

# Seismic Hazard Screening (SHS): Relevant major fault zones

Version 1.4  
21-01-2022

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# Samenvatting

## Introductie

Het Ministerie van Economische Zaken en Klimaat heeft EBN en TNO verzocht een nieuwe methode op te zetten om het risico op seismiteit in te schatten voor geothermieprojecten in Nederland. Een van de onderdelen van deze nieuwe methode is het definiëren en het in kaart brengen van relevante breuken binnen Nederland, welke een hoge potentie hebben om te worden gereactiveerd door middel geothermische productie (Mijnlieff & Jaarsma, 2021). In voorliggend rapport wordt een methode voorgesteld om 1) relevante en seismisch actieve breuken binnen Nederland te filteren vanuit de bestaande TNO breuken database en eventueel aan te passen met behulp van beschikbare SCAN data en 2) om de relevante breuken in kaart te brengen voor verschillende reservoir niveaus. Verder worden er in dit rapport voorbeelden gegeven over het gebruik van de verkregen relevante breuken kaarten.

## Werkwijze

De methode voor het bepalen en karteren van relevante breuken binnen Nederland bestaat uit de volgende stappen:

1. Het definiëren van wat een relevante breuk is, seismische data analyse, en het filteren van de TNO database (sectie 2.2)
2. Het in kaart brengen van relevante breuken voor verschillende reservoir niveaus en het kwantificeren van de onzekerheid in breuk positie op basis van de data dichtheid (sectie 2.3)
3. Het integreren van de relevante breukenkaarten met de resultaten van de studie met betrekking tot de seismically active Larger Roer Valley Graben Area (Böker et al., 2021) (sectie 2.4)

## Kaarten van relevante breuken en de Larger Roer Valley Graben Area (LRVGA) op de verschillende reservoir niveaus (Figuur 0.1)

Met behulp van de bovengenoemde stappen zijn er kaarten gemaakt van de relevante breuken voor de basis van de Upper North Sea Group (NU), de basis van de Rijnland Group (KN), de basis van het Trias (RB) en voor de basis van het Zechstein (ZE). Ook zijn op deze kaarten onzekerheden in de breukpositie gekwantificeerd door middel van het trekken van bufferzones rondom de relevante breuken. Tot slot is op de verkregen kaarten ook de LRVGA weergegeven welke wordt beschouwd als een seismisch actief gebied (zie Böker et al., (2021)).

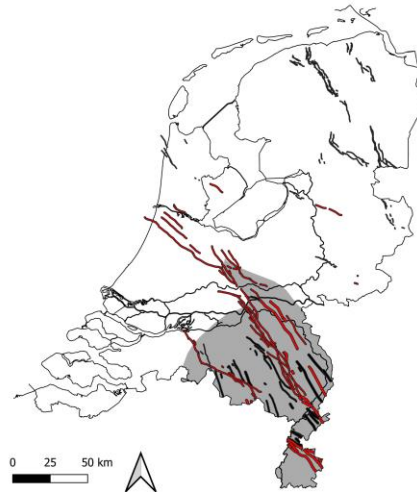
## Gebruik van de verkregen kaarten

Wanneer het aan te boren aquifer, de put locaties en de area of influence (Aoi) (te bepalen met behulp van (Borst et al., 2021))) bekend zijn, kunnen de relevante breukenkaarten (Figuur 0.1) worden gebruikt om te bepalen of een geothermie project dichtbij een potentieel seismisch actief gebied is (i.e. het project valt binnen de buffer zone van een relevante breuk of valt binnen de LRVGA). Dit kan middels de volgende stappen en moet worden uitgevoerd in GIS based software (b.v. QGIS of ARCMAP):

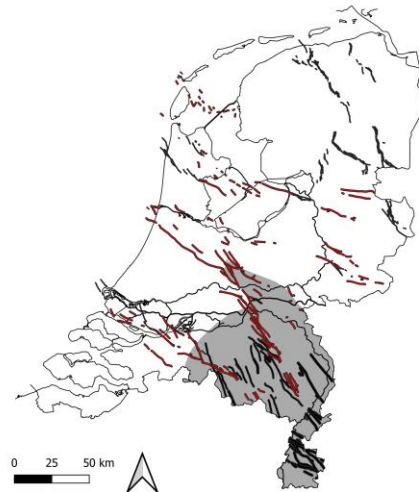
1. Bepaal welke kaart er moet worden gebruikt gegeven het aan te boren reservoir
2. Projecteer de Aoi van het project op de kaart
3. Kijk of de Aoi overlapt met de buffer zone van een van de relevante breuken of dat de Aoi binnen de LRVGA valt.

4. Zo ja, dan moet er verdere analyse binnen de seismische dreigings- en risicoanalyse (Seismic Hazard and Risk Analysis, SHRA) worden uitgevoerd
5. Zo nee, dan kan er worden doorgedaan met de seismic hazard screening methodologie (SHS)<sup>1</sup>.

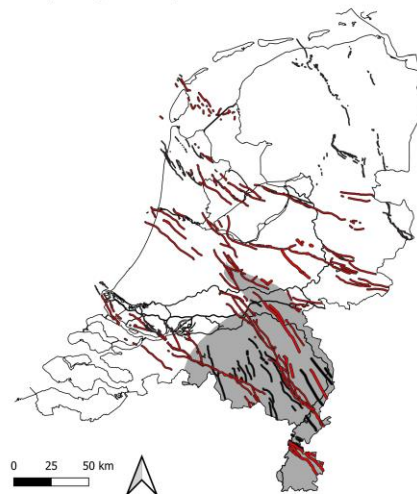
a) Composite map at Base NU



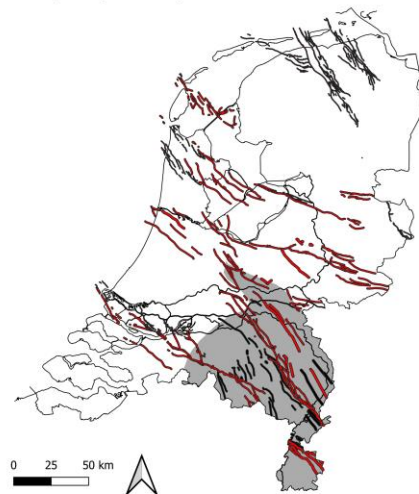
b) Composite map at Base KN



c) Composite map at Base RB



d) Composite map at Base ZE



*Figuur 0.1: a) Kaart met de relevante breuken, bufferzones en de LRVGA op Base Upper North Sea (NU). b) ) Kaart met de relevante breuken, bufferzones en de LRVGA op Base Rijnland Group (KN). c) Kaart met de relevante breuken, bufferzones en de LRVGA op Base Lower Germanic Group (RB). d) Kaart met de relevante breuken, bufferzones en de LRVGA op Base Zechstein (ZE).*

<sup>1</sup> De nieuwe Seismic Hazard Screening (SHS) methode zal bestaan uit een aantal kernelementen. Dit rapport beschrijft het voorgestelde ontwikkelingsproces, de methode en de resultaten voor één van deze kernelementen: het definiëren van grote, relevante breukzones. Uiteindelijk wordt dit kernelement gecombineerd met andere kernelementen en door EBN en TNO-AGE samengevoegd tot één nieuwe SHS-methode. In dit samenvoegingsproces kunnen wijzigingen worden aangebracht in de methoden, drempelwaarden en/of resultaten ten opzichte van de afzonderlijke kernelement rapporten. De methoden, waarden en resultaten die in het huidige rapport worden beschreven, moeten daarom als voorlopig worden beschouwd.

# 1 Introduction

The Ministry of Economic Affairs and Climate Policy has requested EBN and TNO to develop a new method to assess the seismic risk for onshore geothermal projects of the Netherlands. The previous guideline by IF/Q-Con (2016) “Defining the Framework for Seismic Hazard Assessment in Geothermal Projects V0.1” (Q-Con & IF Technology, 2016) was developed in 2016 and should be updated to the current state of the geothermal industry.

The new Seismic Hazard Screening (SHS) method will consist of a number of key-elements. This report describes the suggested development process, method and results for one of these key elements: the definition of relevant major fault zones. Eventually, this key-element will be combined with other key-elements and merged into a single, new SHS method by EBN and TNO-AGE. In this merging process, changes may be made to the methods, values and results as described in the individual key-element reports. The methods, values and results described in the current report should therefore be regarded as preliminary.

The current study addresses the definition, presence and outline of “relevant major fault zones” within The Netherlands, which can potentially be active and/or reactivated by geothermal resource exploitation and are therefore regarded as key elements of the new guideline (Mijnlieff & Jaarsma, 2021). Another item which is discussed in Mijnlieff & Jaarsma, (2021) is the definition and outline of the Roer Valley Graben (RVG) in the southeast Netherlands with natural occurring seismicity. Faults in this area are more likely critically stressed which means that the chance of inducing or triggering activity along these faults, which can lead to induced seismicity, is significantly higher than outside the area. Because of its higher seismic sensitivity the Roer Valley Graben is dealt with as a separate key-element (Definition of the Larger Roer Valley Graben Area (LRVGA), described in Böker et al., (2021)).

The main focus of this report is to present and deliver:

- A definition of the “relevant major fault zones”. The basis for these fault zones definition was formed by the fault subdivision from TNO-GDN. In several workshops with TNO & EBN it was concluded that these zones are characterized by 1) fault sets which bound structural elements in the Dutch subsurface, 2) faults that run (close) to the surface and 3) faults that have been recently seismically active.
- A general workflow for generating the maps as presented in this report which can later be referred to when updates are required.
- A workflow for induced seismic risk evaluation and where needed a reinterpretation of the TNO-GDN Fault data against newly acquired SCAN data.
- Maps of the defined “relevant major faults”. This is done on basis of the TNO-GDN Fault database which is updated with the results of the newly acquired SCAN data. Faults which are regarded as relevant are placed in the relevant fault database and are subsequently extracted along different stratigraphic levels.
- A workflow to define the buffer zone around the relevant faults. The buffer zones are based on the uncertainty in fault location given the respective data position (e.g. 3D data or low density 2D data). Along with the workflow, maps of the buffered faults at each stratigraphic level will be delivered.
- Maps at which the results of this study (buffered relevant faults) and results of Böker et al., (2021) (LRVGA) are integrated.
- Description on how to utilize the acquired maps.

This report is structured as follows. First, the main workflow and all necessary steps for making relevant fault maps (i.e. fault polylines, buffer zones and composite maps) for the purpose of SHS are described (Chapter 2). Second, the utilization of the acquired relevant fault maps is exemplified (Chapter 3). Third, recommendations on how to improve the acquired relevant fault maps is given (Chapter 4). Lastly, the supporting materials are presented.

