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Seismotectonic zones for probabilistic seismic-hazard assessment in Belgium

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Integration module

During the current project phase of the disposal of category A waste – short-lived low and intermediate level waste – ONDRAF/NIRAS must, following the governmental decision of 23 June 2006, develop a near surface disposal facility in Dessel, which is based on the near surface facility disposal design developed by the stola-Dessel partnership during the previous preliminary project phase.

The seismic risk is taken into account by designing the different structures of the disposal facility in such a manner that they can resist to a reference earthquake. This reference earthquake – expressed in terms of magnitude and spectrum – is determined by means of a probabilistic seismic hazard assessment (PSHA). The methodologies for conducting the PSHA and for the determination of the seismic loads on the disposal structures are described in the document "Generic methodology for the seismic loading definition on structures" (NIROND-TR-2009-10, April 2009).

A first input to the PSHA is the determination of seismic source zones, each characterized by an evaluated expected maximal magnitude.

Another input to the PSHA is the site-specific transfer function between the earthquake spectrum at bedrock level and the spectrum on the surface. This transfer function is obtained through a combination of site-specific experimental data and modeling concerning the behaviour of seismic waves in the cover layers. The site-specific data are obtained by means of a site characterization campaign during the current project phase. The data are obtained through seismometers installed at Cretaceous and Boom Clay level and on surface in the immediate vicinity of the disposal site .

Although in the past several seismic source zones studies were performed for Belgium, the exercise was redone based on a combination of geologic, tectonic and seismicity data. In order to create a broader basis for the determination of the zones, two key figures of Belgian geology were involved : Prof. N. Vandenberghe and Dr. M. Dusar. In this exercise, we end up with two models : the more classic approach where 14 different seismic source zones are defined, and an alternative model composed of only two zones (an "active" Roer Valley Graben and the more passive rest of the region concerned).

This report deals with the determination of the seismic source zones. It provides the argumentation for the division of the region into the 14 seismic source zones, and gives a detailed overview of the characteristics of each zone, e.g. the choice of the limits of the zone, information about the instrumental and historical seismicity and the tectonic setting.

Module d’intégration

Au cours de la phase actuelle de projet de dépôt de déchets de catégorie A – des déchets de courte demi-vie de faible et de moyenne activités – l’ONDRAF/NIRAS doit, suivant la décision gouvernementale du 23 Juin 2006, développer une installation de stockage proche de la surface à Dessel, lequel est basé sur le design de l’installation de stockage de surface développé par le partenariat STOLA-Dessel au cours de la phase précédente qualifiée de préliminaire.

L’aléa sismique est pris en compte en adaptant le design des différents structures de l’installation de dépôt de manière à ce qu’elles résistent à une tremblement de terre de référence. Ce tremblement de terre de référence – exprimé en terme d’amplitude et de spectre- est déterminé par une évaluation probabiliste de l’aléa séismique (PSHA). Les méthodologies suivies dans cette évaluation probabiliste pour la détermination des charges séismiques sur les structures de dépôt sont décrites dans le document « Generic methodology for the seismic loading definition on structures” (NIROND-TR 2009-10, April 2009).

Une première entrée au PSHA est la détermination de zones sources de séismes, chacune caractérisée par valeur évalué de l’amplitude maximale attendue.

Une autre entrée au PSHA est la fonction de transfert du site entre le spectre du séisme au niveau du substratum et le spectre à la surface. Cette fonction de transfert est obtenue par une combinaison de données expérimentales obtenues sur site et de modèles servant à déterminer le comportement des ondes séismiques dans les couches de couverture. Les données expérimentales sont obtenues lors de la phase de projet actuel qui consiste en une caractérisation de terrain. Elles sont enregistrées par des séismomètres installés au niveau du Crétacé et de l’Argile de Boom ainsi qu’en surface, à proximité du site de dépôt.

Ce rapport traite de la détermination des zones sources des séismes. Il fournit l’argumentaire permettant la subdivision de la région en 14 zones sources de séismes et donne également un aperçu détaillé des caractéristiques de chaque zone, e.g. le choix des limites de zone, des informations sur la séismicité instrumentale et historique et sur le contexte tectonique.

Integratiemodule

Tijdens de huidige ontwerpfase voor de berging van categorie A afval – dit is kortlevend laag- en middelactief afval – moet NIRAS, in navolging van de regeringsbeslissing van 23 juni 2006, een oppervlaktebergingsinstallatie in Dessel ontwikkelen, gebaseerd op het ontwerp ontwikkeld door het partnerschap stola-Dessel tijdens de voorontwerpfase.

Het aardbevingsrisico wordt in rekening gebracht door de verschillende structuren van de bergingsinstallatie zodanig te ontwerpen dat ze een referentie-aardbeving kunnen weerstaan. Deze referentie-aardbeving, -gekenmerkt door een grootte en een spectrum,- wordt bepaald aan de hand van een probabilistische seismische risicobeoordeling (PSHA). De methodologiën om een PSHA uit te voeren en om de seismische belasting op de bergingsinstallatie te bepalen zijn beschreven in het document "Generic methodology for the seismic loading definition on structures" (NIROND-TR 2009-10, April 2009).

Een eerste gegeven dat nodig is voor een PSHA is de bepaling van de seismische bronzonering, waarbij elke zone gekenmerkt wordt door een geëvalueerd te verwachten maximale aardbevingsgrootte

Een ander invoergegeven voor een PSHA betreft de site-specifieke transferfunctie tussen het aardbevingsspectrum ter hoogte van de "sokkel" en die aan de oppervlakte. Deze transferfunctie wordt bekomen door middel van een combinatie van site-specifieke experimentele gegevens en modelleringen betreffende het gedrag van de seismische golven in de deklagen. De site-specifieke gegevens worden verworven aan de hand van een terreinverkenningscampagne tijdens de projectfase. De nodige gegevens worden bekomen via seismometers geïnstalleerd op het niveau van het Krijt en de Boomse Klei, en aan de oppervlakte in de onmiddellijke omgeving van de bergingssite

Alhoewel in het verleden verschillende zoneringsstudies ter bepaling van seismische brongebieden werden verricht voor België, werd de oefening herdaan op basis van een combinatie van geologische, tectonische en seismische gegevens. Om een breder draagvlak te bekomen bij de afbakening van de zones, werden twee sleutelfiguren van de Belgische geologie betrokken : Prof. N. Vandenberghe en Dr. M. Dusar. Via deze oefening werden twee modellen bekomen: met de meer klassieke benadering werden 14 verschillende zones gedefinieerd, een alternatief model omvat enkel twee zones (de "actieve" Roerdal Slenk en het overige meer passieve deel van de beschouwde regio).

Dit document behandelt de bepaling van de verschillende seismische bronzones. Het beschrijft de argumenten voor de onderverdeling van de beschouwde regio in de 14 zones, en geeft een gedetailleerd overzicht weer van de karakteristieken van elke zone, zoals daar zijn de keuze voor de zonegrenzen, informatie over de instrumentele en historische seismiciteit en het tektonisch kader.

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0 Introduction

Belgium and the rest of NW Europe are located in an intraplate region marked by low tectonic deformation rates and relatively low seismic activity (Figure 2 & Figure 3). The seismicity distribution is both spatially and temporally diffuse. The only exception is the Roer Valley Graben which has a higher and more continuous seismic activity. Due to the low deformation rates it is very difficult to locate and characterise the active faults in the present stress field. Because of this lack of knowledge it is still impossible to perform deterministic hazard calculations with faults as seismic sources. However we can do probabilistic seismic-hazard assessments which are based on seismic source zones in which the seismicity is considered to be homogeneously distributed and for which the activity rate is calculated from statistical analysis of the instrumental and historical earthquake catalogue. The areal extent of these zones could be based on seismicity alone (seismic zonation), or on a combination of geologic, tectonic and seismicity data (seismotectonic zonation). In this report we present our definition of seismotectonic zones for Belgium and the surrounding region that may have a seismic impact in Belgium. First we will present a short history of seismic source-zone models used in previous probabilistic seismic-hazard assessments in our regions.

1 History

There are several previous seismic source-zone models that are also to some degree based on geologic and tectonic data (Figure 1). In the course of the Global Seismic Hazard Assessment Program (GSHAP; [38]), the working group for region 3: North and Northwest Europe published a report ([41] & http://www.seismo.ethz.ch/gshap/ceurope/report.html) compiling the contributions of different large countries (not including Belgium) of North and Northwest Europe in order to set up a seismic source-zone model partly based on geologic data. However, it is still mainly based on the distribution of instrumental seismic activity.

In 2004, the European normative document for building projects in seismic zones was ratified as Eurocode-8 (EN 1998, "Design of structures for earthquake resistance"). To be valid and applicable at national level this EC-8 document needed an additional National Application Document or "NAD". The Belgian NAD of 2002, known as "NBN-ENV 1998-1-1: 2002. NAD-E/N/F" was used for that purpose. A new version of the latter, called National Annexe, is being prepared. The seismic zonation in this NAD was based on probabilistic seismic-hazard calculations by Leynaud et al. [50] , more in particular using their Model 2 seismic source-zone model (Figure 1). The zones in this model have been defined mainly based on earthquake epicentre distribution, but also on geological and geophysical data about the limits of the crustal blocks. This seismic source-zone model consists of 9 zones that cover a large part of the Belgian territory and a limited zone around it, and an additional background zone covering the rest of the area.

The Seismological Station Bensberg, Cologne University also made a seismic source-zone model (Klaus Hinzen, personal communication). This model is also mainly based on earthquake epicentre distribution, but also includes geologic and tectonic information on the German territory.

There seems to be a gradual shift to include more geologic knowledge in the zone definition, especially for smaller scale and more detailed investigations.

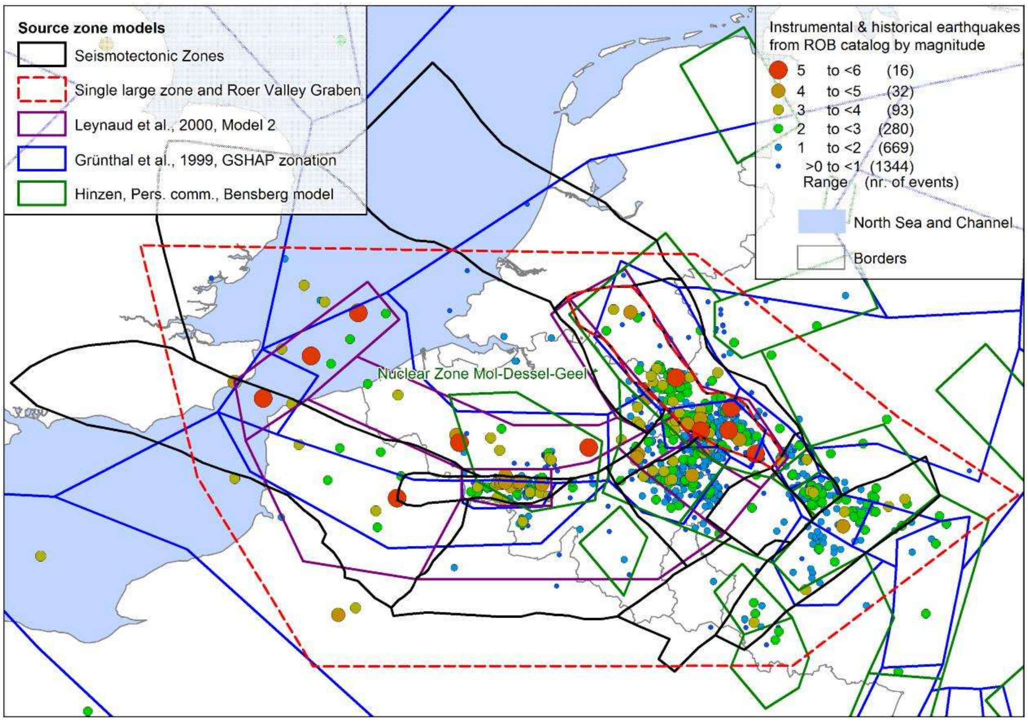

Figure 1 - Different seismic source-zone models and the epicentre and magnitude distribution of the real earthquakes in the ROB catalogue

2 A new seismotectonic model for Belgium

A seismotectonic zone is an area with a certain geological, geophysical and seismological homogeneity within which a uniform occurrence of earthquakes can be supposed. The distinction of the zones is based on all available geologic, tectonic, geophysical and seismological data, namely:

- Seismicity (depth, focal mechanism, frequency, magnitude, ...) (Figure 2 & Figure 3);
- Stress field;
- Geological structure (Figure 5);
- Geophysical properties (Bouguer anomaly map (Figure 7), aeromagnetic map (Figure 8), S-wave velocity perturbation (Figure 9),...);
- Fault type and orientation (Figure 6);
- Geomorphology (Figure 4);
- ...

In a region with sparse and diffuse seismicity, the inclusion of geological and geophysical data in the definition of seismic source zones allows for a finer and more realistic zonation than just drawing zones around clusters of observed seismicity. The choice of the zone boundaries can be better described and referenced using the geological literature and possible alternatives can be discussed (Figure 10). Seismotectonic zones can be viewed as the crustal blocks within the present day stress field. When the limit between two zones is defined by a fault, a choice has to be made which zone that fault belongs to. In those cases, we took care to draw the zone limit some km from the actual fault trace at the surface and on the footwall side of the fault so that the surface projection of the fault at seismogenic depth is entirely within a specific zone. These cases are discussed in the descriptions of the zone boundaries. As the choice of the number of zones and their exact limits is slightly subjective, two external experts were consulted: Prof. Noël Vandenberghe (KULeuven - Earth- and Environmental Sciences) and Dr. Michiel Dusar (Geological Survey of Belgium). Our initial model was adapted according to their opinions. In the following chapter, we give the motivations for establishing and delimiting the seismotectonic zones. The final model has 14 zones that cover the whole of Belgium and a considerable area around it, in order to include all earthquakes that can have an impact on Belgian territory, and more specifically on the nuclear zone of Mol-Dessel (Figure 11).

For each source zone the maximum magnitude has been evaluated, based on the following criteria:

- Magnitude indicated by paleoseismic studies for zones where such data are available;
- Magnitude of the largest historical earthquake for zones where large historical earthquakes have occurred, but where no geological evidence has been found for large active faults;
- Magnitude of the largest earthquake in the historical and instrumental record increased by 0.5 magnitude units for all other zones.

2.1 Zone 1 – Anglo-Brabant Massif

This zone contains the Brabant Massif [49] [25] and the Anglia Basin of the Anglo-Brabant deformation belt. It is a tectonic block of Caledonian age. The part of the Campine basin west of the Lower Rhine Graben is also included in this zone because the faults there seem to have been inactive in the recent geological history.

