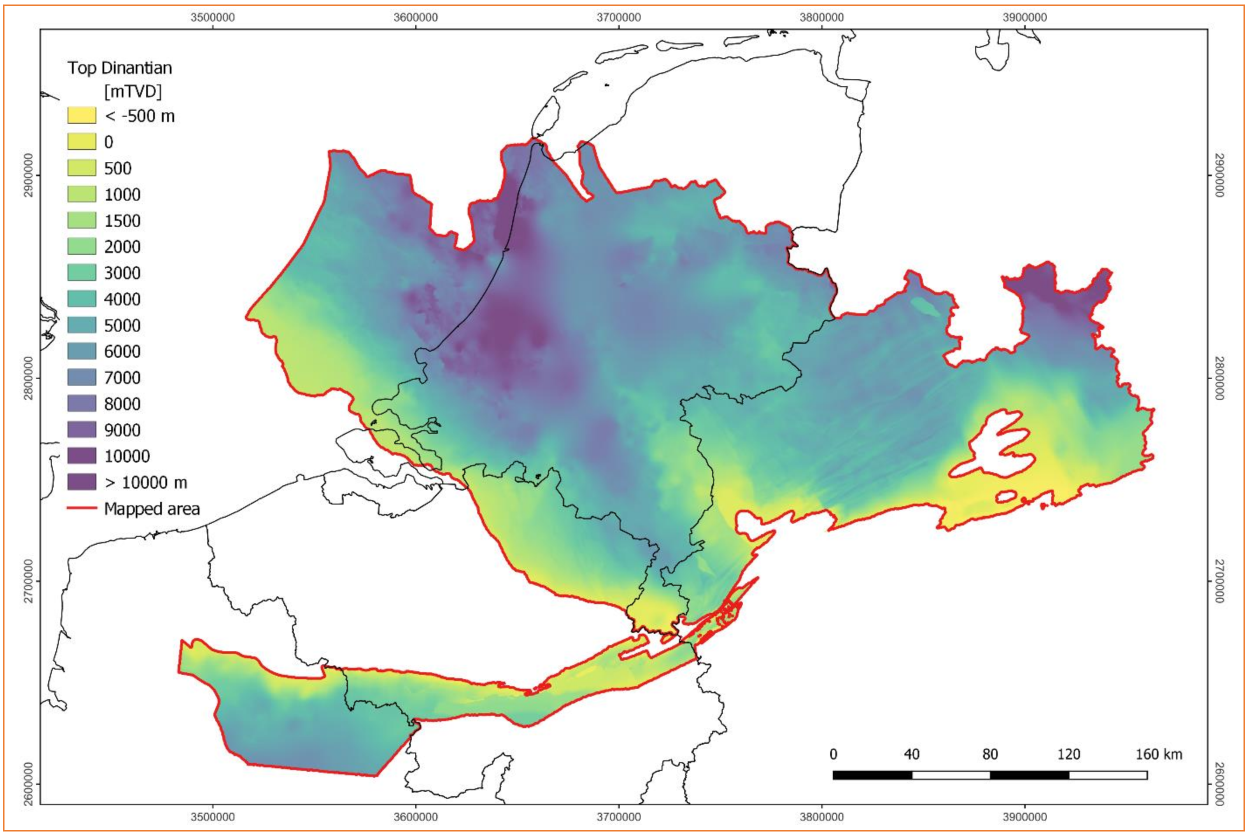


Figure 2 Depth to top Dinantian. Yellow (shallow) = least uncertain. Blue (deep) = most uncertain.