# 2 Main workflow for making relevant fault maps for the purpose of SHS

## 2.1 MAIN WORKFLOW

To define relevant faults in the context of SHS screening, make relevant fault maps, quantify uncertainties and integrate the results with the outcomes of Böker et al., (2021), a workflow has been developed which consists of the following steps (Figure 2-1):

1. Definition of a major relevant fault zone and filtering of the TNO-AGE fault database (section 2.2) (Petrel).
  - 1.1. Describing and loading the TNO-AGE fault database, SCAN lines and KNMI earthquake database in Petrel and QGIS
  - 1.2. Definition of a major relevant fault zone for the purpose of SHS
  - 1.3. Evaluation of the TNO-AGE fault database against the SCAN data
  - 1.4. (Re)interpretation of relevant faults for all available SCAN data
  - 1.5. Filter the TNO-AGE fault database using the criteria defined in step 1.2
2. Polyline extraction and uncertainty quantification (section 2.3) (Petrel and QGIS).
  - 2.1. Definition of relevant stratigraphic levels for the purpose of SHS
  - 2.2. Extract polylines (i.e. intersection line of the fault plane with a stratigraphic horizon) for the relevant faults for the chosen stratigraphic levels
  - 2.3. Merge polylines into shapefiles using QGIS
  - 2.4. Make relevant fault maps for each stratigraphic level
  - 2.5. Definition of buffer zones using the uncertainty in interpretation and available data density
  - 2.6. Make maps of buffer zones around the relevant faults for each stratigraphic level
3. Integration of the results with outline of Larger Roer Valley Graben Area and the generation of composite maps (section 2.4) (QGIS).
  - 3.1. Load the results from the study defining the Larger Roer Valley Graben Area in QGIS
  - 3.2. Generation of composite maps (maps displaying the integrated results)

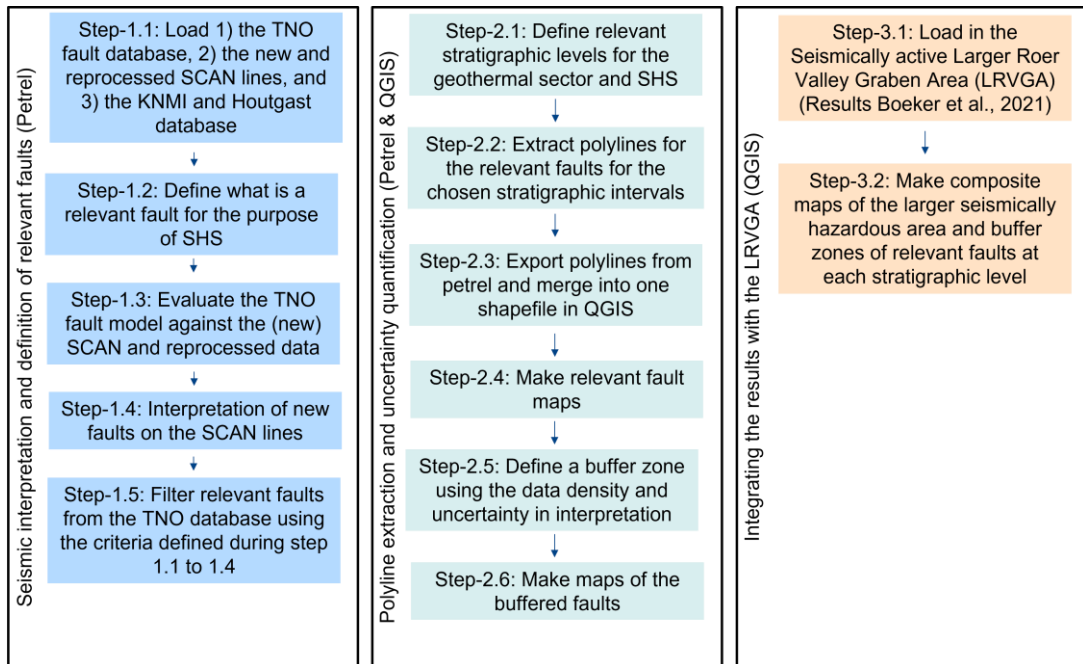


Figure 2-1: The workflow and respective sequence of steps used to define 1) relevant faults for the purpose of SHS, 2) maps of the relevant faults, 3) maps of buffer zones encapsulating the uncertainty in interpretation and 4) composite maps which integrate the Larger Roer Valley Graben outline (Böker et al., 2021) with the acquired results of this study. See text for additional details on the different steps.

## 2.2 DEFINITION OF A MAJOR RELEVANT FAULT ZONE FOR THE PURPOSE OF SHS

The first part of the main workflow is to define relevant faults for the purpose of SHS screening. This is done by:

- 1) Describing and loading the TNO-AGE fault database, SCAN lines and KNMI earthquake database in Petrel and QGIS
- 2) presenting a definition of a major relevant fault zone for the purpose of SHS,
- 3) evaluating the TNO Fault database against the utilized SCAN lines,
- 4) (re)interpretation of faults on each SCAN line which significantly differ from the TNO database
- 5) filtering out relevant faults for the purpose of SHS using the acquired results of the seismic evaluation and interpretation.

The evaluation of faults in the TNO fault database using the available SCAN data was done using Petrel (Figure 2-1).

### 2.2.1 Step 1.2: Description of the databases used in this study

#### The TNO-AGE fault database

The utilized TNO-AGE fault database consists of 3D fault planes and 2D fault polylines (Figure 2-2a), which have been interpreted as part of a larger European campaign (<https://geoera.eu/>). In this model, faults are structured in different levels, namely:

- Level 1) individual faults observable on seismic data,
- Level 2) individual faults observable on seismic data which bound structural elements (e.g. as defined by (Kombrink et al., 2012)) and



- Level 3) statistical centre of defined level 2 faults (Figure 2-2a).

For this study, only level 1 and 2 faults have been used. Faults within the database are named after the structural element in which the respective fault is positioned, the lower-bound of the fault (e.g. ZE: Zechstein) and the upper-bound of the fault (e.g. NU: Upper North Sea). The TNO fault database has not yet been updated with the new SCAN lines.

#### **The SCAN database**

The SCAN data consists of new - and reprocessed seismic lines which are acquired as part of the Seismische Campagne Aardwarmte Nederland (SCAN), executed by EBN and TNO in order to get a better understanding of the subsurface in areas where limited data is available. The SCAN seismic lines utilized in the current study are shown and listed in Figure 2-2b and Table 2-1. These lines were loaded in Petrel and have been used for evaluating the existing faults in the TNO database and reinterpreting faults where necessary.

Both the faults from the TNO database and the SCAN lines have been loaded into a Petrel project. This Petrel project and the fault interpretations (Appendix) will be made available alongside this report.

#### **The KNMI and Houtgast earthquake database**

The original KNMI earthquake catalogue is split into different databases, namely:

1. Earthquakes having an tectonic origin (natural seismicity),
2. Induced earthquakes which are caused by ongoing mining activities,
3. Unclassified earthquakes at which the source is not adequately determined.

The KNMI earthquake catalogue can be accessed via: <https://www.knmi.nl/kennis-en-datacentrum/dataset/aardbevingscatalogus>.

Besides the original KNMI earthquake catalogue, a list with historical earthquakes as defined by Houtgast, (1990) is used. This catalogue contains a compilation of information on reported earthquakes in the past. Although a published critical review on this list is currently lacking (but in preparation) additional comments on the uncertainty of these events were added by the KNMI (KNMI, R&D Seismology and Acoustics, 2021). The list with historical earthquakes used in this study and in Böker et al., (2021) is adjusted based on these comments.

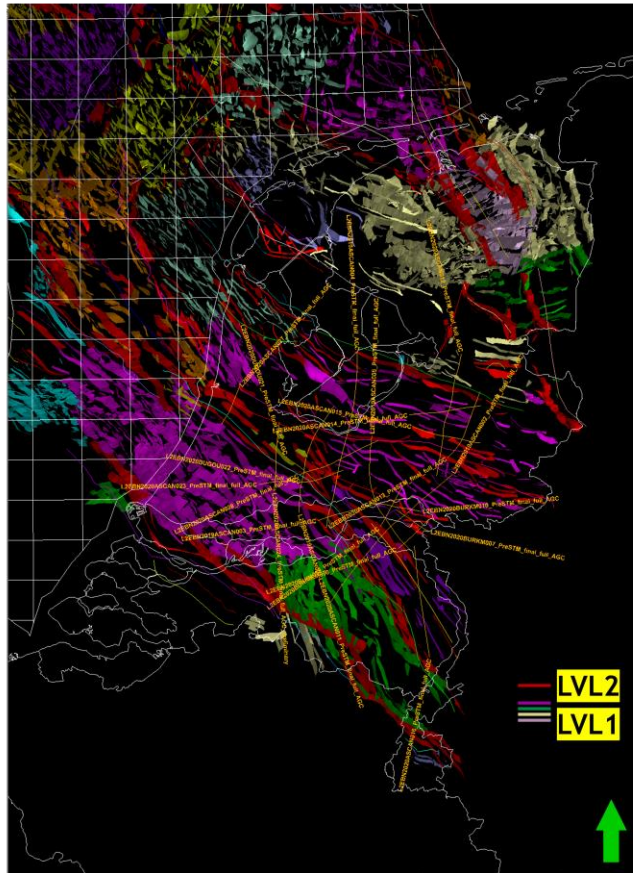
The original Houtgast catalogue can be accessed via:

<http://publicaties.minienm.nl/documenten/aardbevingen-in-nederland-catalogus-van-aardbevingen-t-m-1990-epicentra-in-nederland-waargenomen-verschijnselen-in-nederland-van-bevingen-met-het-epicentrum-buiten-nederland>

The "Tectonic", "Induced" and "Unclassified" datasets contain seismicity events recorded by KNMI and partner organizations, with the latter containing more foreign stations and duplicates of the first two datasets. The "Historic" dataset contains possible seismicity events reported during historic times prior to the installation of the monitoring system (Houtgast, 1990).

In this study, earthquakes classified as tectonic and the adjusted list with historic earthquakes were merged, loaded into QGIS and used in order to

a) TNO Fault database



b) Utilized SCAN lines



Figure 2-2: a) Map view of the 3D fault planes (level 1 and 2) utilized in this study. The colour coding of the level 1 faults is based on the respective structural element (Kombrink et al., 2012) in which the fault is positioned. Level 2 faults are coloured red. b) Map showing the location of the utilized SCAN lines which are also listed Table 2-1.

Table 2-1: Table highlighting the SCAN lines used for defining relevant faults for the purpose of the current study. In addition to line name and line location, the fit of TNO faults on the respective SCAN line and number of (re)interpreted faults are also indicated. The utilized SCAN lines can be downloaded from <https://www.nlog.nl/scan-2d-seismische-data>.

