Seismic Hazard Screening (SHS): Larger Roer Valley Graben Area definition

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Table of Contents

Samenvatting

Het Ministerie van Economische Zaken en Klimaat heeft EBN en TNO verzocht een nieuwe methode op te zetten om het seismisch risico in te schatten voor geothermieprojecten in Nederland. Onderdeel van deze methode is het verifiëren of het invloedsgebied (Area of Influence, AoI) van een geothermieproject binnen de seismisch actieve “Larger Roer Valley Graben Area” (LRVGA) valt of daaraan raakt (Mijnlieff and Jaarsma 2021). Voorliggend rapport beschrijft de definiëring van de LRVGA.

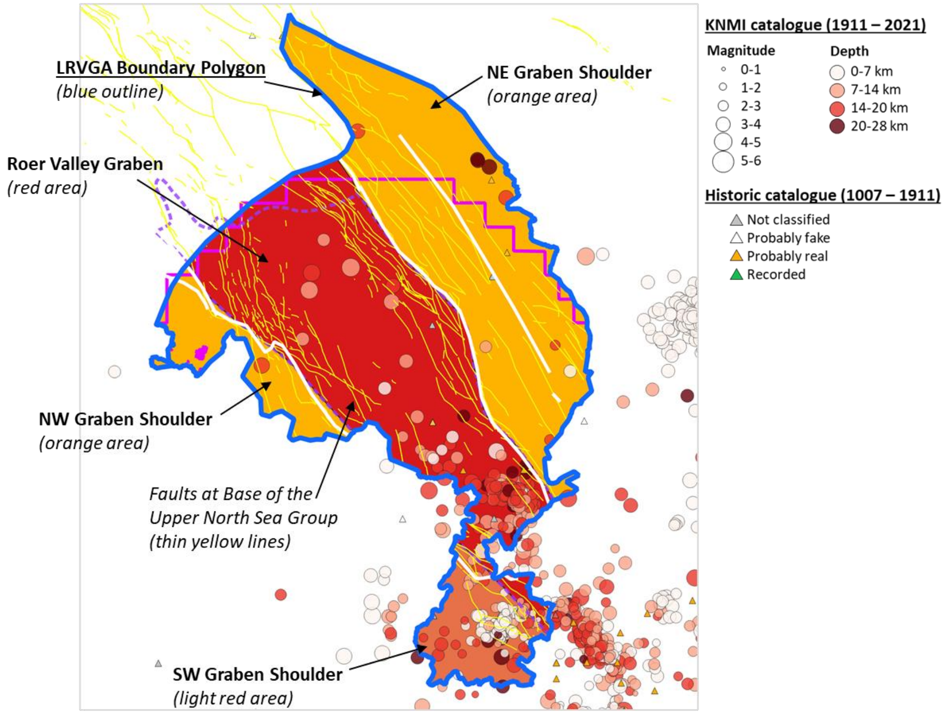
De beschreven workflow om de “Larger Roer Valley Graben Area” (LRVGA) te definiëren neemt alle huidige beschikbare data mee gerelateerd aan: de verwachte grondversnelling (Peak ground acceleration, PGA), de locaties en magnitude van seismische events uit het verleden, geofysische informatie over het zwaartekrachtsveld en seismische lijnen en de oriëntatie en locatie van de huidige breukinterpretaties uit de TNO database.

De polygoon van LRVGA (Figuur 0-1) wordt grotendeels begrensd door de Nederlandse grens, aangezien deze studie zich enkel richt op de LRVGA binnen Nederland. De begrenzing in het noorden is gebaseerd op een combinatie van PGA drempelwaarden en grote breukzones, zodanig dat de meeste waargenomen tektonische aardbevingen uit het verleden binnen de LRVGA polygoon vallen. Deze aardbevingen zijn een indicatie voor kritisch gespannen breuken in de diepere ondergrond (Basement) in dit deel van Nederland.

Belangrijke, potentieel seismisch actieve breukzones buiten de LRVGA worden ook worden meegenomen in de nieuwe Seismic Hazard Screening (SHS) methode, deze zijn in een andere deelstudie uitgewerkt (Boersma, Kwee en Leo 2021).

De LRVGA polygoon zal moeten worden ge-update wanneer (significante) nieuwe data en/of vernieuwde seismische modellen beschikbaar komen. De digitale bestanden en software projecten zijn als bijlage toegevoegd aan dit rapport.

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: de definitie van de LRVGA. 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.



Figuur 0-1: Samengestelde kaart met de LRVGA polygoon aangegeven in blauw. Binnen deze polygoon zijn 4 sub-gebieden aangegeven (rood, licht rood en oranje). Zie Figure 2-6 (pagina 11) voor een gedetailleerde beschrijving.

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 the Larger Roer Valley Graben Area (LRVGA). 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.

This study aims at the compilation of a reference map which outlines the seismically active Larger Roer Valley Graben Area (LRVGA). In the current seismic hazard analysis method (IF Technology & Q-Con 2016) as well as in a recent advice of a panel of professors to the Ministry of Economic Affairs and Climate Policy, special attention is given to the area in SE Netherlands where the occurrence of natural seismicity is undisputed. (Parts of) faults in this area are in some cases approaching a critical stress situation. The purpose of this study is to define the area where faults are evidently in such a stress situation that natural seismicity occurs within a relative short time interval. The chance of inducing or triggering earthquakes (their effect overriding the norms set) is deemed higher in this area than outside this area (Mijnlieff and Jaarsma 2021).

Two viable routes to delineate the Larger Roer Valley Graben Area were proposed in the initial project framing:

1) Utilization of a suitable threshold value from Probabilistic Seismic Hazard Assessment (PSHA) studies such as the latest Peak Ground Acceleration (PGA) map (de Vos 2010).
2) Utilization of a suitable buffer around epicentre locations of earthquakes that are listed in the public catalogues (KNMI Jun-2021, Houtgast 1990).

Although the PSHA approach has predictive capacity for areas without historical earthquake data it is only of indicative nature and cannot be truly validated by observations. Results are considered sensitive to the definition of source zonation and the choice of ground motion prediction equation (de Vos 2010). Also, the PSHA approach defines the area that is affected by natural earthquakes at surface but does not indicate where in the subsurface faults could be critically stressed. In contrast, the second method relies on actual earthquake locations and data but also carries all the uncertainties of the earthquake record. These range from false positives reported in pre-industrial times to progression in spatial density and sensitivity of the monitoring network since 1911. Large events or swarms such as the 1992 Roermond earthquake recurring at low periodicity (e.g. >100 years) may not have been captured in pre-industrial times and/or recognized as such in the database.

This study reconciles the information gained by the above methods with implications of recent tectonic activity seen in the seismic-scale fault network as provided by TNO (GeoERA-HIKE; DGM5).

2 Methods and results

The presented workflow for delineation of the seismically active Larger Roer Valley Graben Area (LRVGA) takes into consideration all presently available data that relate to expected peak ground acceleration (PGA; Section 2.1), the spatial distribution and magnitude of past seismic events (Section 2.2) integrated with geophysical information from the gravity field (Section 2.3) and from key seismic lines (Section 2.4), and the orientation and spatial arrangement of the current fault interpretation level 3 from the TNO fault database and the level 1 faults at the base of the Upper North Sea Group (Section 2.5).