4.4 Structural complexity

Structural complexity is a concept which is difficult to quantify. For the generation of a structural complexity map of the Dinantian in the Interreg North-West Europe area, national geological maps were used of the four participating countries (Figure 3):

- The Netherlands: 'stratpiler' map which basically describes unique stratigraphic successions. The presence or absence of (parts of the) stratigraphic succession are indicative of erosion due to subsidence followed by uplift or non-deposition. The resulting map shows 'quiet' areas in green and orange, and more complex (inverted) areas in blue (updated after Kombrink et al., 2012 and ten Veen et al, 2019).
- Belgium: the geological map of Belgium was used (Loveless et al., 2015). The major units distinguish are the London Brabant Massif where the Dinantian is absent, the Campine Basin to the North, which is considered relatively undisturbed, and the highly complex Ardennes Massif.
- France: the online geological map was used (BRGM, 2023) the contents of which align well with the southern part of Belgium, especially the Ardennes area.
- Germany: a tectonic map of Germany was used (GFZ, 2023).

Figure 4 shows the resulting structural complexity map which clearly reflects the patterns shown in the base maps of Figure 3. The three units that are differentiated are, in order of increasing structural complexity and therefore uncertainty:

1. Stable areas, gentle folding and faulting.
2. Horst and graben areas, inverted basins, complex faulting (normal/reverse).
3. Structurally complex areas with thrust sheets and nappes, intensely folded and faulted.

It is realized that the above mentioned 3-level structural complexity does not fully represent the geological complexity of the area. In areas where the Dinantian was buried deeply and the data quality is low (for instance in the Niederrheinische Bucht), it is hard to determine the structural complexity. However, the construction of a full-blown tectonic complexity map goes beyond the goal of the current study, and the combination of low data density and deep burial in itself already indicated a high uncertainty.