SCAN line	Location	Good fit with TNO faults?	Number of faults (re)interpreted
L2EBN2020BURKM010_PreSTM_final_full_AGC	Wageningen-Lingewaard	Poor (see appendix)	3 (see appendix)
L2EBN2020CUOBR017-L2EBN2020ASCAN018_PreSTM_final_full_AGC	Broekzijde-Hilvarenbeek	Good (see appendix)	15 (see appendix)
L2EBN2020BURKM007_PreSTM_final_full_AGC	Overbetuwe - Berg en Dal	Poor (see appendix)	1 (see appendix)
L2EBN2020BURKM009_PreSTM_final_full_AGC	Arnhem - Wijchen	Reasonable (see appendix)	3 (see appendix)
L2EBN2020DUGOU021_PreSTM_final_full_AGC	Maarsse - Driebergen	Reasonable (see appendix)	0 (see appendix)
L2EBN2020DUGOU022_PreSTM_final_full_AGC	Utrecht - Woudenberg	Reasonable (see appendix)	10 (see appendix)
L2EBN2019ASCAN003_PreSTM_final_full_AGC	Buurmalsen-Renkum	Reasonable (see appendix)	8 (see appendix)

L2EBN2019ASCAN004_PreSTM_final_full_AGC	Buurmalsen - Amersfoort - Zeewolde	Reasonable (see appendix)	9 (see appendix)
L2EBN2019ASCAN001-L2EBN2020ASCAN011_PreSTM_final_full_AGC	Everdingen - Utrecht	Reasonable (see appendix)	9 (see appendix)
L2EBN2019ASCAN002_PreSTM_final_full_AGC	Roer Valley Graben - Nijmegen - Bronckhorst	Good (see appendix)	12 (see appendix)
L2EBN2020ASCAN013_PreSTM_final_full_AGC	Joppe - Haarle	Reasonable (see appendix)	8 (see appendix)
L2EBN2020ASCAN014_PreSTM_final_full_AGC	Epe-Wesepe - Haarle	Poor (see appendix)	3 (see appendix)
L2EBN2019ASCAN005_PreSTM_final_full_AGC	Gelderse Vallei	Poor (see appendix)	6 (see appendix)
L2EBN2020ASCAN012_PreSTM_final_full_AGC	Eerbeek - Wesepe - Dalfsen	Reasonable (see appendix)	4 (see appendix)
L2EBN2020ASCAN023_PreSTM_final_full_AGC	Jutphaas - Utrecht	Reasonable (see appendix)	1 (see appendix)
L2EBN2020ASCAN015_PreSTM_final_full_AGC	Apeldoorn - Joppe	Poor (see appendix)	3 (see appendix)
L2EBN2020ASCAN016_PreSTM_final_full_AGC	Nijmegen - Oploo - Grashoek	Poor (see appendix)	8 (see appendix)
L2EBN2020ASCAN029_PreSTM_final_full_AGC	Heeze - Californië	Reasonable (see appendix)	13 (see appendix)
L2EBN2020BURKM006_PreSTM_final_full_AGC	Heumen - Lingewaard	Reasonable (see appendix)	4 (see appendix)
L2EBN2020ASCAN027_PreSTM_final_full_AGC	Haarlem - Oost	Reasonable (see appendix)	3 (see appendix)
L2EBN2020ASCAN028_PreSTM_final_full_AGC	Utrecht - Amersfoort	Reasonable (see appendix)	6 (see appendix)
NAM_DEEP_Line_Stack_Final-VTI_PreSTM_AGC_ROT	Brabant - Groningen	Good (see appendix)	3 (see appendix)
L2MOB1984A_MZ84-04_PosSTM_final_full_AGC	See appendix	N/A	0 (see appendix)
L2MOB1986A_MZ86-53_PosSTM_final_full_AGC	See appendix	N/A	0 (see appendix)
L2MOB1987A_MZ87-06_PosSTM_final_full_AGC	See appendix	N/A	0 (see appendix)
L2MOB1987A_MZ87-53_PosSTM_final_full_AGC	See appendix	N/A	0 (see appendix)
L2MOB1986A_MZ86-56_PosSTM_final_full_AGC	See appendix	N/A	0 (see appendix)
L2MOB1986A_MZ86-57_PosSTM_final_full_AGC	See appendix	N/A	0 (see appendix)
L2MOB1988A_MZ88-50_PosSTM_final_full_AGC	See appendix	N/A	0 (see appendix)
L2NAM1974F_741009_PosSTM_final_full_AGC	See appendix	N/A	0 (see appendix)

### Tectonic earthquakes (KNMI and Houtgast database)

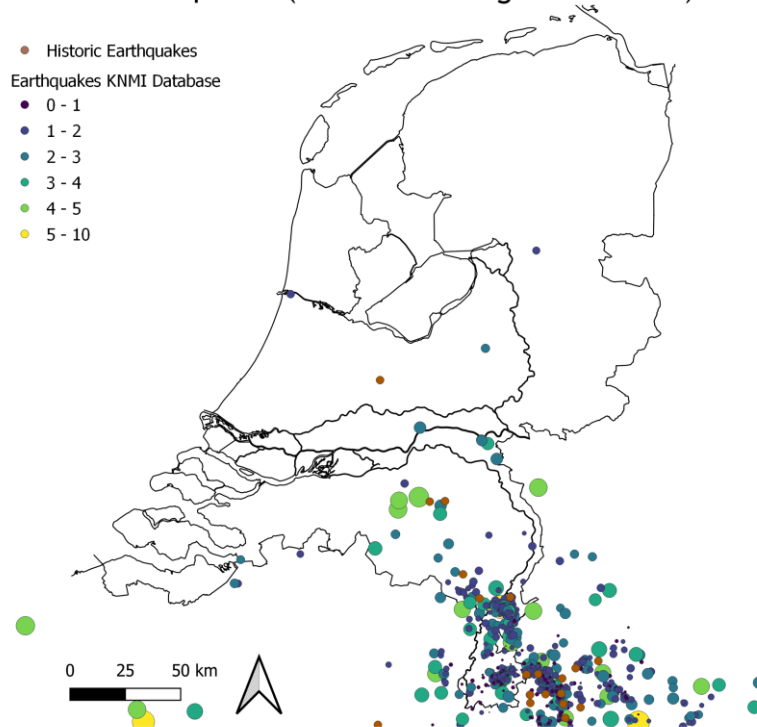


Figure 2-3: Tectonic earthquakes as defined in the KNMI and the adjusted Houtgast 1990 databases. These earthquakes were used for determining the seismically active relevant fault zones (see section 2.2.2). Note that the size and colour of the earthquakes observed by the KNMI denote the magnitude.

#### 2.2.2 Step 1.2: Definition of a major relevant fault zone for the purpose of SHS

The definition of relevant fault zone for the purpose of SHS was established over several meetings which included experts from TNO, EBN, Panterra and IF Technology. The following considerations were used to come up with a pragmatic definition of “major relevant fault zone”:

1. Intertwined, individual fault traces that together form a zone between the major “Jurassic-Cretaceous” structural elements (Kombrink et al., 2012)
2. Individual faults that offset base North Sea Super-Group and end close to base or in the Upper North Sea Group
3. Faults which show relatively large displacement
4. Fault zones which coincide with tectonic seismic events as recorded in the KNMI and Houtgast (1990) earthquake databases.

All faults that do not fall within the definition of relevant fault zone will be dealt with during the later stages of the overall SHS workflow. It appears that Level-2 faults of the existing TNO-GDN Fault database largely coincide with the above list of considerations (see section 2.2.1).

#### 2.2.3 Step 1.3 and 1.4: Evaluation and (re)interpretation of the TNO faults using the available SCAN data

To determine the accuracy and the relevance of each fault within the TNO database, the faults are depicted for each SCAN line (Figure 2-4). From the analysed SCAN data it can be observed that level 2 faults bound structural elements. For example, on SCAN line 002, level 2 faults bound the

Peel Maasbommel High Complex (PMHC) and separate it from the Central Netherlands Basin (CNB) and the Roer Valley Graben (RVG) (Figure 2-4a-c). These faults show significant displacement. Furthermore, a significant number of level 2 faults extend up to the Upper North Sea Group (NU) or even up to surface (e.g. Figure 2-4).

A significant number of Level 1 faults also show large displacement and extend up to the NU (e.g. antithetic faults observed on SCAN line 002 (Figure 2-4c)). However, an equal number of level 1 faults are relatively small, show relatively little displacement and/or are restricted to deeper reservoir layers (e.g. stop at Base North Sea or only occur in the Slochteren Formation).

While the SCAN lines near the RVG (e.g. SCAN-002) indicate that most faults show a reasonable to good fit with the available data, some major faults observed on the seismic are either not present in the TNO database or are misinterpreted (Table 2-1). This is also observed for the other analysed SCAN lines, on which the TNO faults mostly show a reasonable fit (Table 2-1). Therefore, a reinterpretation and adjustment of the TNO faults at the location of the analysed SCAN lines is recommended. Lastly, the TNO faults show a good fit with most of the analysed reprocessed lines (Table 2-1).

The reinterpretation of the different SCAN lines is shown in the appendix and as an example in Figure 2-5c. These reinterpreted faults will be included in the subsequent relevant fault maps (section 2.3.2) at the respective location of interpretation (i.e. utilized SCAN line). However, it should be noted that an update of the TNO fault database using the (re)interpreted faults is beyond the scope of this study and is therefore recommended for future improvements of the results (chapter 4).