2.1 PEAK GROUND ACCELERATION

The most recent PGA maps published for the Netherlands (de Vos 2010), see Figure 2-1a, Belgium (Leynaud, et al. 2000) and Germany (Grünthal, et al. 2018) were loaded into QGIS for visual inspection and cross-border comparison. The three country maps display PGA with 10% (DE: 16%) probability of exceedance during 50 years at a return period of 475 years. An overlay of all three maps in Figure 2-1b shows that they are in good agreement with each other and unanimously predict the strongest ground acceleration on Dutch territory in the south of Limburg, an area that is structurally located on the south-western shoulder of the Roer Valley Graben (Kombrink, et al. 2012).

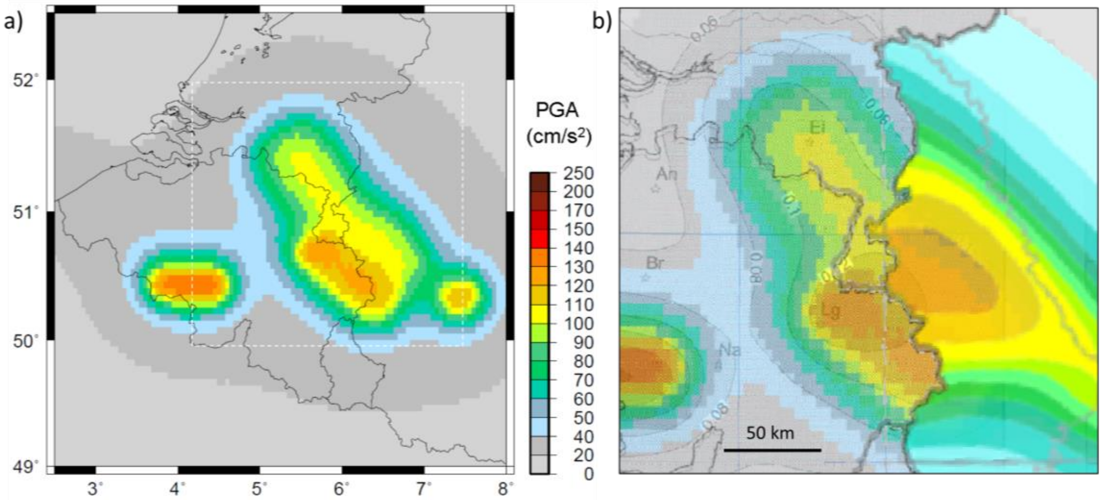


Figure 2-1: Maps of modelled Peak Ground Acceleration (PGA) with 10% probability of exceedance during 50 years at a return period of 475 years. (a) Dutch PGA map (de Vos 2010, Fig.3.3). (b) Overlay of Dutch, German and Belgian PGA maps (see text for references) with warm/dark colours indicating elevated risk.

KNMI provided a contour polygon of the Dutch PGA map at 50 cm/s² (equivalent to 0.05 g; see Figure 2-2) that represents a seismic hazard threshold consistent with the Dutch Guideline for earthquake resilient construction of buildings in Groningen (KNMI Mar-2021, NEN 2020). This polygon serves as relevant probabilistic boundary for delineating the northern boundary of the Dutch LRVGA.

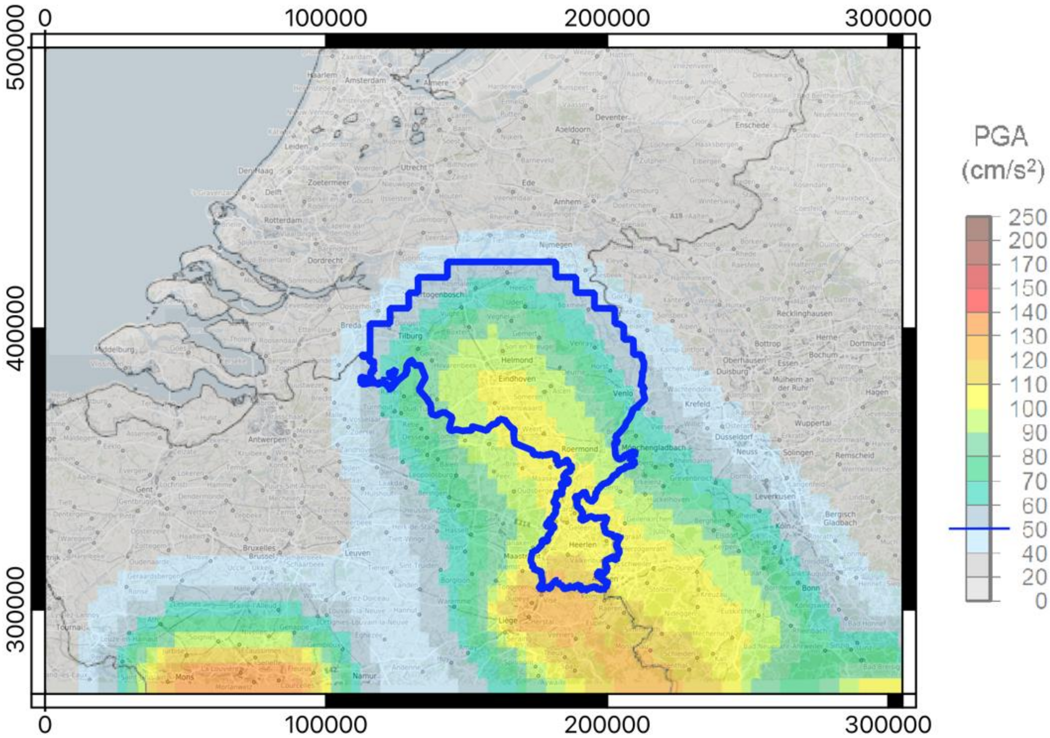


Figure 2-2: Polygon of PGA > 50 cm/s² (blue outline) based on the Dutch PGA map (de Vos 2010) shown in Figure 2-1 (KNMI Mar-2021). Note that the polygon is cropped to country borders.

2.2 EARTHQUAKE CATALOGUE

The original KNMI earthquake catalogue is split into 4 different databases (Table 2-1). 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). The merged modern (recorded) and also those historic (reported) events that came with coordinate attributes (courtesy of KNMI) were processed for basic statistical analysis in Excel, then loaded into QGIS for spatial analysis. Note that induced earthquakes were not detected/classified in the study area.

Table 2-1: Overview table of modern (recorded) and historic (reported) seismic events listed in the respective database files provided by KNMI. NL = Netherlands; RVG = Roer Valley Graben sensu Kombrink et al. (2012).

Record type:	**Recorded**				**Reported**
Event type:	Tectonic	Induced	Unclassified	Merged (modern) database	Historic
Source file:	KNMI_cat_1911 -2021_tect.csv	all_induced.csv	lijst-van-herziene -plaats.csv		KNMI_hist_seism _2021_annot.xlsx
Comment:	incl. events since Nov-2016		incl. more foreign stations (DE, LU, FR)		Some entries with-out coordinates
First entry:	May-1911	Dec-1986	May-1911	May-1911	1007
Last entry:	Jun-2021	Jun-2021	Nov-2016	Jun-2021	Sep-1911
No. entries:	1531	1756	5051	5667	111
No. unique:	616		2380		68
No. duplicates:	2671			0	n/a
Within NL:	471	1749	1733	2220	68
Within RVG:	202	0	182	202	15
Coordinates:	100%				77%

The merged database is discussed in the following paragraphs. Purpose of the discussion is to understand uncertainty and spatial variation, and to classify and filter earthquake data for the integrated map view in Section 2.3.