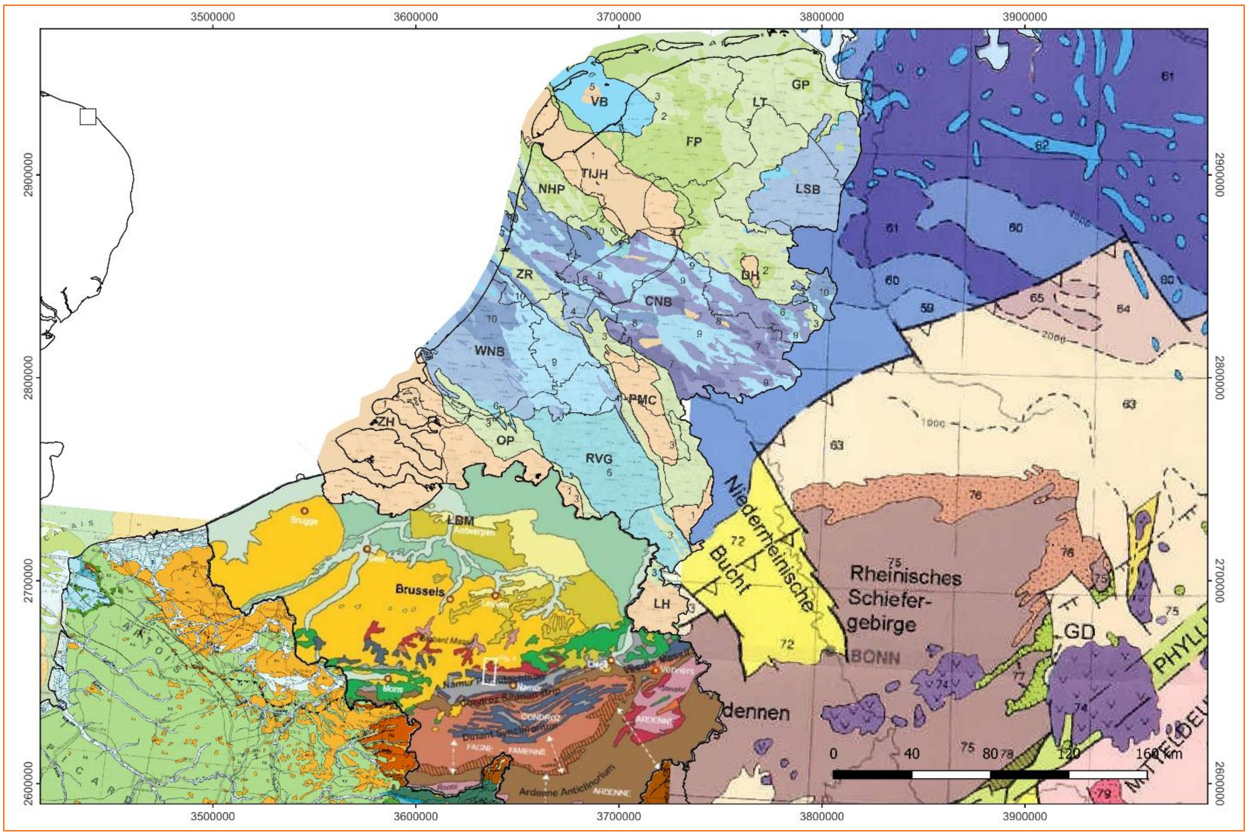


Figure 3 Compilation of geological and tectonic maps for the Interreg NWE area. See text for references.