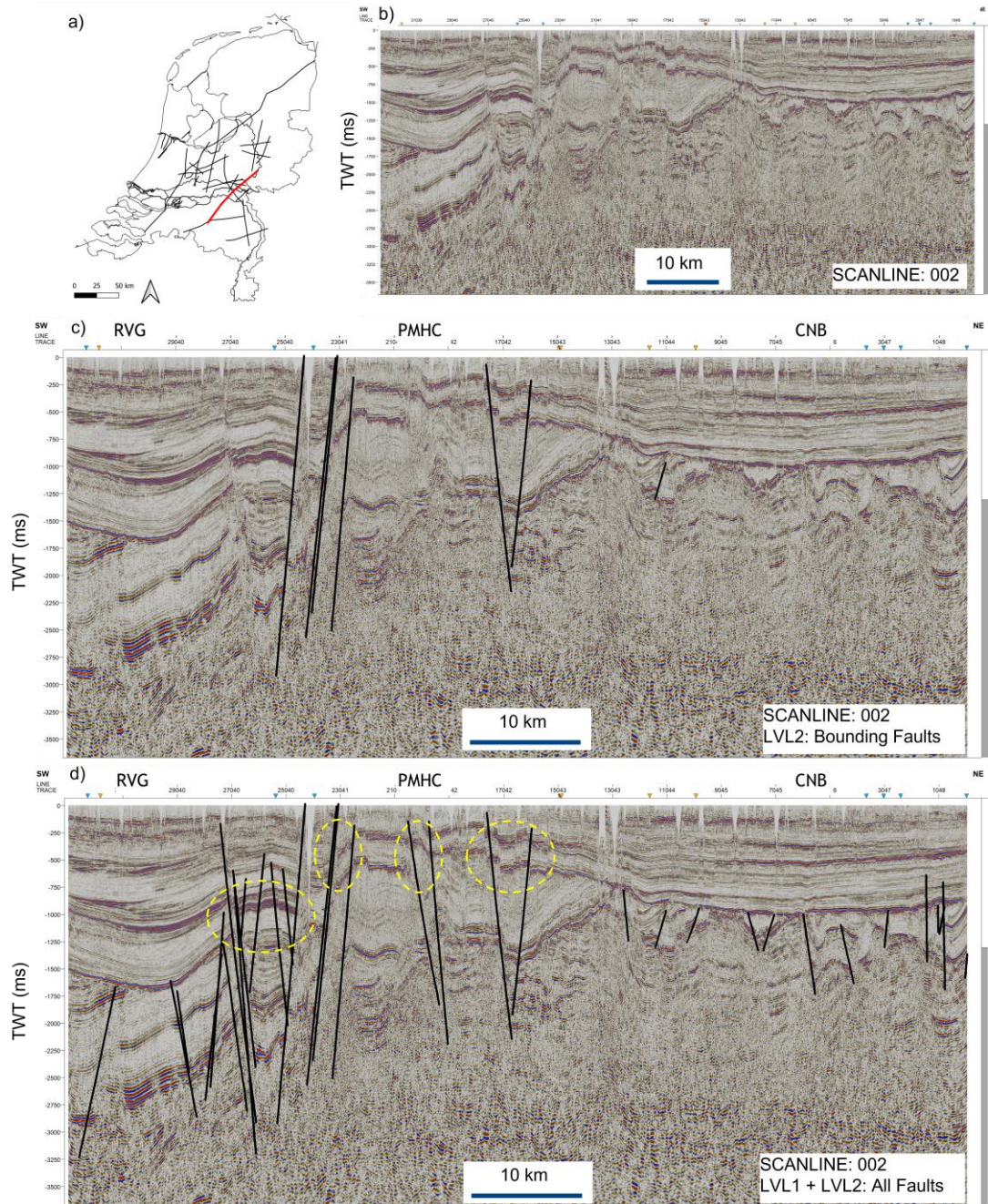


Figure 2-4: Evaluation of the TNO-AGE faults against SCAN line 002 (Roer Valley Graben - Nijmegen - Bronckhorst). a) location of SCAN line 002 highlighted in red. b) Original seismic data. c) Seismic data with level 2 faults (Bounding) highlighted in black. d) SCAN line 002 with all faults from the TNO-AGE fault database (level 1 and level 2) highlighted in black. Faults which displace the NU are encircled.

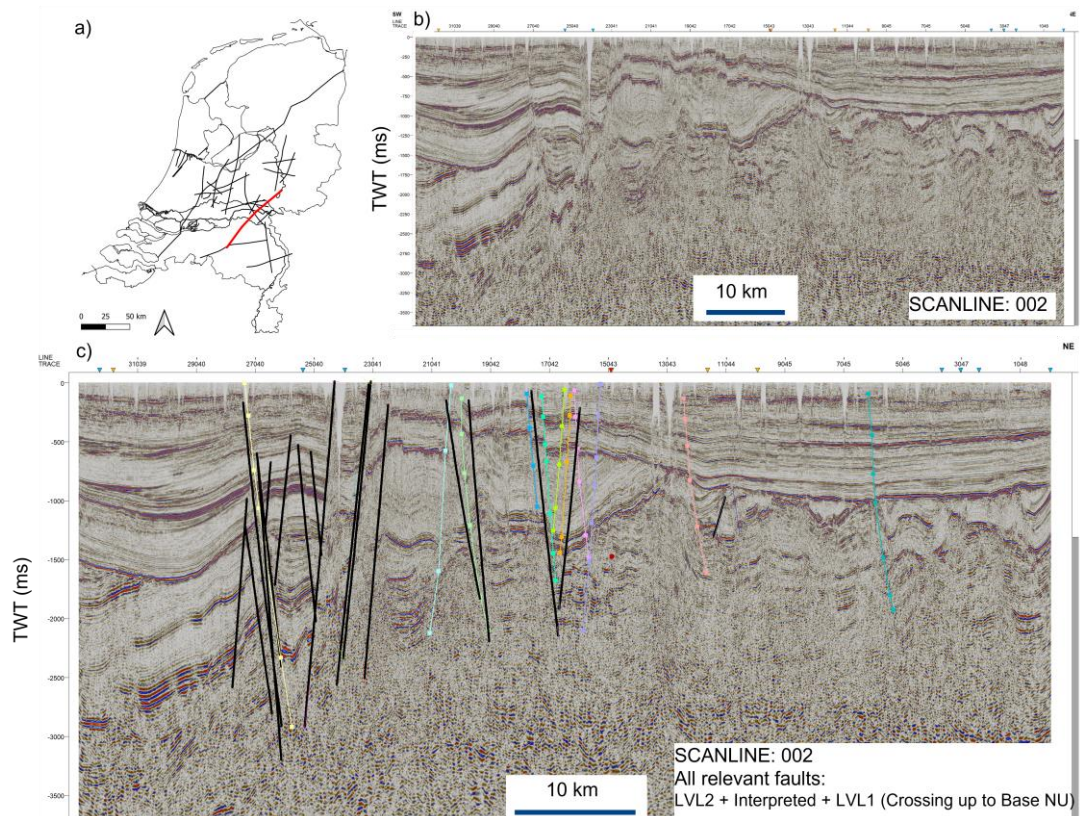


Figure 2-5: Evaluation and reinterpretation of the TNO faults on SCAN line 002 (Roer Valley Graben - Nijmegen - Bronckhorst). a) location of SCAN line 002 highlighted in red. b) Original seismic data. c) Seismic data with level 1 and level 2 faults which penetrate up to NU (section 2.2.4) highlighted in black and suggested reinterpretations depicted as coloured lines.

## 2.2.4

### Step 1.5: Filtering the relevant faults from the TNO-AGE database for the purpose of SHS

Using the criteria for defining relevant faults established during the meetings (section 2.2.2), the TNO-AGE fault database was adjusted and filtered to create the relevant fault database, by 1) including all faults which bound large structural elements (i.e. level 2 faults) (Figure 2-4), 2) filtering the level 1 faults by only including faults which penetrate the Base of Upper North Sea Group (NU)<sup>2</sup>, and 3) add an additional filter on the level 1 faults using the tectonic earthquake data base such that only faults which are in proximity to tectonic events are extracted. The resulting relevant and potentially seismically active fault database is shown in Figure 2-6.

<sup>2</sup> Filtering of the level 1 faults has been done using the object name, which includes the name of the formation where the fault starts and name of formation where the fault ends. i.e. Faults which have a fault end-point naming indicator of NU are included in the relevant fault database. Faults which have other fault end-point naming indicators have been removed.

### Map of seismically active relevant faults

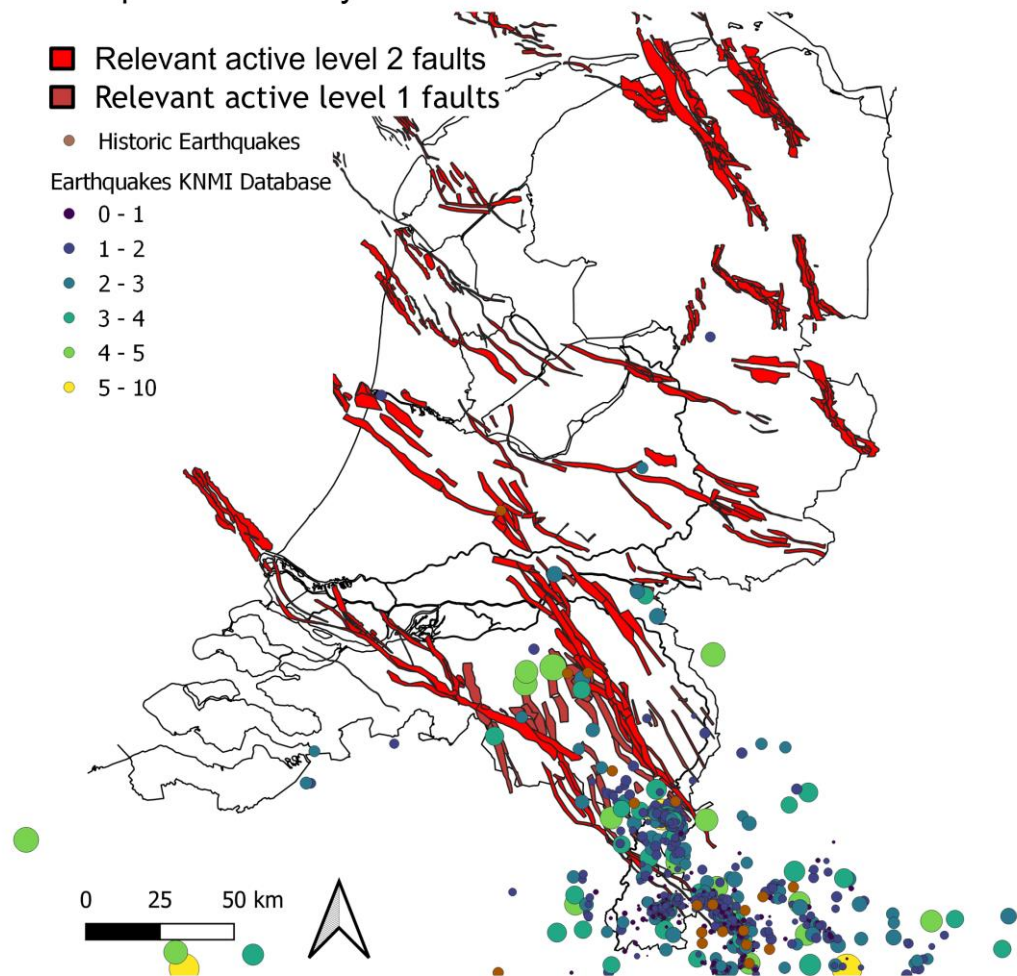


Figure 2-6: Map of the filtered relevant faults from the TNO database after the seismic evaluation steps. Faults are depicted as planes (polygons). High resolution images can be found in the supporting materials (e.g. pptx or QGIS).

## 2.3 POLYLINE EXTRACTION, UNCERTAINTY QUANTIFICATION AND BUFFER ZONE SELECTION

The second part of the main workflow is to 1) define relevant stratigraphic levels, 2) extract the relevant faults, 3) make maps of the relevant faults at each chosen stratigraphic level, 4) quantify the uncertainty and 4) draw buffer zones around the faults and convert them to maps. This polyline extraction, uncertainty quantification and buffer zone selection from the relevant fault database is partly done using Petrel and mostly done using QGIS (see section 6.1) (Figure 2-1).

### 2.3.1 Step 2.1: The chosen stratigraphic levels

Geothermal energy projects mainly consider, and have previously targeted, four reservoir formations, namely: 1) Rotliegend Sandstones, 2) Triassic sandstones of the Lower Germanic Group, 3) the Upper-Jurassic to Lower-Cretaceous sandstone formations and 4) Tertiary sandstones (Pluymaekers et al., 2012). As part of this study these reservoir formations will be represented by the following horizons from DGM Deep V5: 1) Base Upper North Sea Group (NU), 2) Base Rijnland Group (KN), 3) Base Lower Germanic Group (RB) and 4) Base Zechstein (ZE). These four horizons



are considered representative for the main reservoir groups (Pluymaekers et al., 2012; Van Adrichem Boogaert & Kouwe, 1993).

**2.3.2 Step 2.2 to 2.4: Polyline extraction of the relevant faults at the chosen stratigraphic levels**

For the level 2 faults, polylines were extracted from the “relevant fault database” along the chosen four horizons of the DGM Deep V5 model. Polyline extraction was done in Petrel using the surface-surface intersection tool (i.e. convert fault interpretation to a surface and extract polylines along the intersection with the chosen stratigraphic levels). For the seismically active level 1 faults extracted polylines were already present for each stratigraphic level. Therefore, these polylines were only filtered using the methodology described in section 2.2.4 (step 1.5) such that only relevant faults were selected.