Zone boundaries

- The northern limit was fixed just south of a gravimetric lineament, separating higher Bouguer anomalies to the south (thought to be typical of the Brabant Massif) from lower Bouguer anomalies to the north (belonging to the West Netherlands Basin). This limit more or less corresponds to the outline of the Anglo-Brabant Massif in a publication of Van Grootel et al. [70] , and runs from the north-western tip of the Dutch province Noord-Brabant through the Southern Bight of the North Sea. At the English coast the limit changes to a more EW direction at the limit between the Anglo-Brabant Massif and the Eastern England Caledonides. This is also a limit in degree of metamorphism [70] and a gravimetric and magnetic anomaly [48] .
- The eastern limit was put about 2 km west of the Beringen Fault [52] and the Stotert Fault [43] , connected to the fault west of Ravels [26] and continued to the NNW along a gentle gravimetric gradient. These faults more or less correspond to the westernmost border faults of the Lower Rhine Graben system. Although Van Baelen & Sintubin [68] found no evidence for the continuation toward the surface of the Beringen Fault (a Paleozoic fault known from coal mining), all mapping shows systematic displacements in the vicinity of this fault (N. Vandenberghe, pers. comm..), while the distribution of mining subsidence also suggests reactivation of this fault (M. Dusar, pers. comm..). Alternatively, we could use the outline of the Rauw and Poppel faults which are characterized by a higher horizontal gradient of Bouguer anomaly.
- The southern border of the Brabant Massif is characterized by a pronounced gravimetric high. We put the limit just south of this high, which more or less corresponds to the position of the Bordière fault. In the north of France, this limit becomes less clear and the gravimetric high grades into a gravimetric low (interpreted as a granitic batholith or basin)
- The western limit was drawn at the limit between the Anglo-Brabant Massif and the Midlands Microcraton as drawn by Van Grootel et al. [70] . This limit corresponds to both a gravimetric and a magnetic lineament [48] . The Midlands Microcraton is less folded and has a lower degree of metamorphism than the Brabant Massif.

We did not define a separate zone for the Dover Strait as did Leynaud et al. [50] and Grünthal et al. [41] because this was based on a supposed NE-SW trending fault zone or graben structure in the English Channel [18] . The available data do not show evidence of a "Zone Faillée du Pas-de-Calais". The existence of such a structure has also been put to question, and alternative theories for the opening of the English Channel have emerged without the need for a graben [71] [67] .

Alternative proposals could be made to delineate the zone, or even to subdivide it further. In the North Sea, [48] identified a prominent aeromagnetic lineament extending from the coast near Dunkerque towards the NNW. High magnetic anomalies attributed to the Tubize

Formation to the east abruptly stop against this lineament. There is also a gravimetric anomaly with the same orientation, but it is situated 10 to 20 km to the west. On land, the Gravellines fault on the map of Legrand [49] has a similar orientation, but the existence of this fault is contested. If this structure is indeed a fault, then the different positions of the gravimetric and aeromagnetic lineaments indicate that it is probably a low-angle fault. In any case, the relevance of this structure in the current seismotectonic frame is unclear, and we see no reason to draw a zone boundary here. Likewise, we did not find arguments for the “Antwerp - Saint Hubert lineament” [15] in the Brabant Massif, although this lineament is clear in the Ardennes. Another alternative would be to separate the Campine Basin from the Anglo-Brabant Massif. The boundary is situated near a NW-SE oriented Variscan fault system (Nijlen-Hoboken fault, Nijlen hinge line). Although this fault displaces Cretaceous sediments (e.g. [30]), there is no reason to create a separate zone for the Campine Basin, due to the absence of seismicity in this area. Finally, focal mechanisms suggest a possible connection between the easternmost part of this zone and the southern part of the Eastern Campine Zone, which are both characterized by nearly E-W oriented normal faulting.

Instrumental seismicity

The Anglo-Brabant Massif has a moderate seismic activity that is more concentrated around its southern rim. In the first half of the 20th century some earthquakes occurred to the west of Brussels. The largest of these occurred in Zulzeke-Nukerke (near Oudenaarde) on 11 June 1938. With magnitude M_L=5.6 (M_S=5.0), it is the largest earthquake to date on Belgian territory since the start of instrumental recordings at the beginning of the 20th century. Another earthquake, with M_L=4.5, struck Le Roeulx, SSW of Brussels, on 20/06/1995. This event was located at the boundary with the zone of the Mons-Orchies Basin, but its large depth is very unusual for earthquakes in that zone, whereas its focal mechanism (reverse faulting oriented NNE-SSW) corresponds to the orientation of basement faults drawn on subcrop maps of the Anglo-Brabant Massif [49] & [25] . From July to October 2008, a seismic sequence occurred in the area of Court-Saint-Etienne and Ottignies, consisting of ~75 small earthquakes, the largest one with M_L=3.2. Earlier in the 20th century, between 1953 and 1957, the same area experienced a similar sequence, with at least three earthquakes that reached magnitudes (M_L) between 3 and 4.

In the northern part of the region, on Belgian or Dutch territory, there have only been four small earthquakes with maximum magnitude M_L=1.9. On United Kingdom territory the British Geological Survey earthquake catalogue (available online via http://www.earthquakes.bgs.ac.uk) mentions some earthquakes up to magnitude M_L=4.0 in the north of this zone. The ROB catalogue is probably incomplete in this zone because the distance to our seismometers is too large to record and precisely locate these events.

Seismic activity also continues beneath the North Sea. Several earthquakes have been recorded since 1985, with magnitudes up to M_L=3.4. Before 1985, no instrumental events were detected, but this might also be due to the detection limit of our seismic network: the lower magnitude for which our catalogue is considered to be complete is c. 3.0 for the period 1960-1985, and c. 4.0 for the period before.

For some of the instrumental earthquakes, the depth could be determined. These vary between 3 and 19 km. However, the Le Roeulx, 1995 earthquake occurred at a depth of ~24 km, which indicates that the seismogenic zone is relatively thick and might be able to generate larger earthquakes.

Historical seismicity

The only historical earthquake known on Belgian territory in this zone happened near Orp-Jauche, in the east of the province of Brabant Wallon, on 23 February 1828. Its magnitude is estimated at M_L ~ 4.5-5.0. Two larger earthquakes occurred in the North Sea, one on 21 May 1382 and another on 23 April 1449. The magnitudes have been estimated at M_S ~ 6.0 and M_S ~ 5.5, respectively.

Further west on United Kingdom territory, there has been an earthquake near Colchester on 22 April 1884. In the ROB catalogue, the magnitude of this event is undetermined, but the maximum intensity1 is reported to be VIII (EMS-98). The BGS catalogue however attributes a magnitude of 4.6 to this event. This catalogue mentions four other historical earthquakes in this zone with magnitudes estimated between 2.8 and 3.3.

Faults

The magnitudes and locations of the observed earthquakes indicate that the Anglo-Brabant Massif is cross-cut by important fault zones. However, the geological evidence for these faults is sparse. The geological maps of the Brabant Massif by Legrand [49] and by De Vos et al. [25] show several 5-15 km long NW-SE oriented Hercyninan faults, separated by a set of NE-SW oriented faults. In a more recent map [62] , where only faults which demonstrably offset the stratigraphy are indicated, most of these faults have been withdrawn. However, according to Walter De Vos (pers. comm.), there are several indirect but convincing arguments for the existence of these two fault sets. Our own interpretation of the aeromagnetic map also shows many lineaments that could correspond to faults disrupting the stratigraphy.

For the Le Roeulx earthquake in 1995, a focal mechanism was determined which indicates a steeply dipping, NNE-SSW trending reverse fault. The upward projection of this fault plane coincides with the Senne/Senette Valley, a geomorphologic anomaly in the same direction, and with a fault on the map by De Vos et al. [25] .

Another fault zone for which the available information is very sparse and vague is the Bordière Fault, situated at the southern and south-eastern boundary of this zone [49] . The Bordière fault has been demonstrated between Mons, Namur and Liège, with a dextral offset of ~6 km, and significant throw to the south. The development further west into the North Artois shear zone is less clear. A study of mineralisation and remanent magnetism by Muchez et al. [57] indicated that the last activity of this fault took place in the Jurassic. Thus, the Bordière fault is an important tectonic boundary, which slowed down Hercyninan deformation in the Anglo-Brabant Massif, but it is not very likely that it is still active at present.

Evaluated Mmax: M_S=6.0

The largest earthquake observed in this region was the historical event of 21 May 1382 with estimated magnitude M_S ~6.0. Because up to now no faults have been found in this zone with

[1] *Note: Intensity data are indicated in EMS-1998 (European Macroseismic Scale) in Roman numbers ([40] and/or http://www.gfz-potsdam.de/portal/-?$part=CmsPart&docId=2051107 and abridged form in De Putter et al. [24])*

clear geomorphic expression, Camelbeeck et al. [14] argument that probably surface-rupturing earthquakes with magnitudes above 6.0 have not occurred in the recent geologic history. For this reason, we evaluate the maximum expected earthquake for this zone as M_S 6.0.

2.2 Zone 2 – Weald-Artois Zone

This zone comprises the North Artois Shear Zone, a bundle of parallel faults with dextral strike-slip displacement that roughly follow the Hercynian front (or Midi Fault) and that extend across the English Channel into the Weald Basin. In Belgium, this shear zone probably connects with the Mons-Orchies Basin.

Zone boundaries

- The northern limit of this zone was drawn to include some tectonic structures that are thought to be related to the North Artois shear zone: the Mélantois – Tournaisis faulted anticline in Belgium [45] & [31] , and some NW-SE oriented gravimetric lineaments just west of the Belgian border. Further west, the limit steers about 3 km north of the Landrethun fault and the Sangatte fault between Sangatte and Folkestone [32] , [54] & [5] . These faults form the southern limit of a pronounced gravimetric low, which could be a batholith that is part of the Brabant Massif. The limit thus also corresponds to the outline of the Midlands Microcraton [70] . We continued this zone westward to include the Jurassic Weald Basin that was inverted since Late Cretaceous, just like the Artois. This structure is characterized by both a gravimetric low and a magnetic low [48] . The limit was drawn around the magnetic low and around the bundle of Cenozoic and Jurassic-Cretaceous faults on the BGS map “Geologic faults in the UK” [9] .
- The eastern limit was drawn along the eastern border of the gravimetric low, where a broad gradient is supposed to mark the transition to the Ardennes Massif. Further north the limit was drawn outside the Mons and Orchies Basins. As the gravimetric map does not clearly delineate this zone, we have drawn the limit here around the zone with small, deep basins evident on the isohypse map of the top of the Palaeozoic by Minguely (et al.) [54] & [55] . This limit thus steers north of the topographic ridge between Cambrai and Arras, east of the ridge between Lens and Carvin (geographically known as Gohelle and Weppes) that separates the Flemish plain from the Orchies Basin, and south of the Mélantois dome.
- The southern limit of this zone was drawn south of a bundle of parallel gravimetric lineaments, oriented WNW-ESE in England to NW-SE in France, probably corresponding with different faults in the North Artois shear zone (with the exception of the Somme fault, which lies south of this gravimetric bundle). In the Artois and Weald regions, this limit corresponds to the limit of a gravimetric low, but in the English Channel it is rather the southern limit of a relative gravimetric high (Weald-Boulonnais faulted anticline). Towards the east, the expression of these lineaments terminates along a NE-SW oriented transverse line, east of which a broad gravimetric low develops. We continued the southern limit along the southern border of this structure, but this may be subject to future refinement.

- The western limit of the Weald zone was drawn outside some converging faults on the BGS map “Geologic faults in the UK” [9] , and around a N-S oriented relative magnetic high that separates two basins E and W of it. This limit is somehow arbitrary and based on the gravimetric map. It could also be argued to extend the zone further west towards a lineament between Portland and Bristol. However, we do not have seismic data for this zone, and it is located too far away to have an impact on seismic hazard in Belgium.

Instrumental seismicity

The Weald-Artois Zone is marked by a relatively weak instrumental seismic activity, with only a few earthquakes above magnitude M_L=3.0. The largest event occurred very recently, on 28 April 2007 in Folkestone, with magnitude M_L=4.3 and maximum intensity VI (EMS-98). This event was located close to the northern boundary of this zone.

Historical seismicity

In contrast to the relatively low recent activity, this region has experienced some moderate to large historical earthquakes. The Pas de Calais earthquake of 6 April 1580 with estimated magnitude M_S=6.0 was probably situated in this zone. Similar to the 2007 Folkestone earthquake, this event was located close to the boundary with the Anglo-Brabant Massif. Camelbeeck et al. [14] have tentatively linked it with the offshore prolongation of the Sangatte Fault. The smaller historical earthquake of 27 November 1776, with magnitude M_S=4.1 and maximum intensity (onshore) VI (EMS-98), was located in the same area.

The Scarpe Valley was struck by an earthquake of M_S ~4.9 on 2 September 1896. The maximum intensity reached VII (EMS-98). Camelbeeck et al. [14] have tentatively linked this event with the Marqueffles Fault, based on source-zone calculation from the intensity distribution.

Prehistoric seismicity

Several authors have suggested a tectonic origin for the break in topography between the Flemish Plain and the Artois. Most of this is indirect evidence for faulting; however there is one more direct observation: the faulting at the archaeological site near Biache-St-Vaast [17] . At this site located near the Marqueffles fault the Palaeolithic occupation horizon was displaced by two perpendicular sets of strike-slip faults with some normal movement. One set of faults was parallel to the Marqueffles fault. A bone was observed to be broken and offset along one of the faults. This is strong evidence for a sudden fault movement after this horizon was buried. Colbeaux et al. [17] were able to discern two phases of fault activity, in the late Middle Pleistocene and Upper Pleistocene, respectively.

Faults

Several faults are known in this zone and they have a complex history of activity. A recent study has reinterpreted all borehole data of the Artois to evidence the subsidence-uplift history along the major faults [54] & [55] .

Almost no reliable focal mechanisms have been determined in this zone, except for the Folkestone, 2007 earthquake. The solution shows predominantly strike-slip faulting with a small normal component, resulting from either right-lateral movement on a WSW-ENE striking fault plane or left-lateral movement on a NNW-SSE striking fault plane [60] . The latter orientation is more or less compatible with the orientation of the Sangatte fault, but the slip direction is opposite to the geologic dextral strike-slip movement of the North Artois shear zone. In-situ stress measurements in the vicinity of Boulogne indicated a NNW-SSE orientation of maximal horizontal stress [34] which is compatible with a Quaternary right-lateral reactivation of the North Artois Shear Zone [18] .