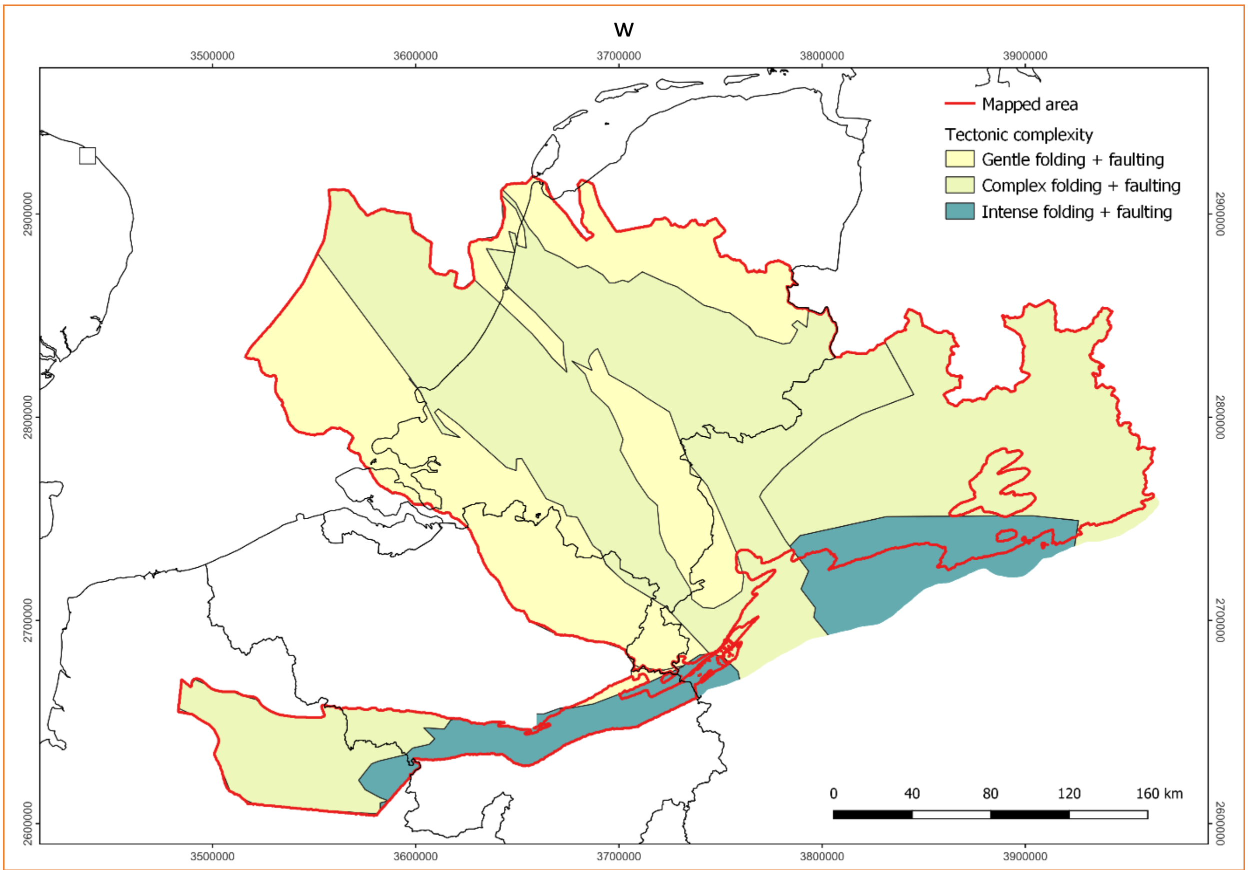


Figure 4 *Tectonic complexity, based on identified tectonic units zones in Figure 3.*

4.5 Colour composite concept

The three maps described in the previous section (Figure 1, Figure 2, Figure 3) each represent part of the uncertainty of the total depth map. However, the combination of the three maps inwto one may facilitate its interpretation. Anoverlay of the three maps mentioned above using different shadings and hatchings will however yield a map that is difficult to read. Therefore, a concept was used which is common in the field of remote sensing, where the combination of satellite images resulting from different sensors of wavelength intervals are combined into a single image.

The technique, referred to as colour composite, uses the fact that colour can be thought of as being constructed from contributions of the primary colours red, green and blue (Figure 5) to join 3 maps into 1. As such, the first map of the composition is depicted in shades of red ranging from black to full red. The second map is assigned shades of black to green whereas the third map contains shades of blue (black to blue).

In all the three maps, the colour shades depict the same confidence levels: black (no colour) represents high uncertainty, whereas full red, green or blue equals low uncertainty. When the three maps are overlain, the resulting composite colours can be interpreted in terms of joined (un)certainty.

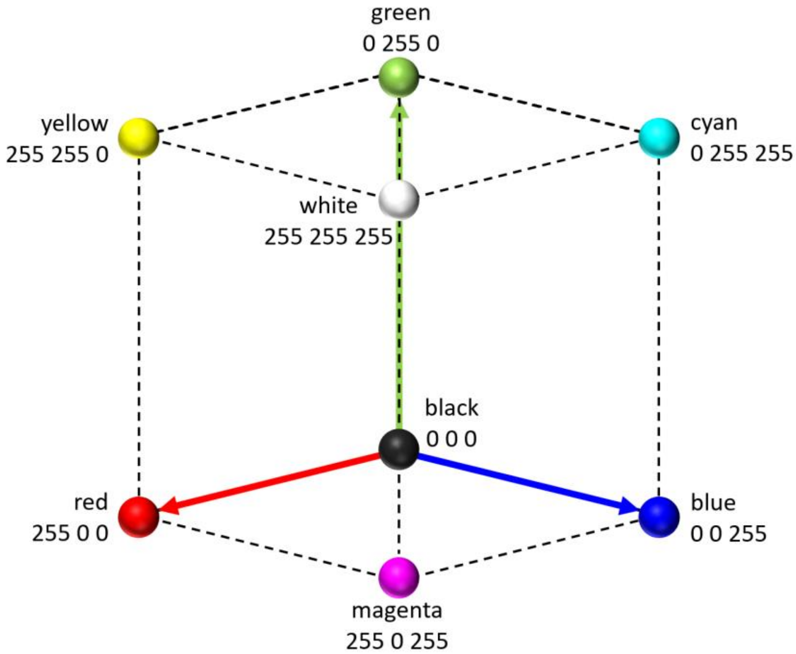


Figure 5 Colour cube illustrating the resulting colours from blending the primary colours red, green and blue.