The extracted/filtered fault polygons were exported as individual shapefiles from Petrel and were merged into single shapefiles for each fault level and stratigraphic horizon using the merge vector layers tool QGIS (See Figure 6-1). The resulting shapefiles of the relevant faults are shown in map view for each stratigraphic level (NU, KN, RB and ZE) in Figure 2-7.

**2.3.3 Step 2.5: Uncertainty quantification using the seismic interpretation and SCAN data**

Most relevant faults extracted from the TNO database only show a reasonable fit with the SCAN lines (see appendix and Table 2-1). This implies that for a significant number of relevant faults large uncertainties exist with regard to the exact fault position. This can for example be seen on SCAN line 029, where the observed inaccuracy between the discontinuity on the seismic data and fault position from the TNO database ranges between 250m and 750m (Figure 2-8). This observation implies an uncertainty in the fault positions of the same order of magnitude in areas with a similar data position. In other examples, observed discontinuities in the seismic data are not included in the TNO fault and new faults have been interpreted (e.g. Figure 2-5 and Figure 2-8).

The observed mismatch between the relevant fault database and the new SCAN lines can best be explained by limited seismic data at the location of the respective SCAN line (Figure 2-9a). For example, SCAN line 029 was acquired at a location where almost no original seismic lines were present and in those areas large inaccuracies were observed (Figure 2-8c & d and Figure 2-9a). These same large inaccuracies are also observed for other SCAN lines at which the original seismic data position is poor (e.g. SCAN Lines: 016, 006, 005 and 027 see appendix). Hence, in areas with a poor data position without new SCAN-lines, the uncertainty on the interpretations is large. In areas where the original seismic data position is good (e.g. where 3D seismic is present), the observed inaccuracy in the fault position is much lower. This can for instance be seen for the reprocessed NAM deep line which shows a relatively good fit between the faults in the database and seismic data and the fault plane positions in areas where 3D data is present (Figure 2-9) (see appendix). In areas with a relatively high density of original 2D lines fault positioning is generally reasonable (uncertainties up to 500m) (e.g. lines within the RVG (Figure 2-5 or Figure 2-9c)).

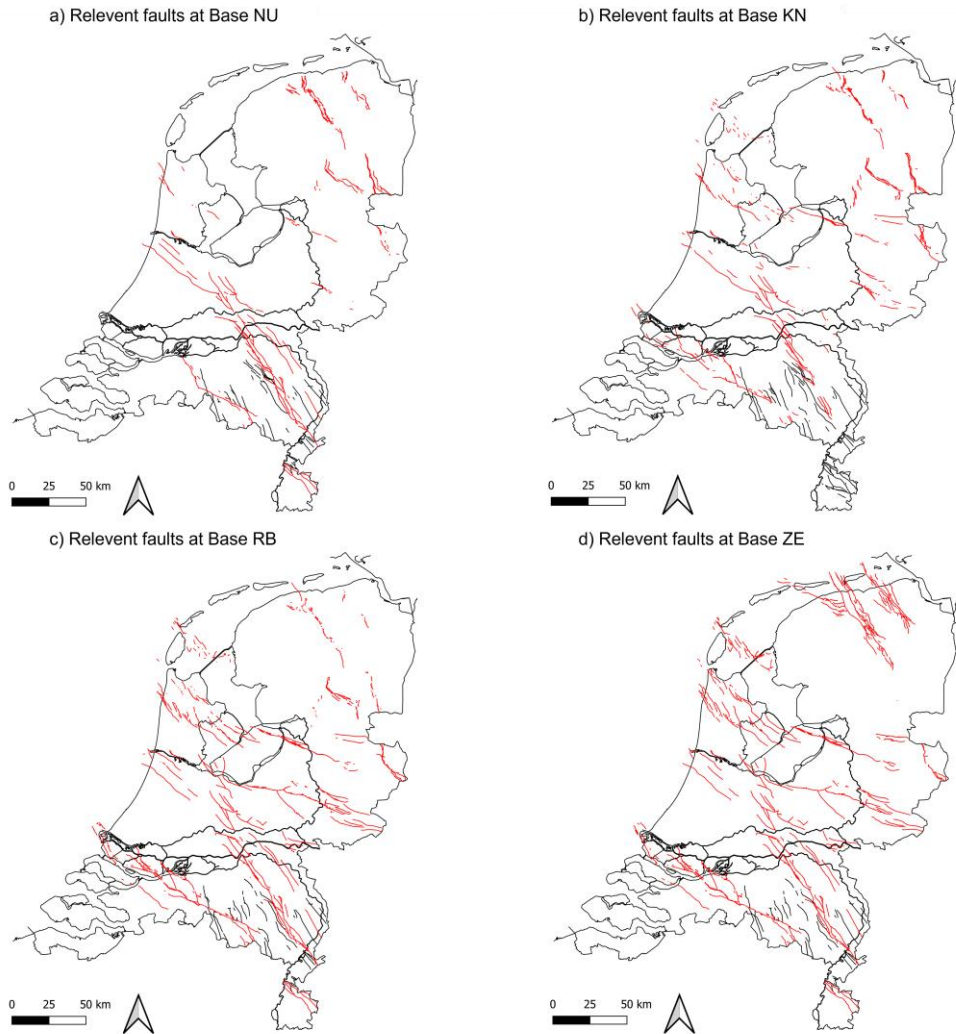


Figure 2-7: Relevant fault maps at the chosen stratigraphic levels. a) Base Upper North Sea (NU), b) Base Rijnland Group (KN), c) Base Lower Germanic Groups (RB) and d) Base Zechstein (ZE). High resolution images can be found in the supporting materials (e.g. pptx or QGIS). For all maps, faults are highlighted by the red (level 2) and black (level 1) lines.

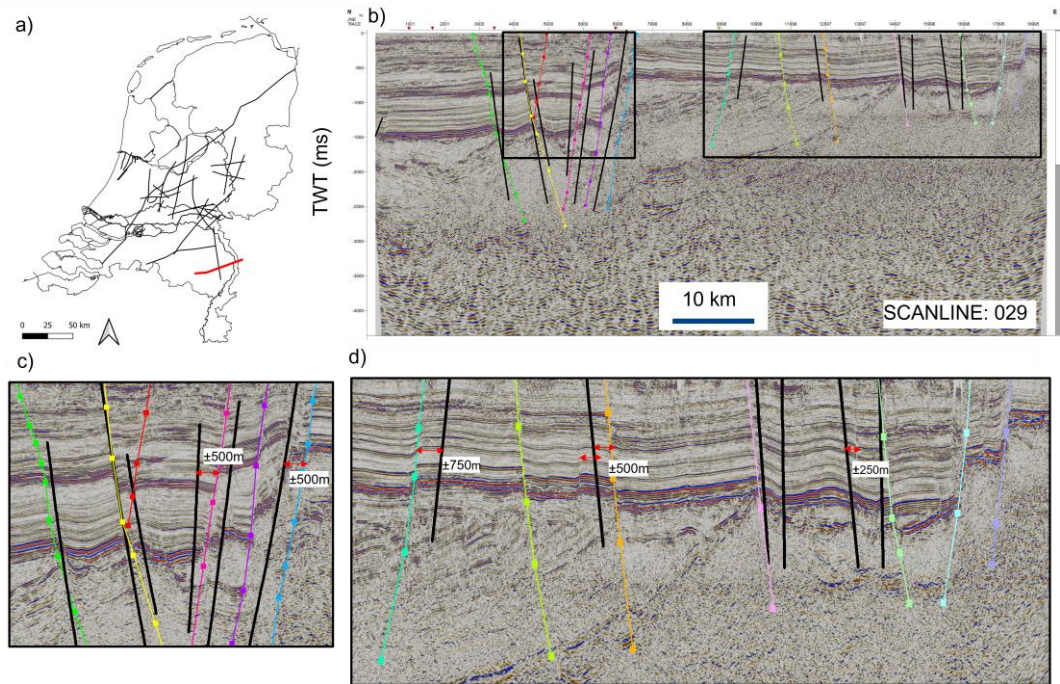


Figure 2-8: a) location of SCAN line 029 highlighted in red. b) Relevant faults depicted on seismic line 029 and the respective location of figures c and d. c-d) Respective inaccuracy between SCAN data and different faults within the TNO Fault database. Faults belonging to the TNO model are highlighted in black. Faults which have been reinterpreted are represented as coloured lines. High resolution images can be found in the supporting materials.

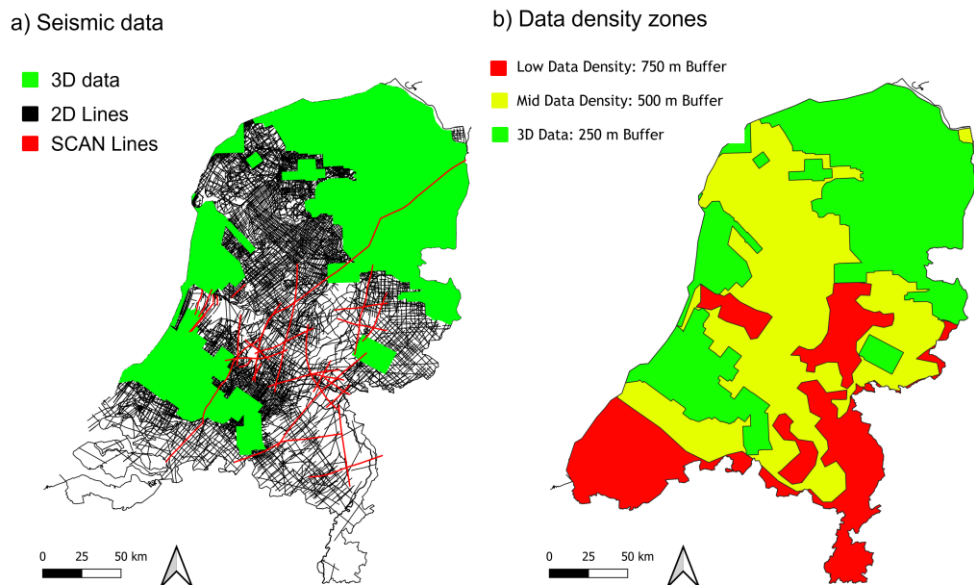


Figure 2-9: a) available seismic data within the Netherlands. b) Different data density zones and respective buffer zone widths based on the available seismic data and uncertainty quantification.

**2.3.4**

**Step 2.6: Maps of the buffer zones around the relevant faults at each stratigraphic level**

To account for the uncertainties deduced for the positioning of the individual faults in the TNO model we propose that buffer zones should be drawn around each relevant fault. In our approach,

the width of these buffer zones is based on the measured inaccuracy (section 2.3.3) and the seismic data positions and is set as follows:

- 1) 3D seismic data is present: Buffer width = 250m
- 2) medium 2D seismic data density: Buffer width = 500m
- 3) low 2D seismic data density: buffer width = 750m

Note that the assigned buffer widths for each data position are relatively conservative with respect to the inaccuracies observed on the SCAN data.