The main active faults within the Artois shear zone are probably the aligned Sangatte fault, Landrethun fault, Ruitz fault, and Marqueffles fault [14] , and this zone probably continues in the Weald zone along the faults of the BGS map "Geologic faults in the UK" [9] .

The North Artois Shear Zone faults supposedly connect with the Mons-Orchies Basin and the Bordière fault, but this is still unclear.

Evaluated Mmax: MS=6.0

The Weald-Artois Zone can produce large earthquakes, as evidenced by the historical event of 6 April 1580 with estimated magnitude M_S ~6.0. In this zone, several faults are known which have lengths of 15 to 40 km [32] , and which also appear to have geomorphic expression. These fault lengths of 15 to 40 km might generate maximal magnitudes up to M_S=6.7 [80] if they ruptured completely. However, it remains unclear whether any of these faults has experienced recent co-seismic displacement (the features observed at Biache-St-Vaast could also be secondary). The paleoseismic study of this zone has only just started and so far the occurrence of surface-rupturing earthquakes in the late Pleistocene or Holocene could not be proven. In the absence of paleoseismic evidence for large earthquakes, we evaluate the maximum expected earthquake as M_S=6.0 from the largest historical earthquake magnitude.

2.3 Zone 3 – Mons-Orchies Basin

This is a relatively small basin in the centre of the Hainaut Province, Belgium, and geologically continuing in France up to the "Méridien de Lens" [55] . The basin probably formed as a pull-apart basin at the transition between the North Artois Shear Zone and the Bordière Fault [27] . However, there is also a dissolved anhydrite layer beneath this basin that may explain part of the subsidence history [21] . The Mons-Orchies Basin is still evident as a depression in the present-day topography.

Zone boundaries

- The northern limit corresponds with the Bordière fault (see Zone 1: Anglo-Brabant Massif), which is distinct in the east but splits up to the west into the North Artois shear zone. In the northwest the limit of this basin is drawn south of the Mélantois dome, and is based on isohypse maps of the Palaeozoic top [55] .
- The eastern limit corresponds more or less with the outline of the Hainaut coal basin [64] and of the sedimentary cover [21] . It was mainly drawn to follow the limit of instrumental seismic activity but corresponds also with gravimetric and magnetic lineaments. This is the transition to the Namur syncline or "structural zone". Alternatively, this zone could be extended up to the Liège-Gulpen zone, as a shear zone along the Bordière fault.

- The southern limit is not clear, and may be subject to change. It was drawn on the northern side of a magnetic high and of a change in topography (higher to the south). This limit is situated south of the surface trace of the Midi Fault, but is not related to this fault. Another possible candidate for this limit was the Sambre River, which delimits the Cretaceous on the geological map, and which also seems to be associated with changes in the topography.
- The western and north-western limit was drawn around the isolated deep basins in the Palaeozoic top (see Zone 2 Weald-Artois Zone). The Orchies Basin does not have the same seismic activity as the Mons Basin, but structurally they may be linked as a pull-apart basin where the Bordière fault splits up to form the North Artois shear zone.

Considering the lack of instrumental seismicity in the Orchies Basin, an alternative would be to limit the zone to the seismically active part of the Mons Basin as in previous seismic source models. There are some differences in evolution between both sub-basins. In comparison to the Orchies Basin, the Mons Basin shows a larger total post-Paleozoic subsidence that mainly occurred during Cretaceous. The vague limit between both basins is oriented SW- NE and is located between Valenciennes and Bernisart [54] & [55] . This vague geologic limit is located about 15 km west of the limit of recent seismic activity, too far to be responsible for this change in activity. The Tertiary evolution of both sub-basins seems comparable. The subsidence in both sub-basins has been accommodated by even smaller basins that have been active at different times and the depocenters have shifted repeatedly in time. For these reasons we have combined both sub-basins into the Mons-Orchies Basin Zone, according to the basin outline in the top of the Palaeozoic [55] . Another alternative would be to continue the Mons-Orchies Basin eastward between the Bordière and Midi Faults, up to the Liège-Gulpen zone. However, it is very unlikely that the Variscan Midi Fault would still be active.

Instrumental seismicity

There is a strong concentration of seismicity which makes the Mons Basin area in the east stand out on the seismicity map, whereas no earthquakes have been recorded in the Orchies Basin in the west. Nine earthquakes of magnitude M_L=4.0 or larger have occurred since the start of the 20th century. The most important events were those of 3 April 1949 near Havré, and of 28 March 1967 near Carnières, both with magnitude M_L=4.5 (M_S=4.3). The earthquakes in the Mons Basin often occur as swarms or seismic sequences (with fore- and aftershocks). The most recent example of this is the swarm of Dour in 1987 which produced 58 earthquakes in the course of 4 months, with a peak of 5 earthquakes per day; three of the shocks reached magnitude M_L=2.5. Other swarms occurred in 1911 (Gosselies-Ransart) and in 1949 (Havré), and also the earthquakes of Strépy (15/12/1965) and Chapelle (16/01/1966) are part of a sequence. The hypocenters of earthquakes in the Mons-Orchies Basin seem to be rather shallow, generally less than 7 km deep. Nevertheless, their depth is large enough to rule out an origin by collapse of mines or of dissolution cavities in the anhydrite layer. Due to the shallow focus, even relatively small earthquakes in this zone can cause damage. An earthquake with magnitude M_L=4.0 can reach maximum intensity VII (EMS-98), but the intensity also decreases rapidly with increasing distance from the epicenter.

Historical seismicity

In contrast to the relatively high instrumental activity, there is no evidence of important historical earthquakes in this region. This indicates that the relatively high present-day activity, with several damaging earthquakes, is rather exceptional, and not representative of the situation in historic times. This, combined with the shallow focus, might indicate a link with the extensive coal extraction in this region (see below). However, not all coal regions display the same kind of activity.

Faults

Earthquake hypocenters indicate that seismicity is limited to the upper 7 km of the earth's crust. The focal mechanisms are very diverse: normal mechanisms, strike-slip fault mechanisms with normal and reverse components, and even reverse mechanisms. It is unclear whether this is due to a lack in quality of measured data, or if it indicates a non-homogeneous stress field. The normal and strike-slip mechanisms north of the Midi Fault fit with a stress field with NNW-SSE oriented maximum horizontal stress and a WSW-ENE direction of minimum horizontal stress. This stress field is compatible with the origin of the Mons Basin as a pull-apart basin within the right-lateral regime of the North Artois shear zone [27] . However, the reverse mechanisms in the Centre-Coalfield, just south of the Midi Fault do not fit in this model.

It has been suggested that the earthquakes in the Mons Basin were caused by collapse of solution holes in deep salt or anhydrite layers [20] & [3] . Seismicity data however show that they are really tectonic in origin. This is indicated by the focal mechanisms that not only show normal movement, but also lateral movement and also by the precise localisation of earthquakes within the seismic swarm of Dour (1987): these earthquakes with normal mechanism occurred at depths of 6 to 7 km, which is far deeper than the dissolving evaporite layers. There is, however, a possibility that these earthquakes are mining-induced, maybe due to the reduced load on the faults from the extracted mass above. This hypothesis needs to be further investigated.

Evaluated Mmax: MS=4.8

The largest observed magnitude in this region is MS=4.3. There are no historical earthquakes to assume larger earthquakes, and the known faults are short. The only possible longer faults would be the Bordière Fault that is supposed to limit the basin to the north, and a hypothetical fault that would bound it to the south. Very few data is available about these faults. For this reason, the maximum magnitude is evaluated as that of the largest historical earthquake, plus 0.5, i.e. MS=4.8.

2.4 Zone 4 – Western Ardennes Massif

The Ardennes massif is a Variscan structure consisting of a strongly deformed basin. We divided it in a western and eastern seismotectonic zone with different seismicity rate along a vague geological boundary. The Western Ardennes Massif spans the southern parts of the Belgian Provinces of Hainaut, Namur, and Luxemburg, and the French Avesnes region.

Zone boundaries

The limits of this zone are mostly defined by other zones.

- The northern limit corresponds with the southern limit of the Mons-Orchies Basin in the west, and with the Bordière fault (southern limit of the Brabant Massif) in the east.
- The eastern limit is a NW-SE oriented line separating a zone of elevated seismic activity in the Eastern Ardennes Massif from more diffuse activity in the Western Ardennes Massif. Leynaud et al. [50] defined this limit as an NW-SE oriented line based only on the seismicity pattern. We have moved this limit further west, and linked it with a broad magnetic gradient, with higher values to the east and lower values to the west; this position also corresponds with a similar, but steeper gravimetric gradient. A possible surface expression of this boundary is the Ourthe River flowing in a rather straight line across several perpendicular geological structures. The limit passes close by the south-western tip of the Stavelot Massif, several thrust faults terminate near this line, and there is a slight change in direction of the Variscan structures on both sides. We are not aware of any geological structure to explain these anomalies and this difference in activity. Possibly it is an old transverse structure comparable to and parallel to the Antwerp-Saint-Hubert lineament [15] , which is thought to offset the Ardennes massifs laterally. An alternative would be to place the zone limit along the Antwerp-Saint-Hubert lineament itself, but this structure is situated further south-westward and further away from the zone of elevated seismic activity. This lineament is also clearly visible on the gravimetric map, and corresponds with a more pronounced change in structural trend (it is the place where the Variscan folds of the Ardennes Massif change direction from E-W to NE-SW). Also, the new geological map 54/5-6 Achêne-Leignon [8] shows several terminations of thrust faults near this line.
- The southern limit was drawn along the southern boundary of a gravimetric high, well south of the outcrop limit of Devonian and Silurian rocks. The difference is due to the continuation of the Ardennes Massifs below the Mesozoic cover up to the Avesnes region. Toward the east the direction changes to WSW-ENE along the northern border of the Mesozoic Trier graben that connects with the Paris Basin [19] , and which we considered as a separate zone.
- The western limit corresponds with the limit of the gravimetric low included in the North of France zone.

Instrumental seismicity

This zone is characterised by sparse and diffuse seismicity. The largest event occurred during the only seismic sequence in this zone between 1992 and 1993 at Beaumont-Barbençon, and had magnitude M_L=3.6 and M_S=3.4

All other earthquakes in this zone had magnitudes smaller than M_S=3.0.

Historical seismicity

No large earthquakes are known. The largest events are the 10 May 1855 Braine-le-Comte earthquake with maximum intensity V (EMS-98), and the 17 September 1879 Warmifontaine earthquake, which had a maximum intensity of only III (EMS-98). This latter event might have been induced by underground slate extraction.

Faults

The most obvious faults in this zone are the Variscan thrust faults with E-W to WSW-ENE direction, parallel to the fold axes. The stress required to reactivate these thrust faults is higher than the stress needed to reactivate normal or reverse faults. Information about other faults in this zone is scarce, except for the Antwerp-Saint Hubert lineament proposed by Chacksfield et al. [15] . North of the Midi/Bordière Fault zone, there is not much evidence for this hypothetical fault, but south of it such a fault with sinistral strike-slip component is in good agreement with the aeromagnetic map. We can discern two similar structures, one along which the eastern boundary of this zone was drawn, and another along or just west of the Meuse River south of Namur. They also correspond with changes in the trend of fold axes and faults. We therefore suppose that they were pre-existing fault zones in the crustal blocks beneath the Midi thrust that moved laterally during the Variscan thrust faulting, and possibly also acted as lateral ramps, in relation to the eastern termination of the Caledonian Brabant Massif.

Evaluated Mmax: MS=3.9

The largest observed magnitude in this region is M_S 3.4. Up to now there is no data that would suggest that larger earthquakes may happen in this zone. Therefore, the maximum magnitude is evaluated as M_S=3.9 (addition of 0.5 magnitude units to largest known event).

2.5 Zone 5 – Eastern Ardennes Massif

This zone comprises the eastern part of the Ardennes Massif, excluding the Eifel volcanic region. It is characterized by a relatively high level of observed seismic activity, but not as high as in the bordering Roer Valley Graben.

Zone boundaries

The northern limit corresponds with the southern limit of the Liège-Gulpen zone. It is drawn along the southern branch of the Midi fault, which also corresponds with the southern limit of a relative gravimetric high, the northern limit of a broad magnetic high (indicating deep magnetic crust according to Chacksfield et al., [15]), and also with the southern (erosional) limit of Cretaceous deposits.

The eastern limit is defined by the southern Roer Valley graben. This limit is drawn such that all known faults that are part of the Feldbiss fault bundle are included in the Roer Valley Graben.

The southern limit is drawn along the northern border of a NE-SW trending Mesozoic graben structure (Trier Graben, zone 13) that connects with the Paris Basin in the west, and extends eastward up to the point where Palaeozoic rocks are again outcropping. This graben is clearly visible on the gravimetric map. There are other, smaller grabens with the same trend in the larger Ardennes Massif [19] , such as the Malmédy Graben (part of the Eastern Ardennes Massif), and the Neuwied Basin (zone 11). At the eastern end of the Trier Graben, the limit of the Eastern Ardennes Massif is drawn around the Eifel zone. It makes a sharp north-westward turn along a small relative gravimetric low, and then turns again north-eastward, staying south of a gravimetric and magnetic high, and north of a zone with elevated seismic activity. The boundary in this region was mainly based on the extent of the Eifel plume (low-velocity zone in the upper mantle) and of the associated volcanism (see Zones 11 and 12) [63] .

The western limit was discussed in the previous section.

Instrumental seismicity

The observed seismicity in the Eastern Ardennes Massif is lower than in the Roer Valley Graben, but higher than most other zones. Since the beginning of the 20th century, several earthquakes occurred with magnitude M_L=4.0 or higher. The most important of these happened on 14 January 1928 between Malmédy and Kalterherberg (Germany) close to the German-Belgian border, and had magnitude M_L=4.4 (M_S=3.7) and maximum intensity VI (EMS-98).

The geographical distribution of the epicentres is rather diffuse but some clustered zones exist with NNW-SSE orientation. The most striking example of such a cluster is located in the centre of the Stavelot Massif (Cambrian and Ordovician). Along this zone are situated: the earthquake of Malmédy 12/05/1989 (M_L=2.9), some isolated low-magnitude earthquakes, and the Hautes-Fagnes seismic sequence between October 1989 and May 1990 with 452 microtremors, 7 of them with magnitude M_L > 2.0. Another cluster with the same orientation occurred south of Aachen in May 1911. These earthquakes had local magnitudes up to 3.5 – 4.2.