In the Roer Valley Graben, sensitivity of the seismicity monitoring system reached a first milestone in the late 1970s as can be inferred from the onset of a steady slope in the cumulative curve (blue) in Figure 2-3. The same curve indicates further improvements on the monitoring system following the swarm of seismic events associated with the Roermond Earthquake in April 1992, i.e. more events fall above the detection limit so that the slope of the cumulative curve becomes even steeper than in the preceding period from 1975 to 1992. Increase in the number of detected earthquakes is clearly related to improvements of the monitoring system.

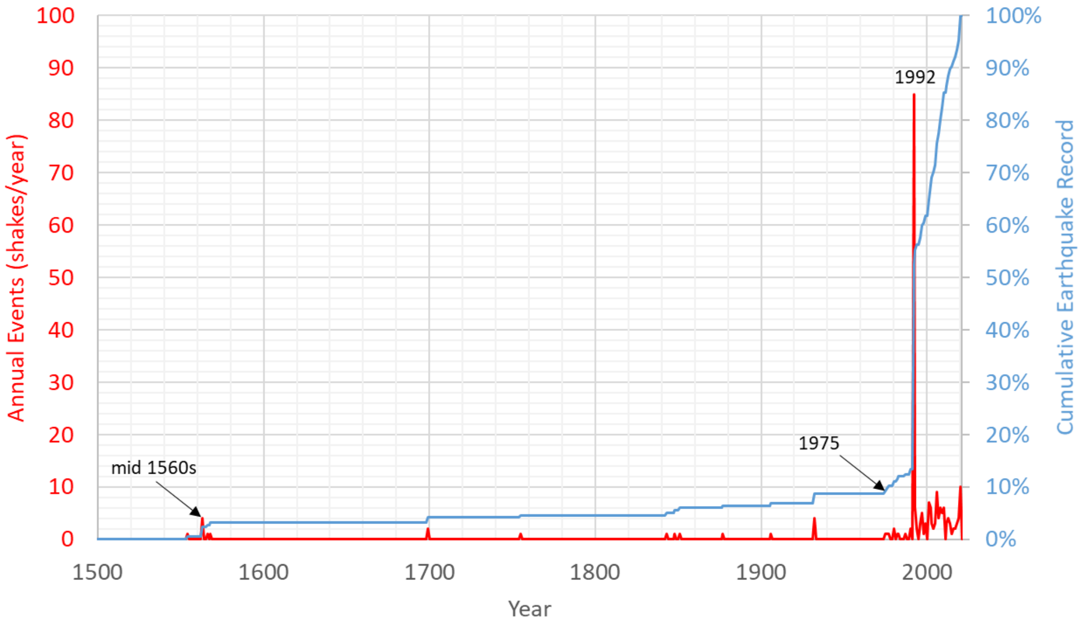


Figure 2-3: Timeline of seismic events reported (n = 15) and recorded (n = 202) in the Roer Valley Graben area sensu Kombrink et al. (2012). Note breaks in slope of cumulative curve (blue) in 1975 and 1992. See text for brief discussion.

With the intention to adequately reflect that sensitivity (detection threshold, seismic magnitude) and accuracy (hypocentre) of recorded events improved over time, it was decided to conduct the screening for systematics in depth, seismic magnitude and frequency on a subsample filtered for all events recorded in the Roer Valley Graben since the year 1980.

The magnitude versus depth plot in Figure 2-4 shows a funnel-like shape. Events shallower than 15km typically have a wider spread in magnitude (0.1 to 4) compared to deeper events (1 to 2.5). The downwards directed trend in gradual convergence of earthquake magnitude is strikingly symmetric within the lower crust (Yudistira, Paulssen and Trampert 2017) between 15 and 25km. The top of this depth window, i.e. near the top of the lower crust, coincides with the 5.8 magnitude “Roermond event” (near Linne) in April 1992 that represents a significant outlier from the funnel-like pattern described above. The histograms in Figure 2-4 indicate that most events fall into a depth range of 15-19km with a modal magnitude of just below 2.

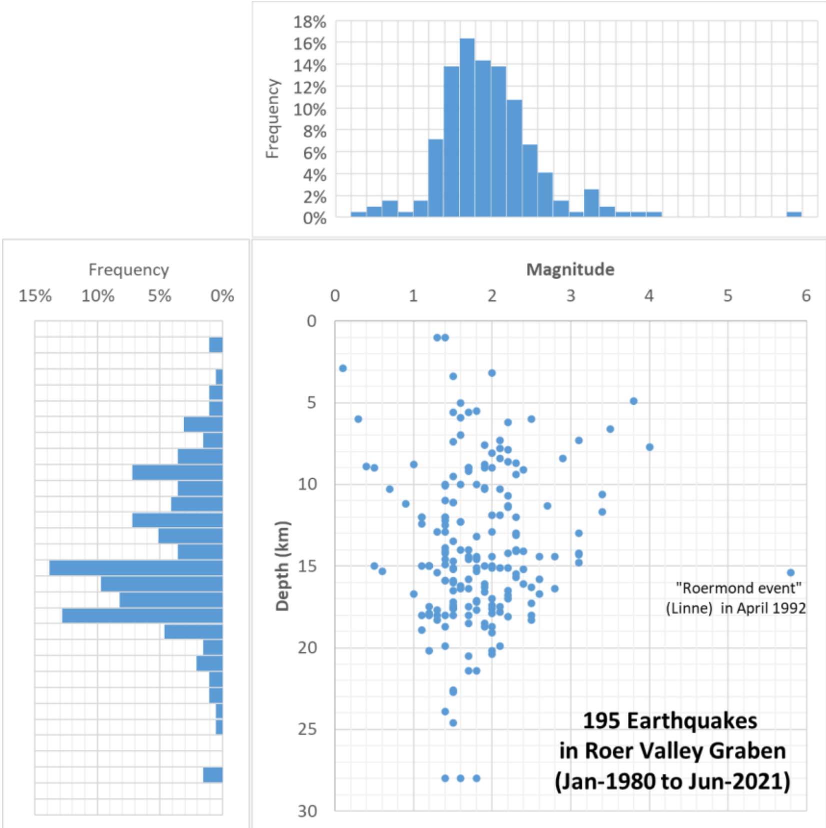


Figure 2-4: Distribution of tectonic earthquake magnitude versus depth in the Roer Valley Graben since 1980.

In the KNMI database, each seismic event is allocated to a location not only in terms of epicentre coordinates but also in terms of postal codes ("place" attribute). Though postal codes do not have any geological meaning, they do provide a useful spatial component that allows to investigate the frequency of earthquake in the RVG, such as in terms of magnitude and depth as displayed in Figure 2-5. The highest frequency of events in the Roer Valley Graben since 1980 occurred in Sint Odiliënberg (just south of Roermond) which is also quite representative in (average) depth and magnitude as inferred previously from Figure 2-4.