The polygons defining the different data positions were generated in QGIS as follows:

1. The 3D data polygon (Figure 2-9b) is the outline of all 3D surveys onshore The Netherlands which were merged into a single polygon using the dissolve tool (Figure 6-3).
2. The mid data density polygon (Figure 2-9b) was drawn in QGIS using a 2D seismic line density grid (see QGIS project provided with the documentation). The gaps in the polygons were created using the symmetrical difference tool in QGIS (Figure 6-4).
3. The remaining areas were assigned to have low data density (Figure 2-9b)

The acquired polygons were subsequently utilized to automatically select faults from the relevant fault database (Figure 2-2 and Figure 2-6), assign a respective data position and calculate the respective buffer distance, as follows:

1. Faults which fall within the 3D data polygon were selected using the select by location tool and whilst having *are within* toggled on (Figure 6-5). The selected faults were given a data position of 3D data in the field calculator.
2. Faults which fall within and/or cross the mid data density data polygon were also selected using the select by location tool and whilst having *are within / intersect* toggled on (Figure 6-5). The selected faults were given a data position of 2D\_mid data in the field calculator.
3. The remaining faults were not given a data position (i.e. low data density) such that the data position remained at *null*.
4. Once the data position for each relevant fault was assigned, the buffer distance was calculated as an attribute using the field calculator (Figure 6-6) at each chosen stratigraphic level.
5. Lastly, a buffer was automatically drawn around each relevant fault using the buffer tool and the respective distance within the attribute table (Figure 6-7). For example, a fault which is positioned within the low data density zone will have buffer distance of 750m. Using the buffer tool, a polygon was drawn around the respective fault at a distance of 750m on either side, thereby creating a polygon having a total width of 1.5 km (Figure 2-10).

The resulting fault buffer zone maps for each stratigraphic level (NU, KN, RB and ZE) are shown in Figure 2-10. These maps show that faults in the Northern part of the Netherlands have relatively thin buffer zones (250m on either side), whereas faults positioned in RVG or PMHC are characterised by buffer zone widths of 500m to 750m on either side (Figure 2-10). By assigning these conservative buffer zones, the uncertainty in fault position at each point is largely covered (e.g. Figure 2-8).

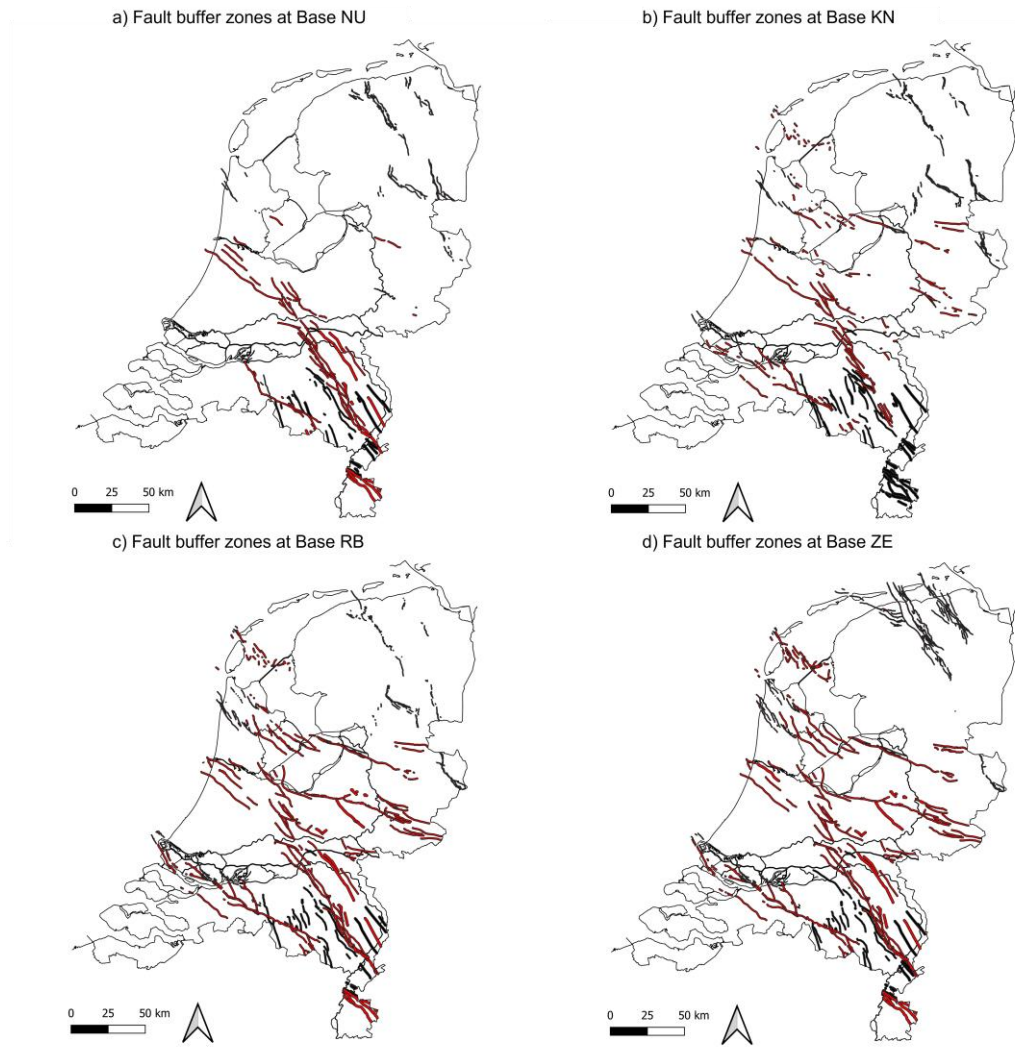


Figure 2-10: a) Fault buffer zones at Base Upper North Sea (NU). b) Fault buffer zones at Base Rijnland Group (KN). c) Fault buffer zones at Base Lower Germanic Group (RB). d) Fault buffer zones at the Base Zechstein (ZE). High resolution images can be found in the supporting materials (e.g. pptx or QGIS). For all maps, faults are highlighted by the red (level 2) and black (level 1) lines.

## 2.4 COMPOSITE MAPS OF RELEVANT FAULTS AND SEISMICALLY ACTIVE AREAS

The third part of the main workflow is to integrate the buffer zone maps (Figure 2-10) with the outline of the seismically active Roer Valley Graben Area (as defined in Böker et al., (2021)) in order to generate composite maps which highlight significantly faulted areas (i.e. within the buffer of a relevant fault) and seismically active areas. This integration is done in QGIS.

### 2.4.1 Step 3.1: The Larger Roer Valley Graben Area

The Larger RVG Area (LRVGA) is regarded as seismically active and most tectonic earthquakes in The Netherlands also occur in this area (e.g. Balen et al., 2005). As part another key-element study (Böker et al., 2021) a polygon was generated of the LRVGA in which faults should be regarded as critically stressed and within which further action within the Seismic Hazard and Risk Analysis (SHRA) will be required. The acquired polygons of the LRVGA are shown in Figure 2-11. Note that

the rationale behind the polygon shape is given the respective documentation of Böker et al., (2021).

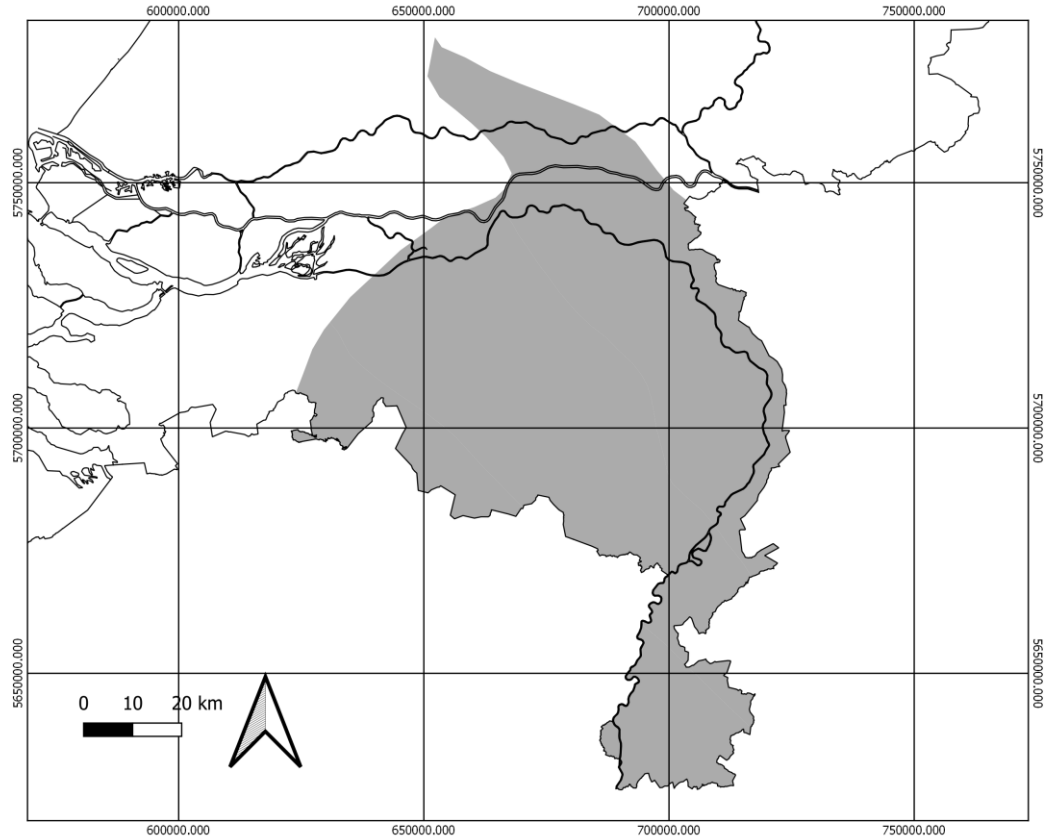


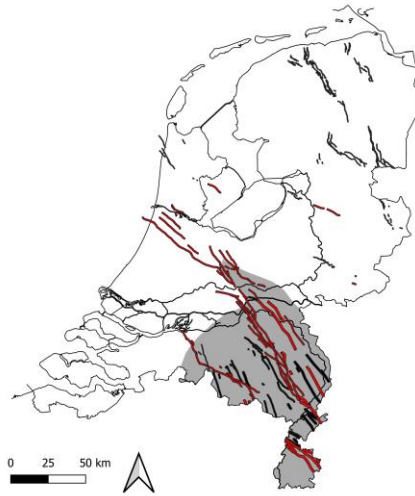
Figure 2-11: Map of the LRVGA with boundary polygon (highlighted grey). See documentation Böker et al., (2021) for additional details on the derived LRVGA polygon.