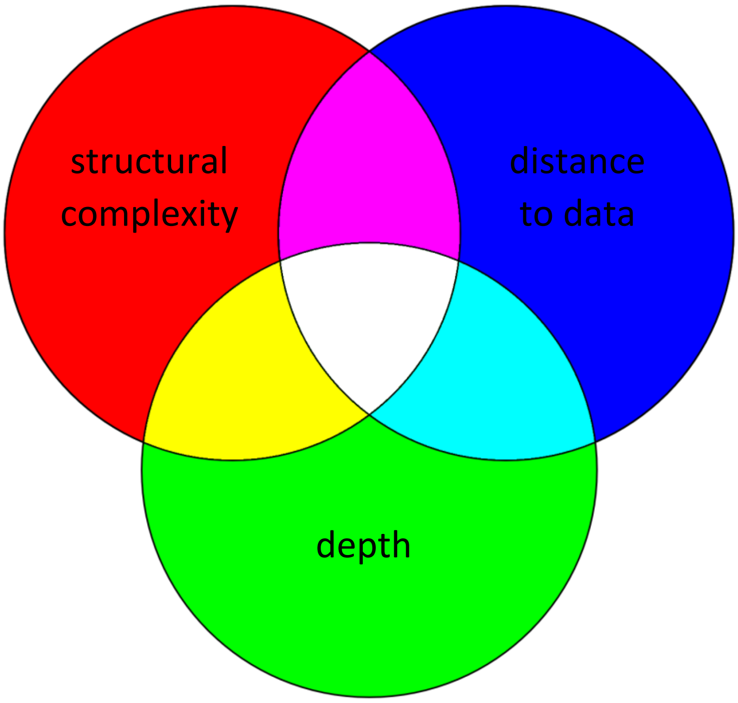


Figure 6 Colours resulting from blending / overlay

Table 1 interpretation of the resulting colours of the data confidence map (Figure 7) in terms of the three underlying maps

resulting colour	underlying maps: red band: structural complexity	green band: depth	blue band: data density
black	high	deep	low
white	low	shallow	high
red	low	deep	low
green	high	shallow	low
blue	high	deep	high
yellow	low	shallow	low
magenta	low	Deep	high
cyan	high	shallow	high

Data confidence map Top Dinantian

Figure 7 shows the three individual sources of uncertainty maps (structural complexity in red (top left, Figure 7A), depth in green (top right, Figure 7B) and data type and distance in blue (bottom left, Figure 7C)).

The resulting composite is shown in Figure 7D (the bottom right quarter). The colours can be interpreted as follows:

- Black: dark shades indicate a large joined uncertainty, i.e., all three contributing maps have a high uncertainty.
- White: light shades indicate a low uncertainty for all three components.
- Red: high uncertainty for depth and data density, less structural complexity.
- Green: high uncertainty for structural complexity and data density, depth is shallow.
- Blue: high uncertainty for structural complexity and depth, high data density.
- Yellow (R + G) indicates high structural complexity uncertainty but shallow depth and high data density. This is for instance visible at the northern border of the London Brabant Massif.
- Cyan (G + B) is indicative of low data density, shallow and tectonically less complex.
- Magenta (R + B) of large depth, high data density and low structural complexity.

Appendix A provides a higher resolution version of the uncertainty map.