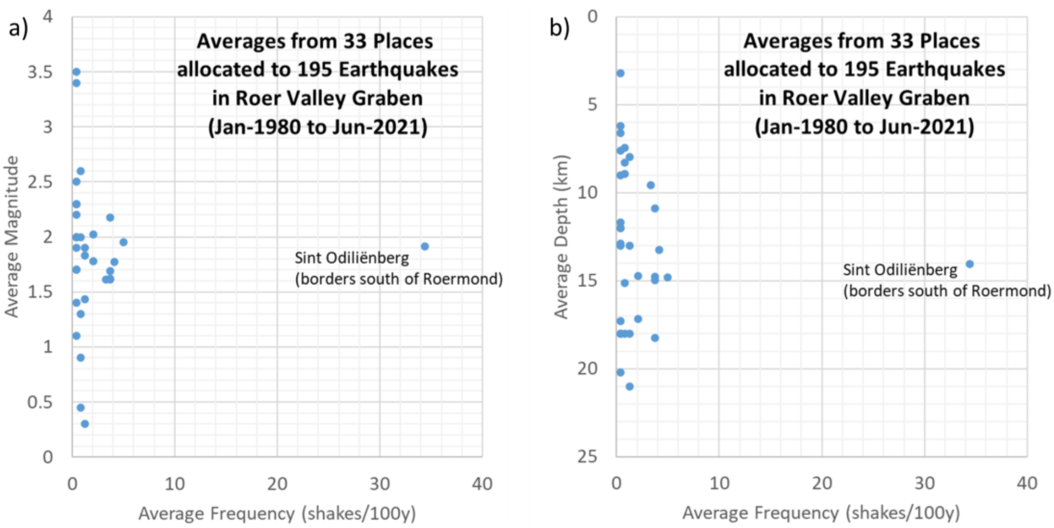


Figure 2-5: Frequency vs. (a) magnitude and (b) depth of seismicity in the Roer Valley Graben since 1980 per allocated "place".

In addition to the modern (recorded) database, KNMI kindly provided a work-in-progress table of the historic (reported) earthquakes (Houtgast 1990); see Table 2-1 for basic statistics. Here, reported events are currently under scrutiny in terms of location, false positives (e.g. gun shots, extraterritorial events etc.) and inferred magnitude. The current status of this work has been translated into a simplified scheme such as “recorded” (early 1990s), “probably real”, “probably fake” and “not classified”. These categories were used to complement the integrated map display in Chapter 2.3 (excl. some 23% of historic events that did not come with coordinates).

2.3 INTEGRATED MAP DISPLAY AND STRUCTURAL STYLE

An integrated map was compiled in QGIS. The following elements of interest were included:

- PGA maps and KNMI’s hazard polygon (see Chapter 2.1)
- KNMI earthquake catalogue (merged recorded and historic databases, see Chapter 2.2)
- Seismic-scale fault centre lines (level 1, DGM5, www.nlog.nl)
- Major fault system centre lines (level 3, GeoERA-HIKE, courtesy of TNO)
- Structural outline of the Roer Valley Graben (Kombrink, et al. 2012)
- Bouguer anomaly map (www.nlog.nl)
- Recently shot and reprocessed 2D seismic data (SCAN, www.nlog.nl)

The resulting map display in Figure 2-6 is discussed in the following paragraphs.

The Roer Valley Graben as a whole is characterised by a gravity low whereas its south-western and north-eastern structural boundaries *sensu* Kombrink et al. (2012) are defined by the centre lines of major fault zones (level 3).

Earthquakes in the Dutch part of the graben are concentrated in the wider Roermond area where seismic hypocenters are generally much deeper and earthquakes on average larger in magnitude compared to the south-western graben shoulder in the south of Limburg. In the central and north-western part of the study area earthquakes occur at a much lower spatial density and frequency compared to the wider Roermond area. One event was recorded south of Tilburg on the western graben shoulder, whereas most of the Peel-Maasbommel Complex, which borders the graben to the east, has seen sparse tectonic activity. Historical earthquakes predominantly occurred in the vicinity of events recorded since 1911. The PGA-derived seismic hazard polygon as defined in Chapter 2.1 encompasses all earthquakes except for those in the central north and north-eastern part of the Peel-Maasbommel Complex (Peel and Venlo Blocks).

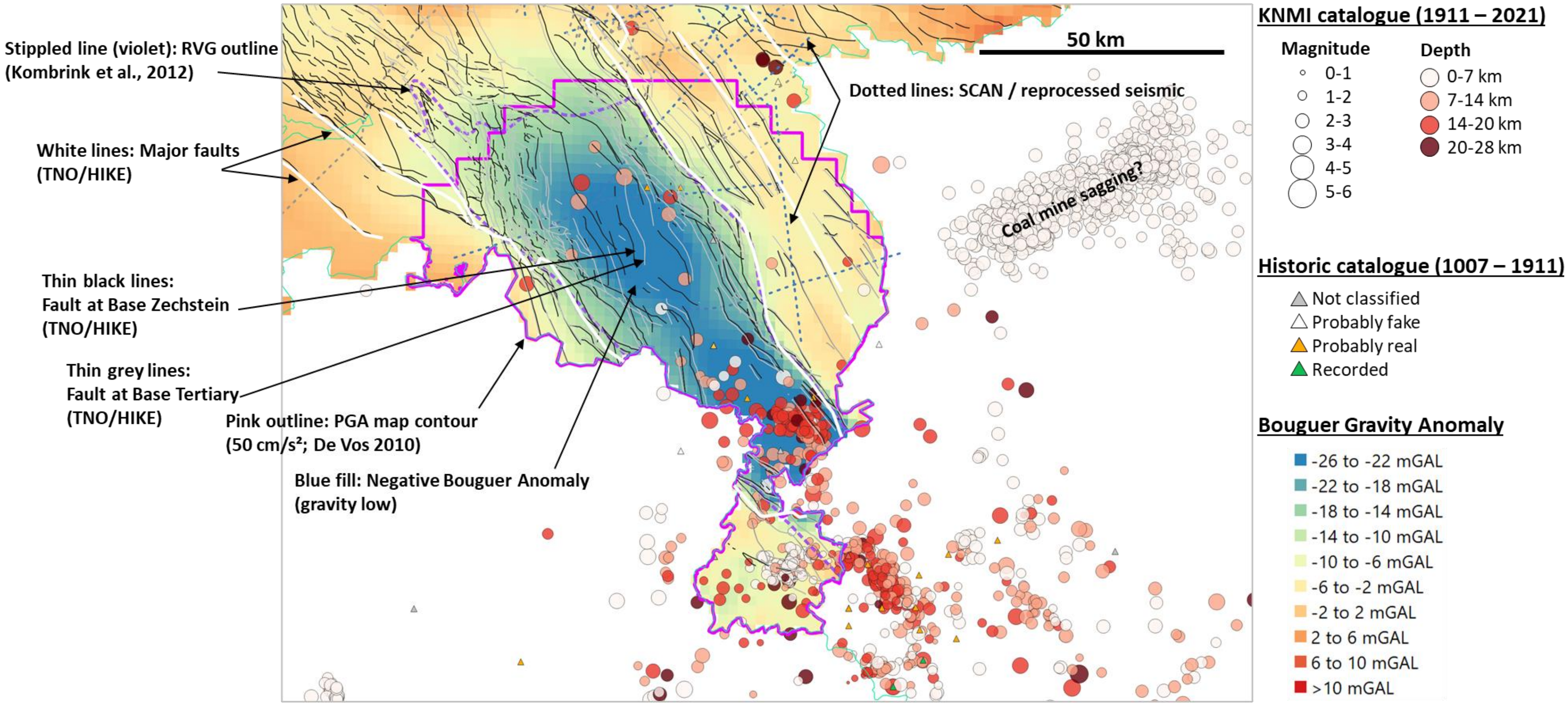


Figure 2-6: Composite map display of earthquakes, faults and relevant geophyiscal data in the greater Roer Valley Graben area. See text for discussion. The background map is the Bouguer gravity map, with blue colours indicating less gravity, thus thicker sedimentary record on top of deeply buried crystalline basement. The white lines are major faults from the TNO database.