#### 2.4.2

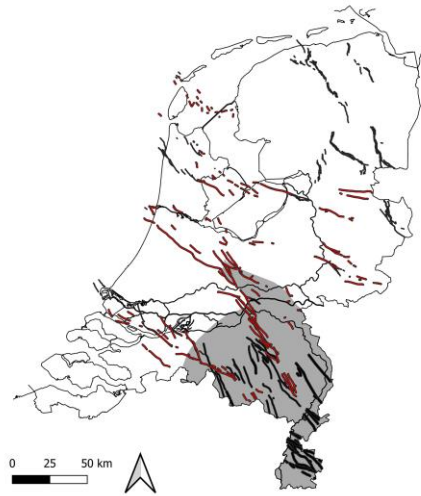
##### Step 3.2: Composite maps at each stratigraphic level

The final product of this study is a composite map integrating the fault buffer zones at each stratigraphic level with the polygon of the seismically active LRVGA (Figure 2-12). These maps highlight polygons within which further action is required within the SHRA, since they indicate one or more of the following: 1) large faults which bound larger structural elements, 2) large seismically active faults crossing into the Upper North Sea Group and 3) the seismically active LRVGA. A full explanation on how to utilize these maps for the purpose of SHS is given in chapter 3.

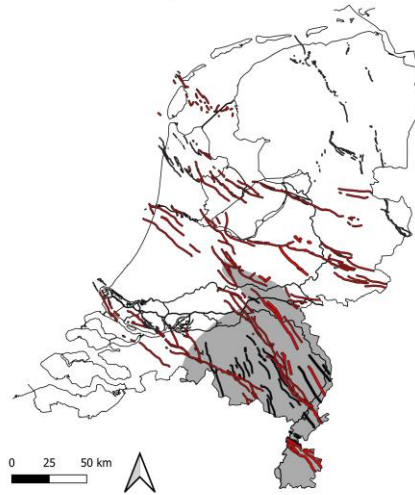
a) Composite map at Base NU



b) Composite map at Base KN



c) Composite map at Base RB



d) Composite map at Base ZE

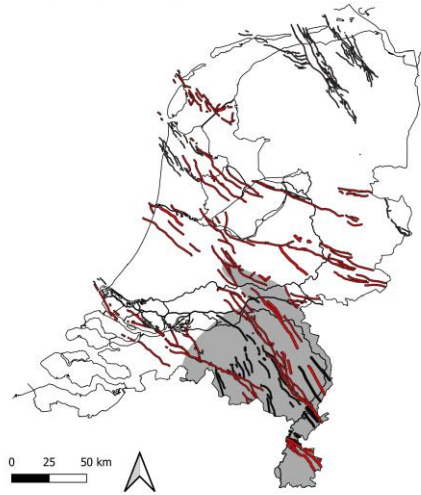


Figure 2-12: a) Composite map at Base Upper North Sea (NU). b) Composite map at Base Rijnland Group (KN). c) Composite map at Base Lower Germanic Group (RB). d) Composite map at the Base Zechstein (ZE). High resolution images can be found in the supporting materials (e.g. pptx or QGIS). For all maps, faults are highlighted by the red (level 2) and black (level 1) lines. The LRVGA is indicated by the grey polygon.

# 3 Utilization of the composite maps for purpose of SHS

To demonstrate which composite map should be used given a geothermal reservoir target and how to utilize the composite maps once a potential target and drilling location is known, a reference table has been constructed (Table 3-1). For example, from the reference table it can be derived that when targeting the Delft Sandstone reservoir, the composite map at the Base Rijnland should be used (Table 3-1 and Figure 2-12b). Alternatively, when targeting the Slochteren Sandstone reservoir, the composite map at the base of Zechstein should be used (Table 3-1 and Figure 2-12d).

Once the geothermal target, well location and the area of influence (Borst et al., 2021) are known, the composite map is used to determine whether the Area of Influence of the geothermal project is near a potentially seismically hazardous area (i.e. relevant fault and/or within LRVGA). This is done using the following steps (preferably in a GIS based software (e.g. QGIS or ARCMAP):

1. Determine which composite map to use given the targeted geothermal reservoir
2. Plot / draw the Area of Influence (Aol) on the map given the results of Borst et al., (2021) Check whether your Aol overlaps with or touches the LRVGA or any buffer zones surrounding the relevant faults
3. If yes, then further action is required within the SHRA
4. If not, then proceed with the SHS methodology

However, it should be noted that the exact consequences and subsequent proceedings of the above described steps are to be defined by EBN and TNO-AGE upon integration of all key-elements into one single, new SHS-workflow.

Table 3-1: Reference table for linking different aquifers to their respective composite map.

Targeted aquifer as defined in ThermoGIS (Pluymaekers et al., 2012)	Utilized stratigraphic level and composite map
North Sea Group: <ol style="list-style-type: none"> <li>1. Voort</li> <li>2. Steensel</li> <li>3. Vessem</li> <li>4. Basal Dongen Sand</li> <li>5. Reusel</li> <li>6. Heers Sand</li> <li>7. Swalmen</li> </ol>	Composite map at base Upper North Sea (NU) (Figure 2-12a)
Lower Cretaceous: <ol style="list-style-type: none"> <li>1. Friesland Sst</li> <li>2. Gildehaus Sst</li> <li>3. Bentheim Sst</li> <li>4. Rijswijk Sst, Berkel Sst, Ijselmonde Sst</li> </ol>	Composite map at base Rijnland (KN) (Figure 2-12b)
Jurassic: <ol style="list-style-type: none"> <li>1. Delft Sst</li> </ol>	Composite map at base Rijnland (KN) (Figure 2-12b)
Triassic: <ol style="list-style-type: none"> <li>1. Upper Germanic Group (Rot Fringe Sst)</li> <li>2. Lower Germanic Group (Hardeggen Sst, Detfurth Sst, Volpriehausen Sst)</li> </ol>	Composite map at Base Lower Germanic Group (RB) (Figure 2-12c)



Permian:

1. Upper Rotliegend (Slochteren Sst)

Composite map at the Base Zechstein (ZE)

(Figure 2-12d)

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# 4 Recommendations for future improvements

**4.1 INCLUDING THE NEW INTERPRETATIONS OF RELEVANT FAULTS IN THE TNO FAULT DATABASE**  
In the current versions of relevant fault (Figure 2-7), buffer zone (Figure 2-10) and composite maps (Figure 2-12) the interpretations made on the SCAN lines are included but limited to the location of interpretation (i.e. point data). Furthermore, the faults within the TNO database surrounding the new interpretations have not been adjusted. Therefore, we believe that the relevant fault database can be improved by including the new interpretations and/or adjusting existing faults using the new interpretations. We propose that this can be done by using one of the below described workflows, namely:

1. GIS shapefile adjustment: extend the interpreted fault shapefiles at each stratigraphic level using a GIS based software and the trend (fault strike and dip) observed in the surrounding faults of the TNO model. Once the shapefiles of the interpreted fault have been adjusted the buffer zones need to be recomputed using the workflow as described in chapter 2.
2. Full Petrel based model adjustment: Adjustment of the fault database by using the reinterpretations made on the SCAN lines and making new interpretations on the surrounding seismic data. Once the reinterpretation of the relevant fault database has been finished, the new relevant fault database needs to be extracted at each stratigraphic level (Steps 2.2 to 2.4) and the buffer zones need to be recomputed (Step 2.6).

## 5 References

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<https://doi.org/10.1017/S001677460000041X>
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# 6 Appendices

## 6.1 TOOLS AND FORMULAS USED IN QGIS

The QGIS tools utilized to generate the fault and buffer zone maps.

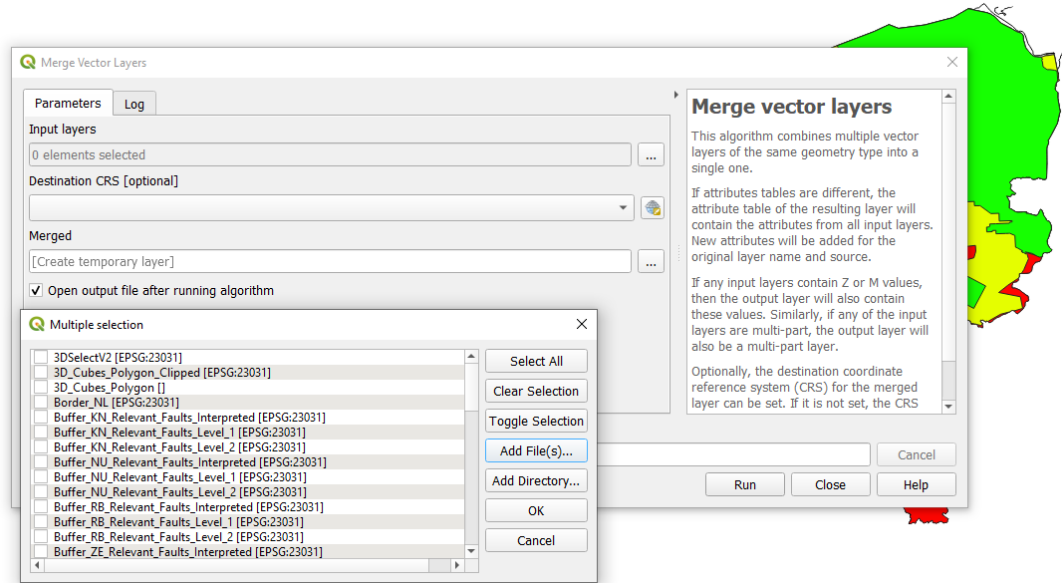


Figure 6-1: The merge vector layer tool used for generating the shapefiles of the relevant faults from the individual fault polygons extracted from Petrel.

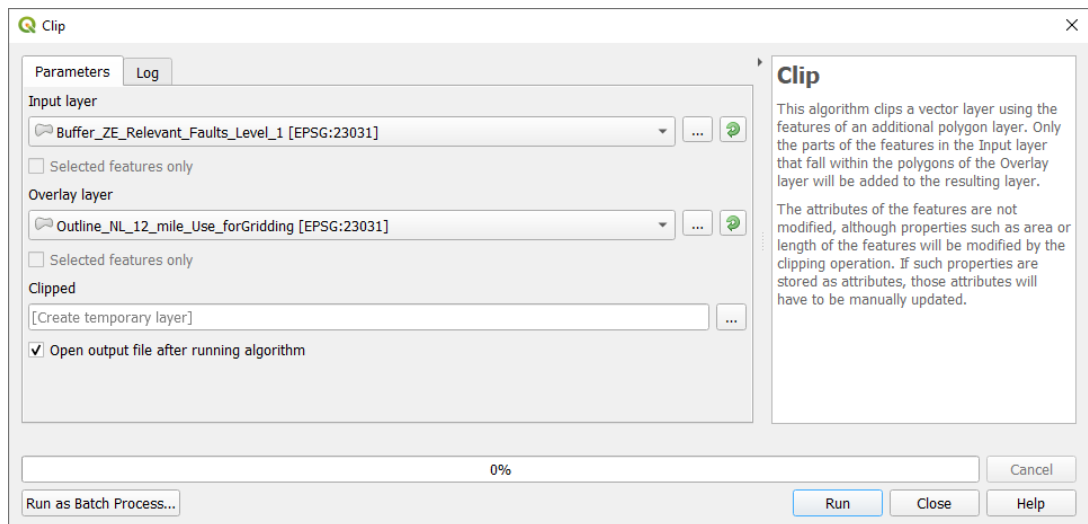


Figure 6-2: The clip tool used for clipping the faults and other polygons to the 12 mile outline.