We can also delimit some zones with a SW-NE orientation. Examples of these are: the deep earthquakes below the Stavelot Massif; a zone located NW of the Stavelot Massif which includes the Sprimont earthquake of 27 December 1988 (M_L=3.5), the Manderfeld area at the border with the Eifel volcanic zone, and some earthquakes in the north of the Grand Duchy of Luxemburg.

Historical seismicity

Although there are no large instrumental earthquakes in the Eastern Ardennes Massif, the historical data clearly indicate that large earthquakes have occurred in the past. The largest known earthquake on Belgian territory is situated in this zone: the 18 September 1692 earthquake with epicentre close to Verviers which destroyed several churches and castles in the area between Liège, Aachen and Verviers. Damage was widespread, even up to England. The magnitude of this earthquake is estimated at M_S=6.3, and the maximum intensity reached VIII (EMS-98) [14] .

Faults

The earthquake cluster within the Stavelot Massif is the only one that can be linked with a known fault. This zone of activity extends NNW-SSE over a distance of about 15 km. Focal mechanisms of the earthquakes in this zone indicate normal slip directions, and left-lateral slip with an important normal component [13] . Detailed localisation of the earthquakes in the Hautes-Fagnes seismic swarm show that they define a fault plane trending NNW-SSE and dipping 70° toward the east. This cluster probably occurred on the Hockay fault zone, which consists of a series of left-lateral faults with normal component that have the same direction. Some other faults are parallel to the Hockay Fault zone, and the swarm south of Aachen in 1911 may have occurred on one of these.

The depth distribution of the earthquakes in the Stavelot Massif is remarkable. The earthquakes of the Hockay fault zone are all situated at a depth between 5 and 9 km, while all other earthquakes are situated deeper, between 15 km and 25 km. In between both depth ranges is a hiatus. This could indicate a mechanical decoupling between the upper and lower parts of the seismogenic zone. The deeper earthquakes below the Stavelot Massif also seem to be related to faults with a different orientation than the Hockay fault zone: rather SW-NE, parallel to the old Hercynian faults. It is still unclear which of these fault systems produced the large earthquake of Verviers in 1692.

The earthquakes south of the Stavelot Massif also show a SW-NE alignment. The earthquakes in the Manderfeld area have depths of 18 to 22 km, which is deeper than one would expect for a region just next to the volcanically active Eifel zone. The three earthquakes that were recorded in the north of the Grand Duchy of Luxemburg since 1985 all had a shallow focus of less than 6 km.

The earthquakes NW of the Stavelot Massif have strike-slip focal mechanisms. Their depth varies between 7 and 22 km. The focal mechanism of the Sprimont earthquake indicates right-lateral slip on an E-W oriented fault plane, or left-lateral slip on a N-S oriented fault. The alignment of the other epicentres indicates that the first possibility is the most probable.

The stress field in the Eastern Ardennes Massif is characterised by SSW-NNE oriented minimum horizontal stress and WNW-ESE oriented maximum compression. These directions are intermediate between those of the Roer Valley Graben and those of the Liège-Gulpen Zone.

Evaluated Mmax: MS=6.3

The largest observed earthquake in the Eastern Ardennes Massif is the historical M_S=6 ¼ Verviers earthquake of 18/09/1692. We suspect that this represents the largest possible earthquake in this zone [14] . Larger earthquakes would rupture the whole brittle crust up to the surface, and thus leave a geomorphic trace with considerable length. The search for fault traces in the Eastern Ardennes Massif is difficult due to the relatively steep morphology and the unknown faulting mechanism (strike-slip or normal). There may still be some traces of surface-rupturing earthquakes, for example along the Hockay Fault zone, but so far no obvious major fault scarp was found [22] , [4] & [14] , contrary to the Roer Valley Graben zone. For this reason, we evaluate the maximum magnitude for this zone as M_S=6.3.

2.6 Zone 6 – Liège-Gulpen Zone

This zone is defined based on a rather constant occurrence of strike-slip mechanisms in WSW-ENE directions (although the perpendicular direction is possible too). Most of these have a shallow focus, although depths up to 22 km are observed near the boundary with the Roer Valley Graben. East of the Liège-Gulpen zone, the Roer Valley Graben shows a striking bend. The western border fault of the Roer Valley Graben shows large complexity in this area, and a large portion of the recent seismicity is concentrated here.

Zone boundaries

- The northern limit of this zone corresponds with the Bordière fault, and thus with the southern limit of the gravimetric high defining the southern limit of the Brabant Massif.

This gravimetric limit is not so well-defined in this area, however, and seems to split up in several branches. We traced the limit of the zone along the Visé-Puth flexure, which is the most northerly branch, and has a SSW-NNE direction [47] & [61] . It is also a clear but undulating gravimetric (and magnetic) gradient. The undulations are probably due to the ESE-WNW oriented normal faults (the Demer faults), which bound small grabens that terminate against the western, uplifted side of this flexure [28] . These faults are only a few km long, and their throw increases from a few tens of meters in the west, to a few hundreds of meter in the east. The eastern end of this limit is drawn where some known faults related to, but outside the Roer Valley graben, show a change in direction from NW-SE to WNW-ESE.

- The eastern limit of this zone is drawn west of the Heerlerheide fault, which is considered as the western outward branch of the border fault system of the Roer Valley graben.
- The southern limit is drawn along the southernmost branch of the Midi fault (see Eastern Ardennes Massif Zone). This corresponds with a faint gravimetric gradient with higher values to the north. It also corresponds with the southern outcrop limit of relatively continuous Cretaceous (and Tertiary) deposits of the Pays de Herve.
- The western limit is drawn in alignment with the western limit of the Eastern Ardennes Massif. This line traverses the Midi-Bordière fault zone along a narrow gravimetric low and along some anomalous peaks in aeromagnetic data. This line also coincides with two linear river sections, the Hoyoux and the Méhaigne, which are tributaries on either side of the River Meuse.

Instrumental seismicity

Since the start of the seismic measurements, two earthquakes have caused significant damage (intensity VII EMS-98), both in the vicinity of Liège: the first on 21 December 1965 with magnitude ML=4.3 at Ans-Vottem, and the second more important earthquake at Liège on 8 November 1983 with magnitude ML=5.0 (MS=4.7).

In the Dutch part of this zone there have been some smaller events that were perceived by the population. The most recent example is the Gulpen earthquake of 17 October 1988 with magnitude ML=3.5, which was felt within a radius of 50 km (intensity IV).

Historical seismicity

Some historical damaging earthquakes located in the Aachen-Maastricht area (e.g., on 23 August 1504 and 13/01/1714) might have their epicentre in the Liège-Gulpen Zone, but it is more likely that they occurred in the Roer Valley Graben (see there for more details on these events). In our database, their epicentres are located in the Roer Valley Graben zone, but the uncertainty on the location is larger than the distance to the zone boundary. In the rest of this zone, away from the boundary with the Roer Valley Graben zone, there are no known historical earthquakes, except for a small event on 7 February 1867 which was felt south of Liège (intensity III EMS-98).

Faults

The focal mechanisms in this zone show mainly strike-slip mechanisms. In the western part of the zone these have a small reverse component, whereas they are more extensional in the east, near the boundary with the Roer Valley Graben. The earthquakes near Liège most probably had right-lateral focal mechanisms with small reverse component along a WSW-ENE oriented fault zone dipping 70° to the N, and the hypocentral depths were only 4-7 km [13] . However, another possibility would be left-lateral slip on a NNW-SSE oriented fault dipping slightly to the E. The WSW-ENE structural direction is clearly present in the Bordière Fault and also in the Variscan Midi Fault and fold axes. The NNW-SSE direction, parallel to the Roer Valley Graben faults, can be observed on the aeromagnetic map, as a lineament between Vottem and Paifve. There is a similar lineament closer to Liège, between Mons-lez-Liège and Hollogne-sur-Geer, but this has a NW-SE direction. Gullentops & Claes [44] have drawn two NNW-SSE, E-dipping, normal faults in the Liège-Gulpen Zone. These are the Lanaye and Warsage faults, part of the Bilzen Fault Bundle. Most other faults in the Bilzen Fault Bundle have only been drawn north of the Liège-Gulpen zone. These faults form the south-western boundary of the Campine Plateau.

Close to the Belgian-Dutch border, near Gulpen, the focal mechanisms show either E-W right-lateral or (more likely) N-S left-lateral faulting. Hypocentral depths vary between 2 and 22 km in this area. However, the faults in this area are mainly NNW-SSE to WNW-ESE oriented, connecting with border faults of the Roer Valley Graben.

Similar to the Mons-Orchies zone, the Liège-Gulpen Zone has been mined (shallow) for coal, and also for chalk, marl and phosphates. Considerable amounts of material have been extracted from underground galleries, and to make this mining possible, the groundwater was lowered. Given the lack of damaging historical earthquakes with epicenter in this region, the larger number of recent earthquakes, and the rather shallow focus of most of the events, it seems possible that they have been induced by changes in load and/or water pressure. This possible link merits further investigation. However they might also be tectonic earthquakes due to activity of some faults within the complex structural geometry.

Evaluated Mmax: MS=5.2

The largest magnitude earthquake observed in the Liège-Gulpen Zone occurred at Liège in 1983. Its magnitude was MS=4.7. There are most probably no historical earthquakes located in this zone; however, the historical earthquakes with uncertain location in the Roer Valley Graben, close to the boundary with this zone, have estimated magnitudes up to MS=5.5. We applied the arbitrary increment of 0.5 to the maximum observed magnitude within this zone and thus evaluate the maximum magnitude as MS=5.2. This value may need to be revised if new information would indicate that historical earthquakes presently attributed to the Roer Valley Graben are situated in this zone.

2.7 Zone 7 – Roer Valley Graben

The Roer Valley Graben is the central subsiding region of the Lower Rhine Rift System (also sometimes referred to as the Lower Rhine Embayment). This rift system, to which also the Eastern Campine Zone (zone 8) and the Peel-Venlo Zone (zone 9) belong, consists of a series of subsiding grabens or rifts and rising horsts that are separated by northwest-southeast oriented normal faults. This system is situated in the border region between the Netherlands, Germany and Belgium, and extends over a distance of about 200 km from Bonn in the southeast up to the confluence area of Rhine and Meuse in the northwest. The Roer Valley Graben is one of the most seismically active regions in "stable" continental Northwest Europe. It is an actively subsiding region with has been periodically reactivated since the Late Oligocene with relatively high rate of deformation [23] & [37] . On the Bouguer anomaly map, it corresponds with a pronounced gravimetric low.

Zone boundaries

- The northern limit corresponds with the northern limit of the gravimetric low. At this point, the Rijen fault disappears. This is also the northernmost point where instrumental seismicity occurs in the graben (e.g., the 1932 Uden earthquake). This limit is probably a flexure above a deeper fault that controls the different evolution of the Roer Valley Graben and the West Netherlands Basin [53] .
- The eastern limit is defined by the Peelrand fault in the north and by the Erft fault in the south. The limit is drawn about 2 to 4 km east of these faults, which have been mapped by Ahorner [1] .
- The southern limit corresponds with the southern limit of known Quaternary faults. At this point, the Lower Rhine Rift System and the Roer Valley Graben more or less lose their expression in the morphology and on the Bouguer gravity anomaly map. Brunnacker & Boeningk [10] report an antiform (uplifted area) in the Rhine Main Terrace profile, which can be correlated with a horst in the Laacher See area. Our limit is located just north of this uplifting zone, which is included in the Neuwied Basin Zone (see Zone 11).
- The western limit is drawn 2 to 4 km west of the Rijen, Grote Brogel, and Heerlerheide faults in the north, and along the outer envelope of the faults within the Feldbiss fault bundle in the south, based on maps of Dusar et al. [29] and of Ahorner [1] . Thus, the limit lies significantly west of the main gravimetric gradient, particularly in the south.

Instrumental seismicity

The Roer Valley Graben is one of the most seismically active zones onshore NW Europe, and has a higher and more constant activity rate than the surrounding zones. The areal repartition of the epicentres shows some clusters with a lot of events, sometimes clearly aligned along faults, but also regions with fewer or no events. Since the start of seismic measurements, beginning 20th century, four earthquakes have occurred there with magnitude M_L=5.0:

1. Uden on 20/11/1932, M_L=5.0 on the north-eastern border of the graben
2. Euskirchen on 14/03/1951, ML=5.7 (MS=5.3) on the south-eastern border
3. Roermond: 13/04/1992, ML=5.8 (MS=5.4) in the centre of the eastern border
4. Alsdorf: 22/07/2002, ML=5.1 (MS=4.6) along the western border with the Liège Gulpen Zone.

Earthquakes with magnitudes larger than M_L =5.5 have an average recurrence time between 50 and 60 years, and have caused considerable damage. The most important one was without any doubt the Roermond earthquake of 1992. However, it is still regarded as a moderate earthquake since it caused no surface displacements. It was one of the largest events of the last century in Central and Northwest Europe. It was felt within a radius of about 450 km around the epicentre, notably in The Netherlands, Belgium, Germany and parts of the United Kingdom, France and Czechia.

The Alsdorf earthquake is situated in a remarkable cluster of seismic activity that occurred mainly within the last ten years along the western border of the Roer Valley Graben near Aachen. In this area the graben axis and its border faults show a bend in the area where the Liége-Gulpen Zone borders on the graben. On this border zone, near Voerendaal (Dutch Limburg), an earthquake swarm was recorded between December 2000 and August 2001. It consisted of about 150 earthquakes of which 13 had a magnitude larger than 2.0, with the strongest one on 23 June 2001 reaching magnitude M_L=3.9 (KNMI, http://www.knmi.nl/VinkCMS/explained_subject_detail.jsp?id=37830).

The Belgian part of the graben has produced some earthquakes with magnitudes between 3 and 4, among which the earthquake of Stamproy, close to the Belgian-Dutch border, on 25 June 1960 (M_L=4.0), the earthquake of Kinrooi on 29 June 1976 (M_L=3.7), and the earthquake of Maaseik on 22 may 1982 (M_L=3.7).

The focal depth of the instrumental earthquakes ranges from 5 to 20 km indicating a seismogenic zone of up to 20 km thick.

Historical seismicity

From historical archives we know that also in the pre-instrumental period strong and damaging earthquakes have happened, particularly in the southern part of graben. Since 1350, seven earthquakes had M_S between 5.0 and 6.0. The strongest earthquake that we know so far occurred on 18 February 1756 near Düren (Germany). This earthquake with an estimated magnitude of M_L=6.1 (M_S=5.7) was part of a seismic crisis between the year 1755 and 1760 during which more than 240 earthquakes were perceived, 9 of which had estimated magnitudes higher than M_S=4.0. Other important historical earthquakes were situated near Aachen (earthquakes of 1504, 1640, 1690, and 1755), and near Herzogenrath (earthquakes of 1873 and 1877), close to the boundary with the Liège Gulpen Zone. In the northern part of the Roer Valley Graben there are no known historical events.