Figure 2-7 offers a notional interpretation of the deep fault network in a transtensional tectonic regime. The mapped epicentre locations indicate that tectonic activity switches between the two major graben boundary faults that follow the north-eastern and south-western margins. The switch-overs must be accommodated by transfer fault zones that appear to be characterized by comparably less critical stress regimes (less earthquakes compared to deep boundary faults). The proposed deep-seated fault pattern is in agreement with the orientation and spatial arrangement of the overlying seismic-scale faults and it also matches the subtle detachment of two gravity lows along one of the inferred transfer faults in the central part of the graben (see spatial separation between the two darkest blue areas indicated in Figure 2-7).

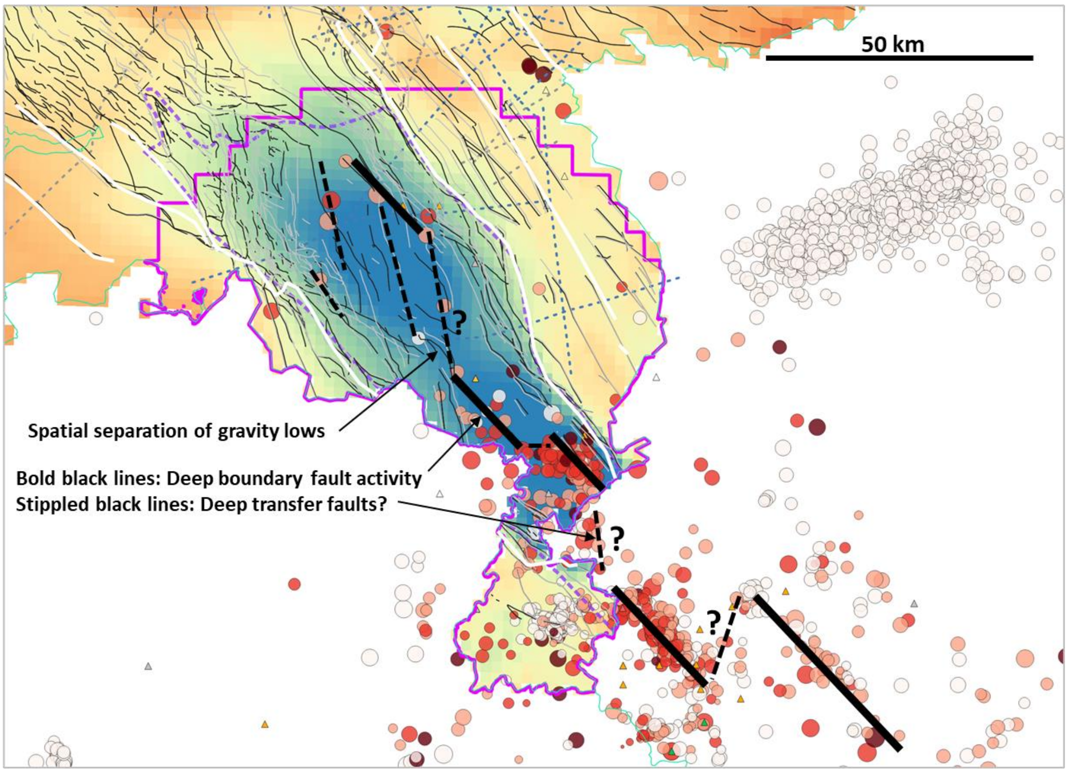


Figure 2-7: Notional interpretation of the deep-seated fault activity in the Roer Valley Graben. See Figure 2-6 for detailed legend.

2.4 SEISMIC CROSS-SECTIONS

Previous research in the Roer Valley Graben (RVG) supports the validity of relating deep earthquakes to relatively shallow (<5km) fault systems as mapped on seismic (Worum, et al. 2004). The displays of the seismic lines are limited to 3.5 to 6 seconds, which is equivalent to some 5 to 10 km depth. A selection of three profiles that are based on modern 2D seismic (SCAN) was scrutinized in an attempt to relate earthquakes to seismic-scale faults. Following the structural grain, earthquakes were carefully projected onto the profile lines from a maximum distance of 30-40km. The variation of the projection limit depends on transecting fault continuity and distance to neighbouring profile lines. Note that the hypocentre uncertainty is estimated at some 5-20km dependent on the state of the monitoring system at the time of each event (KNMI, pers. comm.).

Profile 1 in Figure 2-8 represents the longest line that runs from the western graben shoulder across the RVG and Peel-Maasbommel Complex (PMC) into the Central Netherlands Basin (CNB) to the east. Along this line, most earthquakes in the RVG area relate to the eastern graben boundary fault. Note additional seismic activity at the western boundary fault of the CNB, i.e. one earthquake central inside the PMC and another on the western graben shoulder.

Profile 2 in Figure 2-9 crosses the entire width of the RVG and also covers the shoulder areas on either side of the graben. Earthquakes with the largest magnitudes were detected in the central and eastern part of the RVG, only one or two seismic events relate to the western margin.

Profile 3 in Figure 2-10 represents the southernmost line that incorporates modern 2D seismic on its eastern side. Again, the eastern boundary fault of the RVG is significantly more active compared to the west and compared to the graben shoulders. The culmination of events within a ca. 30km wide zone along the inner western margin of the RVG indicate the downward extension of the complex boundary fault system seen on seismic. Most of these earthquakes relate to the Roermond area to the southeast of this profile line.