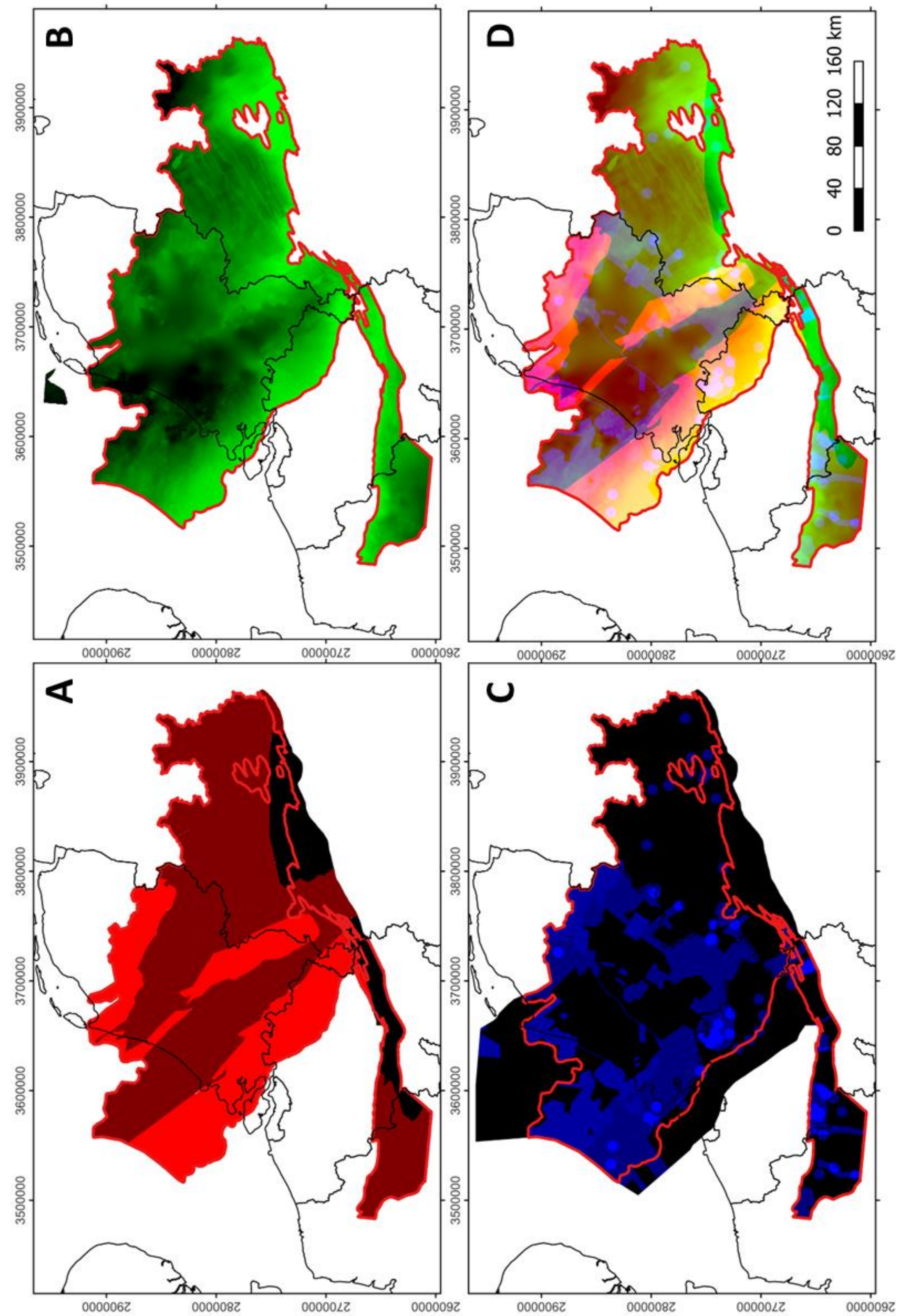


Figure 7 *Uncertainty composite map (D) , composed of (A) tectonic complexity (red), (B) depth (green) and (C) data availability (blue). Dark shades indicate areas of high uncertainty (i.e., large distance to data, large depth, large structural complexity).*

5 Conclusions and recommendations

5.1 Conclusions

In this report, a concept workflow for estimating the uncertainty of the Top Dinantian depth map is outlined. A concept version of an uncertainty map, based on preliminary versions of the underlying maps, is presented.

Mappable sources of uncertainty are the data type and density, the depth, and the structural complexity. Of all three, maps of varying level of detail were constructed. The three maps were integrated into a single map representing the uncertainty of the depth Dinantian map. This composite map represents a qualitative interpretation of the (un)certainty. While more detailed methods to calculate the depth in a quantitative way do exist, this is considered too challenging for the current depth Dinantian map because of the heterogeneity of the data, and the fact that for the data sparse or poor areas only a very rough estimate of the depth uncertainty can be given.