Prehistoric seismicity

A review of the paleoseismic investigations conducted by the Royal Observatory of Belgium since 1996 is given in [14] , [74] & [75] . These studies focused mainly on the Geleen Fault (part of the southwestern border fault of the Roer Valley graben) in Belgium. The first paleoseismic trenches were excavated across the Bree fault scarp, a 10-km-long portion of the Geleen fault that runs through the Middle Pleistocene main terrace of the Meuse River, and is well expressed in the morphology. These trenches provided strong evidence for the occurrence of large, surface-rupturing earthquakes on this fault in the recent geologic past. In one trench, six paleoearthquakes were identified, five of which occurred in the past ~100 kyr. The three youngest paleoearthquakes could be correlated along the entire Bree fault scarp, and caused vertical displacements of ca. 0.5 – 1.0 m. The most recent paleoearthquake was shown to have a Holocene, most likely even late Holocene, age, but could not be dated more precisely. The return period could only be loosely determined, and ranges between ca. 14 and 23 kyr. Additional indications for the coseismic nature of faulting were found in the form of colluvial wedges and the association with various types of soft-sediment deformation. These findings contradicted the then general consensus that faulting in the Roer Valley Graben occurs largely aseismic (e.g., [2]).

In more recent years, the investigation was extended to the adjacent section of the Geleen fault in the Belgian Meuse River valley. The surficial sediments in this area are much younger (predominantly late Weichselian to Late Glacial), and thus record less cumulative vertical offset. Consequently, the geomorphic expression of the fault is strongly reduced, and generally does not exceed that of other landforms. Using electric-resistivity tomography and ground-penetrating radar, we were able to identify the fault in the shallow subsurface, and we found evidence for a left stepover a few hundreds of meters wide. Two paleoseismic trenches were excavated south of this stepover. We found evidence for a late Holocene paleoearthquake in both trenches. Radiocarbon and OSL dating constrain the event between 2.5 ± 0.3 and 3.1 ± 0.3 kyr, and between 2790 ± 20 and 3770 ± 50 calibrated years before AD 2005, respectively [72] . We paid particular attention to the identification of the prefaulting soil and the overlying scarp-derived colluvium, which are primary coseismic evidence. In both trenches this event is associated with liquefaction, including a series of sand blows and a gravel dike. These features are unambiguous evidence for strong co-seismic shaking. In one trench, we identified a second paleoearthquake which was OSL-dated between 15.9 ± 1.1 and 18.2 ± 1.3 ka kyr [72] . The interval between both events has a two-sigma range of 11,800 – 16,800 yr.

The ages obtained for the two paleoearthquakes on the Geleen Fault in the Meuse River valley are in relatively good agreement with those obtained in the trenches along the Bree fault scarp. This raises the possibility that the Geleen fault defines a single, 27-km-long rupture segment, which would be capable of producing MW=6.7 (± 0.3) earthquakes. The stepover between both parts of the fault is less than 500 m wide, which is probably not sufficient to stop propagation of a large M6+ earthquake. However, the data also demonstrate that the stratigraphic and dating resolution are not sufficient to distinguish between this hypothesis and the possible occurrence of two different large earthquakes closely spaced in time, on the two segments separately, in which case the size of the paleoearthquakes would "only" be MW=6.3 (± 0.3). However, the value of MW=6.7 is more consistent with the observed surface displacements.

We have also participated in the investigation of two other trenches in the graben, on the Peelrand fault in the Netherlands [69] , and on the Rurrand fault in Germany [73] , with similar results. On the other hand, a recent trench study on the southeastern portion of the Geleen fault near Born in the Netherlands [46] concluded that there is no evidence for large, surface-rupturing earthquakes. However, their descriptions are conflicting, while they also appear to have overlooked features such as fault terminations and a fault-zone unconformity. Finally, the Geological Survey of Nordrhein-Westfalen has investigated three paleoseismic trenches in the German part of the graben. The results of these studies have not yet been published, but preliminary results are available on their website: (http://www.gd.nrw.de/a_pjyp01.htm).

Faults

The faults in this zone are relatively well known because they are evident in the morphology, and offset late Pleistocene fluvial deposits. They are NW-SE oriented, nearly purely normal faults. Borehole correlations and seismic-reflection profiles have demonstrated that these faults have a long-lasting activity, and extend down to a depth of at least 2 km. Most probably, they extend much deeper, down to the base of the seismogenic layer at 20 km depth, as indicated by instrumental earthquakes.

Van Baelen & Sintubin [68] compiled the available data on the faults in the Roer Valley Graben. The western border of the graben is defined by the wide Feldbiss fault zone, showing a left-stepping pattern, and comprising amongst others the Kirspenicher, Stockheimer, Merode, Sandgewand, Feldbiss, Geleen, Heerlerheide, Grote Brogel, Reppel, Bocholt, Veldhoven, Rijen and Riel faults. The eastern border of the Graben is a narrower and straighter zone which comprises the Swist, Erft, Brüggener, Horremer, Kentener, Lövenicher, Rurrand, Second Peel and Peel Boundary Faults. The geologically recent displacements on the eastern border fault zone are larger than those on the western border zone, and also the geomorphic expression is larger [53] & [37] . It should be noted that our paleoseismic studies of the Geleen fault provide information on the recurrence of large earthquakes along a single seismogenic source in the Roer Valley Graben. The total length of active faults is in excess of 350 km, however, and some of these faults are likely more active than the investigated Geleen Fault.

Evaluated Mmax: MS=6.7

The largest observed earthquake was the historical Düren earthquake of 18 February 1756, with magnitude MS=5.7. In this zone, however, paleoseismic investigations provide evidence for the existence of active faults that have produced co-seismic surface ruptures in the past, with surface displacements of 0.5 – 1.0 m, and rupture length of 12 – 28 km. Based on empirical relationships between segment length and moment magnitude, and between surface offset and moment magnitude (Wells & Coppersmith, 1994), the magnitude of these large paleoearthquakes can be estimated as MW=6.7 (± 0.3) [14] . The maximum magnitude for the Roer Valley Graben is thus evaluated as MS=6.7. This is a full magnitude unit above the observed maximum.

2.8 Zone 8 – Eastern Campine Zone

This zone comprises the western Lower Rhine Rift System outside the Roer Valley Graben. It spans central Limburg and the eastern part of the province of Antwerp, and extends into The Netherlands. This zone is a transition zone between the Roer Valley Graben and the Anglo-Brabant Massif.

Zone boundaries

1. The northern limit was drawn in alignment with the northern limit of the Roer Valley graben, along a gravimetric gradient in WSW-ENE direction. This gradient is thought to correspond with a deep flexure perpendicular to the graben direction. This deep structure influenced the differential development of the Roer Valley Graben versus the West Netherlands Basin [53] .
2. The eastern limit corresponds with the main border fault zone of the Roer Valley graben, see Zone 7.
3. The southern limit coincides with the northern limit of the Liège-Gulpen zone, see Zone 6.
4. The western limit is the border with the Anglo-Brabant Massif, see Zone 1.

As discussed earlier in the description of zone 1, an alternative proposal could be made to combine the southern part of the Eastern Campine Zone and extreme eastern part of the

Brabant Massif into a small separate zone which has nearly E-W oriented normal faults, based on focal mechanisms, and a higher seismicity than the rest of the Eastern Campine Zone. Another alternative would be to include the whole Campine Basin in this zone, but the lack of a clear limit between the Brabant-Massif and the Campine Basin makes this problematic.

Instrumental seismicity

The seismic activity since the start of the 20th century is concentrated in the southern part of this zone, close to the boundaries with the Liège-Gulpen and Roer Valley Graben zones. The largest earthquake, with magnitude ML=4.5 (MS=4.3), happened near Niel-bij-As on 18 February 1971. Three earthquakes occurred close to Bilzen, on 23 February 1925 with magnitude ML=4.1, on 10 January 1970 with magnitude ML=3.4, and on 16 July 1985 with magnitude ML=3.0.

Another magnitude ML=3.5 event occurred near Genk-As on 10 March 1963. Some smaller earthquakes with magnitude below 3.0 are situated in this zone. Some of the larger earthquakes in this zone locally caused slight damage.

The focal depths in this zone vary between 4 and 20 km.

Historical seismicity

No historical earthquakes can be attributed with certainty to this zone.

Prehistoric seismicity

In a paleoseismic study of the Rauw fault [76] & [56] , no evidence was found for large, surface-rupturing earthquakes since ca. 30.000 years. Several large cryoturbations were observed, but the contact between the white Mol Sands and the overlying Quaternary deposits (dated younger than 30.000 years) was not vertically displaced. However, the ~2.5 million years old Mol Sands are reported to be vertically displaced by 15 m [42] . During the Cromerian (770-300 kyr.), after a supposed renewed activity of the Rauw fault, the Rhine-Meuse River was attracted towards the hanging wall, and the slightly gravelly Lommel sands were deposited. Differential erosion from the Elster until the Late Weichsel resulted in a residual gravel layer of the partly eroded Lommel sands and in a slope on which the gravel could be displaced westward [78] . This is indirect evidence for fault movement (with unknown amount), up to the Cromerian. The paleoseismic trench revealed a large erosional hiatus which made it impossible to study the possible fault activity before 30.000 years ago.

Faults

Several faults are known in this region. Most of them are NNW-SSE oriented with mostly vertical displacements down to the east. Toward the south of this zone, their orientation changes to NW-SE. These faults are parallel to the Roer Valley Graben faults, and have a similar geologic history. However, the slip rate was smaller. During the Quaternary, there is some indirect evidence for activity of the Rauw fault, which would have changed the course of the Rhine-Meuse River during the Cromerian and caused the deposition of the Lommel sands and Zutendaal Gravel. These deposits are the substrate of the Campine Plateau. The morphology of this plateau does not show clear fault scarps, but it has been eroded since the time of deposition: the most recent erosion phase took place during the Last Glacial Maximum.

This indicates that surface rupturing has not continued here, at least since the Last Glacial Maximum about 14 kyr ago, but possibly even since 300 kyr.

Focal mechanisms in the south of the zone and in a small part of the neighbouring Anglo-Brabant Massif indicate N-S oriented extension and normal faulting along E-W oriented faults. This would indicate a 50° rotation of the stress field with respect to the Roer Valley Graben and to the regional field. This E-W orientation may be related to the Bilzen Fault Bundle. On the other hand, most other known Quaternary faults in the south of the Eastern Campine zone have NW-SE orientation.

Evaluated Mmax: MS=4.8

The largest observed magnitude in the Eastern Campine Zone is MS=4.3. Faults are present in this region with the same orientation as the active faults in the nearby Roer Valley Graben, and with Tertiary and early Quaternary displacements. No evident geomorphic fault scarps are present, however, and a paleoseismic study could not evidence recent movements, younger than 30.000 years on the Rauw Fault. Therefore, we consider the occurrence of larger earthquakes unlikely, and evaluate the maximum magnitude as MS=4.8 (addition of 0.5 magnitude units to largest known event).

2.9 Zone 9 – Peel-Venlo Zone

This zone comprises the eastern Lower Rhine Rift System outside the Roer Valley Graben.

Zone boundaries

- The northern limit was drawn in alignment with the northern limit of the Roer Valley graben, along a vague gravimetric gradient in WSW-ENE direction that intersects the gravimetric high of the Peel Block and the gravimetric low of the Venlo Graben. Our limit corresponds more or less with the transition from the Peel Horst to the Maasbommel High.
- The eastern limit was drawn a few km east of the Viersen Fault. It is the western limit of a clear gravimetric high, corresponding to the Rhenish Massif.
- The southern limit was drawn in continuation with the southern border of the Roer Valley Graben (see Zone 7) slightly north of, but not exactly parallel to a gravimetric ridge.
- The western limit is drawn east of the main faults of the Roer Valley Graben (see Zone 7).

Instrumental seismicity

The instrumental seismicity is diffuse and relatively low in magnitude. The largest event occurred near Mönchengladbach on 9 August 1963, and had magnitude M_L=3.6 (M_S=3.4), and maximum intensity V (EMS-98). Several smaller events occurred here, and the focal depths are between 4 and 20 km.

Historical seismicity

No known historical earthquakes are located in this zone.

Prehistoric seismicity

The Geologische Dienst Nordrhein-Westfalen investigated a paleoseismic trench on the Viersen Fault within this zone. This study has not been published so far, except for some preliminary findings on their website: http://www.gd.nrw.de//a_pjyp03.htm .

Faults

There are several known faults in this zone that are parallel to the Roer Valley Graben system. Several of these are associated with topographic scarps, and displace Pleistocene deposits, indicating their recent movement [1] . If these are due to co-seismic slip, earthquakes of magnitudes of M_W~6.5 should be taken into account here, considering fault lengths of 15 to 30 km and a thickness of the seismogenic layer of about 20 km [80] .

Evaluated Mmax: MS=3.9

The largest observed magnitude in the Peel-Venlo Zone was M_S=3.4. So far, there is no published evidence for larger earthquakes in this zone. As a result, we evaluate the maximum magnitude as M_S=3.9 (increment of 0.5 magnitude units above largest known event) for the time being. However, if the paleoseismic study of the Viersen fault by the Geologische Dienst Nordrhein-Westfalen would discover evidence of surface-rupturing earthquakes in the recent geologic past, the maximum magnitude will need to be revised and might rise to about M_W~6.5.

2.10 Zone 10 – West Netherlands Basin

The West Netherlands Basin is a zone of subsidence connecting the Roer Valley Rift System with the Tertiary grabens in the North Sea. It has a common tectonic origin and similar Mesozoic evolution as the Roer Valley Rift System, but its Neogene evolution is characterized by uniform subsidence instead of fault-controlled deformation [81] .

Zone boundaries

- The north-eastern limit was drawn along the NE edge of the Zandvoort Ridge and the IJmuiden High and continues some km SW of the Indefatigable Fault Zone. Thus, the Zuiderzee Basin and the Broad Fourteens Basin [53] are not included in this zone. They have experienced Neogene rifting and thus belong to another zone which is outside of this zone model because it is too far from Mol/Dessel/Geel and outside of the region of completeness of our earthquake catalogue. This line is the NE boundary of a relative gravimetric high that separates two zones with lower values of the Bouguer anomaly, and it also corresponds with a faint aeromagnetic anomaly [48] .
- The south-eastern limit coincides with the northern limits of the Eastern Campine Zone, the Roer Valley Graben Zone and the Peel-Venlo Zone.
- The south-western limit is the border with the Anglo-Brabant Massif (see Zone 1).
- The north-western limit was drawn at the transition between the West Netherlands Basin and the Sole Pit Basin, mainly based on Gibbard et al [39] . This limit is not visible in the aeromagnetic data [48] , but it bounds some gravimetric highs and lows that are elongated

in a perpendicular direction. This limit may correspond to a deep (transverse) fault that influenced the basin development.