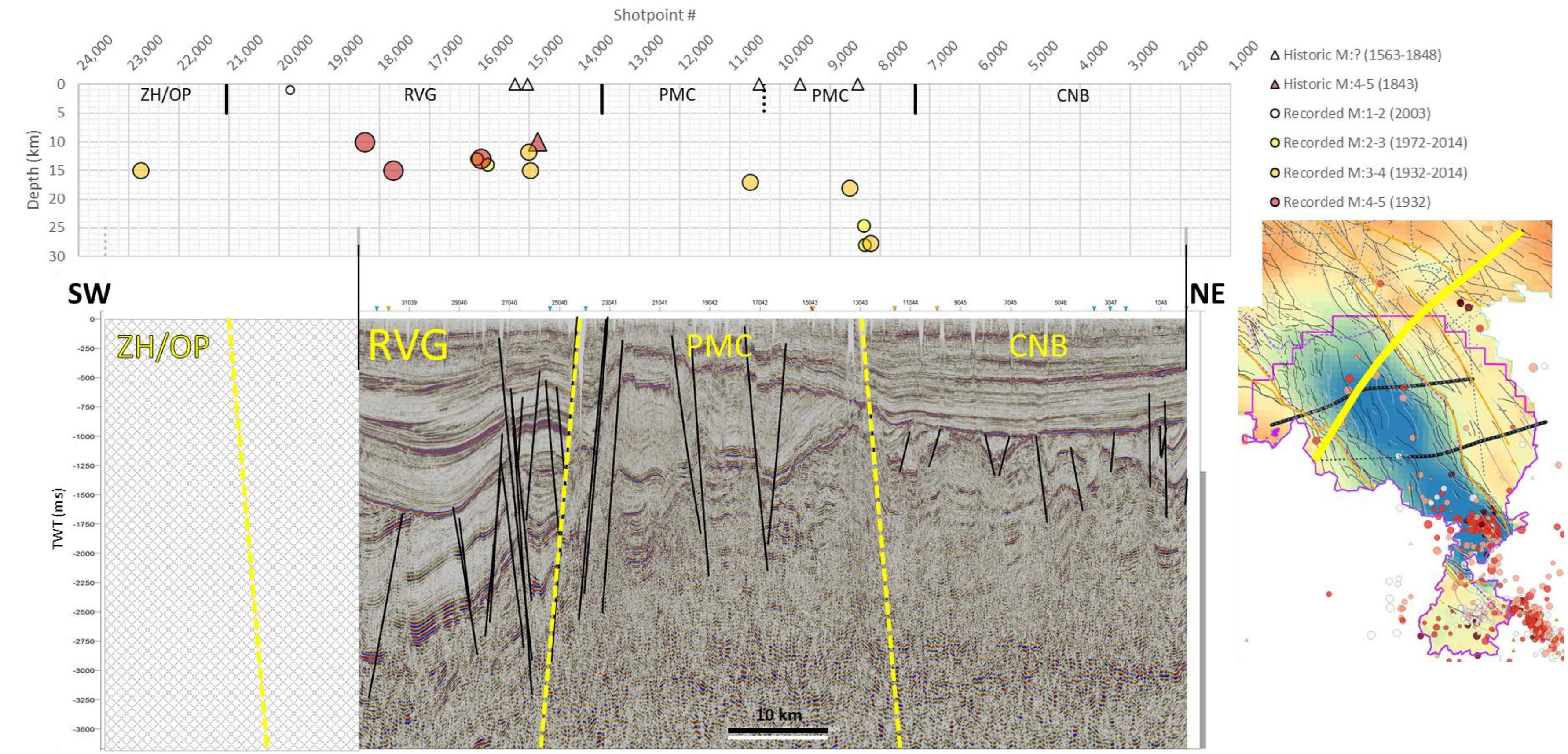


Figure 2-8: Profile 1 (SCAN line 2, extended to SW) with seismic line and projected earthquakes (max. 30km away). Main bounding faults that delineate the structural elements are marked as stippled yellow lines. Most earthquakes in the RVG area relate to the eastern graben boundary fault. Note additional seismic activity at the western boundary fault of the CNB, i.e. one earthquake central inside the PMC and another on the western graben shoulder (ZH/OP). RVG = Roer Valley Graben; ZH = Zeeland High; OP = Oosterhoud Platform; PMC = Peel-Maasbommel Complex (Peel block to the west, Venlo Block to the east); CNB = Central Netherlands Basin. Note that the seismic scale is in time, and 3500 msec TWT is probably in the order of 6-8 km depth, and shallower than the earthquake hypocentres.

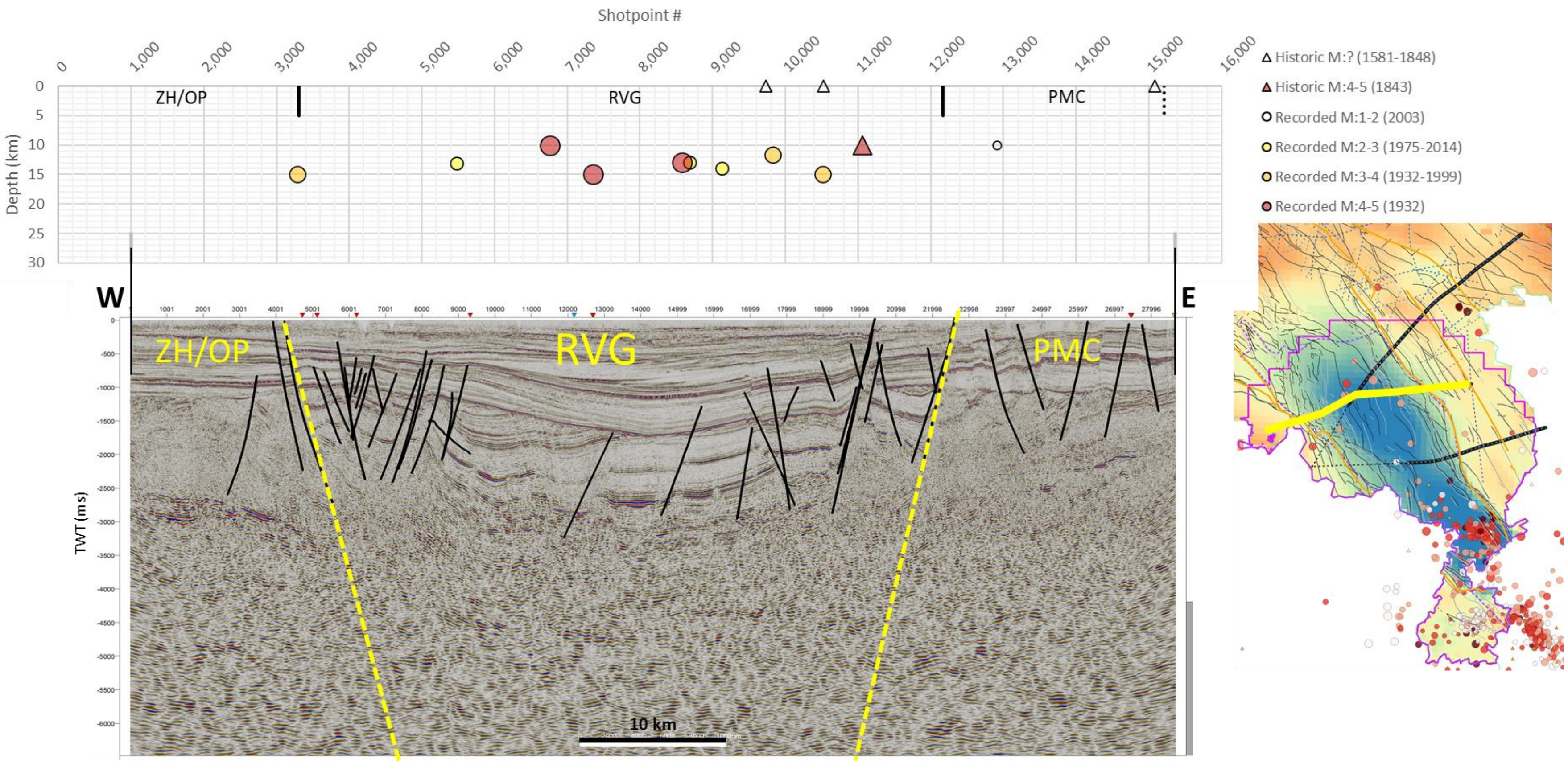


Figure 2-9: Profile 2 (SCAN line 17/18) with seismic line and projected earthquakes (max. 30km away). Main bounding faults that delineate the structural elements are marked as stippled yellow lines. Earthquakes with the largest magnitudes were detected in the central and eastern part of the RVG, only one or two seismic events relate to the western margin. RVG = Roer Valley Graben; ZH = Zeeland High; OP = Oosterhoud Platform; PMC = Peel-Maasbommel Complex (Peel block to the west, Venlo Block to the east); CNB = Central Netherlands Basin.