Although uncertainty maps can also be made for the Base Dinantian depth map, the thickness map and temperature map, we have not addressed them in this report. At the moment, it is not useful to determine these individual uncertainty maps. For example, in some parts of the Netherlands (west and central Netherlands), the Top Dinantian is buried deeper than current 2D seismic trace depth. This data first needs to be reprocessed to ~5 to ~7 seconds TWT (energy content, source strength and spread length allowing) in order to properly determine the depth (and thus thickness) of the Dinantian.

In large parts of NRW no seismic data is available at all, hence improvements should be made in the availability of seismic data coverage. For these areas, the uncertainty in the depth map is already large, making the additional uncertainties from lack of reservoir properties of thickness negligible.

The complexity map shown in this report is based on the depth and data maps that were available during the writing of the report prior to June 2023. This means that both the data distribution and depth maps can be slightly different from the final versions delivered within the DGE Rollout project. The resulting complexity map should therefore be seen as a proof of concept, rather than as a definitive complexity map.

5.2 Recommendations

5.2.1 Seismic data acquisition

The main recommendation is that the current Top Dinantian depth map should be improved through the acquisition of more (seismic) data. In large parts of the mapped area, no seismic data at all is available. The Dutch SCAN seismic acquisition program, financed by the government and coordinated by EBN, is a good example of public data acquisition for geothermal exploration purposes in data-sparse areas.

When they become available, the interpretations from the newly acquired DGE Rollout line in Belgium and SCAN lines in the Netherlands should be incorporated to improve the quality of the depth Dinantian map.

From the uncertainty map, it is also visible that large parts of NRW lack regional seismic (2D or 3D) data coverage. Seismic data acquisition in NRW will significantly reduce uncertainties in the Top Dinantian depth map.

5.2.2 Bore hole data acquisition

Drilling new wells that penetrate the Dinantian within the Interreg outline is recommended for improving seismic tie-to well. From the data availability map, it is observed that at present, there are large areas (e.g., onshore The Netherlands) that have reasonable seismic coverage, but lack wells that have penetrated the Dinantian. This hampers identification of the Dinantian in the seismic data. In contrary, large parts of NRW or Wallonia have good Dinantian well density but lack seismic coverage.

5.2.3 Other data acquisition

Additional data from for example wells and petrophysical studies (e.g., borehole temperature data and/or cores) will be beneficial to other uncertainties not addressed in this study but which are relevant for determining the geothermal potential of the Dinantian (e.g., temperature model and reservoir properties).

5.2.4 Uncertainty modelling

A detailed uncertainty modelling workflow incorporating each of the individual contributing components of the Dinantian will enable the construction of quantitative uncertainty maps for depth, thickness, and geothermal potential.

5.2.5 Tectonic map

The three-level structural complexity used in this study does not fully represent the geological complexity of the entire region. The used class definitions are subjective to a certain extent – a clear definition of 'gentle', 'complex' and 'intense' folding or faulting does not exist. The construction of an integrated, regional tectonic map goes beyond the goal of the current study.

In order to improve the tectonic complexity/uncertainty map, gravity modeling may be a useful tool.

5.2.6 Geothermal potential risk map

Should additional data become available, uncertainty maps should also be constructed for the Base Dinantian depth map, the thickness map, temperature map, and reservoir properties map. This means that, apart from seismic data acquisition, downhole temperatures and permeabilities (e.g., from petrophysical data, core measurements etc) should be measured. Because the petrophysical properties are to a large extent determined by the geological history (burial, uplift, erosion, karst, faulting, diagenesis), a petrophysical properties model should be constructed which takes this history into account.

All these uncertainties from the various individual components (e.g., depth, thickness, reservoir properties etc) should be combined in a Common Risk Segment (CRS) map. This map visualises the combined contribution of each uncertainty for the Dinantian geothermal potential.

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Appendix A: Top Dinantian depth uncertainty map