Alternatively, we could extend this zone northward to include the Sole Pit Basin where the large instrumental Dogger Bank earthquake occurred in 1931 (see further). Both the Sole Pit Basin and the West Netherlands Basin are part of the Cenozoic rift system that also includes the Lower Rhine Rift System.

Instrumental seismicity

Only 2 earthquakes in the ROB catalogue are located in this zone, and their magnitude has not been determined. The Dutch catalogue mentions M_L=3.5 for the 02/05/1928 Tiel earthquake, and also mentions 4 smaller events (Lijst met tektonische aardbevingen in Nederland: http://www.knmi.nl/seismologie/tectonische-bevingen-nl.pdf). At that time, the Belgian seismic network was not yet able to measure earthquakes with magnitudes smaller than M_L~4.0 at that distance. Also the British Geological Survey earthquake catalogue (available online via http://www.earthquakes.bgs.ac.uk) mentions one event with magnitude M_L=1.6 in this zone on 7 November 1990, but this catalogue does not mention the 1928 Tiel event.

Historical seismicity

There are no known historical earthquakes located in this zone.

Faults

Several WNW-ESE to NW-SE oriented faults have been active in the Mesozoic, but these have not been reactivated during the post-Oligocene rifting in the Roer Valley Rift System and its offshore continuation in the Broad Fourteens Basin [53] or in the Sole Pit Basin. The present-day stress field is characterized by NE-SW extension, similar to the Roer Valley Rift System [81] .

Evaluated Mmax: MS=3.9

Based only on the ROB catalogue, Mmax is below the cut-off limit determined for seismic hazard calculation. Based on the Dutch catalogue, the largest observed magnitude in this zone is M_L=3.5 (M_S=3.4). Adding an increment of 0.5, we evaluate the maximum magnitude for the West Netherlands Basin as M_S=3.9. However, the Sole Pit Basin just west of this zone has known a large instrumental earthquake: the Dogger Bank earthquake of 7 June 1931 (M_L=6.1 based on the BGS catalogue, equivalent to M_S 5.8). We consider the Sole Pit Basin as a separate seismotectonic zone because of its Neogene activity. It is situated outside of the region of completeness of the ROB catalogue and also too far away from Belgian territory and Mol/Dessel/Geel to cause large effects and thus it is not included in this zone model.

2.11 Zone 11 – Neuwied Basin

This zone consists of two sub-blocks, separated by a SW-NE oriented fault, the Andernach Fault. The northern block is a horst structure, the Ahr Mountains, while the southern block is a rectangular basin bounded by faults on all sides, the Neuwied Basin sensu stricto [10] & [7] . In the Bensberg source-zone model, both sub-blocks are considered as separate zones (Hinzen, personal comment).

Zone boundaries

- The north-eastern limit was drawn in alignment with the eastern limit of the Peel-Venlo Zone, along a gravimetric gradient that separates high values of the Bouguer anomaly to the east from low values within this zone. In the southern half of this zone there is also a clear geomorphic lineament, associated with the Sayner Fault.
- The south-eastern limit is drawn south of the Koblenz fault, bounding the Neuwied Basin. This fault is associated with a geomorphic scarp. South of this line the gravity values are higher, except for an elongated gravimetric low in the southward prolongation of the Lower Rhine Rift System that is considered as part of the Hunsrück-Taunus zone.
- The south-western limit was drawn in alignment with the western limit of the Roer Valley Graben, along a gravimetric gradient that separates higher values to the west from lower values within this zone.
- The north-western limit coincides with the southern limits of the Roer Valley Graben and the Peel-Venlo Zone, see there.

The northern, eastern and southern boundaries also correspond more or less with the eastern outline of the zone of 2 to 3% reduction in modelled S-wave velocity in the depth range of 31 to 100 km that was evidenced by the Eifel Plume Project [63] & [http://www.uni-geophys.gwdg.de/~eifel/]. This reduction in V_S is attributed to a temperature rise of 200 to 300°C. This boundary connects well with the extent of the Eifel volcanism since the Tertiary [51] .

An alternative interpretation would be to extend this zone toward the southeast across the Hunsrück-Taunus Massif (See zone 14) along the elongated gravimetric low. This zone would then connect the Upper with the Lower Rhine Grabens.

Instrumental seismicity

This zone has a large concentration of small earthquakes. The largest observed earthquakes were: 20 January 2000 Grafschaft (M_L=3.7; M_S=3.5), 3 August 2007 Ochtendung (M_L=3.7), and 22 May 2004 Mulheim (M_L=3.6).

Historical seismicity

The only known historical earthquake in this zone is the 2 September 1869 Engers earthquake which has caused a maximum intensity of VI (EMS-98). No magnitude value was estimated so far for this earthquake.

Faults & Volcanism

Two major fault directions are present in this zone: the first NW-SE in alignment with the Roer Valley Graben faults, and the other perpendicular to this direction. Several of these are seismically active and have displaced Tertiary deposits [3] and Quaternary terraces [10] & [59] . These faults are also visible in the morphology and on the Bouguer gravity anomaly map. See also the description of the boundaries of this zone.

The Quaternary East Eifel volcanic field is situated in this zone [51] . Its activity started around 0.6 Ma, and the most recent activity was the 11 kyr BP Laacher See eruption. This timing is concurrent with the major uplift phase of the Rhenish Massif, suggesting a common origin: a mantle plume. The eruptive centres are aligned along mainly NW-SE axes but locally also NE-SW and N-S axes occur [65] . The mantle plume is still present, and so it is likely that the activity has not come to an end.

Evaluated Mmax: MS=4.0

The largest observed instrumental magnitude in this zone is M_S=3.5. Adding an increment of 0.5 magnitude units, we evaluate the maximum magnitude for the Neuwied Basin as M_S=4.0. This value may become a little higher if we can determine a more precise magnitude for the historical 1869 Engers earthquake.

2.12 Zone 12 – Eifel Zone

This zone is the southern prolongation of the Eastern Ardennes Zone, but it has a much lower seismic activity, which is probably due to the influence by the Eifel plume. It is an area of Pleistocene uplift [35] & [36] . Similar to the Neuwied Zone (see zone 11), the northern, western and southern boundaries of this zone correspond more or less with the western outline of the zone of 2 to 3% reduction in modelled S-wave velocity in the depth range of 31 to 100 km that was evidenced by the Eifel Plume Project ([63] & [http://www.uni-geophys.gwdg.de/~eifel/]. This boundary corresponds well with the extent of the Eifel volcanism since the Tertiary [51] .

Zone boundaries

- The north-eastern limit coincides with the south-western limit of the Neuwied Basin, see Zone 11.
- The south-eastern limit was drawn north of the Permian Wittlich Basin, which belongs to the Trier Graben. It is marked by a gravimetric and topographic low. The limit then continues east along a narrow gravimetric low as the limit with the Hunsrück-Taunus Massif. This line corresponds with the direction of the main structures and faults within the Palaeozoic massif, but also with the course of the Mosel River.

- The south-western limit corresponds partly with the southern limit of the Eastern Ardennes Zone (see Zone 5). The limit with the Trier Graben is drawn as a straight line intersecting the gradual termination of the graben faults more or less at the contact between Triassic and Devonian on the geologic map. The graben faults start to turn north here, toward the Eifel Depression. The Bouguer gravity anomaly shows a gradual rise from the SW to the NE of this line, but the main lineations are in the perpendicular direction.
- The north-western limit coincides with the south-eastern limit of the Eastern Ardennes Massif, see there. This boundary corresponds well with the extent of the Eifel volcanism on the Geological map of Nordrhein-Westfalen, C5506 Bonn [11] .

Instrumental seismicity

Only few small earthquakes have been recorded in this zone. The largest measured magnitude is ML=3.0 (MS=2.9).

Historical seismicity

No historical earthquakes are known.

Faults & Volcanism

This zone is intersected by a N-S fault zone, the Eifel Depression [58] , which consists of a series of en-echelon grabens in SW-NE direction that were mainly active from Triassic to Lower Jurassic. This fault zone links the Trier Graben with the Drove Graben and the Roer Valley Graben. These grabens possibly reactivated some Variscan SW-NE thrust faults. The geologic maps also show several N-S, E-W and NW-SE faults. Bussmann & Lorenz [12] assumed that the Tertiary magma rise in the Hocheifel volcanic field made use of the E-W and N-S fractures, while the Quaternary magma rise in the West Eifel occurred mainly along NW-SE fractures, reflecting changing stress directions.

Quaternary volcanic activity occurred in this zone up to around 11 kyr BP. The mantle plume is still present, however, and thus probably the zone can become active again.

Evaluated Mmax: MS=3.4

The largest measured magnitude is M_S=2.9, and thus applying the increment of 0.5 in the absence of more specific information, we evaluate the maximum magnitude for the Eifel Zone as M_S=3.4.

2.13 Zone 13 –Trier Graben

This zone comprises the Permian-Jurassic graben system between Luxemburg and Trier, and also includes the Wittlich Basin.

Zone boundaries

- The north-eastern limit corresponds with the limit of the Eifel Zone and was drawn around the Permian Wittlich Basin [58] .
- The south-eastern limit was drawn south of the faults bounding the Trier Graben on the geologic map [19] , and along gravity lineaments. The gravity anomaly is not constant along this line. In the southwest there is a gravity low south of the boundary, while further

northeast there is a gravity high, corresponding to the Hunsrück-Taunus Massif. This line more or less coincides with the course of the Mosel River.

- The south-western limit is not so clear, marking the gradual transition with the Paris Basin. We drew the line outside the zone with clear gravity anomaly lineations that correspond with the NE-SW graben direction. Beyond this boundary the gravity values are relatively lower and the lineations are oriented E-W. Topographically, the Trier Graben Zone is also more elevated than the region to the south.
- The north-western limit coincides with the southern limit of the Ardennes Massif, and was drawn north of the graben faults on the geologic map and along a vague gravity anomaly.

Instrumental seismicity

This zone has only few and small recorded earthquakes, and the largest observed magnitude is M_L=1.2 (M_S=1.4).

Historical seismicity

No known historical earthquakes are situated in this zone.

Faults & Volcanics

Several NE-SW faults bounding this graben are indicated on geologic maps [19] & [3] . These faults are also evidenced by gravity lineaments. Volcanism related to the Eifel volcanism started during the Cretaceous with eruptions in the Wittlich Graben, which is part of this zone [51] .

Evaluated Mmax: MS=1.9

The largest observed magnitude in this zone is M_S=1.4. Adding an increment of 0.5 magnitude units, we evaluate the maximum magnitude as M_S=1.9.

2.14 Zone 14 – Hunsrück-Taunus Massif

This zone was loosely based on the seismic zonation from Bensberg (Hinzen, personal communication), but we combined their Pfalz-Saar and Rhenish shield zones and adapted the limits to fit the geologic data. This is a zone with elevated instrumental seismicity.

Zone boundaries

- The north-eastern limit was drawn along the Palaeozoic outcrop limit of the Taunus Mountains, part of the Rhenish Shield, at the boundary with the Hessian Trough.
- The north-western limit coincides with the south-eastern limits of the Trier Graben and the Neuwied Basin, see zone 11 and 13. It continues NE along an elongated gravimetric low between gravimetric highs, and along parallel river valleys. This structure probably corresponds with the Lahn Syncline that contains part of the Giessen Nappe.
- The south-eastern limit was drawn south of the Palaeozoic outcrop limit of the Hunsrück and Taunus Mountains, and south of a clear gravimetric high. This corresponds with an important fault, the Hunsrück Southern Border Fault [77] & [58] .

- The south-western limit is drawn north of a marked gravimetric low, and also corresponds with the southern outcrop limit of Palaeozoic rocks. This line marks the limit with the Paris Basin.

Instrumental seismicity

This zone has an elevated seismic activity, especially compared to the Trier Graben and the Eifel Zone. Many small earthquakes were recorded here with maximum observed magnitude ML=3.9.

Historical seismicity

The largest historical earthquake in this zone struck St. Goar on 29 July 1846 with magnitude MS=4.8 and maximum intensity VII (EMS-98).

Faults

The Hunsrück southern border fault (Südrand Störung) is a well-known fault [35] with Mesozoic normal slip down to the south. This fault forms the border with the Saar-Nahe basin in the west, and continues in the border fault between the Taunus Mountains and the Upper Rhine Graben toward the east. This fault zone is part of the Rheic Suture between the Rhenohercinian and Saxothuringian Zones [77] . In this zone, there are several faults parallel to this Variscan structure.

There are also several NNW-SSE faults in the southward prolongation of the Roer Valley Graben, some with proven neotectonic activity.

Evaluated Mmax: MS=5.3

The largest observed earthquake was the St. Goar earthquake of 1846 with magnitude MS=4.8. Applying the increment of 0.5 magnitude units, the maximum magnitude in this zone is estimated as MS=5.3.

3 Alternative model: Two-zone model

In addition to the seismotectonic model, we have defined a second source-zone model: the two-zone model, consisting of the Roer Valley Graben and the so-called "Single Large Zone", which encompasses the entire region outside of the Roer Valley Graben (Figure 11 and Figure 1). This alternative model is justified by the observation that the Roer Valley Graben is characterized by rather continuous seismicity, whereas in the region outside, the temporal and spatial distribution of seismicity is diffuse. The few larger earthquakes in this area have all occurred in different places, which are typically not characterized by sustained seismicity. Furthermore, in many areas with elevated seismic activity during the instrumental period (since 1900), the activity was not constant through time. Regions can suddenly become active, and after a period of activity become inactive again for a long time. This behaviour suggests that seismicity is episodic, clustered, and migrating, similar to what has been found for other continental intraplate areas [66] . Consequently, the period for which we have information, one century for instrumental data and about 7 centuries of historic earthquake data, is short compared to the time between large earthquakes at a given place, and may bias our views of seismic hazard and earthquake recurrence by focusing attention on presently active structures. One approach to address this difficulty is to consider the whole area as a single zone with equal probability of earthquake occurrence. Within this zone, the next large earthquake is likely to occur in a place that has not been affected during the observation period. The only exception in our region of interest is the Roer Valley Graben. During the whole observation period this region has had a relatively high and constant rate of activity with several larger instrumental and historical earthquakes. The spatial distribution of the larger events is relatively uniform, although smaller earthquakes are clustered in space and time. The relation between earthquakes and the faults on which they occur is much better established in the Roer Valley Graben, because the focal mechanisms and fault orientations indicated by the distribution of epicentres are in agreement with fault scarps evident in the morphology, and with the results of paleoseismic investigations.