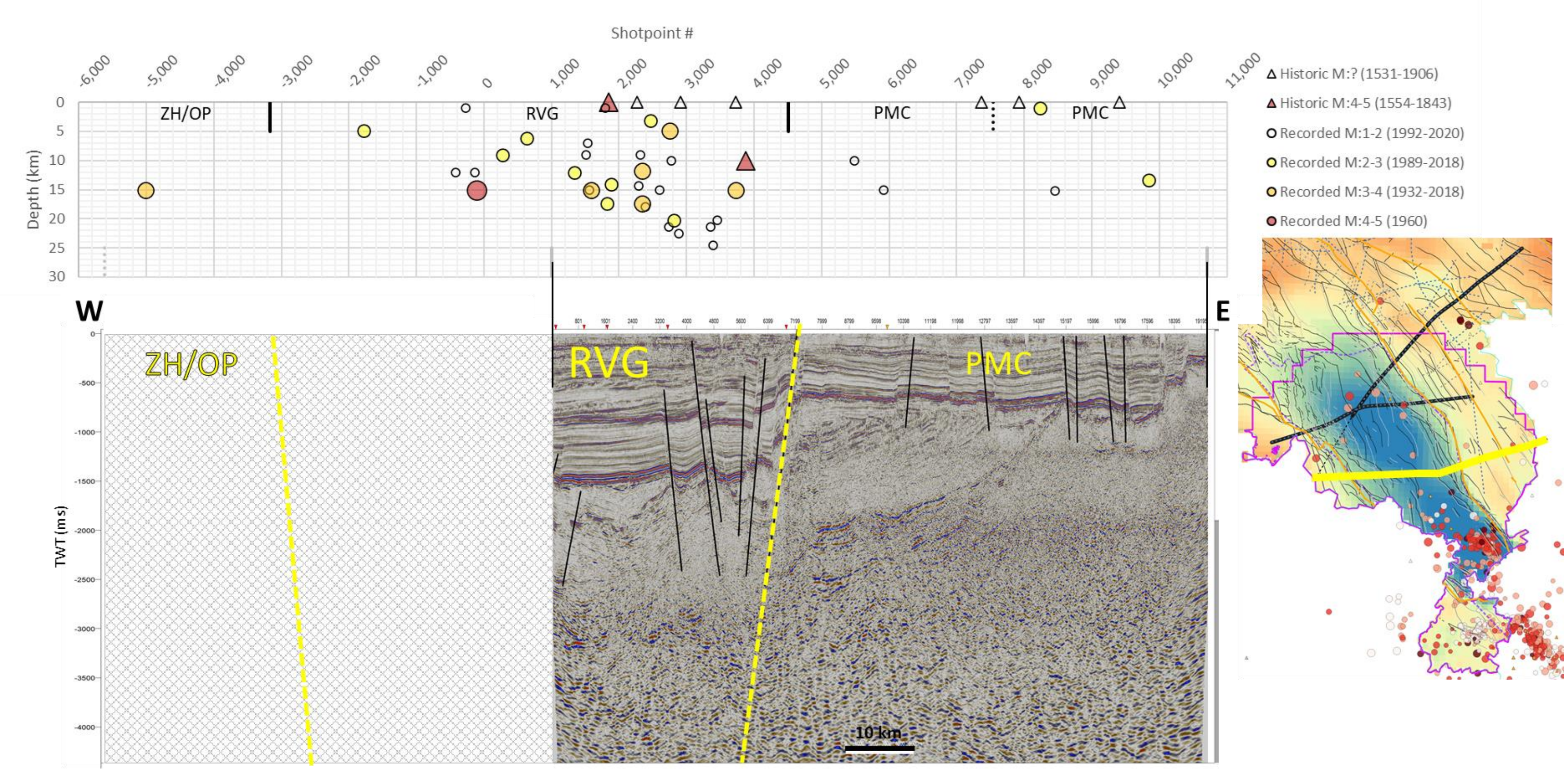


Figure 2-10: Profile 3 (SCAN line 29, extended to W) with seismic line and projected earthquakes (max. 40km away). Main bounding faults that delineate the structural elements are marked as stippled yellow lines. Again, the eastern boundary fault of the RVG is significantly more active compared to the west and compared to the graben shoulders. The culmination of events within a ca. 30km wide zone along the inner western margin of the RVG indicate the downward extension of the complex boundary fault system seen on seismic. RVG = Roer Valley Graben; ZH = Zeeland High; OP = Oosterhoud Platform; PMC = Peel-Maasbommel Complex (Peel block to the west, Venlo Block to the east); CNB = Central Netherlands Basin.

2.5 DEFINITION OF SEISMICALLY ACTIVE LRVGA

Given the data at hand and uncertainties involved, it was decided that the LRVGA outline should equally reflect upon all relevant information such as PGA-based seismic hazard polygon, occurrence of earthquakes and presence of seismic-scale fault centre lines at the Base of the Upper North Sea Group (Base NU). These shallow fault extensions were active in relatively recent geological times (few million years; see also (Boersma, Kwee en Leo 2021)) so that the proposed LRVGA outline is based on the combination of (1) most recent fault activity at shallow depth, (2) stressed basement as indicated by the record of deep earthquakes, and (3) threshold expectations in ground acceleration as indicated by the probabilistic geomechanical modeling of de Vos (2010).

The resulting polygon of the seismically active LRVGA is displayed in Figure 2-11 (blue outline). Most of the coloured polygon infill is bound by country borders in the west, south and east. The north-western boundary is defined by smoothing the PGA threshold polygon discussed in Chapter 0 (note that the ragged outline of this reference polygon represents cell size artifacts so that smoothing is indeed a valid procedure). The central northern boundary is drawn in such a way that it includes all the earthquakes recorded in the Peel-Maasbommel Complex while tracing the boundaries of this structural element (Kombrink, et al. 2012) to its narrowest point in the north-west.

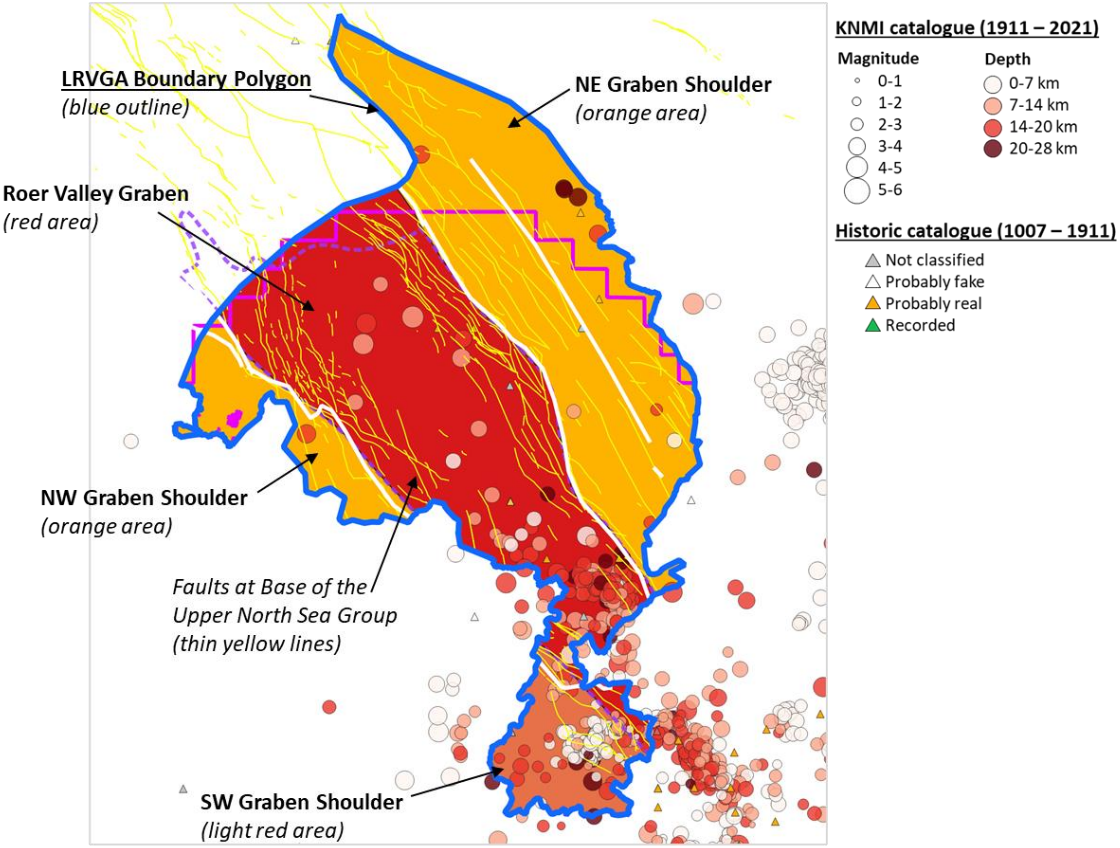


Figure 2-11: Composite map of the LRVGA (blue outline) with boundary polygon split into 4 sub-areas (red, light red, orange). Rationale of polygon definition is explained in the text. See Figure 2-6 for supplementary annotation of secondary map elements.