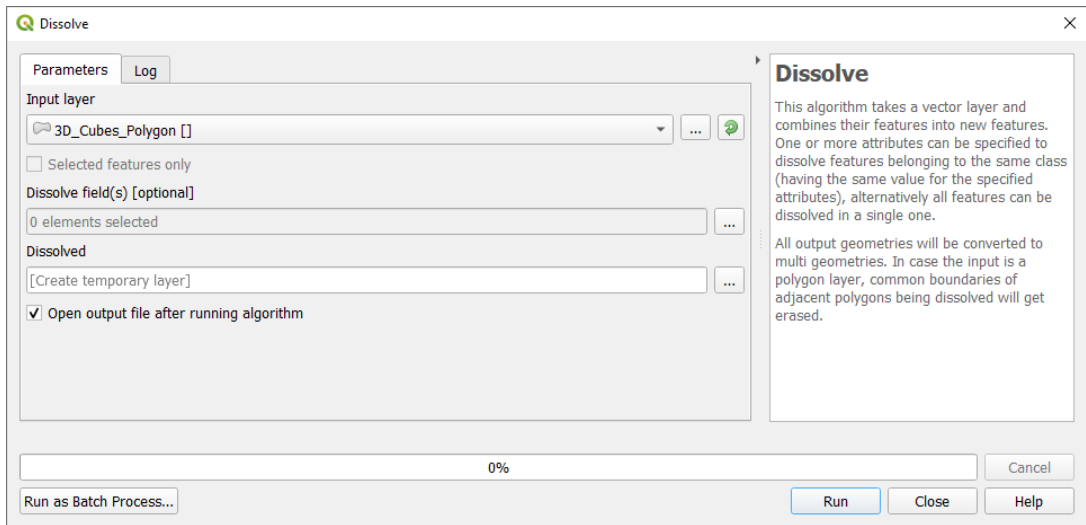


Figure 6-3: The dissolve tool utilized for merging individual features within a shapefile.

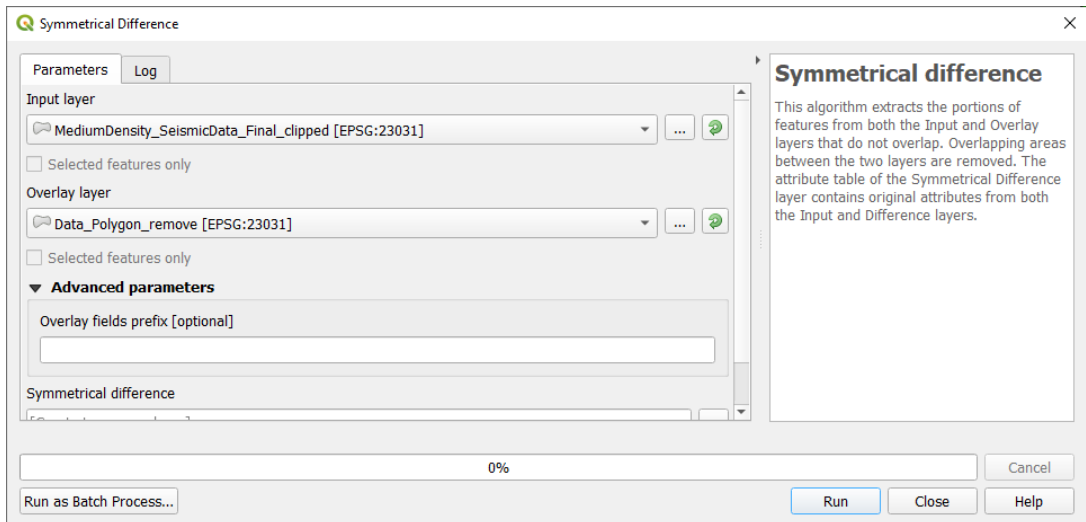


Figure 6-4: The symmetrical difference tool used for generating the mid data density polygon.

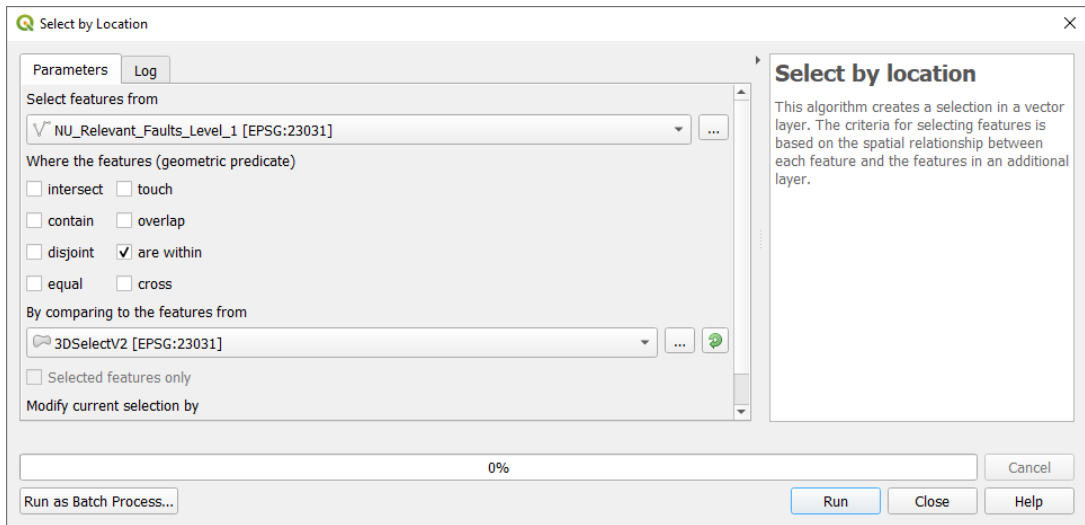


Figure 6-5: The select by location tool used for selecting fault using the different data density polygons.

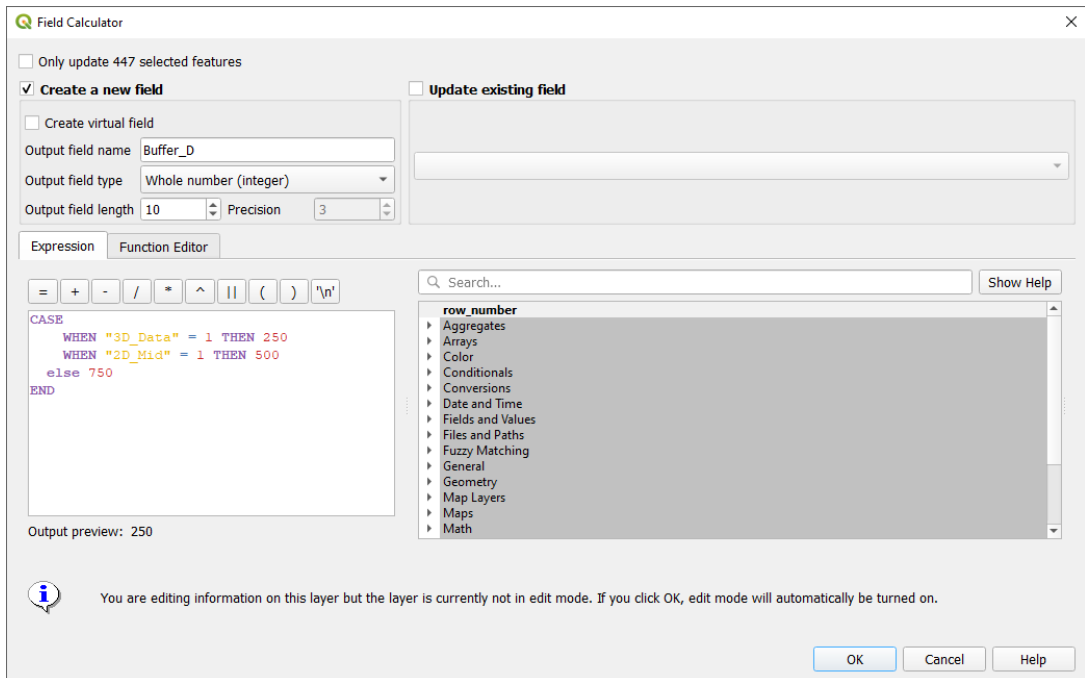


Figure 6-6: The field calculator used for computing the buffer distance for each relevant fault based on its respective data position

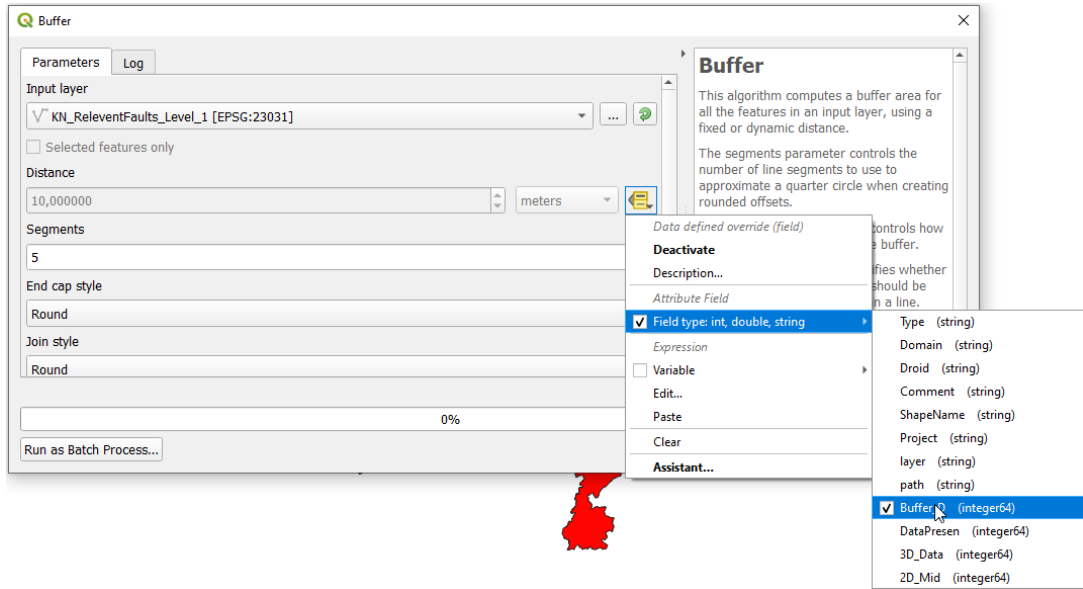


Figure 6-7: The buffer tool used for drawing the buffer zones around each respective relevant fault given the respective Buffer distance attribute.

## 6.2 SEISMIC INTERPRETATION OF ALL SCAN LINES

The full evaluation and interpretation of each SCAN - and reprocessed line as listed in Table 2-1 is given the attached documents:

WP-05\_Interpretation off all SCAN-Lines.pdf (converted from pptx (55 MB))

WP-05\_Interpretation off all SCAN-Lines.pptx (High resolution images (1.0 GB))

## 6.3 SUPPORTING PETREL AND QGIS PROJECTS

Alongside this document the full petrel and QGIS projects are delivered.