Zone boundaries

The boundaries of the Roer Valley Graben are the same as for the Roer Valley Graben in the seismotectonic model, see zone 7.

The Single Large Zone is drawn as a tight box around most of the seismicity in the ROB catalog. It extends as far as the seismotectonic model, except for the western part of the Weald-Artois Zone, and the northern parts of the Anglo-Brabant Massif and the West Netherlands Basin, Earthquakes in these areas are not likely to cause large effects on Belgian territory due to attenuation.

Evaluated Mmax

The evaluated maximum magnitude was determined the same way as in the seismotectonic model, which results in M_S=6.7 for the Roer Valley Graben zone, and M_S=6.3 (from the Eastern Ardennes Massif) for the Single Large Zone.

4 Figures

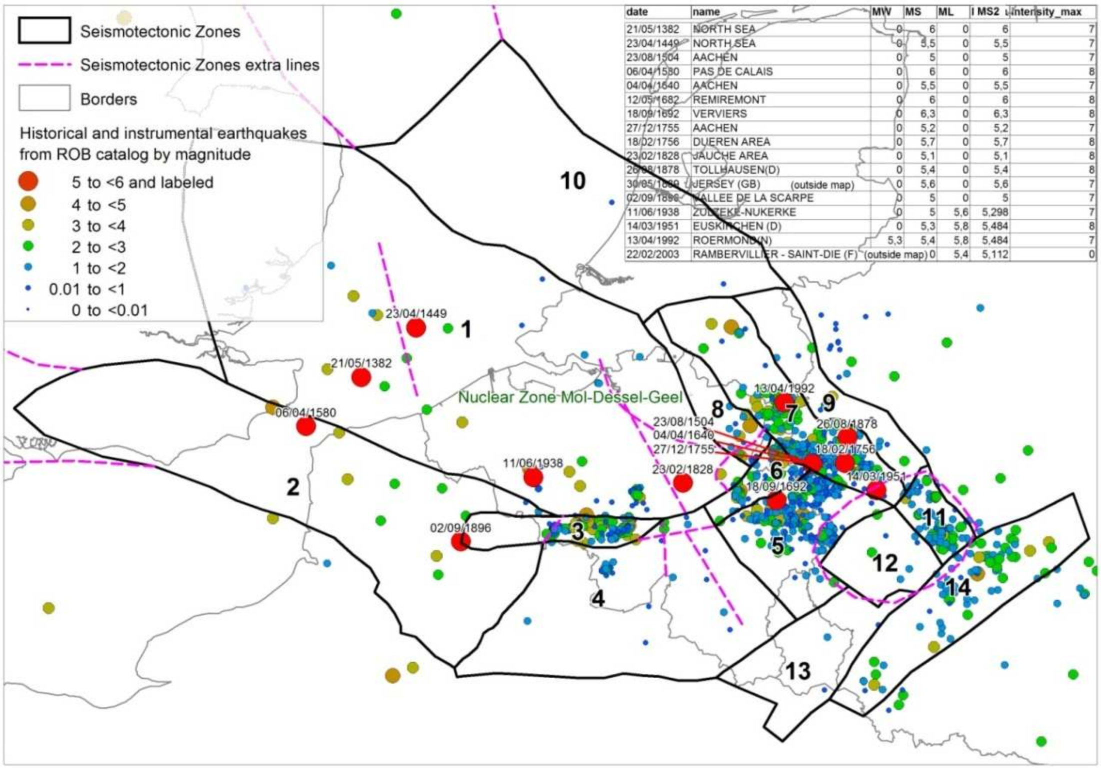

Figure 2 - Seismotectonic zones and historical and instrumental earthquakes scaled by unified recalculated MS2 magnitude. Events of magnitude 5 and above are labelled and shown in the table.

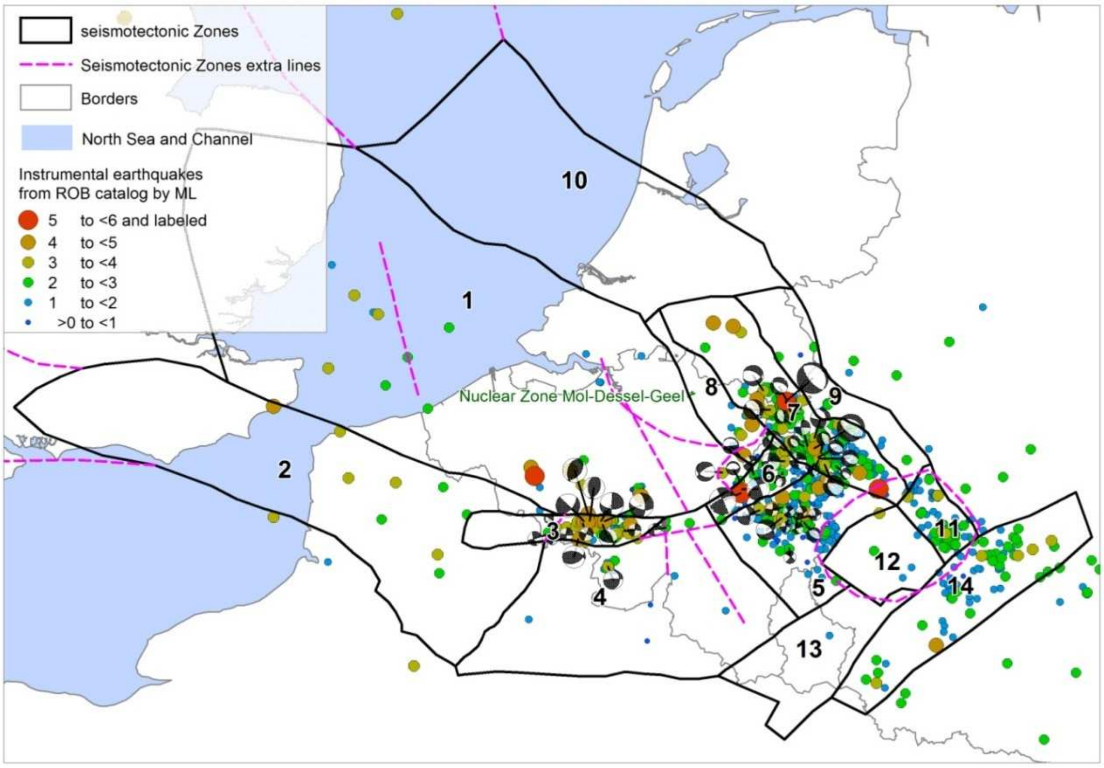

Figure 3 - Seismotectonic zones and Instrumental earthquakes scaled by ML. The available focal mechanisms are shown as lower hemisphere projection.

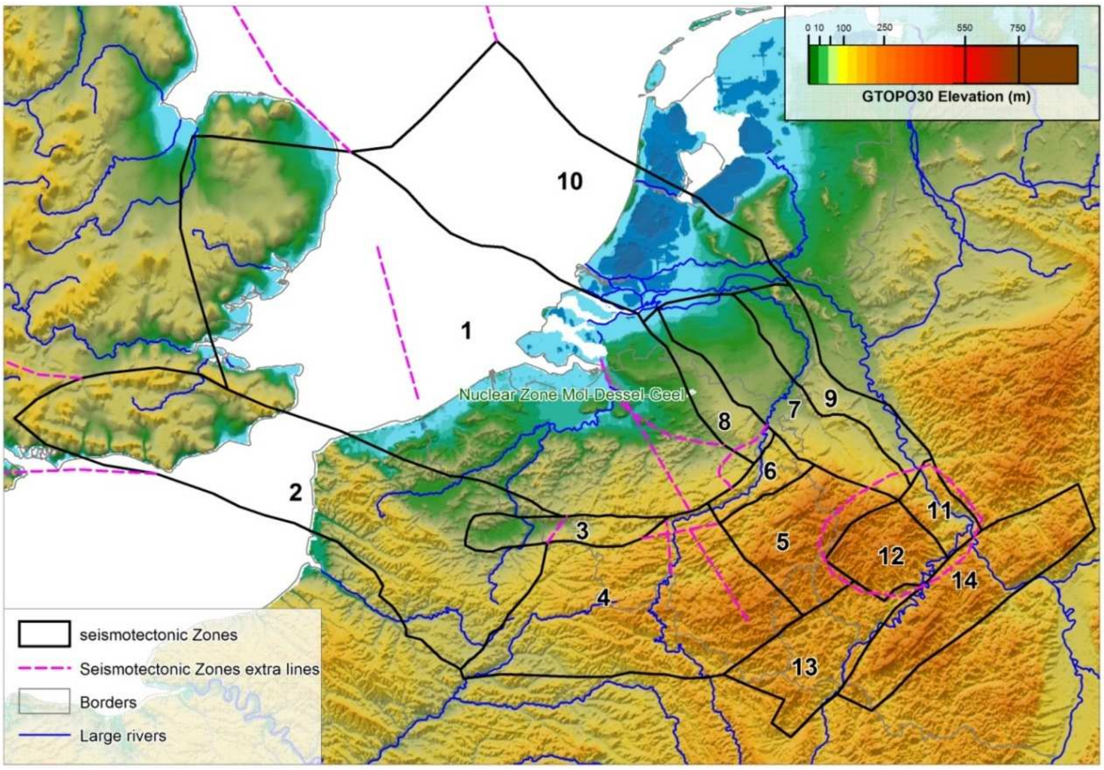

Figure 4 - Seismotectonic zones and topography (GTOPO30)

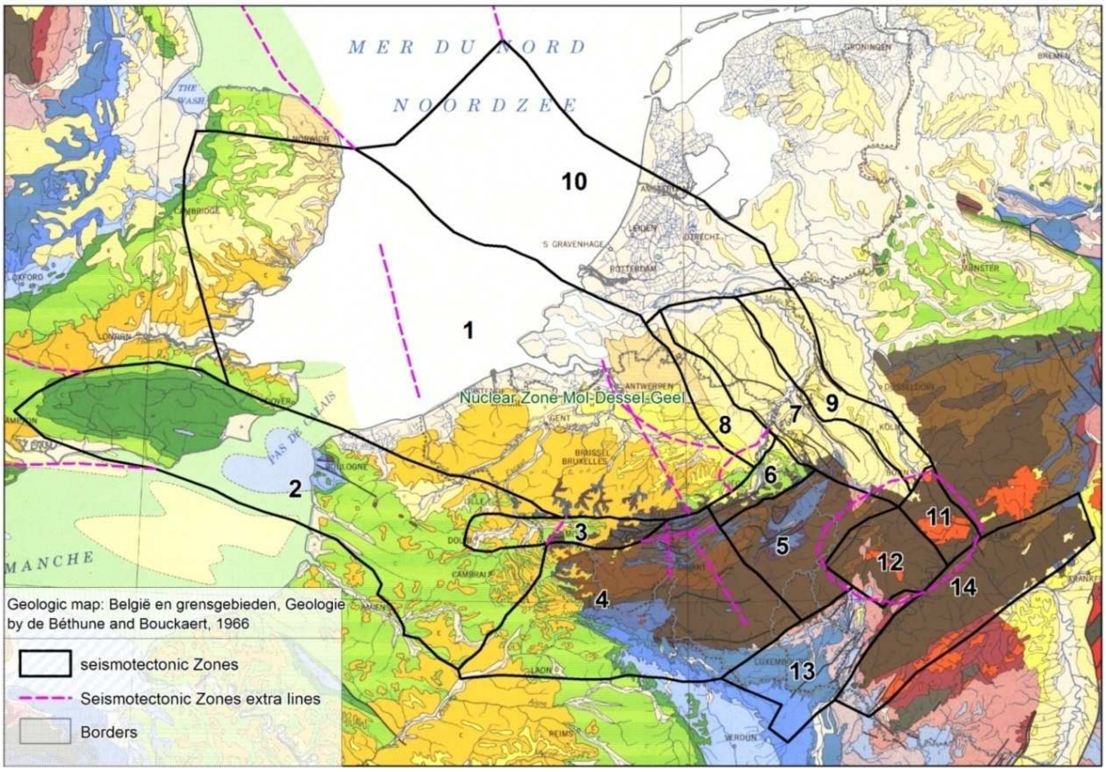

Figure 5 - Seismotectonic zones and the geologic map [19] .

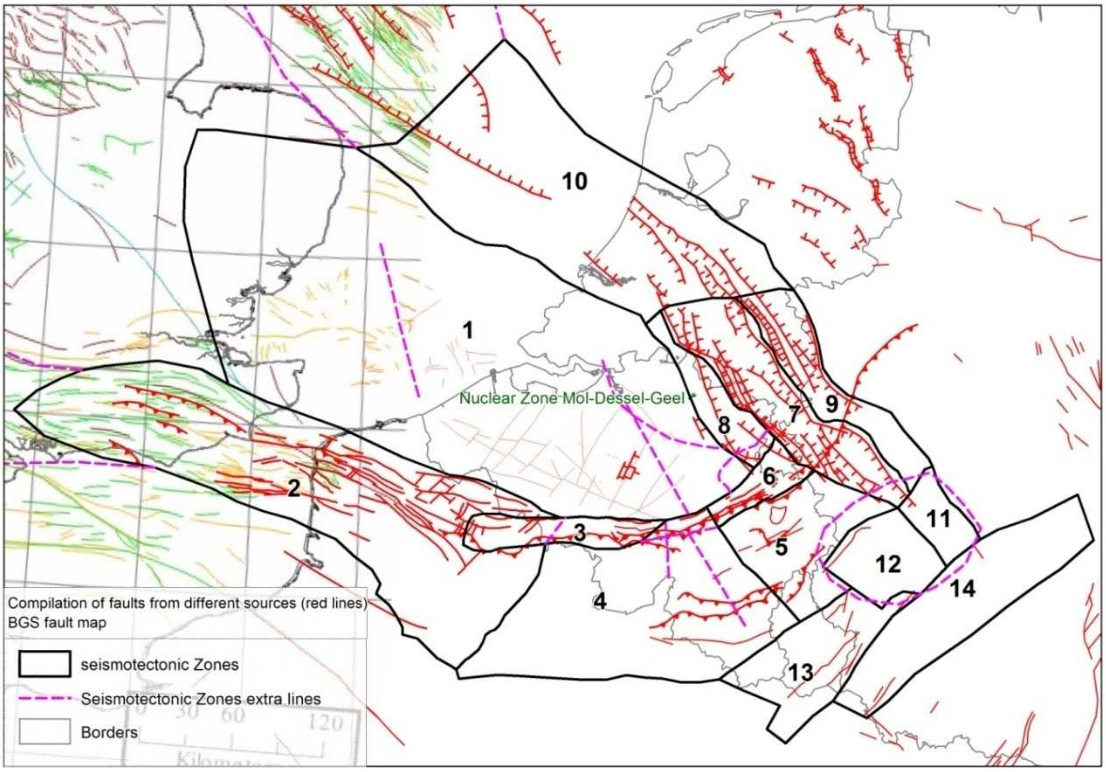

Figure 6 - Seismotectonic zones and a compilation of faults from different sources. Background map is part of the Geological fault map of the UK [9] .