The LRVGA polygon in Figure 2-11 is dissected by the Roer Valley Graben outline as defined by Kombrink et al. (2012) and confirmed by TNO/HIKE in 2020, resulting in 4 different sub-areas that may be of use in further evaluations within the Seismic Hazard and Risk Analysis (SHRA) process.

The NW and NE graben shoulders (orange areas in Figure 2-11) are associated with less earthquake activity compared to the remainder of the LRVGA. Particularly the NW shoulder has seen least seismicity and deep-seated faults that reach into the Tertiary are relatively rare. The south of Limburg (light red area in Figure 2-11) has few faults in the

Tertiary because it thins out onto older rocks that are exposed at surface in the southwestern half of the area. In contrast to the proper Roer Valley Graben as defined by Kombrink et al. (2012; red area in Figure 2-11), earthquakes recorded in the south of Limburg are predominantly shallow (<7km), and we can only speculate to what extent tremors from coal mine sagging are involved in triggering seismicity (compare to German Ruhr area in Figure 2-6) because none of these events were classified as such in the KNMI database.

As indicated above, more detailed differentiation of the 4 sub-areas of the LRVGA is possible with respect to the presence of Tertiary faults. The theory is that critically stressed faults are active in recent geological times and hence have an expression at surface or, more conservative, at the Base Upper North Sea. Figure 2-11 shows the faults at Base Upper North Sea level (equiv. Base Tertiary), which are concentrated on the RVG boundary faults and on the NE and NW graben shoulders. Centrally in the northern part of the RVG, there appear much less faults offsetting the Base Tertiary. This might present the option to define geothermal projects within the North Sea Group away from faults. Below the Tertiary, however, the fault density is expected to be much higher so that the risk of connections to stressed fault segments persists.

3 Conclusions & Recommendations

3.1 SEISMICALLY ACTIVE LARGER ROER VALLEY GRABEN AREA

The presented workflow for delineation of the seismically active Larger Roer Valley Graben Area (LRVGA) takes into consideration all presently available data that relate to expected peak ground acceleration (PGA), the spatial distribution and magnitude of past seismic events, geophysical information from the gravity field and from key seismic lines, and the orientation and spatial arrangement of the current fault interpretation at the base of the Upper North Sea Group.

Most of the LRVGA in Figure 2-11 is readily bound by country borders because it is clipped to the outline of The Netherlands. Domestic boundaries in the north-eastern and central northern part of the study area are effectively delineated from a combination of PGA threshold and major fault zones such that the LRVGA polygon encompasses the entire record of tectonic earthquakes as an indicator for critically stressed basement in this part of the Netherlands.

Results of this work package complement the fault buffer zones presented in (Boersma, Kwee en Leo 2021).

3.2 FUTURE UPDATES

The LRVGA polygon will need to be updated in the future when (significant) new data and/or revised seismicity models become available.

It is recommended to introduce regular (e.g. annual) screenings for new earthquakes that fall outside the current definition of the LRVGA. The same recommendation holds for released updates in the historic (pre-industrial) event database that is currently under revision by KNMI. In addition, the findings of this report must be reflected upon future updates of the PGA map such as currently executed by KNMI.

Once the structural interpretation of recently acquired and reprocessed 2D seismic lines is incorporated in future issues of the national Digital Geological Model (e.g. DGM6), delineation and continuity of seismic-scale faults that extend into the shallow overburden should be updated and their current absence along the central and north-western leg of the graben axis as displayed in Figure 2-11 should be validated. Confirmed absence of shallow faults in this area could potentially indicate somewhat lower risk of induced seismicity compared to the graben boundary zones and shoulder regions.

Digital files and software projects for future validation and updates are enclosed with this report (see Chapter 5).

4 References

Boersma, Q., J. Kwee, en C. Leo. *Seismic Hazard Screening (SHS): Relevant major fault zones.* TNO-AGE & EBN, 2021.

de Vos, D. *Probabilisitic Seismic Hazard Assessment for the Southern part of the Netherlands (MSc thesis).* Utrecht: Utrecht University, 2010, 58.

Grünthal, G., D. Stromeyer, C. Bosse, F. Cotton, en D. Bindi. „The probabilistic seismic hazard assessment of Germany—version 2016, considering the range of epistemic uncertainties and aleatory variability.” *Bull Earthquake Eng* 16 (2018): 4339–4395.

Houtgast, G. *Aardbevingen in Nederland - Catalogus van aardbevingen tm 1990.* De Bilt: KNMI (publicatie 179), 1990, 166.

IF Technology & Q-Con. „Defining the Framework for Seismic Hazard Assessment in Geothermal Projects 5 V0.1.” 2016.

KNMI. *Earthquake Catalogue.* De Bilt, Utrecht, 24 June Jun-2021.

KNMI. *Seismic Hazard Polygon.* Memo, De Bilt: KNMI, Mar-2021, 2.

Kombrink, H., et al. „New insights into the geological structure of the Netherlands; results of a detailed mapping project.” *Netherlands Journal Geoscience, Geologie en Mijnbouw* 91 (2012): 419-446.

Leynaud, D., D. Jongmans, H. Teerlynck, en T. Camelbeeck. „Seismic hazard assessment in Belgium.” *Geologica Belgica* 3, nr. 1-2 (2000): 67-86.

Mijnlieff, H., en B. Jaarsma. *Voorstel voor aanpassing van de methodiek voor screening van seismiciteitsdreiging biy geothermie - Finale versie Februari 2021.* Utrecht: TNO-AGE & EBN, 2021, 38.

NEN. *NPR 9998:2020 – Beoordeling van de constructieve veiligheid van een gebouw bij nieuwbouw, verbouw en afkeuren – Geïnduceerde aardbevingen – Grondslagen, belastingen en weerstanden.* Nederlandse praktijkrichtlijn, Delft: Nederlands Normalisatie Instituut, 2020.

Worum, G., J.-D. van Wees, G. Bada, R. T. van Balen, S. Cloetingh, en H. Pagnier. „Slip tendency analysis as a tool to constrain fault reactivation: A numerical approach applied to three-dimensional fault models in the Roer Valley rift system (southeast Netherlands).” *Journal of Geophysical Research* 109, nr. B02401 (2004): 1-16.

Yudistira, T., H. Paulssen, en J. Trampert. „The crustal structure beneath The Netherlands derived from ambient seismic noise.” *Tectonophysics* 721 (2017): 361-371.

5 List of Enclosures

- QGIS project and file repository (shapefiles, grids, geotifs)
- Excel project with (merged) KNMI Earthquake database
- Coordinate listings LRVGA polygon