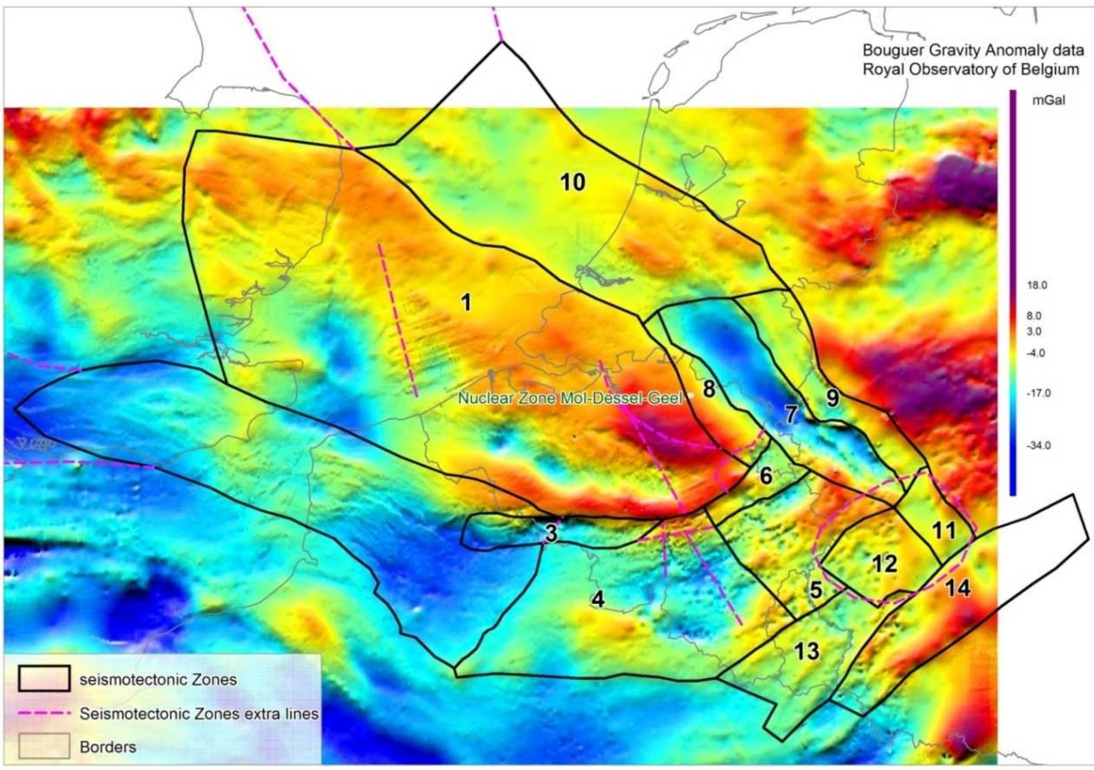

Figure 7 - Seismotectonic zones and Bouguer gravity anomaly data (compiled by ROB).

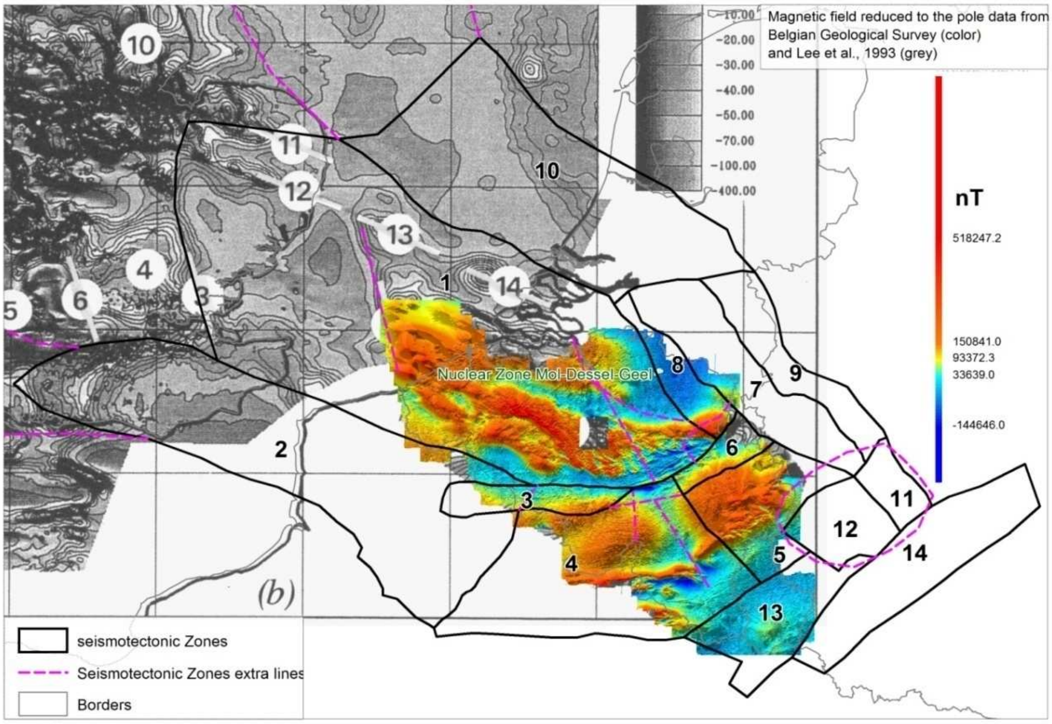

Figure 8 - Seismotectonic zones and Magnetic field reduced to the pole data (Royal Belgian institute of Natural Sciences and [48]).

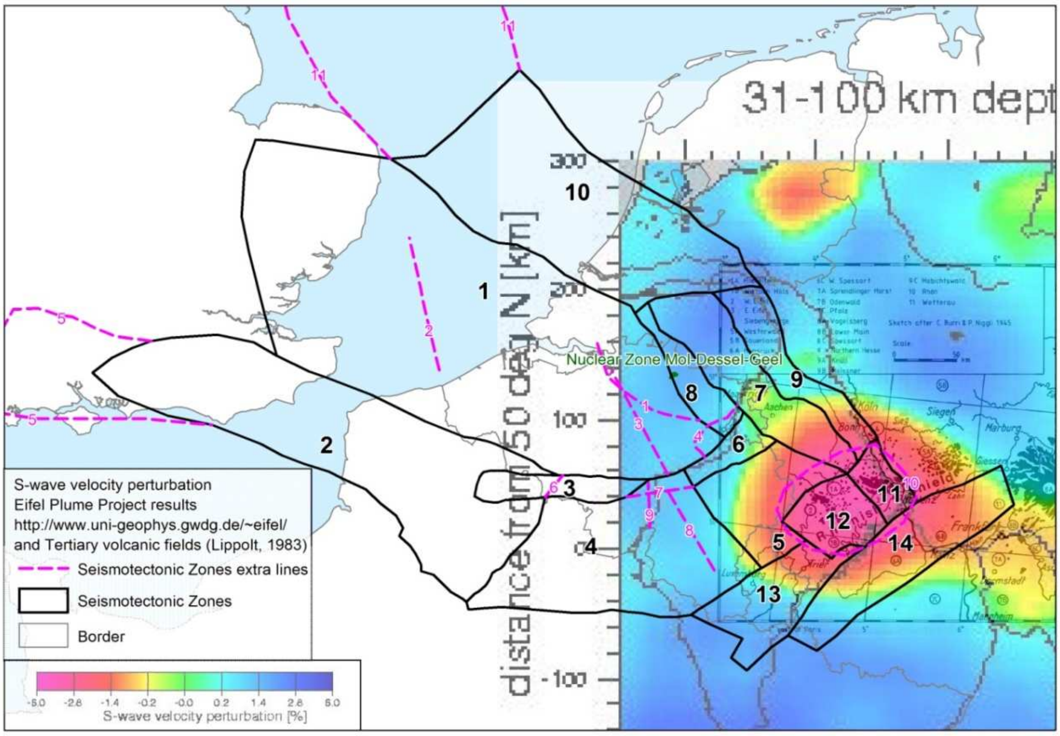

Figure 9 - Seismotectonic zones and the S-wave velocity perturbation between 31 and 100 km depth by the Eifel Plume. Background map shows the Tertiary and Quaternary volcanic fields [51] .

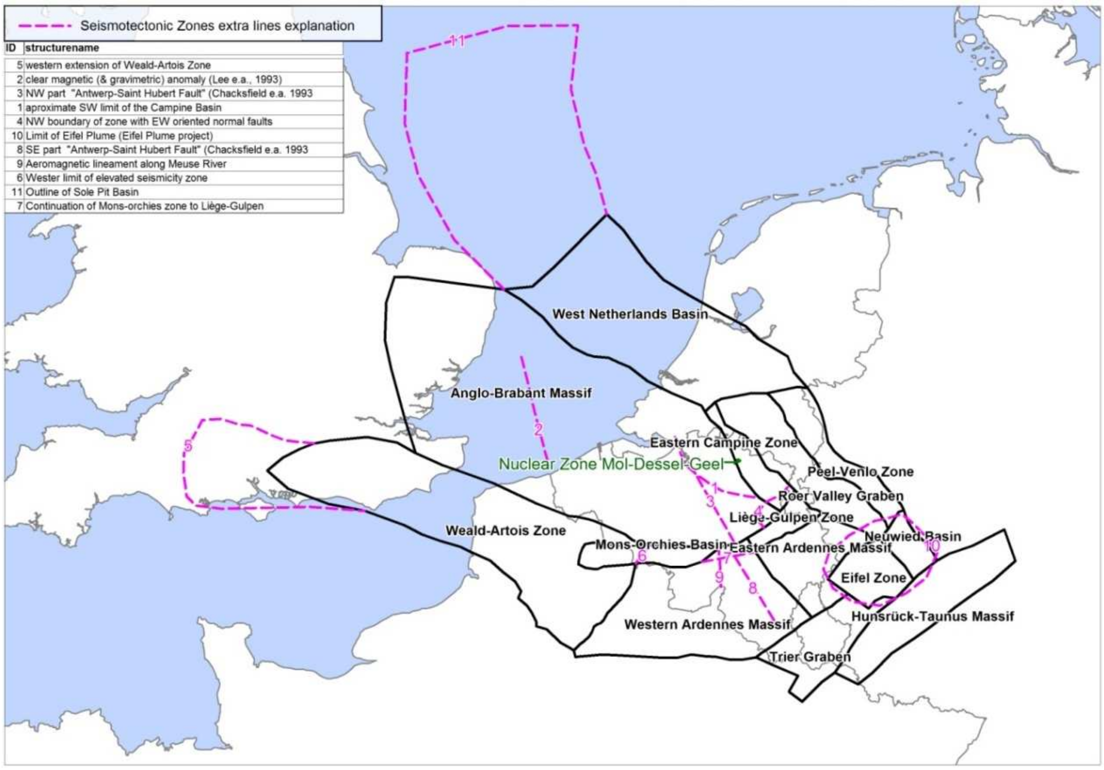

Figure 10 - Seismotectonic zones and explanation of the numbered extra lines that are discussed in the text as alternative zone boundaries.

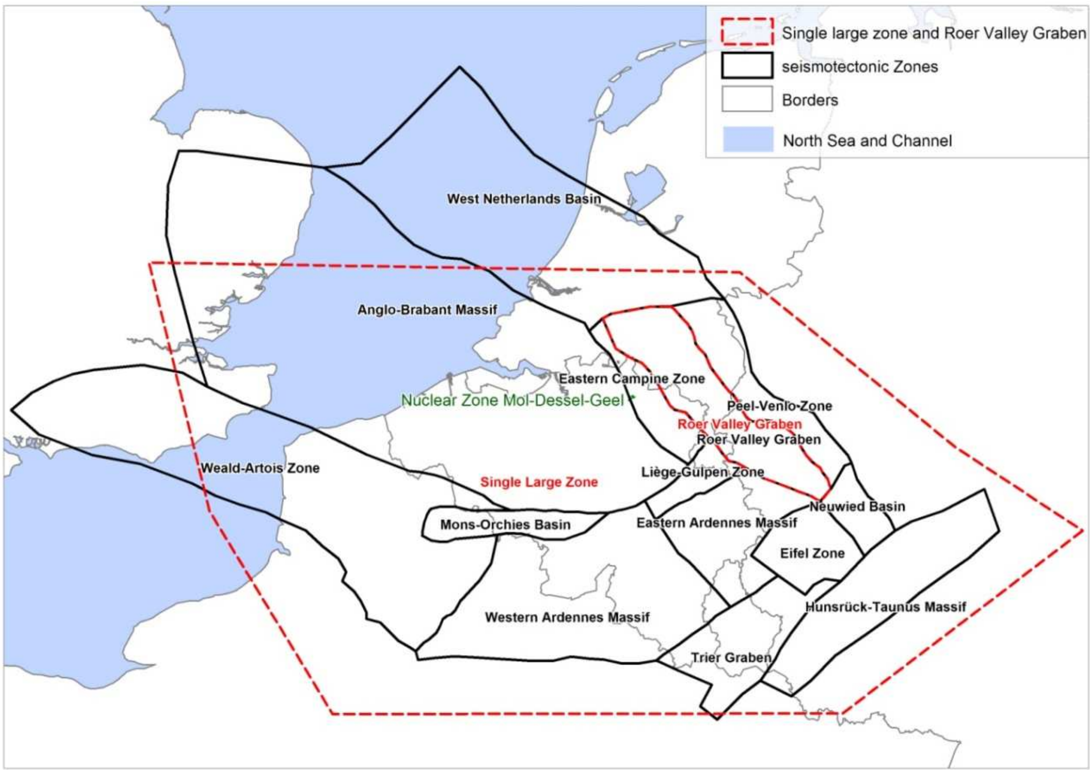

Figure 11 - Seismotectonic Zones Model and Two-Zone Model.

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